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## DIAGRID FAÇADE DESIGN FOR PUBLIC POOL BUILDING USING DIFFERENTIAL EVOLUTION

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### ABSTRACT

*This paper discusses a set of façade design alternatives for form-finding problem focusing on conceptual phase. In this respect, the aim of the research is to propose a multi-objective optimization approach for a façade design of public pool building. We present a set of solutions belonging to Self-adaptive Multi-objective Ensemble Differential Evolution (JE\_DEMO) and Self-adaptive Multi-Objective Differential Evolution (JDEMO) algorithm. We focus on maximization of daylight performance and minimization of structural displacement. Based on results, two algorithms presented competitive results. Contributions are presented based on objectives functions as new trade-offs and proposed JE\_DEMO algorithm for design problems.*

### KEYWORDS

Diagrid façade design; performance-based design; computational design; multi-objective optimization; differential evolution.

### 1. INTRODUCTION

Building envelopes are complex systems involving

multiple requirements in the sense of architecture and engineering. In addition, these requirements contain numerous objectives that are conflicting in most of the cases.

In the field of architecture, designing façade is one of the most complex tasks. At this point, the role of the architect is not only facing with design concerns, but also to present a well performed daylight solution at the final process. This statement can be supported by some reasons:

- Daylight, which provides the natural lighting, is basic requirement for human being's daily life (Li & Tsang, 2008),
- Performance based design may support to reduce building's artificial lighting usage, as well as enhance indoor climate (Chatzikonstantinou, Ekici, Sariyildiz, & Koyunbaba, 2015).

Based on these statements, it is possible to say that openings of buildings need much attention for daylight performance.

In the literature, there are several works on façade design related to our research. In this study (Kim, 2012), authors are considered the optimization for daylight performance in the façade system. The computational optimization produces alternatives in

terms of opening forms. In the literature (Chatzikonstantinou et al., 2015), authors are attempted to identify façade configurations, including elements of the glass panel frames and construction materials. The overall purpose of the study is to maximize daylight performance of the building. Several scenarios are formulated in the manner of multi-objective optimization. Based on this study, it is possible to say that façade design has a significant effect on both daylight distribution and structural performance (Chatzikonstantinou et al., 2015; Perera & Sirimanna, 2014). This argument can be discussed over an example. For instance, while increasing the façade division count with bigger size of profiles, structural performance present satisfactory results. However, this fact causes to block natural daylight distribution for interior space. For this reason, daylight and structural performance are two conflicting objectives in the design task of building envelope.

Diagrid, as a façade pattern, is one of the most preferred design elements for building's envelope. According to (Leonard, 2007), diagonal elements created to the pattern of diagrid. Regarding to preferring diagrid form as façade element, numerous benefits can be shown as follows (Panchal & Patel, 2014):

- Reducing displacement,
- Requiring less structural elements,
- Increasing structural resistance and efficiency,
- So, use of materials more efficiently.

In this study, we deal with the design process of diagrid façade for public pool building as multi-objective optimization problem. The objectives are to maximize daylight performance (*PDF*) and minimize the displacement of the façade structure ( $v$ ) with the aim of finding near-optimal design scenarios. *JE\_DEMO* and *JDEMO* algorithms, which are based on differential evolution (DE) optimization algorithm, are used in this research.

The remaining paper is outlined as follows: Section 2 introduces the façade model. Section 3 presents the problem definition with the details of explanation façade model. Section 4 shows optimization algorithms. The computational optimization results over the problem are argued in Section 5. Finally, Section 6 concludes the study.

## 2. PARAMETRIC FAÇADE MODEL

Our scenario focuses on a parametric design of a pool building for the public use located in Bornova,

Izmir, Turkey, having 38°27'N latitude, 27°12'E longitude and 17m altitude. While designing a building, location properties become significant to handle actual natural lighting data. Izmir is approximately whole days of year sunny so it can be an advantage for architects to improve daylight performance of a building in Izmir. Specifically, project site of this study is also suitable for making use of daylight. The problem entails the decisions regarding the design of façade elements and frames.

We consider daylight and structural objectives, which are conflicting. To realize this complex study, we solve the problem dividing into three phases, which are generation of shape, performance evaluation, and optimization for identifying façade configurations. To do this, required notations with explanations are stated in Table I.

The building in our case study is including pool area, service functions (i.e. changing rooms, rest rooms, cleaning rooms, and so forth), café for public usage, and the main entrance area as shown in Fig. 1. To realize this research, we focus on the design of pool unit.

In addition, this building includes two different pools for both adults and children. The dimensions of the one designed for adults are 25 m by 20 m, while the dimensions of one for children usage are 10 m by 15 m. The floor height of the pool is as decision variables.

**Table 1** Notations and Explanations of Façade Model

Notations and Explanations of Façade Model	
<i>Not.</i>	<i>Exp.</i>
$d_v$	Count of vertical division of diagrid façade
$d_h$	Count of horizontal division of diagrid façade
$b_i$	Inner frame of base section
$b_o$	Outer frame of base section
$h_i$	Inner frame of height section
$h_o$	Outer frame of height section
$th_i$	Inner frame thickness
$th_o$	Outer frame thickness
$w_{if}$	Inner frame width
$w_{of}$	Outer frame width
$h_r$	Right front height of diagrid façade
$h_l$	Left front height of diagrid façade

The diagrid façade, which is located to the south part of the building, is composed of double pane glazing. Since façade design cannot be divided into just

diagrids, sub-elements of triangles are generated. So that, combination of quad and triangle elements reveals the whole diagrid form. After generating the main façade design, frame is supported through the connection points located around the building's skin. The number of support points depends on the number of façade elements, which are made of steel material. When division count of façade design increase, count of support points are increasing. A detailed explanation of the structure components is presented in Fig. 2.

The main purpose of this study is to minimize  $v$ , and to maximize  $PDF$ . These objectives, which are conflicting, have an important role on the façade configuration. In addition, two constraints are defined in order to discover façade alternatives in acceptable margins. The first constraint function is focusing on the value of  $DF$  in order to reduce usage of artificial lighting during day hours. The second constraint is related with  $v$  in order to present well-performed façade alternatives in terms of structural performance.

Regarding the decision variables of the problem, we take into account dimensions of façade elements, profile sections, and floor height. Especially, in order to keep diversity of design solution in search space, façade elements are constituted as two different decision variable group. These are main (outer) frame variables and sub (inner) frame variables. An example of final design after these steps is illustrated in Fig.3.

### 3. PROBLEM DEFINITION

#### 3.1. Objective Functions

In this research, the first objective function is formulated as to minimize  $v$  and the other objective is formulated as to maximize  $PDF$  as follows:

$$\text{Min} \left( v, \frac{1}{PDF} \right) \quad (1)$$

Subject to:

$$PDF \geq 2 \quad (2)$$

$$v \leq 0.05m \quad (3)$$

where  $PDF$  refers to performance of daylight for specific measurement points. Notations, types, ranges, and units of considered decision variables, are shown in Table II.

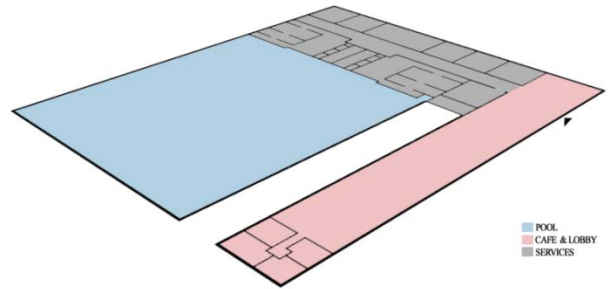


Figure 1 Building Plan Diagram.

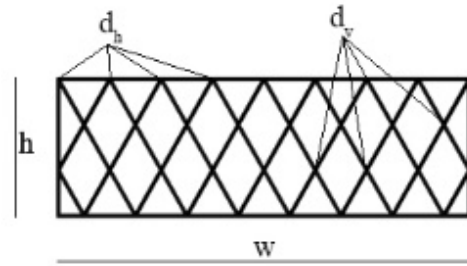


Figure 2 Diagram Façade Components

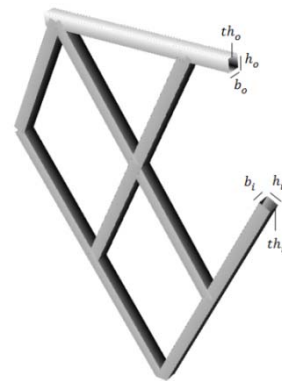


Figure 3 Diagrid Façade Construction Diagram

Table 2 Decision Variables of the Model

Decision Variables of the Model			
Notation	Type	Range	Unit
$d_v$	Integer	[3, 7]	Count
$d_h$	Integer	[6, 16]	Count
$h_r$	Real	[6, 15]	meter
$h_f$	Real	[6, 15]	meter
$b_i$	Real	[5, 50]	centimetre
$b_o$	Real	[5, 50]	centimetre
$h_i$	Real	[5, 50]	centimetre
$h_o$	Real	[5, 50]	centimetre
$th_i$	Real	[0.10, 0.30]	centimetre
$th_o$	Real	[0.10, 0.30]	centimetre

### 3.2. Daylight Objective

DF is the ratio of the illuminance level between inside ( $E_{inside}$ ) and the outside ( $E_{outside}$ ) of the indoor space under overcast sky at a specific point (Waldram, 1925). We determine 19 measurement points on the floor to calculate DF for each point in the pool area that is shown in Fig. 4. In our case, each measurement point's DF is combined in order to reach PDF objective function as follows:

$$PDF = Avg(DF_{Pt_{1, \dots, 19}}) \quad (4)$$

where

$$DF = \frac{E_{inside}}{E_{outside}} \cdot 100\% \quad (5)$$

According to LEED criteria, less than 2% DF for 75% of overall measuring points causes usage of artificial lighting during the day hours (Moon & Spencer, 1942). Related to this fact extra electrical equipment consumption is needed. Based on this reason constraint function expressed in equation (2). To employ DF calculation during the optimization process, a plug-in called DIVA (Jakubiec & Reinhart, 2011) is utilized.

### 3.3. Displacement Objective

In order to find the equilibrium state of the diagrid façade design, displacement ( $v$ ) of the structural elements is considered.  $v$  is calculated by the help of Karamba 3D (Preisinger et al., 2018) plugin, which works in Grasshopper 3D (McNeel, 2013) environment, as follows:

$$F = K \times v \quad (6)$$

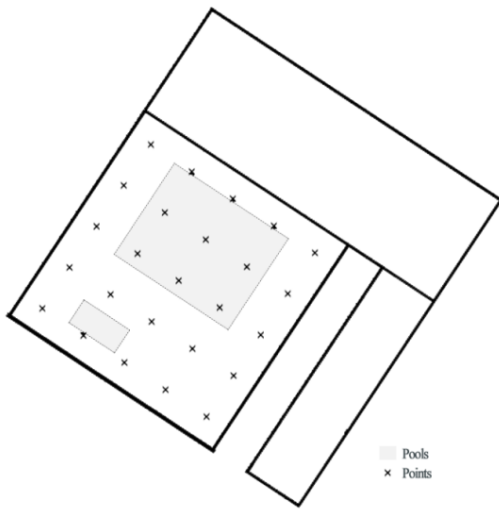


Figure 4 DF points on the floor in the pool area.

where: ( $K$ ) is the stiffness of the diagrid façade structure and ( $F$ ) is the loading force. From the point of load combination of two categories, namely dead loads and wind loads are situated. In accordance with equation (3), structural performance of each generated solution during the optimization process is kept within safety margins. From the standpoint of load combination, permanent actions ( $G_k$ ) are taking into consideration for the buildings. The weight of the structure and all architectural components of the building can be shown as main components of  $G_k$ . As another action on buildings, variable actions ( $Q_k$ ) can be mentioned (i.e. the wind pressure, snow weight). According to TS EN 1990:2002, the general formula of the load combination is as follows:

$$\sum_{f(x)} \gamma_G \cdot G_{k,j} + Y_{Q,i} = Q_{k,i} + \sum_{f(x)} \gamma_{Q,i} \cdot \Psi_{0,i} \cdot Q_{k,i} \quad (7)$$

where  $\gamma_G$  states the partial factor for permanent action,  $\gamma_Q$  presents the partial factor for variable action and,  $\Psi_0$  is the combination factor,  $Q_{k,i}$  represents the leading variable action and the other variable actions. Based on this statement, following load combination is considered to realize this study as follows:

$$F = 1.35DL + W \quad (8)$$

where  $DL$  presents the dead load, and  $W$  states wind load of each generated alternative during the evolutionary computation process. To calculate  $DL$  as first step, following equation is implemented to generative model:

$$DL = \sum_{i=1}^n W_{str_i} \quad (9)$$

where  $W_{str_i}$  corresponds the weight of  $i$ th structural elements in the diagrid façade frame. Summation of each weight of structural element starting from  $i = 1$  to  $n$  gives the total  $DL$  for each alternative. From the point of  $W$ , Eurocode standards (Cook, 2007) which specifies structural requirements within the European Union, is considered in this study. The basic wind velocity in the case region is considered as follows:

$$V_b = C_{dir} \cdot C_{season} \cdot V_{b,0} \quad (10)$$

where  $V_b$  corresponds the basic wind velocity,  $C_{dir}$  states the directional factor and,  $C_{season}$  matches the seasonal factor, and  $V_{b,0}$  is the fundamental value of basic wind velocity. In accordance with the TS EN 1991-1-4:2007,  $C_{dir}$  and  $C_{season}$  is assumed as 1. Since the case study is located in Izmir, Turkey,  $V_{b,0}$  is supposed as 26 m/s. Based on equation (10),  $V_b$  is determined as 26 m/s at the end. To calculate basic

wind pressure ( $q_p$ ) and the mean wind velocity ( $V_m(z)$ ), following equations are taken into consideration:

$$q_p = \frac{\rho}{2} \cdot V_b^2 \quad (11)$$

$$V_m(z) = c_r(z) \cdot c_o(z) \cdot v_b \quad (12)$$

where  $\rho$  is the density of air considered as 1.25kg/m<sup>3</sup>,  $c_r(z)$  states the roughness factor and,  $c_o(z)$  corresponds the orography factor that is usually taken as 1.0. To determine  $c_r(z)$  at height  $z$ , equation (13), (14), and (15) are considered as follows:

$$c_r(z) = k_r \cdot \ln\left(\frac{z}{z_0}\right) \text{ for } z_{min} \leq z \leq z_{max} \quad (13)$$

$$c_r(z) = c_r(z_{min}) \text{ for } z \leq z_{min} \quad (14)$$

$$k_r = 0.19 \left(\frac{z}{z_{0,II}}\right)^{0,07} \quad (15)$$

where  $k_r$  states the terrain factor,  $z$  corresponds the height we consider for the study,  $z_0$  represents the roughness length,  $z_{min}$  expresses the minimum height considered as 2.0m,  $z_{max}$  states the maximum height assumed as 200.0 m, and  $z_{0,II}$  presents the terrain category II assumed as 0.05m. Once we calculate  $V_b$ ,  $q_p$ , and  $V_m(z)$  in accordance with the mentioned equations above, pressure of the peak wind velocity [ $q_p(z)$ ] at  $z$  height is calculated as follows:

$$q_p(z) = [1 + 7 \cdot I_v(z)] \cdot \frac{1}{2} \rho \cdot V_m^2(z) \quad (16)$$

where  $I_v(z)$ , which represents turbulence intensity at  $z$  height, is defined by using equation (17), and (18) as follows:

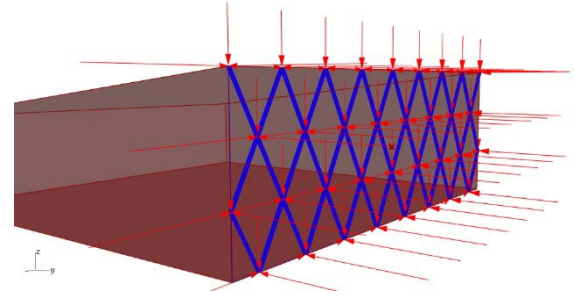
$$I_v(z) = \frac{k_I}{c_o(z) \cdot \ln\left(\frac{z}{z_0}\right)} \text{ for } z_{min} \leq z \leq z_{max} \quad (17)$$

$$I_v(z) = I_v(z_{min}) \text{ for } z \leq z_{min} \quad (18)$$

where  $k_I$  corresponds the turbulence factor that is assumed as 1. To calculate the wind force ( $F_w$ ) on our case, as final step, following equation is computed for each generated solution:

$$F_w = c_s \cdot c_d \cdot c_f \cdot q_p(z_e) \cdot A_{ref} \quad (19)$$

where  $c_s \cdot c_d$  states the structural factor that is also considered as 1.0 in most of cases as a standard value,  $c_f$  is the force coefficient of the structure we focus on,  $q_p(z_e)$  represents the peak velocity pressure at  $z_e$  height, and  $A_{ref}$  is the reference area that we implement our wind load force. Illustration of applied loads is shown in Fig. 5.



**Figure 5** Load Combinations

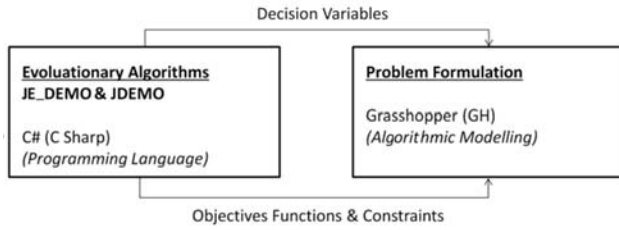
## 4. OPTIMIZATION ALGORITHMS

Regarding the multi-objective optimization problems (MOPs), many researches have been published in the current literature. Through the years, Evolutionary Algorithms (EAs) have become one of the most common optimization algorithm type. In this respect, considering of EAs to MOPs are denoted as Multi-Objective Evolutionary Algorithms (MOEAs). In general, genetic operators regarding to EAs are employed to MOEAs for solving MOPs. With respect to implementation of these algorithms, benchmark and engineering problems are widely focused.

Differential Evolution (DE), which is proposed by (Price, Storn, & Lampinen, 2005; Storn & Price, 1995), is attracted much attention in the literature (Das & Suganthan, 2011; Mezura-Montes, Miranda-Varela, & del Carmen Gómez-Ramón, 2010). Based on this, we can say that satisfactory solutions for both unconstrained and constrained MOPs are presented by DE (Abbass, 2002; Abbass, Sarker, & Newton, 2001; Hernández-Díaz, Santana-Quintero, Coello Coello, Caballero, & Molina, 2006; Madavan & Biegel, 2002; Robič & Filipič, 2005; Santana-Quintero, Hernández-Díaz, Molina, Coello, & Caballero, 2010; Tušar & Filipič, 2007; Xue, Sanderson, & Graves, 2003; Zamuda, Brest, Boskovic, & Zumer, 2007).

During the evolutionary stage, mutation factor (F) and crossover rate (CR) play a vital role in DE. Concerning this topic, self-adaptive DE (JDE) is capable to update F and CR determining a certain of probability for each generation (Brest, 2009; Brest, Greiner, Boskovic, Mernik, & Zumer, 2006). The algorithm is turned out a very simple and efficient EA, with a small modification on the control parameters of DE. Based on JDE with mentioned modifications above, DEMOWSA is proposed (Zamuda et al., 2007) by using the properties of

DEMO for MOPs (Robič & Filipič, 2005; Tušar & Filipič, 2007).



**Figure 6** GH and DE algorithms interaction

As mentioned above, DE with multi-objective strategy, is one of the most popular EAs for MOPs. In this research paper, inspiring from DEMO with some modifications, JE\_DEMO is proposed. To deal with problem on hand, JE\_DEMO is compared to the JDEMO. Difference between two optimization methods mentioned in the following sections. The flow of the study is illustrated in Fig. 6.

#### 4.1. Multi-objective Self Adaptive Differential Evolution (JDEMO)

DE is discussed by Das et al. (Das, Mullick, & Suganthan, 2016) in a review paper with its success considering the latest approaches developed. Pseudo code for single objective basic DE is shown in Fig. 7.

```

Begin
  t = 0
  Produce initial target population  $x_i^t \quad i = 1, \dots, N$ 
  Compute  $f(x_i^t)$  for  $i = 1, \dots, N$ 
  For t = 1 to MAXGEN Do
    For i = 1 to N Do
      Choose uniform random numbers
       $p \neq q \neq r \neq i \in (1, N)$  :
       $k = rand() \% D$ 
      For j = 1 to D Do
        If  $rand_j[0, 1) < CR$  or  $j = k$  Then
           $u_i^{j,t+1} = x_p^{j,t} + F \times (x_q^{j,t} - x_r^{j,t})$ 
        Else
           $u_i^{j,t+1} = x_i^{j,t}$ 
        End If
      End For
      If  $f(u_i^{t+1}) \leq f(x_i^t)$  Then
         $x_i^{t+1} = u_i^{t+1}$ 
      Else
         $x_i^{t+1} = x_i^t$ 
      End If
    End For
    If  $f(u_i^{t+1}) \leq f(x_i^t)$  Then
       $x_i^{t+1} = u_i^{t+1}$ 
    Else
       $x_i^{t+1} = x_i^t$ 
    End If
  End For
  t = t + 1
End For
End

```

**Figure 7** Pseudo code of DE/rand/1/bin

JDE, which is easy to implement on basic DE, is capable to converge much faster than the DE for high dimensional and complex problems. In the procedure of JDE,  $F_i$  and  $CR_i$  values are assigning for each individual. For the initial population,  $CR_i$  is taken as 0.5, while  $F_i$  is defined as 0.9. For further generations, each value is updated as follows:

$$F_i^{t+1} = \begin{cases} F_{min} + R_1 \cdot F_{max} & \text{if } R_2 < p_1 \\ F_i^t & \text{otherwise} \end{cases} \quad (20)$$

$$CR_i^{t+1} = \begin{cases} R_3 & \text{if } R_4 < p_2 \\ CR_i^t & \text{otherwise} \end{cases} \quad (21)$$

where  $R_j \in \{1,2,3,4\}$  are random numbers, which are uniformly distributed between 0 and 1. Determining probability of self-adaptive procedure, we define  $p_1$  and  $p_2$  that are both taken as 0.1. On the other hand,  $F_{min}$  is defined as 0.1, while  $F_{max}$  is 0.9. In order to extend JDE described above to multi-objective constrained optimization problems, the combination of the target ( $x_i$ ) and trial ( $u_i$ ) populations is determined. Afterwards, we make use of non-dominated sorting (Deb, Pratap, Agarwal, & Meyarivan, 2002). The outline of the multi-objective JDE denoted as JDEMO is given in Fig. 8.

- 
- Step 1: Set  $t = 0$  and create a random target population  $X_t$  for  $N$  size.
  - Step 2: Apply mutation and crossover strategies to  $X_t$  for getting  $U_t$  for  $N$  size.
  - Step 3: If the termination criteria is satisfied, stop and return  $X_t$ .
  - Step 4: Combine two populations as  $R_t = X_t \cup U_t$
  - Step 5: Apply the fast non-dominated sorting procedure for  $R_t$  and define non-dominated fronts  $f_1, f_2, \dots, f_k$  in  $R_t$ .
  - Step 6: For  $i = 1, \dots, k$ , do the following phases:
    - Step 6.1: Calculate the crowding distance of solutions in  $f_i$ .
    - Step 6.2: Create  $X_{t+1}$  as follows:
      - if  $|X_{t+1}| + |f_i| \leq N$ , then set  $X_{t+1} = X_{t+1} \cup f_i$
      - if  $|X_{t+1}| + |f_i| > N$ , then add the least crowded  $N - |X_{t+1}|$  solutions from  $f_i$  to  $X_{t+1}$ .
  - Step 7: Apply mutation and crossover operators to  $X_{t+1}$  and get  $U_{t+1}$  for  $N$  size.
  - Step 8: Set  $t = t + 1$  and return to Step 3.
- 

**Figure 8** JDEMO Algorithm

#### 4.2. Multi-objective Self-Adaptive Ensemble Differential Evolution (JE\_DEMO)

In this paper, considering the previous explanations, JDEMO is extended with the ensemble approach inspiring from Tasgetiren et al. (Tasgetiren,



Suganthan, Pan, Mallipeddi, & Sarman, 2010), Mallipeddi et al. (Mallipeddi, Suganthan, Pan, & Tasgetiren, 2011), and Das et al. (Das & Suganthan, 2011; Mezura-Montes et al., 2010). The main difference between JE\_DEMO and JDEMO is explained in the following lines. JDEMO employs only one mutation strategy, which is presented in Fig.6. With this approach, JDEMO benefits from three different individuals ( $x_p^j, x_q^j$ , and  $x_r^j$ ) to generate mutant population. This way of generating mutated individuals is totally different than genetic algorithm's approach. On the other hand, JE\_DEMO uses several mutation strategies for each individuals. Therefore, three mutation strategies are employed to each individual to generate the mutant population. To do this, each decision variable has values pool for competition of producing better future offspring according to their success in the past generations. Following mutation strategies ( $M_i$ ) are used in this research:

$$M_1: v_i^{j,t+1} = x_p^{j,t} + F(x_q^{j,t} - x_r^{j,t}) \quad (22)$$

$$M_2: v_i^{j,t+1} = x_{best}^{j,t} + F(x_q^{j,t} - x_r^{j,t}) \quad (23)$$

$$M_3: v_i^{j,t+1} = x_i^{j,t} + F(x_{best}^{j,t} - x_i^{j,t}) + F(x_p^{j,t} - x_q^{j,t}) \quad (24)$$

where p, q, r are randomly selected individuals from the target population ( $p \neq q \neq r \neq i \in (1, \dots, N)$ ). Considering this,  $j = 1, \dots, D$  and  $F > 0$ . The outline JE\_DEMO algorithm is given in Fig. 9.

## 5. COMPUTATIONAL RESULTS AND DISCUSSION

As we mentioned before, two optimization algorithms, namely JE\_DEMO and JDEMO are considered. For the optimization process, both runs are completed through a computer with Intel i5 core processor at 3.1 GHz, with 28 GB Ram Gskill dualkitx2 (1333 MHz) Kingston hyperx, and 480 GB solid-state drive. For both algorithms, population size is taken as 100. During the optimization, 10 generations took approximately 1.6-hour cpu time. Due to the lack of time, optimization process is stopped after 50 generations. Fig. 10. shows the Pareto chart solutions gained after this process.

For analysing the performance of algorithms, we discuss the hypervolume (HV) indicator that is calculating the volume of the non-dominated portion of the objective space (Bader & Zitzler, 2011). In order to calculate the HV for the JE\_DEMO

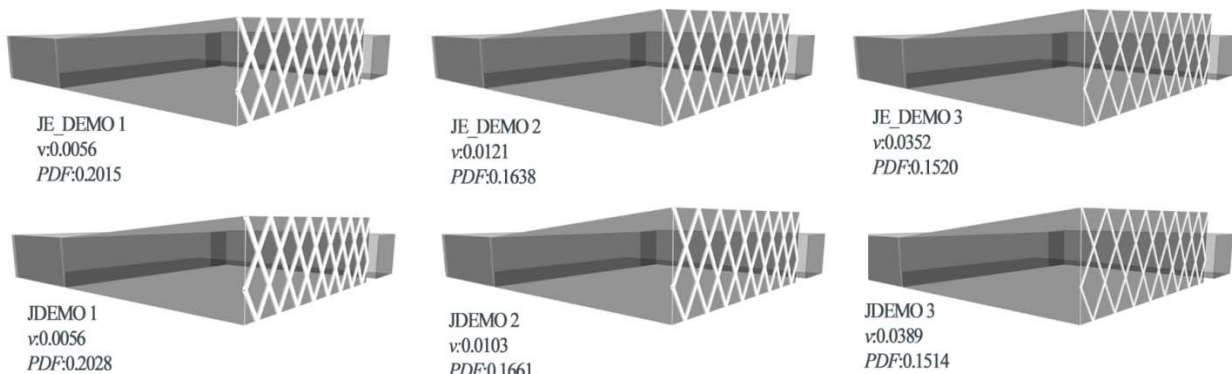
- 
- Step 1: Set  $t = 0$  and  $M_{\max} = 3$  and create a random target population  $X_t$  for  $N$  size.
- Step 2: Assign a mutation strategy to each individual randomly  
 $M_i = \text{rand}() \% M_{\max}$  for  $i = 1, \dots, N$
- Step 3: Apply  $F$  and  $CR$  parameters to  $X_t$  for getting  $U_t$  for  $N$  size.
- Step 4: If the termination criteria is satisfied, stop and return  $X_t$ .
- Step 5: Combine two populations as  $R_t = X_t \cup U_t$
- Step 6: Apply the fast non-dominated sorting procedure for  $R_t$  and define non-dominated fronts  $f_1, f_2, \dots, f_k$  in  $R_t$ .
- Step 7: For  $i = 1, \dots, k$ , do the following phases:  
 Step 7.1: Calculate the crowding distance of solutions in  $f_i$ .  
 Step 7.2: Create  $X_{t+1}$  as follows:  
 • if  $|X_{t+1}| + |f_i| \leq N$ , then set  $X_{t+1} = X_{t+1} \cup f_i$   
 • if  $|X_{t+1}| + |f_i| > N$ , then add the least crowded  $N - |X_{t+1}|$  solutions from  $f_i$  to  $X_{t+1}$ .
- Step 8: Apply mutation and crossover operators to  $X_{t+1}$  and get  $U_{t+1}$  for  $N$  size.
- Step 9: Set  $t = t + 1$  and return to Step 4.
- 

**Figure 9** JE\_DEMO Algorithm

algorithm, we employed 42 non-dominated solutions whereas for JDEMO, we used 51 non-dominated solutions.

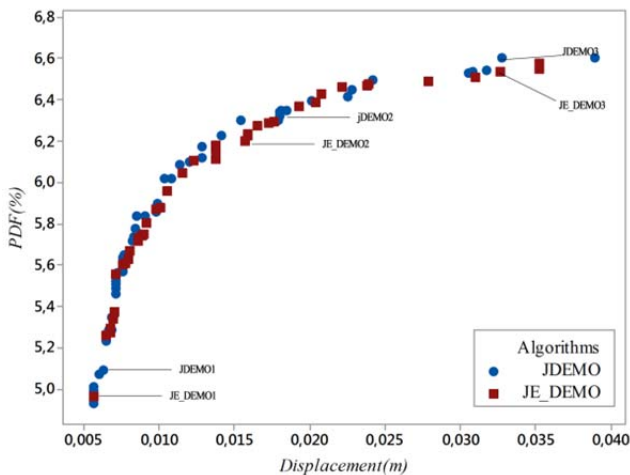
Comparing the optimization results from two different groups, PDF and  $v$  results are slightly different. The reference points are taken as the maximum value for each objective amongst both algorithms' results. HV values are found as 0.84295 and 0.84633 for JE\_DEMO and JDEMO, respectively. For the JE\_DEMO, the objective values are discovered between 4.96 and 6.55 for PDF. From the point of  $v$ , range between 0.0057 to 0.0353 is obtained. For the JDEMO, while range between 4.93 to 6.60 is presented for PDF, the alternatives are determined for  $v$  between 0.0056 and 0.0328.

From the point of comparing architectural features of JE\_DEMO and JDEMO results, the minimum and maximum results of  $h_r, d_v, d_h, th_{if}, w_{if}, th_{of}, h_l$  are similar. However, for  $h_{if}, h_{of}, w_{of}$ , JE\_DEMO is presented different results than JDEMO. Three alternatives for each algorithm are selected from non-dominated solutions that are shown in Fig.10. We may observe that the results obtained by JE\_DEMO and JDEMO algorithms in terms of PDF and  $v$  are slightly different from each other. Solutions notated as JE\_DEMO3 and JDEMO3, inner frame of height section ( $h_i$ ) and outer frame of height section ( $h_o$ )



**Figure 11** Pareto-Front Solutions attained with JE\_DEMO and JDEMO

are less than the other results. Therefore, these results provide more transparency on the diagrid façade from the point of interior space. According to investigation through the non-dominated solutions, it is observed that wider and longer frame elements are presenting better structural performance. However, this fact causes to block natural lighting. To enhance natural daylighting with smaller façade elements, it is noted that size of the thickness of the main diagrid elements are increasing.



**Figure 10** Pareto-front approximations

## 6. CONCLUSION

In this paper, we addressed an architectural design problem of public pool building using a computational optimization-based approach. For the sake of architectural and engineering concerns, diagrid shape was determined as the main façade element. To reach desirable solutions for this problem, performance of daylight and structure was taken into consideration. For this respect, objective functions were structured as minimization of  $\nu$  that corresponds the structural performance, and

maximization of  $PDF$  that presents the daylight performance. In addition, to keep the optimization search space in acceptable margins for these objective functions, two constraints are tackled. Two types of the DE, which are JDEMO and JE\_DEMO, were compared in order to solve this problem. To present best-trade off alternatives, two algorithms are presented similar objective function ranges at the end. However, as shown in Fig. 10, JDEMO is capable to discover some alternative solutions, which cannot be founded by JE\_DEMO, in the search space.

The main contributions of this paper are explained from the perspective of objectives and algorithms. As first contribution, we presented a trade-off between structure and daylight performance. In literature, trade-offs such as daylight and energy or structural performance and material usage mostly studied. However, design of the structure affects the daylight performance, so energy consumption. Therefore, presented trade-off should be carried out during the early stage of the design process, as well. Secondly, we proposed JE\_DEMO, which has not implemented to architectural optimization problem before, in this study. To prove the success of JE\_DEMO, we compared with J\_DEMO, which was used for many real-world and benchmark problems in engineering domain. We observed that JE\_DEMO presented competitive results with J\_DEMO. Due to No Free Lunch Theorem (Wolpert & Macready, 1997), comparing different heuristic optimization methods is highly important. The reason of this is global optimization approach is not possible, which is capable of solving all the problems in the universe. Since design problems are unique because of the location, design concerns, design parameters, user preferences, economical reasons, and plot area, architects/designers/engineers should consider more

than one heuristic optimization method to cope with the problem on hand.

For further study, displacement on the glass frame can be considered for different types of façade panels. In addition, façade frames can be evaluated by considering more than one material type to select the most appropriate one. Finally, other MOEAs and swarm intelligence algorithms with different constraint handling methods can be implemented.

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