



# An improved constrained differential evolution using discrete variables (D-ICDE) for layout optimization of truss structures



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## ARTICLE INFO

### Article history:

Available online 8 May 2015

### Keywords:

( $\mu + \lambda$ ) Improved differential evolution (IDE)  
Archiving-based adaptive tradeoff model (ArATM)  
Improved ( $\mu + \lambda$ ) constrained differential evolution (ICDE)  
Discrete-ICDE (D-ICDE)  
Discrete variables  
Truss layout optimization

## ABSTRACT

Recently, an improved ( $\mu + \lambda$ ) constrained differential evolution (ICDE) has been proposed and proven to be robust and effective for solving constrained optimization problems. However, so far, the ICDE has been developed mainly for continuous design variables, and hence it becomes inappropriate for solving layout truss optimization problems which contain both discrete and continuous variables. This paper hence fills this gap by proposing a novel discrete variables handling technique and integrating it into original ICDE to give a so-called Discrete-ICDE (D-ICDE) for solving layout truss optimization problems. Objective functions of the optimization problems are minimum weights of the whole truss structures and constraints are stress, displacement and buckling limitations. Numerical examples of five classical truss problems are carried out and compared to other state-of-the-art optimization methods to illustrate the reliability and effectiveness of the proposed method. The D-ICDE's performance shows that it not only successfully handles discrete variables but also significantly improves the convergence of layout truss optimization problem. The D-ICDE is promising to extend for determining the optimal solution of other structural optimization problems which contain both discrete and continuous variables.

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## 1. Introduction

Truss layout optimization is one of the most important and challenging areas in the structural optimization field. By considering the size and shape variables simultaneously, the layout optimization problem can give more accurate design due to the coupling influences between two variables and also achieve more material savings than purely size optimization (Gholizadeh, 2013). The problem is considered to be more challenging owing to the different natures of the variables. The main difficulty lies in treating the discrete variables together with continuous variables, whereas traditional optimization methods normally treat design variables as continuous ones. So far, many meta-heuristic algorithms belonging to the evolutionary algorithm family have yielded practical and improved solutions to many structural optimization problems dealing with discrete variables. The most popular methods include genetic algorithm (GA) (Dede, Bekiroğlu, & Ayvaz, 2011; Rajeev & Krishnamoorthy, 1992), ant colony

optimization (ACO) (Camp & Bichon, 2004), harmony search (HS) (Lee, Geem, Lee, & Bae, 2005), evolutionary strategy (ES) (Chen & Chen, 2008), particle swarm optimization (PSO) (Kaveh & Talatahari, 2009), firefly algorithm (FA) (Gandomi, Yang, & Alavi, 2011), etc.

The efficiency of the above methods for solving the structural optimization problems has also been investigated by many researchers. For example, Wu and Chow (1995) utilized the GA with discrete size and continuous configuration variables. Hasançebi and Erbatur (2001) proposed an improved GA by combining the GA with annealing perturbation and adaptive design space reduction strategies. Fourie and Groenwold (2002) improved the PSO by introducing new elite operators. Recently, Kaveh and Khayatizad (2013) proposed a new method termed the ray optimization method in dealing with the similar problem, while Gholizadeh (2013) introduced a hybrid algorithm integrating a cellular automata and the PSO.

Among the members of the evolutionary algorithm family, the differential evolution (DE) proposed by Storn and Price in 1995 (Storn & Price, 1997) is a robust and reliable technique. The DE is outstanding with three main advantages including: (1) the true global minimum is always found in the search space regardless of initial points; (2) the convergence is fast; and (3) there is less tunable parameters compared to the GA (Karaboga & Cetinkaya,

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2005). As many other evolutionary algorithms, the DE is a population-based method, which models the stochastic evolution processes of the nature including mutation, cross-over and selection process which enable the population to iteratively evolve to the best solutions. The mutation and cross-over mechanism create the necessary diversity of the population, while the selection facilitates the exploitation for better candidates in the search region. During the last decades, the DE has continuously been improved and demonstrated much potential in addressing complex structural constrained optimization problems (COPs), motivating many research works in this field. For instance, Zhaoliang, Hesheng, and Pengfei (2009) applied the DE for designing optimal truss structures with continuous and discrete variables. Wu and Tseng (2010) applied a multi-population differential evolution with a penalty-based, self-adaptive strategy to solve the COP of the truss structures. Recently, Wang and Cai (2010) introduced a new variant of DE termed an  $(\mu + \lambda)$  constraint differential evolution methods (CDE) for solving general COPs. They also proposed a mean to enhance the search capability of the DE via the orthogonal cross-over operator (Wang, Cai, & Zhang, 2012). Hernandez, Leguizamon, and Mezura-Montes (2013) developed a hybrid version of the DE based on two novel mutation operators. In general, researchers mainly focused on two central improvement strategies; increasing the diversification mechanism and efficiently handling the constraints violations.

Following this trend, Jia, Wang, Cai, and Jin (2013) proposed an improved  $(\mu + \lambda)$ -constrained differential evolution (ICDE). This version of the DE combines an improved  $(\mu + \lambda)$ -differential evolution (IDE) with an archiving-based adaptive tradeoff model (ArATM). The IDE search engine is to enhance the population diversity by generating three new offsprings from the current population. Three different mutation strategies are employed in this process. The ArATM then defines three different selection mechanisms to deal with the constraint violations, in which infeasible individuals in the promising area can be selected for the next generation. The combination of IDE and ArATM in the ICDE foster both the diversity and the convergence of the population, improving efficiently the performance of conventional DE.

However, since the ICDE method are currently designed for optimization problem with continuous variables. In applications related to discrete or integer variables, the ICDE becomes inappropriate owing to two main obstacles: (i) the obtained results may be far from the permissible value and (ii) the continuous search space contains large amount of inadmissible values, leading to waste in computational cost. This paper hence proposed a novel variables handling technique to help the ICDE overcome these two disadvantages in solving optimization problems with both discrete and continuous variables. The new method is called Discrete-ICDE (D-ICDE). In the proposed technique, the set of discrete variables is transformed into a set of continuous integer variables accordingly. The formulation of the technique is applied to the initial and mutation phases in a manner that new individuals are ensured to be admissible while the diversification of the population is maintained. The D-ICDE is then applied for the truss layout optimization problem under constraints of stress, displacement and buckling limitations. Five numerical examples are performed and compared to state-of-the-art methodologies to illustrate the reliability and effectiveness of the D-ICDE.

The paper is organized as follows. General concepts related to the truss layout optimization problems and the DE are introduced in Section 2. The ICDE is briefly described in Section 3, and the ICDE using discrete variables handling technique (D-ICDE) is presented in Section 4. Section 5 performs numerical examples, and some conclusions are withdrawn in Section 6.

## 2. Basic concepts of truss layout optimization problem and differential evolution (DE) algorithm

This section will shortly introduce the mathematical model of the general truss layout optimization problem and the principal of the differential evolution (DE) algorithm.

### 2.1. Truss layout optimization problem

The truss layout optimization problem can be described in mathematical formulations as below:

$$\begin{aligned} \min \quad & f(\mathbf{x}) = \sum_{i=1}^j \rho_i x_i l_i \\ \text{s.t} \quad & \begin{cases} \Delta(\mathbf{x}) \leq [\Delta], \sigma(\mathbf{x}) \leq [\sigma], \lambda(\mathbf{x}) \leq [\lambda] \\ \mathbf{x} = \{x_i^l \leq x_i \leq x_i^u\}, \quad i = 1, 2, \dots, j, \dots, n \end{cases} \end{aligned} \quad (1)$$

where  $f(\mathbf{x})$  is the objective function measuring the weight of the structure;  $\mathbf{x}$  is a  $D$ -dimensional vector of  $n$  design variables, containing the size and shape variables of the truss elements;  $\rho_i$  is the material density of the  $i$ th member;  $l_i$  is the length of the  $i$ th member;  $\Delta(\mathbf{x})$  is the displacement, determined within the allowable displacement  $[\Delta]$ ;  $\sigma(\mathbf{x})$  is the element stress, determined within the allowable stress  $[\sigma]$ ;  $\lambda(\mathbf{x})$  is the buckling stress, determined within the allowable buckling stress  $[\lambda]$ ;  $x_i$  is the  $i$ th design variable, determined between the lower bound  $x_i^l$  and upper bound  $x_i^u$ ,  $i = 1, 2, \dots, j$  are the indices representing the area design variables while  $i = j + 1, \dots, n$  are the indices representing the nodal coordinates.

### 2.2. Differential evolution (DE) algorithm

Differential evolution (DE) proposed by Storn and Price (1997) was proven to be one of the most promising global search methods and widely used to solve continuous optimization problems for many kinds of structures. This paper hence employs the DE in association with some novel techniques to solve the problem of layout truss optimization. An original scheme of the DE consists of four main phases as

#### 2.2.1. Phase 1: initialization

Create an initial population  $\mathbf{P}_t$  of  $NP$  individuals by randomly sampling from the search space

#### 2.2.2. Phase 2: mutation

Generate a new mutant vector  $\mathbf{v}_i$  from each current individual  $\mathbf{x}_i$  based on mutation operations. Four popular mutation operations used in the DE algorithm as follows

$$\text{- Rand/1 : } \mathbf{v}_i = \mathbf{x}_{r_1} + F \times (\mathbf{x}_{r_2} - \mathbf{x}_{r_3}) \quad (2)$$

$$\text{- Rand/2 : } \mathbf{v}_i = \mathbf{x}_{r_1} + F \times (\mathbf{x}_{r_2} - \mathbf{x}_{r_3}) + F \times (\mathbf{x}_{r_4} - \mathbf{x}_{r_5}) \quad (3)$$

$$\begin{aligned} \text{- Current - to - rand/1 : } \mathbf{v}_i \\ = \mathbf{x}_i + F \times (\mathbf{x}_{r_1} - \mathbf{x}_i) + F \times (\mathbf{x}_{r_2} - \mathbf{x}_{r_3}) \end{aligned} \quad (4)$$

$$\text{- Current - to - best/1 : } \mathbf{v}_i = \mathbf{x}_i + F \times (\mathbf{x}_{\text{best}} - \mathbf{x}_i) + F \times (\mathbf{x}_{r_1} - \mathbf{x}_{r_2}) \quad (5)$$

where integers  $r_1, r_2, r_3, r_4, r_5$  are randomly selected from  $\{1, 2, \dots, NP\}$  such that  $r_1 \neq r_2 \neq r_3 \neq r_4 \neq r_5$ ; the weighting factor  $F$  is randomly chosen between 0 and 1; and  $\mathbf{x}_{\text{best}}$  is the current best individual in the population;

After mutation, the components  $v_{ij}$  of mutant vectors  $\mathbf{v}_i$  are modified if the boundary constraints are violated. The modified procedure is conducted as follows:

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