Multi-objective mixed-integer evolutionary algorithms for building spatial design

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Curriculum Vitae

Koen was born on the 27th July 1990 in Berkel en Rodenrijs. After graduating with a B ICT from The Hague University of Applied Sciences in 2012, he completed his MSc at Leiden University in 2014. Under the supervision of Michael Emmerich, Hèrm Hofmeyer (Eindhoven University of Technology), and Thomas Bäck he conducted the research presented in this doctoral thesis at the same university. Currently, still in Leiden, he is a post-doctoral researcher in meta-algorithmics supervised by Holger Hoos.

Glossary

(building) spatial design

The design of the external and internal geometrical shape (of a building)

binary space / the space of binary numbers / $\mathbb{B}^n \in \{0,1\}^n$

The space of n-tuples of integers restricted to two possible values, usually zero and one

categorical / nominal discrete space

The space of tuples of categorical variables (usually encoded by integers)

decision / variable / search / design space

The space of candidate solutions in the chosen representation

discrete space

The space of tuples of integers and categorical variables (usually encoded by integers)

feasible space

The space of solutions that do not violate any constraints

hypervolume (indicator) / $\mathcal{S}$-metric

The volume covered by a set of points relative to a reference point

infeasible space

The space of solutions that violate one or more constraints

integer space / the space of integer numbers / $\mathbb{Z}^n$

The space of n-tuples of whole numbers; positive numbers, and possibly also negative numbers and zero

mixed-integer space

The space of tuples containing a combination of real and discrete values

objective space / solution space

The space of solution/objective performances, typically a subset of $\mathbb{R}^m$, where m is the number of objective functions

real space / the space of real numbers / continuous space / $\mathbb{R}^n$

The space of real vectors of dimension n

space

Part of a building spatial design, e.g. a room, corridor, atrium, etc.

structural component

Structural component of a building, e.g. a beam, strut, slab, etc.

structural design

The set of structural components with their position and properties, which circumvents and distributes forces

subspace

Part of a more general collection; integer space is a subspace of real space, for instance

supercube

A superstructure to encode building spatial designs

superstructure

A design space representation that represents a relevant subset of the entire design space and each element of the superstructure is a solution that is encoded by a vector of constant length

superstructure free

A design space representation that is not encoding solutions by using a superstructure

Acronyms

AEC
Architecture, Engineering, and Construction

BGO
Bayesian Global Optimisation

BIM
Building Information Modelling

BP
Building Physics

CAD
Computer Aided Design

CD
Co-evolutionary Design

CFD
Computational Fluid Dynamics

EA
Evolutionary Algorithm

EDS
Enhanced Directed Search

EMO
Evolutionary Multi-Objective Optimisation

EMOA
Evolutionary Multi-Objective Optimisation Algorithm

ES

Evolution Strategy

FE

Finite Element

FEM

Finite Element Method

HIGA-MO

Hypervolume Indicator Gradient Ascent Multi-Objective Optimisation

HIGA-MO-SC

Hypervolume Indicator Gradient Ascent Multi-Objective Optimisation SuperCube

HVI

Hypervolume (Indicator)

MEMO

Memetic Multi-Objective Optimisation

MEMO-SC

Memetic Multi-Objective Optimisation SuperCube

MIES

Mixed-Integer Evolution Strategy

MINLP

Mixed-Integer Nonlinear Programming

MOMI

Multi-Objective Mixed-Integer

MOMIES

Multi-Objective Mixed-Integer Evolution Strategy

MOP

Multi-Objective Optimisation Problem

NSGA-II

Nondominated Sorting Genetic Algorithm II

ODE

Ordinary Differential Equations

PF

Pareto front

PFA

Pareto front approximation

RC

Resistance/Capacitance

SD

Structural Design

SMS-EMOA

$\mathcal{S}$-Metric Selection Evolutionary Multi-Objective Algorithm

SMS-EMOA-SC

$\mathcal{S}$-Metric Selection Evolutionary Multi-Objective Algorithm SuperCube

XML

eXtensible Mark-up Language

Symbols

α ratio between desired and current volume

$\mathbf{B}$ binary matrix

$b^{\ell}_{i,j,k}$ indicator of activity for a specific cell belonging to a specific space for the supercube

C heat capacity

c accumulation coefficient

CV number of constraint violations

D geometry of a space in the movable sizeable representation

d number of decision variables

$\mathbf{d}$ vector of nominal discrete decision variables

d_j size of a specific depth division of the supercube

E Young's modulus

$\mathbf{e}_j$ j-th standard basis in $\mathbb{R}^d$

$f(\cdot)$ objective function

$\mathbf{F}$ mapping between $\mathbf{X}$ and $\mathbf{Y}$

$\mathbf{f}(\cdot)$ vector of objective functions

FS fixed number of steps

$G(\cdot,\cdot)$ Gaussian distribution

$g(\cdot)$ equality constraint function

G_{norm} normalised subgradient

$H(\cdot)$ hypervolume of a set of objective vectors

$h(\cdot)$ inequality constraint function

$\mathcal{H}_{\mathbf{F}}(\cdot)$ hypervolume of a set of decision vectors

h_k size of a specific height division of the supercube

I inner product of normalised HVI subgradients in two consecutive iterations

$\mathbf{I}$ integer matrix

IM initialisation mutations

IT initialisation technique

k thermal conductivity

κ maximum number of generations that an individual can stay in the population

$\mathbf{K}$ stiffness matrix of an element

L coordinates of the location of a space's origin in the movable sizeable representation

Λ Lebesgue measure

λ offspring population size

λ_k tournament size

lb lower bound

M heightmap

m number of objectives

MC continuous mutation probability

MP mutation probability

MT mutation type probability

μ parent population size

N_{cells} number of cells

N_{cont} number of continuous variables

N_d number of divisions in depth for the supercube

N_{dims} number of decision variables in a given supercube

N_h number of divisions in height for the supercube

N_{spaces} number of spaces

ν Poisson's ratio

N_w number of divisions in width for the supercube

p cumulative value of I

pen penalty value

p_{live} live load

$p_{w,p}$ wind load, pressure

$p_{w,s}$ wind load, suction

$p_{w,sh}$ wind load, shear

Q_c cooling power

Q_h heating power

$\mathbf{r}$ vector of continuous decision variables

$\boldsymbol{\rho}$ reference point

ϱ density

RP recombination probability

$\mathbb{S}$ set of solutions

s a space in the moveable sizeable representation

S_A total outside surface area

$\mathbf{s}$ a vector of spaces in the moveable sizeable representation

S_d total outside surface area of depth vectors

s_d shape depth

$sgn(\cdot)$ sign function

S_h total outside surface area of height vectors

s_h shape height

σ step size of continuous variables

ς step size of integer variables

ST step size technique

S_w total outside surface area of width vectors

s_w shape width

t thickness

τ_1 Local learning rate

τ_2 Global learning rate

T_c cooling set point temperature

T_g ground temperature

T_h heating set point temperature

$U(\cdot, \cdot)$ Uniform distribution

ub upper bound

$\mathbf{u}$ displacement vector of an element

V_0 total volume

V_c current volume

w_i size of a specific width division of the supercube

X finite set of decision vectors

x decision variable

$\mathbf{X}$ vector of concatenated decision vectors

$\mathbf{x}$ vector of decision variables

Y finite set of objective vectors

y objective value

$\mathbf{Y}$ vector of concatenated objective vectors

$\mathbf{y}$ vector of objective values

$\mathbf{z}$ vector of integer decision variables

ζ step size of nominal discrete variables