IALCCE'08 Symposium, Varenna

Cost versus Sustainability of Reinforced Concrete Building Frames by Multiobjective Optimization

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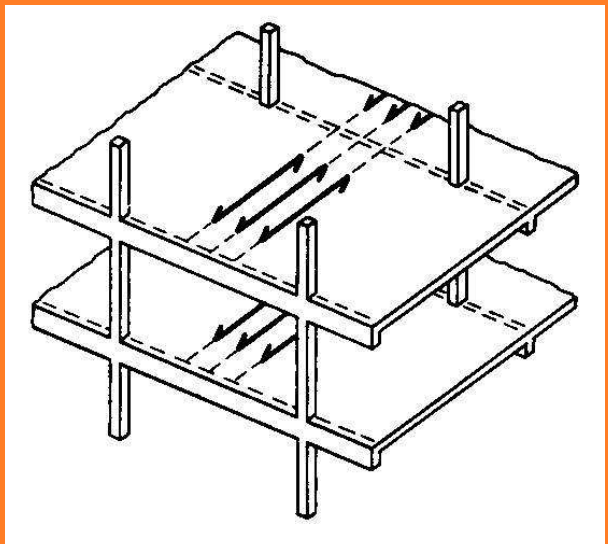

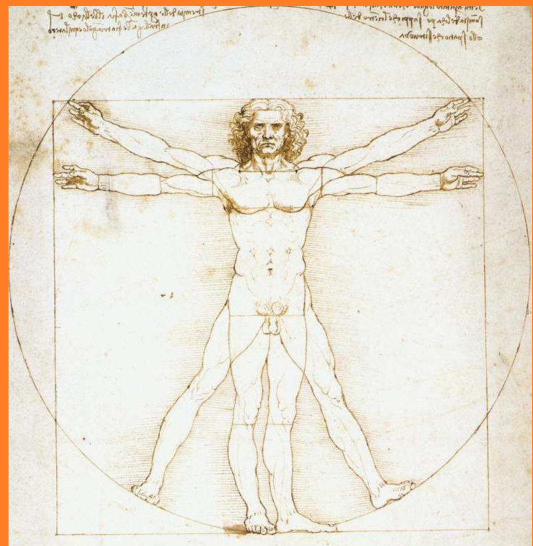

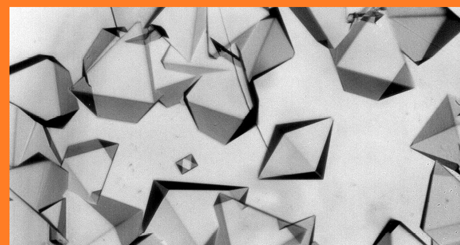

universidad politécnica de valencia (spain) / departamento de ingeniería de la construcción

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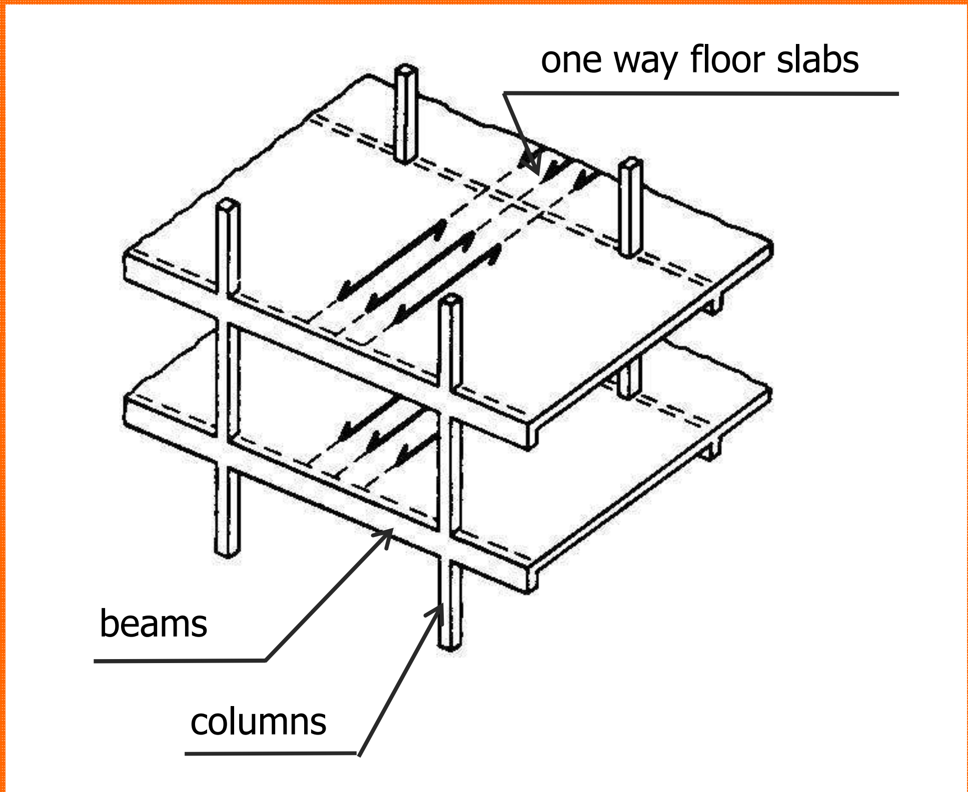
1. introduction.

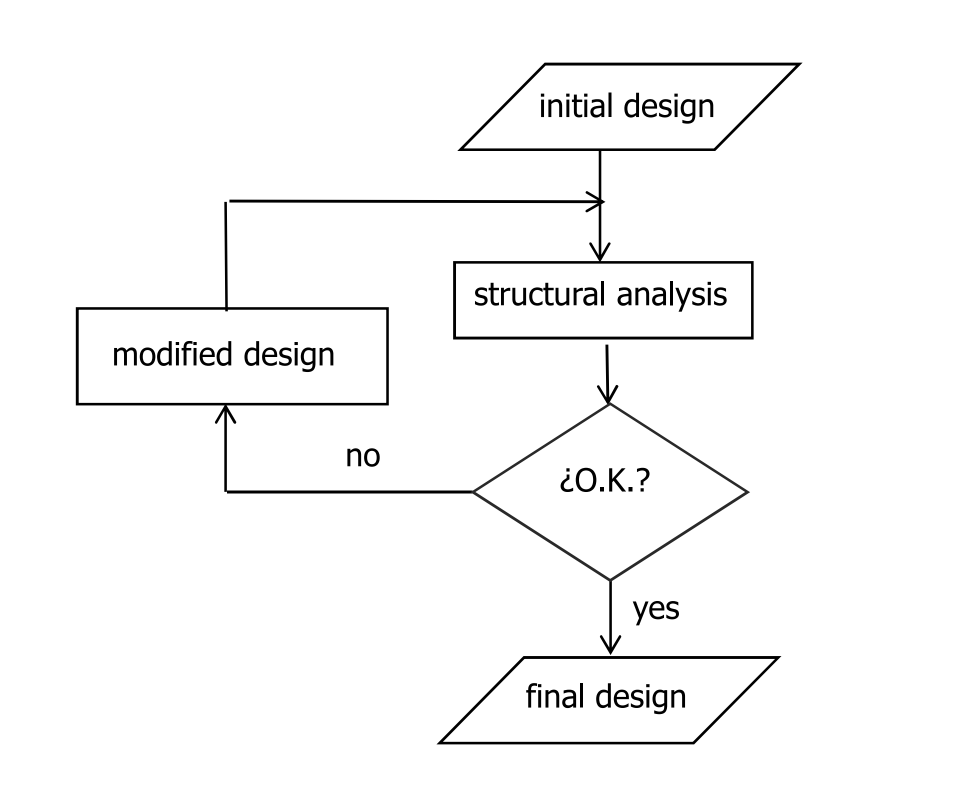
reinforced concrete building frames

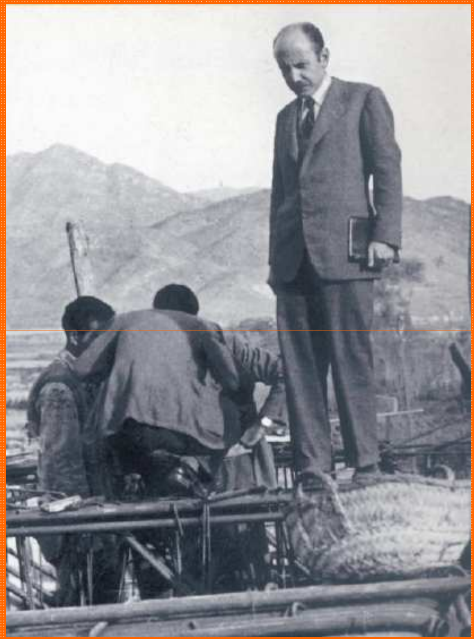


RC frame = columns + beams

1. introduction.

- traditional approach to design:





prof. Fernández Casado, one of the most important structural engineers of the Spanish tradition

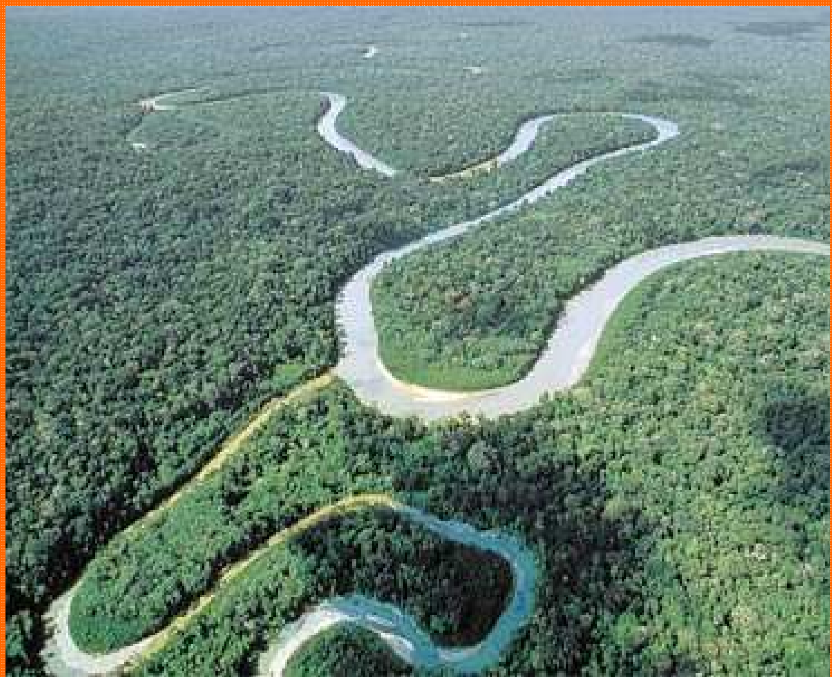
1. introduction.

- alternative approach:

OPTIMAL STRUCTURE: minimum cost

...

multiobjective optimization (cost, sustainability, construction schedules…)

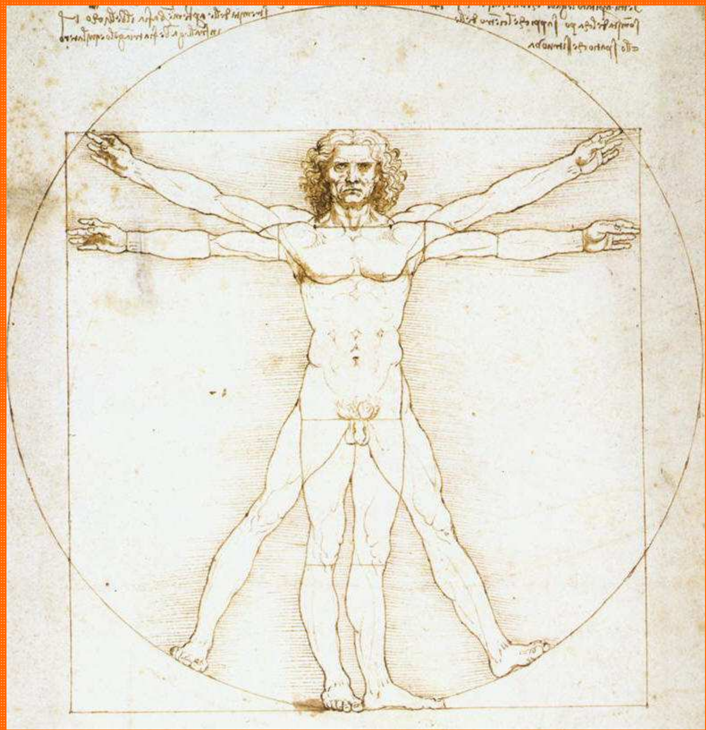


Amazonic jungle

train station (Berlin Hauptbahnhof) under construction

1. introduction.

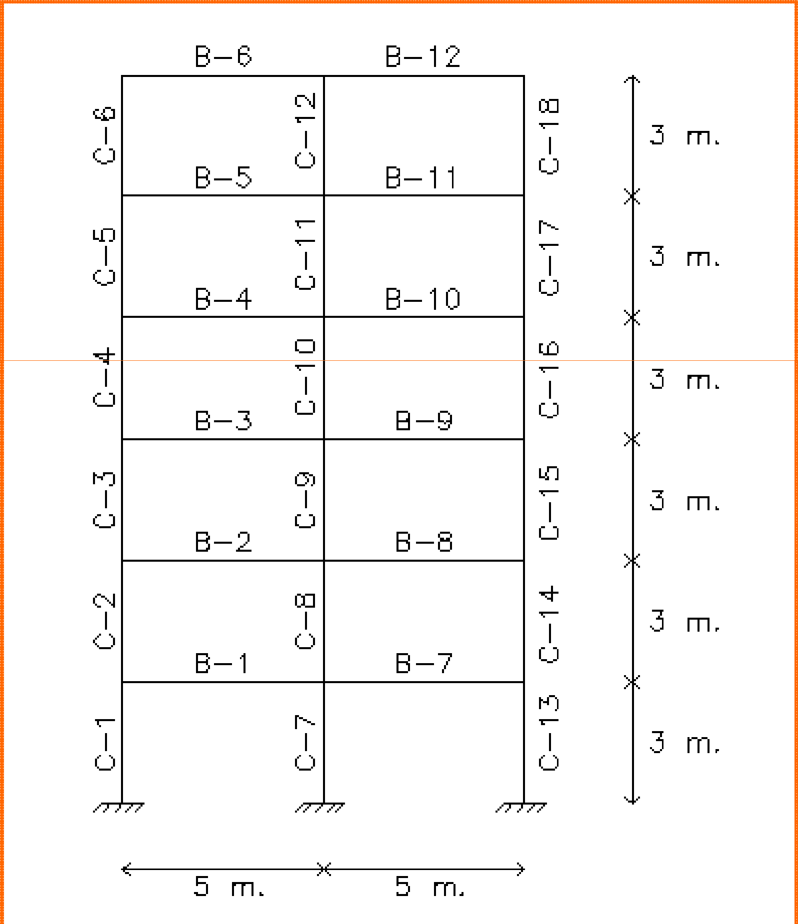
objective: to develop an algorithm that is able to find the optimal RC frame when considering both, economic cost and sustainability.



Vitrubian Man, Leonardo’s ideal of proportion

1. introduction.

case study:



horizontal and vertical loads according to Spanish codes

(6 elementary load cases and 48 different load combinations)

2. optimization problem definition.

- **general statement** of the optimization problem:

optimize	$\vec{f} = (f_1(\vec{X}),\ldots,f_n(\vec{X}))$	vector of objective functions
	$\vec{X}=(x_1,\ldots,x_n)$	design variables
	$\vec{P}=(p_1,\ldots,p_m)$	parameters
satisfying:	$g_i(\vec{X},\vec{P})\leq 0 \quad i=1,\ldots,k$	constraints

feasible solutions vs. non feasible solutions

2. optimization problem definition.

2.1 objective functions.

- economic cost, C :

$$C = \sum_{columns} (C_{STEEL} + C_{FORMWORK} + C_{CONCRETE}) + \sum_{beams} (C_{SCAFFOLDING} + C_{FORMWORK} + C_{STEEL} + C_{CONCRETE})$$

where $C_i = p_i \times m_i$,

p_i: construction unit price

m_i: quantities of construction units

Construction unit prices, p_i

Unit	Description	Cost (€)
kg	Steel B-400	1.27
kg	Steel B-500	1.30
m^3	Concrete C-25	78.40
m^3	Concrete C-30	82.79
m^3	Concrete C-35	98.47
m^3	Concrete C-40	105.93
m^3	Concrete C-45	112.13
m^3	Concrete C-50	118.60
m^2	Formwork in beams	25.05
m^2	Formwork in columns	22.75
m^2	Scaffolding for beams	38.89

2. optimization problem definition.

2.1 objective functions.

- environmental cost, EC :

$$EC = \sum_{columns} (EC_{STEEL} + EC_{CONCRETE}) + \sum_{beams} (EC_{STEEL} + EC_{CONCRETE})$$

where $EC_i = d_i \times m_i$,

d_i: material environmental cost

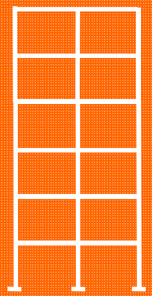
m_i: quantities of materials

Environmental cost of the frame materials, d_i obtained using Ecoindicator 99.

Unit	Description	Environmental Cost
kg	Steel B-400	61
kg	Steel B-500	61
m^3	Concrete C-25	39100
m^3	Concrete C-30	41400
m^3	Concrete C-35	42000
m^3	Concrete C-40	50200
m^3	Concrete C-45	55600
m^3	Concrete C-50	61300

2. optimization problem definition.

2.2. design variables.

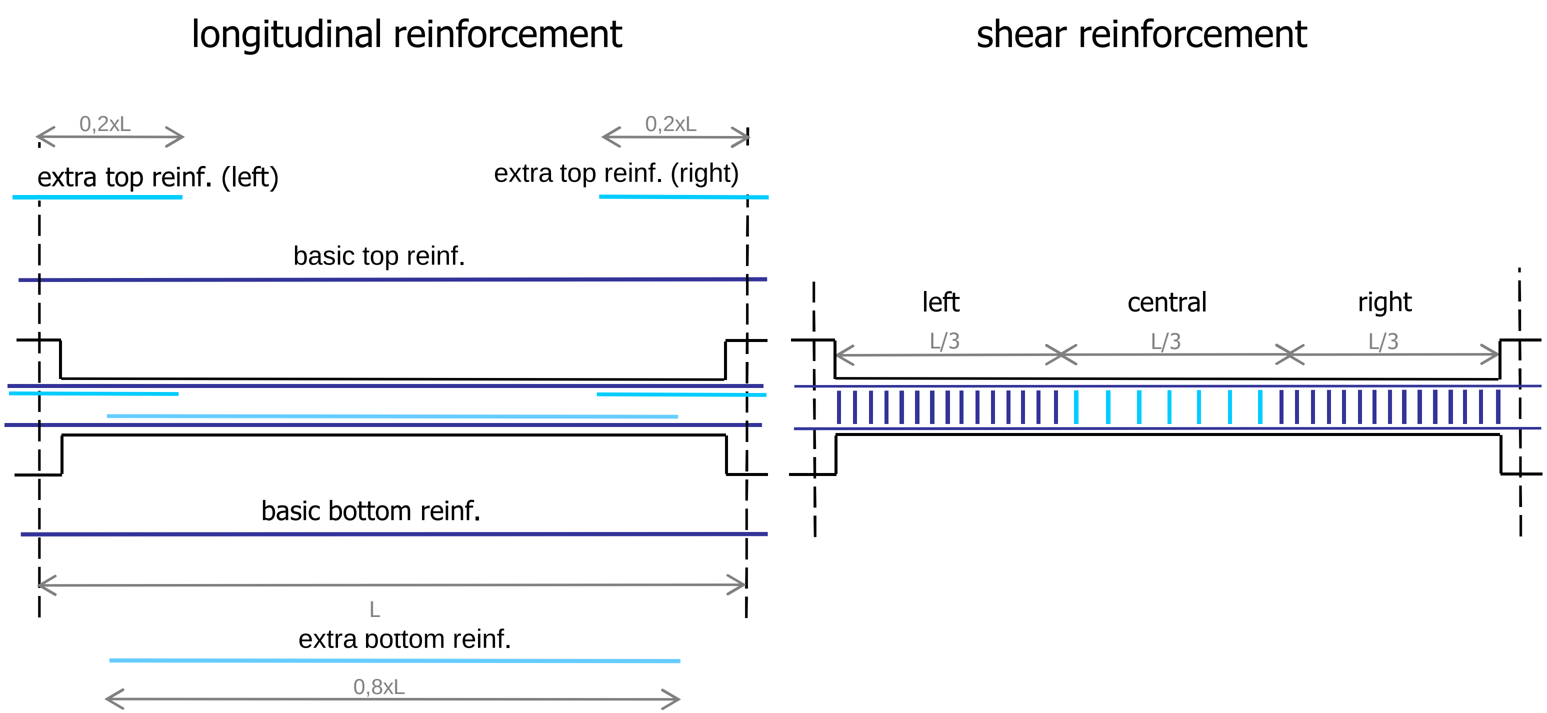


115 variables:

- steel reinforcement strength
- 6 concrete grades
- 36 cross sections of beams and columns
- 72 types of steel reinforcement

all of them are discrete

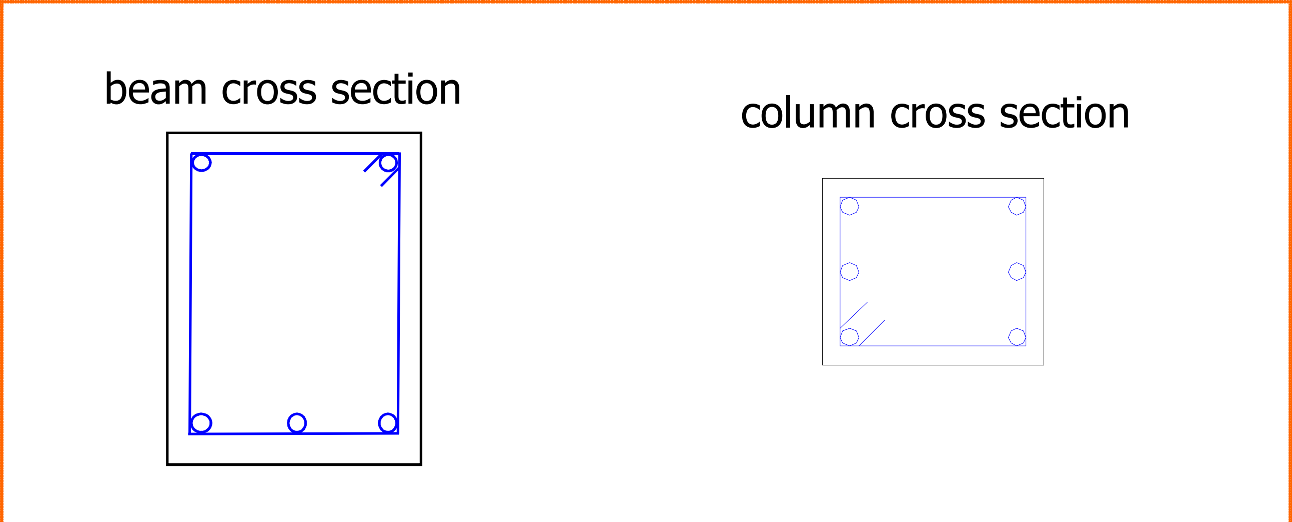
beams reinforcement setup



2. optimization problem definition.

2.3. structural constraints.

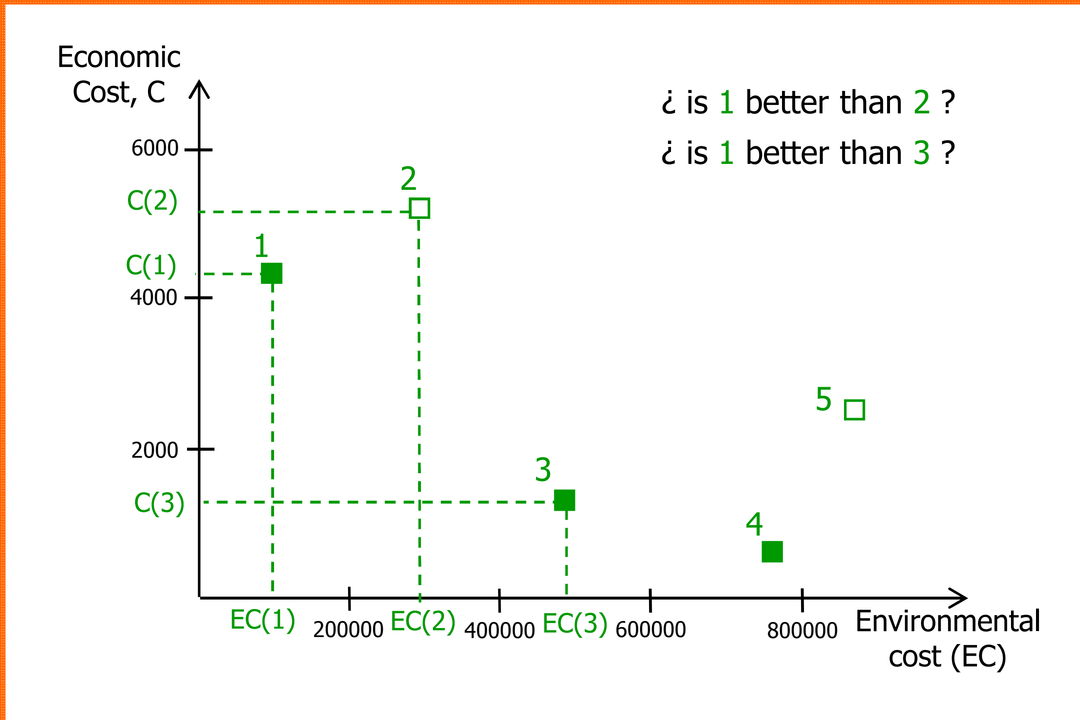
- Ultimate Limit States (ULS): flexure, shear, buckling.
- Service Limit States (SLS): deflections, cracking.
- Drifts.
- constructability: e.g. minimum and maximum distances among reinforcement bars, ties spacing...



3. optimization procedure.

the two objective functions considered are in opposition

PARETO SET OF SOLUTIONS

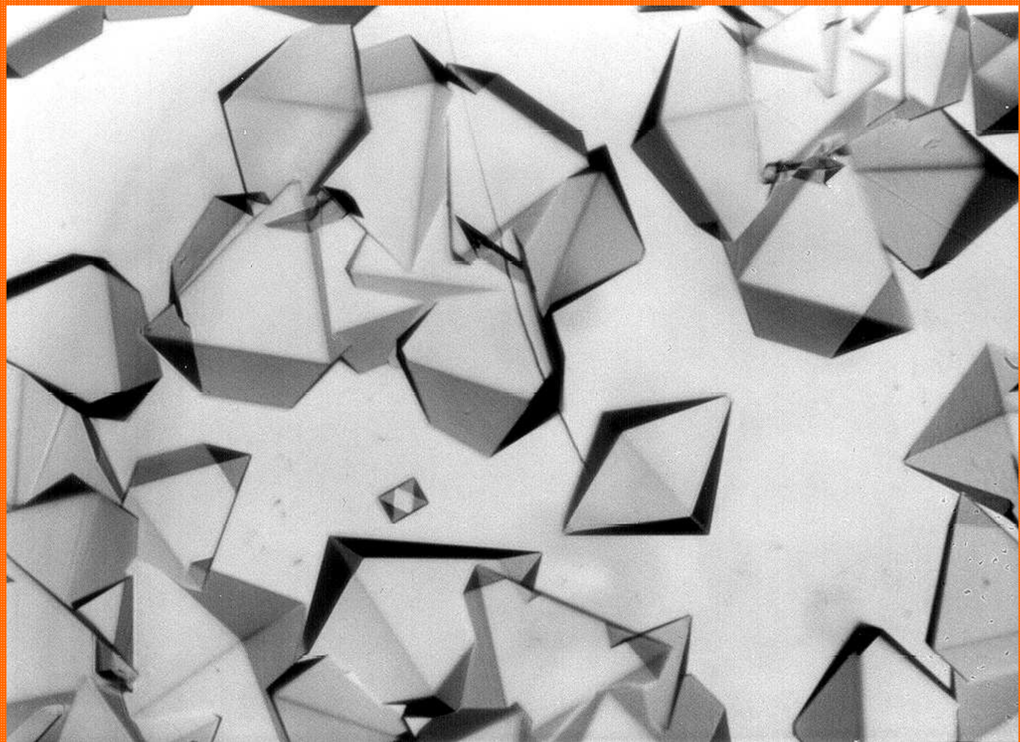


Pareto Set of Solutions: 1, 3 , 4

3. optimization procedure.

Suppapitnarm Multiobjective Simulated Annealing, SMOSA (2000)

based on the analogy of crystal formation from masses melted at high temperatures and let cool slowly



3. optimization procedure.

SMOSA.

1) Creation of an initial random solution S_1 .

2) Creation of a new solution S_2 (through a small random move of the values of some of the variables that define S_1)

3) If S_2 is Pareto Optimal + S_2 is feasible $\Big\}$ S_2 replaces S_1 as working solution; S_2 becomes a member of the Pareto Set

If S_2 is not Pareto Optimal + S_2 is feasible $\Big\}$ S_2 replaces S_1 with a probability:

$$p = \frac{1}{e^{\Delta f_1 / t_1} \; e^{\Delta f_2 / t_2}}$$

$\Delta f_i = f_i(S_2) - f_i(S_1)$ difference in the objective function values.

"t_i" temperature for "i" objective, it is reduced every "L_M" iterations

(L_M : Markov chain)

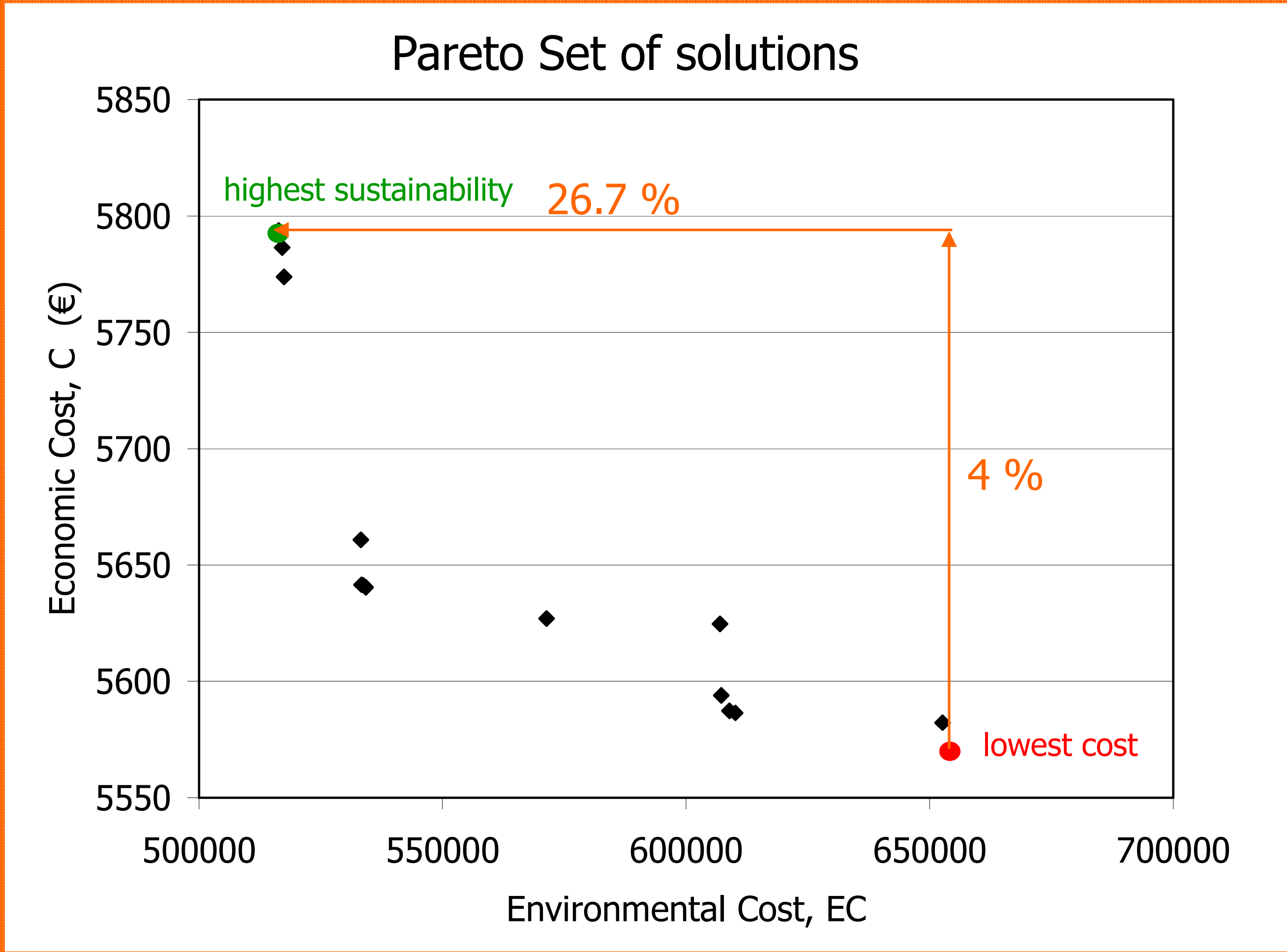
4) back to 2) until a stop criterion is satisfied.

4. results.

software programmed in Fortran

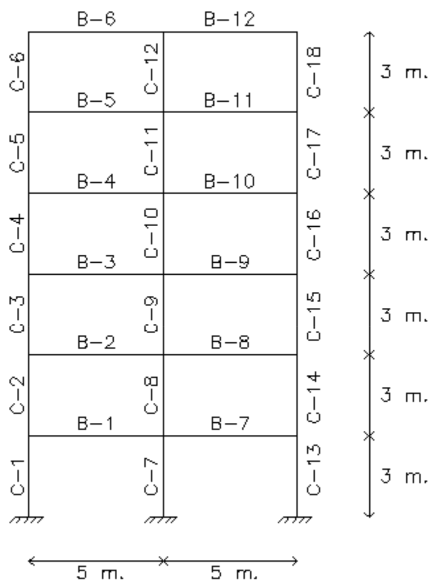
calibration of the algorithm: L_M=135000 ; r = 0.8 ; move up to 3 variables.

CPU computing time: 80 min in a Pentium IV of 3.2 GHz.



4. results.

lowest environmental cost solution



Beam results

Name	Dimensions		Top reinforcement		
	Depth (cm)	Width (cm)	Base	Extra Left	Extra Right
B-1	48	20	3φ10	3φ16	3φ20
B-2	50	20	3φ16	1φ16	2φ16
B-3	48	20	4φ16	-	2φ12
B-4	42	20	5φ16	1φ16	-
B-5	46	20	2φ25	-	-
B-6	47	20	2φ25	1φ10	1φ12

Name	Bottom reinforcement		Shear reinforcement		
	Base	Extra	Left	Central	Right
B-1	3φ10	2φ12	φ10/25	φ6/20	φ8/15
B-2	4φ12	1φ12	φ8/20	φ6/20	φ10/25
B-3	2φ12	2φ20	φ8/20	φ6/20	φ8/20
B-4	4φ16	2φ20	φ8/20	φ6/20	φ10/25
B-5	3φ20	2φ20	φ10/25	φ6/30	φ10/25
B-6	3φ20	3φ20	φ10/25	φ6/30	φ10/25

Column results

Name	Dimensions		Long. Reinf.		
	a (cm)	b (cm)	Corner	b side	Ties
C-1	35	25	4φ12	–	φ6/15
C-2	35	25	4φ16	–	φ6/15
C-3	30	25	4φ16	–	φ6/15
C-4	30	25	4φ12	4φ12	φ6/15
C-5	30	25	4φ12	4φ12	φ6/15
C-6	30	25	4φ20	–	φ6/20
C-7	40	30	4φ12	2φ12	φ6/15
C-8	40	25	4φ12	–	φ6/15
C-9	40	25	4φ12	–	φ6/15
C-10	35	25	4φ12	–	φ6/15
C-11	30	25	4φ12	–	φ6/15
C-12	25	25	4φ12	–	φ6/15

Concrete and steel results

Characteristic concrete compressive strenght, fck (28 days)	
RC elements from ground to 4^{th} floor:	35 MPa
RC elements 5^{th} and 6^{th} floors:	25 MPa

Characteristic reinforcement yield strength, fyk 500 MPa

5. conclusions.

this work shows :

- the capability of SMOSA for the optimization of cost and sustainability of complex RC structures.

- more sustainable solutions than the lower cost solutions are available at a cost increment acceptable in practice.

Thank you for your attention !

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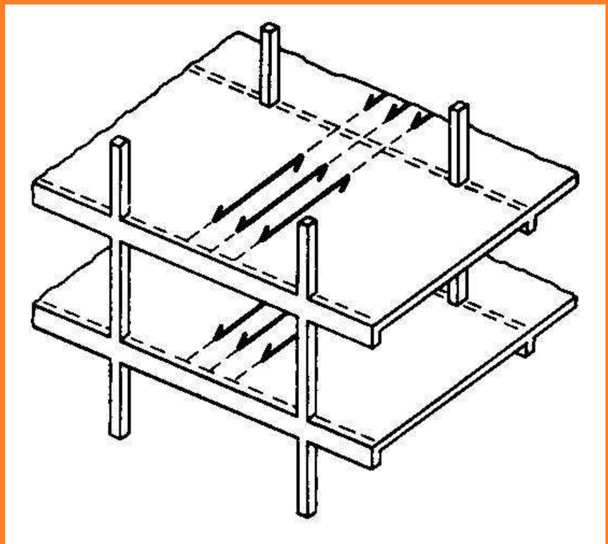

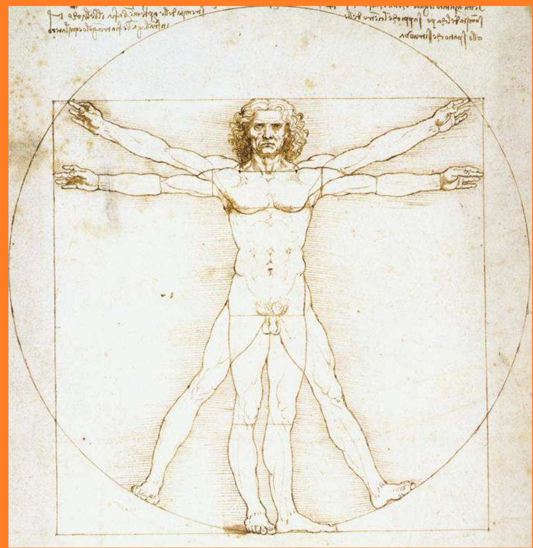

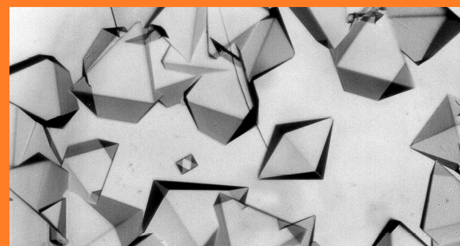

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