Optimizing the economic, environmental and technical performance of concrete mixes with fly ash and recycled concrete aggregates

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Presented by:
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Outline

1. Introduction

Sustainable concrete

Supplementary cementing materials

- Fly ash (FA)
- Metakaolin
- Rice husk ash
- Limestone
- Silica fume
- Natural pozzolans
- Granulated blast furnace slag

Recycled aggregate

- Recycled concrete aggregate (RCA)
- Recycled masonry aggregate
- Mixed recycled aggregate
- Construction and demolition recycled aggregate

Emissions to air

Energy

Raw materials

Toxicity to water and soil

2. Mix compositions and categories

Concrete mixes composition

Mixes [a]	Fine RA (%)	Coarse RA (%)	FA (%)
M1; M1-SP	0	0	0
M2; M2-SP	100	0	0
M3; M3-SP	50	0	30
M4; M4-SP	0	0	60
M5; M5-SP	100	0	60
M6; M6-SP	0	100	0
M7; M7-SP	100	100	0
M8; M8-SP	50	100	30
M9; M9-SP	0	100	60
M10; M10-SP	100	100	60

[a] M and M-SP are concrete mixes without and with SP (1% of binder's weight)

Standards and details for each selected category

Categories	Abbreviation	Units	Test specimen size	Standard
Compressive strength	$f_{cm,cube}$	MPa	150x150 mm	(EN 12390-3, 2009)
Modulus of elasticity	E_{cm}	GPa	Ø150x300 mm	(LNEC E 397, 1993)
Carbonation	K_{ac}	mm	Ø150x40 mm	(LNEC E 391, 1993)
Chloride ion penetration	D_{nssm}	m^2/s	Ø150x50 mm	(LNEC E463, 2004; Nordtest BUILD NT, 1999)
Cost	-	Euros	Cubic meter	-
Global warming potential	GWP	kg CO_2 eq	Cubic meter	LCA methodology (EN 15804, 2012; ISO 14040, 2006)
Non-renewable primary energy resources	PE-NRe	MJ	Cubic meter	LCA methodology (EN 15804, 2012; ISO 14040, 2006)

3. Difficulties regarding optimization

Decision-influencing issues

Examples:

Optimize construction materials based in characteristics measured in different **units.** For example, strength and durability of concrete.

The **weight** of each category may not be the same and changes according to its application.

The highest ranked construction material (best one) may not necessarily be an **optimal** choice for the selected application.

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4. Application of CONCRE*Top*

Profile of the multi-criteria decision method for concrete optimization - CONCRE***Top***

*** Step i**

Specify the application

Specify the demanded characteristics for concrete

*** Step ii**

Selection of main categories

e.g.:

- f_{cm}
- E_{cm}
- k_{ac}
- D_{nssm}
- GWP
- PE-NRe
- Cost

*** Step iii**

Ranking of main categories

(ranking mixes in five groups according to actual values and from best to worst in relative to each other)

- Green
- Chartreuse
- Yellow
- Orange
- Red

*** Step iv**

Standardization of categories

Ranking mixes from high to low impact (1-0)

Step v

Scenarios and CONCRE*Top* factor

- Green
- Strength
- Service life
- Cost
- Business as usual

*** Step vi**

Threshold values

- Workability
- Strength
- Durability
- EI
- Cost

*** Step vii**

Final decision:

- Applicable
(Ranking of optimality)

- Not applicable

4. Application of CONCRE*Top*

Optimization Process:

Specification of the application (step i)

- ❑ Select the application → the optimization process will be different according to the application

- ❑ Study the application → specify the required characteristics of concrete (if available) in order to consider them as threshold values and select the optimal mix.

- ❑ If the specific characteristics of concrete for the selected application are uncertain → the following scenarios were proposed with different threshold values, in order to cover most of the construction cases (the majority of concrete applications):

- Business as usual;
- **Green →** <u>sustainable residential houses</u>**;**
- Strength;
- Service life;
- Cost.

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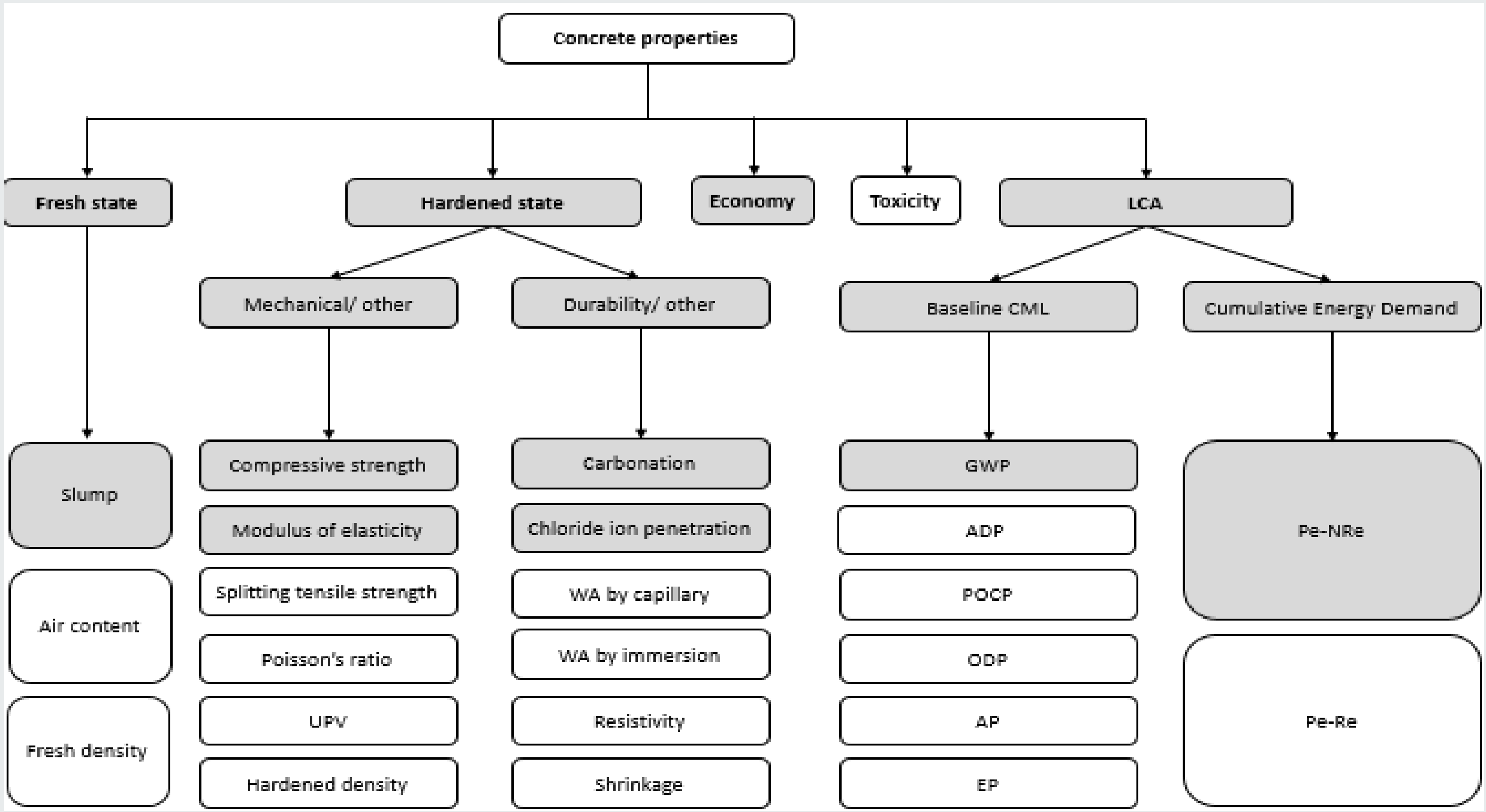
- Not applicable

4. Application of CONCRE*Top*

Optimization Process:

Selection of main categories (step ii)



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- **Not applicable**

4. Application of CONCRE*Top*

Ranking of concrete mixes according to their performance

Concrete mixes	Slump (cm)	$f_{cm,cube}$ (MPa)		E_{cm} (GPa)		D_{nssm} ($\times 10^{-12}$ m^2/s)		Carbonation "k_{ac}" (mm year$^{0.5}$)	GWP (kg CO_2 eq)	PE-NRe (MJ)	Cost (€/m^3)
		28 days	365 days	28 days	365 days	28 days	365 days				
M1	7.3	55.8	61.3	43.8	47	12.6	7.9	11.3	361.6	1949.5	79.9
M1-SP	8.5	73.5	83	51.4	55.7	6.4	3.9	1.6	364	1983.2	90.1
M2	8.1	45	51.5	34.7	39	16.2	9.8	26.9	360	1936.2	76.7
M2-SP	8.8	54.1	63.7	39.9	42.6	9.4	5.5	7.8	362.5	1970.8	86.7
M3	8.3	36.4	57.2	38.3	46.3	8.9	3	37.7	267.9	1572.2	71
M3-SP	8.9	60.4	79	43.9	50.2	4.2	1.0	4.2	270.3	1605.6	81.1
M4	7.2	24	42.2	38	46.1	11.2	3.1	61.58	175.9	1209.7	65.3
M4-SP	8.1	42.4	58	40.7	47.7	5.4	1.1	59.84	178.7	1248.1	75.5
M5	8.5	21.5	40	32.3	41.4	13.2	3.3	66.4	174.2	1194.5	62.2
M5-SP	8	37.1	57	34.4	42	6.6	1.3	51.83	176.6	1228.5	72.1
M6	7.6	51.9	59.2	37.1	41.4	14	8.5	15.35	331.1	1528.6	74.6
M6-SP	8.8	63	73	43.5	47.7	7.6	4.6	1.5	331.8	1538.2	84.5
M7	8.1	42	50.2	28	31.4	18.1	10.6	30.3	330.3	1525.4	71.6
M7-SP	8.9	49	60.6	33.9	35.8	10.6	6.1	9	331	1534.9	81.2
M8	8.8	33	56.6	32.5	40	9.3	3.2	42.3	237.6	1153.9	65.8
M8-SP	8.7	53.8	74	38.3	44	4.6	1.1	12.2	238.3	1163.4	75.5
M9	8.6	23	41	33	41.1	11.9	3.2	59.8	145	783.1	59.9
M9-SP	8.8	38	59	38.3	43.6	5.9	1.2	57.1	145.7	792.6	69.8
M10	7.3	21	38	26.9	35.3	14.2	3.6	66.3	144.2	779.1	57
M10-SP	8.9	32.3	54	30.1	35.5	7.3	1.4	44	144.8	788.7	66.6

4. Application of CONCRE*Top*

$$x_{ij} = \frac{X_{ij} - \min_i (X_{ij})}{\max_i (X_{ij}) - \min_i (X_{ij})} \quad (1)$$

$$x_{ij} = \frac{\max_i (X_{ij}) - X_{ij}}{\max_i (X_{ij}) - \min_i (X_{ij})} \quad (2)$$

Ranking and standardization of the concrete mixes

f_{cm} (28 days)		f_{cm} (365 days)		E_{cm} (28 days)		E_{cm} (365 days)		D_{nssm} (28 days)		D_{nssm} (365 days)		Carbonation		GWP		PE-NRe		Cost	
M1-SP	1.00	M1-SP	1.00	M1-SP	1.00	M1-SP	1.00	M3-SP	1.00	M3-SP	1.00	M6-SP	1.00	M10	1.00	M10	1.00	M10	1.00
M6-SP	0.80	M3-SP	0.91	M3-SP	0.69	M3-SP	0.77	M8-SP	0.97	M4-SP	0.99	M1-SP	1.00	M10-SP	1.00	M9	1.00	M9	0.91
M3-SP	0.75	M8-SP	0.80	M1	0.69	M4-SP	0.67	M4-SP	0.91	M8-SP	0.99	M3-SP	0.96	M9	1.00	M10-SP	0.99	M5	0.84
M1	0.66	M6-SP	0.78	M6-SP	0.68	M6-SP	0.67	M9-SP	0.88	M9-SP	0.98	M2-SP	0.90	M9-SP	0.99	M9-SP	0.99	M4	0.75
M2-SP	0.63	M2-SP	0.57	M4-SP	0.56	M1	0.64	M1-SP	0.84	M5-SP	0.97	M7-SP	0.88	M5	0.86	M8	0.69	M8	0.73
M8-SP	0.62	M1	0.52	M2-SP	0.53	M3	0.61	M5-SP	0.83	M10-SP	0.96	M1	0.85	M4	0.86	M8-SP	0.68	M10-SP	0.71
M6	0.59	M7-SP	0.50	M3	0.47	M4	0.60	M10-SP	0.78	M3	0.79	M8-SP	0.84	M5-SP	0.85	M5	0.66	M9-SP	0.61
M7-SP	0.53	M6	0.47	M8-SP	0.47	M8-SP	0.52	M6-SP	0.76	M4	0.78	M6	0.79	M4-SP	0.84	M4	0.64	M3	0.58
M2	0.46	M9-SP	0.47	M9-SP	0.47	M9-SP	0.50	M3	0.66	M8	0.77	M2	0.61	M8	0.58	M5-SP	0.63	M7	0.56
M4-SP	0.41	M4-SP	0.44	M4	0.45	M2-SP	0.46	M8	0.63	M9	0.77	M7	0.56	M8-SP	0.57	M4-SP	0.61	M5-SP	0.54
M7	0.40	M3	0.43	M6	0.42	M5-SP	0.44	M2-SP	0.63	M5	0.76	M3	0.44	M3	0.44	M7	0.38	M6	0.47
M9-SP	0.32	M5-SP	0.42	M2	0.32	M5	0.41	M7-SP	0.54	M10	0.73	M8	0.37	M3-SP	0.43	M6	0.38	M4-SP	0.44
M5-SP	0.31	M8	0.41	M5-SP	0.31	M6	0.41	M4	0.50	M1-SP	0.70	M10-SP	0.35	M7	0.15	M7-SP	0.37	M8-SP	0.44
M3	0.29	M10-SP	0.36	M7-SP	0.29	M9	0.40	M9	0.45	M6-SP	0.63	M5-SP	0.22	M7-SP	0.15	M6-SP	0.37	M2	0.40
M8	0.23	M2	0.30	M9	0.25	M8	0.35	M1	0.40	M2-SP	0.53	M9-SP	0.14	M6	0.15	M3	0.34	M1	0.31
M10-SP	0.22	M7	0.27	M8	0.23	M2	0.31	M5	0.35	M7-SP	0.47	M9	0.10	M6-SP	0.15	M3-SP	0.31	M3-SP	0.27
M4	0.06	M4	0.09	M5	0.22	M7-SP	0.18	M6	0.29	M1	0.28	M4-SP	0.10	M2	0.02	M2	0.04	M7-SP	0.27
M9	0.04	M9	0.07	M10-SP	0.13	M10-SP	0.17	M10	0.28	M6	0.22	M4	0.07	M1	0.01	M1	0.03	M6-SP	0.17
M5	0.01	M5	0.04	M7	0.04	M10	0.16	M2	0.14	M2	0.08	M10	0.00	M2-SP	0.01	M2-SP	0.01	M2-SP	0.10
M10	0.00	M10	0.00	M10	0.00	M7	0.00	M7	0.00	M7	0.00	M5	0.00	M1-SP	0.00	M1-SP	0.00	M1-SP	0.00

4. Application of CONCRE*Top*

Profile of the multi-criteria decision method for concrete optimization - CONCRE***Top***

*** Step i**

Specify the application

Specify the demanded characteristics for concrete

*** Step ii**

Selection of main categories

e.g.:

- f_{cm}
- E_{cm}
- k_{ac}
- D_{nssm}
- GWP
- PE-NRe
- Cost

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Standardization of categories

Ranking mixes from high to low impact (1-0)

Step v

Scenarios and CONCRE*Top* factor

- Green
- Strength
- Service life
- Cost
- Business as usual

*** Step vi**

Threshold values

- Workability
- Strength
- Durability
- EI
- Cost

*** Step vii**

Final decision:

- Applicable (Ranking of optimality)

- Not applicable

4. Application of CONCRE*Top*

Optimization Process:

Scenarios and CONCRE***Top*** factor (step v)

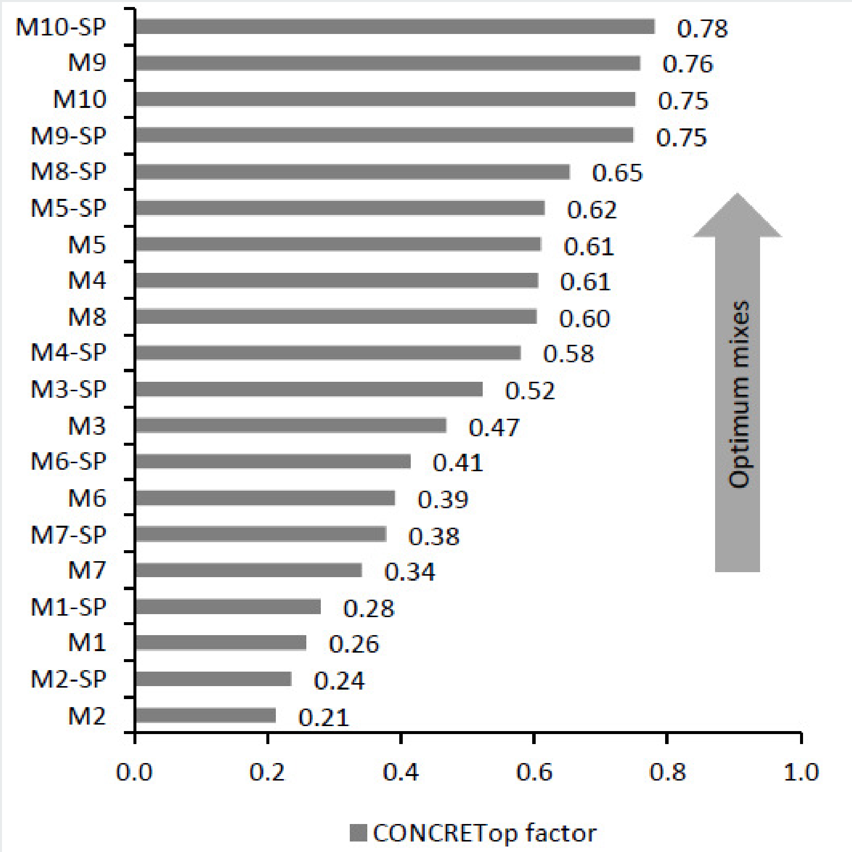
- Ranking mixes
- One step closer to find the optimum mix

Weight of each scenario

Categories	Factors	Scenarios				
		Business as usual	Green	Strength	Service life	Cost
Mechanical behaviour	S	**40%**	**10%**	**50%**	**10%**	**30%**
Compressive strength	*S1*	*80%*	*80%*	*80%*	*80%*	*80%*
s1 at early age	S1e	100%	0%	0%	0%	0%
s1 at longer age	S1l	0%	100%	100%	100%	100%
Modulus of elasticity	*S2*	*20%*	*20%*	*20%*	*20%*	*20%*
s2 at early age	S2e	100%	0%	0%	0%	0%
s2 at longer age	S2l	0%	100%	100%	100%	100%
Durability	D	**20%**	**10%**	**10%**	**50%**	**10%**
Chloride	*d1*	*33%*	*33%*	*33%*	*33%*	*33%*
d1 at early age	d1e	100%	0%	0%	0%	0%
d1 at longer age	d1l	0%	100%	100%	100%	100%
Carbonation	*d2*	*67%*	*67%*	*67%*	*67%*	*67%*
LCA	L	**0%**	**50%**	**10%**	**10%**	**10%**
GWP	*l1*	*0%*	*50%*	*50%*	*50%*	*50%*
PE-NRe	*l2*	*0%*	*50%*	*50%*	*50%*	*50%*
Cost	C	**40%**	**30%**	**30%**	**30%**	**50%**

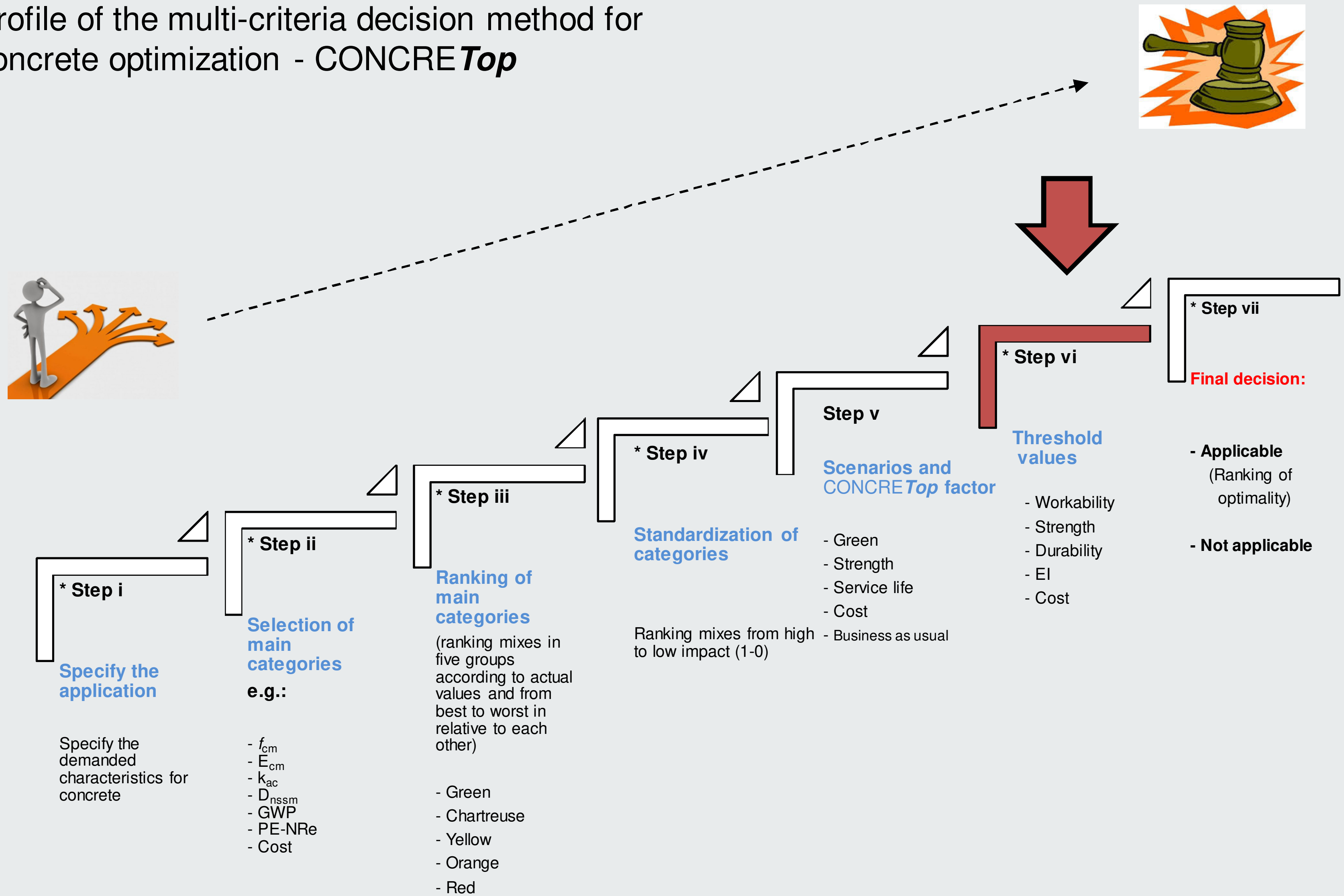
4. Application of CONCRE*Top*

Optimization of the concrete mixes according to green scenarios without considering threshold values



4. Application of CONCRE*Top*

Profile of the multi-criteria decision method for concrete optimization - CONCRE***Top***



Optimization Process:

Threshold values (step vi)

Specific boundaries for the characteristics of structural concrete according to different scenarios

Scenarios	$f_{ck}/f_{ck,cube}$ - E_{cm}	Carbonation resistance [a]	Chloride resistance	GWP	PE-NRe	Cost
Business as usual	C20/23 - 30	Fair	Moderate	High	High	High
Green	C20/23 - 30	Fair	Moderate	**Low**	**Low**	High
Strength	**C35/45 - 34**	Fair	Moderate	High	High	-
Service life	C20/23 - 30	**Good**	**High**	High	High	-
Cost	C20/23 - 30	Fair	Moderate	High	High	**Medium**

a The carbonation resistance can be neglected in marine concrete (concrete under water) or be fair for structures close to the sea

The ranked mixes based on the CONCRE***Top*** are compared with the threshold values to decide the applicability of mixes for each selected application.

4. Application of CONCRE*Top*

Optimizing concrete mixes for sustainable residential house in the "GREEN" scenario

Ranked mixes	CONCRE***Top*** factor	Threshold	Applicable	Reasons
M6-SP F 0% C 100% FA 0% SP 1%	0.41	Strength = 45/55 - 36 Carbonation R. = Very good Chloride R. = Very high GWP = Low PE-NRe = Low Cost = Very high	NO	The cost is very high.
M1-SP	0.28	Strength = 55/67 - 38 Carbonation R. = Very good Chloride R. = Very high GWP = Medium PE-NRe = Low Cost = Very high	NO	The cost is very high. For the green scenario, the GWP is expected to be lower than medium.
M1	0.26	Strength = 40/50 - 35 Carbonation R. = Good Chloride R. = Very high GWP = Medium PE-NRe = Low Cost = High	NO	For the green scenario, the GWP is expected to be lower than medium.
M2-SP	0.24	Strength = 35/45 - 34 Carbonation R. = Very good Chloride R. = High GWP = medium PE-NRe = Low Cost = Very high	NO	The cost is very high. For the green scenario, the GWP is expected to be lower than medium.
M2	0.21	Strength = 30/37 - 33 Carbonation R. = Good Chloride R. = Moderate GWP = Medium PE-NRe = Low Cost = High	NO	For the green scenario, the GWP is expected to be lower than medium.

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4. Application of CONCRE*Top*

Optimization Process:

Final decision (step vii)

Ranked mixes	CONCRETop factor	Threshold values (§6.1)	Applicable	Reasons
Name of mix (mix composition)	(0 - 1)	fck/fck,cube - Ecm Carbonation resistance Chloride resistance GWP PE-NRe Cost	Yes or NO	• According to threshold values

Applicable concrete mixes for the sustainable residential house according to the "Green" scenario

Mixes	M10-SP	M9	M10	M9-SP	M8-SP	M5-SP	M5	M4	M8	M4-SP	M3-SP	M3	M6	M7-SP	M7
Fine RA (%)	100	0	100	0	50	100	100	0	50	0	50	50	0	100	100
Coarse RA (%)	100	100	100	100	100	0	0	0	100	0	0	0	100	100	100
FA (%)	60	60	60	60	30	60	60	60	30	60	30	30	0	0	0
SP (%)	1	0	0	1	1	1	0	0	0	1	1	0	0	1	0
CONCRE*Top* factor	0.78	0.76	0.75	0.75	0.65	0.62	0.61	0.61	0.6	0.58	0.52	0.47	0.39	0.38	0.34

5. Conclusions

Conclusions

- The optimum concrete mixes may not be easily chosen by comparing the performance of concrete in each dimension (e.g. quality, cost and EI). In practical terms, for each selected application, it relies on the CONCRE***Top*** factor and threshold values;

- Mixes produced with high incorporation ratios of FA and RCA (e.g. M9 and M10 with and without SP) are not anticipated to be an optimal choice according to their individual characteristics, but their characteristics comply with the threshold values and their CONCRE***Top*** factors are the highest;

- The optimal mix (e.g. for sustainable house) may not necessarily be the one with the highest result in the demanded characteristic (e.g. EI). In practical terms, it is chosen by the combined performance in all the characteristics;

- Broadly speaking, in this method, the mixes are judged based on their performance on all characteristics, not in just one characteristic (dimension).

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For more information:

- Kurda, R., de Brito, J., Silvestre, J. D. (2019). **CONCRETop - A multi-criteria decision method for concrete optimization.** ***Environmental Impact Assessment Review**,* 74, pp. 73-85.
- Kurda, R., de Brito, J., Silvestre, J. D. (2019). **CONCRETop method: Optimization of concrete with various incorporation ratios of fly ash and recycled aggregates in terms of quality performance and life-cycle cost and environmental impacts.** ***Journal of Cleaner Production***, 226, pp. 642-657.
- Kurda, R., Silvestre, J. D., de Brito, J. (2018). **Life cycle assessment of concrete made with high volume of recycled concrete aggregates and fly ash.** ***Resources, Conservation & Recycling**,* 139, pp. 407-417.
- Kurad, R., Silvestre, J. D., de Brito, J., Ahmed, H. (2017). **Effect of incorporation of high volume of recycled concrete aggregates and fly ash on the strength and global warming potential of concrete.** ***Journal of Cleaner Production,*** 162, pp. 485-502.

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CONCRETop OPTIMIZATION

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