LIFE CYCLE ANALYSIS OF RECYCLED AGGREGATE CONCRETE WITH FLY ASH AS PARTIAL CEMENT REPLACEMENT

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Abstract

This paper presents a part of the results obtained within the frame of the SCOPES joint research project – a scientific collaboration between ETH Zürich and Faculty of Civil Engineering, University of Belgrade. One of the goals of the project was to produce recycled aggregate concrete with fly ash as partial cement replacement, which would have mechanical and durability-related properties adequate for structural concrete. At the same time the aim was to replace as much as possible natural resources with waste materials to achieve environmental and cost efficiency. Three mixtures of recycled aggregate concrete were designed with percentages of cement replacement with fly ash equal to 0%, 19% and 38%. Equal compressive strength was set as the design goal and environmental impact assessment was based on that fact. The results of these tests showed that it was possible to reach the same 28-day compressive strength for all three concretes with established mix design procedures. The environmental impacts of the tested concretes types were assessed using the standardized methodology of Life cycle assessment (LCA). The assessment was based mostly on local LCI data and on typical conditions in Serbia. Regarding the impact of fly ash, three different allocation procedures were tested: ’no-allocation’, ’mass allocation’ and ’economic allocation’. Comparative environmental assessment showed that environmental benefits from replacing a part of the cement with fly ash could be gained in the ’no-allocation’ and the ’economic allocation’ case. In the case of ’mass allocation’, all calculated environmental impacts were higher for recycled aggregate concrete with fly ash.

Keywords:

Recycled aggregate concrete; fly ash; LCA; environmental impact; allocation

1 INTRODUCTION

Having in mind environmental, cost and social effects, the concrete industry is regarded as the most significant one within the construction and building materials industry. Considering the volume of produced concrete and number of built concrete structures (roughly 25 billion tons of concrete are produced globally each year, or over 3.8 tons per person per year [1]), the problem of the concrete environmental impact forms a significant part of the global problem of sustainable development. The specific amount of harmful impacts embodied in a concrete unit is, in comparison with other building materials, relatively small. However, due to the high global production of concrete, the final negative environmental impact of concrete structures is significant: a large consumption of natural resources (aggregates for cement and concrete and energy), large CO2 emissions (due to cement production) and a large amount of produced construction and demolition (C&D) waste.

So far a lot of effort has been put into finding sustainable solutions for concrete as a structural material, since concrete is the most widely used in structures. Most of this research was directed towards the partial replacement of cement with

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supplementary cementitious materials (fly ash, blust furnace slag, silica fume etc.) or towards the complete replacement of cement with alkali activated binders. The main aim was to reduce the CO2 emissions since cement production is its major source. The other extensively investigated approach was to replace natural aggregates with recycled ones in order to decrease the natural resources consumption and amount of generated C&D waste.

Research done so far showed that it was possible to produce a concrete which can be used in some structural applications, with partial replacement of cement with fly ash (FA), depending on the amount of replacement [2, 3, 4]. The same goes for the concrete made with partial replacement of natural aggregate (NA) with recycled concrete aggregate (RCA) [5, 6, 7, 8]. The question is then raised if it is possible to produce a structural concrete by replacing both cement and aggregates with waste materials, FA and RCA. And how it would affect the environmental impact of concrete.

2 OBJECTIVES

The objective of the work presented here was to replace as much as possible natural resources in concrete with waste materials to achieve environmental efficiency. To obtain this goal the attempt was made to produce the concrete with partial replacement of cement with FA and partial replacement of NA with RCA, using local Serbian resources. Such concrete should have mechanical and technological properties complying to the requirements for structural concrete. Life cycle assessment (LCA) was performed to estimate the environmental impacts of those concretes.

3 METHOD

An experimental program was carried out to obtain the mix proportions of three different recycled aggregate concrete (RAC) types, so that all of them have the same compressive strength and workability:

RAC_FA0 – recycled aggregate concrete with no fly ash

RAC_FA19 - recycled aggregate concrete with 19% replacement of control RAC_FA0 cement mass with fly ash

RAC_FA38 - recycled aggregate concrete with 38% replacement of control RAC_FA0 cement mass with fly ash

Recycled aggregate concrete was made with coarse RCA and fine NA (sand). In concretes where part of the cement was replaced with FA (RAC_FA19 and RAC_FA38), a part of the aggregates was also replaced with FA. Maximum aggregate content that could be replaced was determined on the basis of the required aggregate mixture particle size distribution according to standard [9].

Selected environmental impacts of these three concrete types were calculated using LCA for the part of the concrete's life cycle which includes the production of aggregates, cement and FA production, production of ready-mixed concrete and transport.

3.1 Mix proportions and properties of concrete

Coarse recycled aggregate was obtained from a demolished reinforced concrete structure which has been exposed to weather conditions for more than thirty years. The crushing of the demolished concrete and screening into three particle sizes, 4/8 mm, 8/16 mm and 16/32 mm, was performed in a mobile recycling plant. Fine natural aggregate, size 0/4 mm, was river aggregate (Morava river). Properties of recycled and natural aggregates are shown in Table 1.

Aggregate type	Dry density (kg/m^3)	Absorption (%)
0-4 mm NA	2573	1.2
4-8 mm RCA	2309	4.6
8-16 mm RCA	2370	3.7
16-32 mm RCA	2372	3.8

Table 1: Properties of NA and RCA.

Fly ash was obtained from the coal-fired power plant "Nikola Tesla B" (TENT) in Obrenovac, Serbia, while blended Portland cement CEM II/A-M (S-L) 42.5R was used. This type of cement has additions (grinded slag and limestone) up to 20% of the total mass. The chemical composition and physical properties of FA and cement are presented in Table 2.

Property	Cement CEM II 42.5R	Fly ash
SiO_2 (%)	21.04	58.24
Al_2O_3 (%)	5.33	20.23
Fe_2O_3 (%)	2.37	5.33
$SiO_2+Al_2O_3+Fe_2O_3$	-	83.80
TiO_2 (%)	-	0.45
CaO (%)	60.43	7.62
MgO (%)	2.43	2.01
P_2O_5 (%)	-	0.00
SO_3 (%)	3.55	2.21
Na_2O (%)	0.22	0.52
K_2O (%)	0.70	1.51
MnO (%)	-	0.03
LOI (%)	3.53	2.10
Fineness (>45 μm, %)	-	11.71
Specific gravity ($kg/m^{3)}$)	3040	2075

Table 2: Chemical and physical properties of cement and fly ash.

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A series of laboratory tests were carried out to obtain the target compressive strength (35 MPa) and target workability (slump equal to 15 cm). The final mix proportions and properties are shown in Table 3. Compressive strength was tested on 100-mm cube samples and values reported in Table 3 are the mean values from three compressive strength test results.

Concrete mixtures with high content of FA were very dry and incoherent in their fresh state and it was necessary to add a certain amount of superplasticizer to obtain a workable mixture. It was noticed that small changes of the superplasticizer content resulted in a significant change in workability. For example, 1.54 kg/m3 and 2.57 kg/m3 of superplasticizer caused RAC_FA19 and RAC_FA38 mixtures to turn into flow, respectively. However, with a somewhat smaller amount of superplasticizer, a required slump of 15 cm can be obtained.

3.2 Environmental assessment

The environmental assessment was performed using LCA methodology, and particularly for the impact assessment, the Institute of Environmental Sciences (CML) baseline method [10] was used.

The goal of this study was to compare the environmental impact of the production of three types of ready-mixed RAC in Serbia: RAC_FA0, RAC_FA19 and RAC_FA38. The analysis was limited to a 'cradle-to-gate' level (extraction and production of constituent materials, production of concrete and transport) and the system boundaries are shown in Figure 1. Since the superplasticizer mass was lower than 0.15% of the concrete mass, its impacts were neglected.

To enable the choice of functional unit only in mass units (in this case one cubic meter of concrete), it is necessary that all analysed different types of concrete fulfil the same functional requirements. This means that they must have the same strength (mechanical properties), workability and durability. For that reason, the mix proportions were determined so that all types of concrete have the same compressive strength and workability. Besides, it was assumed that the durability of analysed concretes was similar if they were exposed to non or low aggressive conditions.

Regarding the production of recycled concrete aggregate, the cut-off rule was applied, i.e. no impacts from parent natural aggregate concrete (NAC) production and all the impacts from recycling were allocated to the RCA production. Production of RCA included the recycling process itself (in a mobile recycling plant, typical for Serbia), transportation of the mobile recycling plant to the demolition site and landfilling of the recycling waste which cannot be used as RCA (assumed recovery rate equal to 60%). For each campaign of 2500 t the mobile plant (20 t) is transported at a distance of 200 km.

Life cycle inventory (LCI) data for aggregate, cement and concrete production, as well as for FA treatment, were site-specific data, obtained from local Serbian suppliers whose products were used for the concrete mix [11,12]. Emission data for diesel production and transportation, natural gas distribution and transport that couldn't be collected for local conditions were taken from the Ecoinvent database [13, 14].

The environmental impact categories included in this work were: abiotic depletion, climate change (global warming as indicator), ozone layer depletion, eutrophication, acidification and photochemical oxidant creation (POC) – summer smog. Besides, the cumulated energy requirement was calculated and expressed as 'energy use'. They were calculated using an original excel-based software made for life cycle inventory and life cycle impacts calculation. As already mentioned, for category indicators calculation the CML methodology [10] was used. It should be pointed out that this methodology does not include solid waste production/landfill capacity as an impact category, or consider sand and stone as abiotic resources that can be depleted.

Transport distances were estimated for the construction site located in Belgrade, the capital of Serbia. For this case, the typical transportation distances and types are as shown in Table 4.

Regarding the RCA transport distance (100 km), it was assumed that the demolition site (which was a source of demolished concrete) is located at 100 km distance from Belgrade.

Since FA is no longer considered as merely waste but as a useful by-product [15], it carries a part of the environmental load of the electricity production in the coal-fired power plant (primary process – main product), besides the load from its own treatment prior to utilization in concrete (secondary process – by-product). Secondary process includes only the transport from electromagnetic separator to the storage silo which is a pneumatic process powered by electricity in the power plant TENT [12].

For the calculation of the part of the primary process environmental load which should be allocated to FA, three types of allocations were considered:

'No allocation' – FA was considered as waste; only impacts from secondary process were included

'Mass allocation' – impacts of primary process were allocated between the main product and by-product according to the ratio of their masses.

The mass allocation coefficient C_m can then be calculated as [16]:

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$$C_m = \frac{m_{byproduct}}{m_{mainproduct} + m_{byproduct}} \quad (1)$$

where $m_{byproduct}$ is FA mass and $m_{mainproduct}$ is electricity mass.

'Economic allocation' – impacts of primary process were allocated between the main product and by-product according to the ratio of their prices.

The economic allocation coefficient C_e can then be calculated as [16]:

$$C_e = \frac{(\varepsilon \cdot m)_{byproduct}}{(\varepsilon \cdot m)_{mainproduct} + (\varepsilon \cdot m)_{byproduct}} \quad (2)$$

where ε is the price per unit of material, and m is the mass of material produced during the process.

For the production of 1 kWh of electricity, 1.290 kg of coal is consumed, while 0.194 kg of fly ash and 0.013 of bottom ash is generated [12]. The mass of the electricity (main product) is calculated as the mass of equivalent coal:

$$m_{mainproduct} = 1.290 - 0.194 - 0.013 = 1.084kg \quad (3)$$

and the mass allocation coefficient $C_{m,FA}$ is:

$$C_{m,FA} = \frac{0.194}{1.084 + 0.194} = 0.152 \quad (4)$$

The cost of fly ash and electricity in Serbia is 1.8€/ton and 0.025€/kWh, respectively. The economic allocation coefficient $C_{e,FA}$ is then:

$$C_{e,FA} = \frac{0.194 \cdot \frac{1.8}{1000}}{1 \cdot 0.025 + 0.194 \cdot \frac{1.8}{1000}} = 0.014 \quad (5)$$

With the allocation coefficients $C_{m,FA}$ and $C_{e,FA}$, the impacts of the primary process (electricity production) were allocated to FA production in the 'mass allocation' and 'economic allocation' case, respectively.

Type of concrete	Cement	Water	Aggregate: Fine (river)	Aggregate: Coarse (recycled)	Fly ash	Super plastic.	w/c[1]	w/b[2]	Slump	Compress. strength
	(kg/m³)						/	/	(cm)	(MPa)
RAC-FA0	308	185+39[3]	593	1102	/	/	0.52	0.52	16	35.3
RAC-FA19	250	201+44[3]	500	870	288	1.54	0.81	0.37	35[4]	36.5
RAC_FA38	192	180+45[3]	500	899	346	2.57	0.94	0.335	40[4]	36.3

1) water-to-cement ratio
2) water-to-binder (cement+fly ash) ratio
3) additional water amount
4) flow value

Table 3: Mix proportions and properties of concrete.

Material	Route: From	Route: To	Transport distance (km)	Transport type
River aggregate	Place of extraction	Concrete plant	100 x 2	Barge 10000 t
Cement	Cement factory	Concrete plant	100 x 2	Truck 16-32 t
Fly ash	Power plant	Concrete plant	50 x 2	Truck 16-32 t
Recycled aggregate	Recycling plant[1]	Concrete plant	100 x 2	Truck 16-32 t
Waste from recycling	Demolition site	Landfill	30 x 2	Truck 16-32 t
Mobile recycling plant [2]		Demolition site	200	Truck 16-32 t

1) Recycling is performed in mobile plant at demolition site
2) For each campaign of 2500 t the mobile plant (20 t) is transported at a distance of 200 km

Table 4: Transport distances and types.

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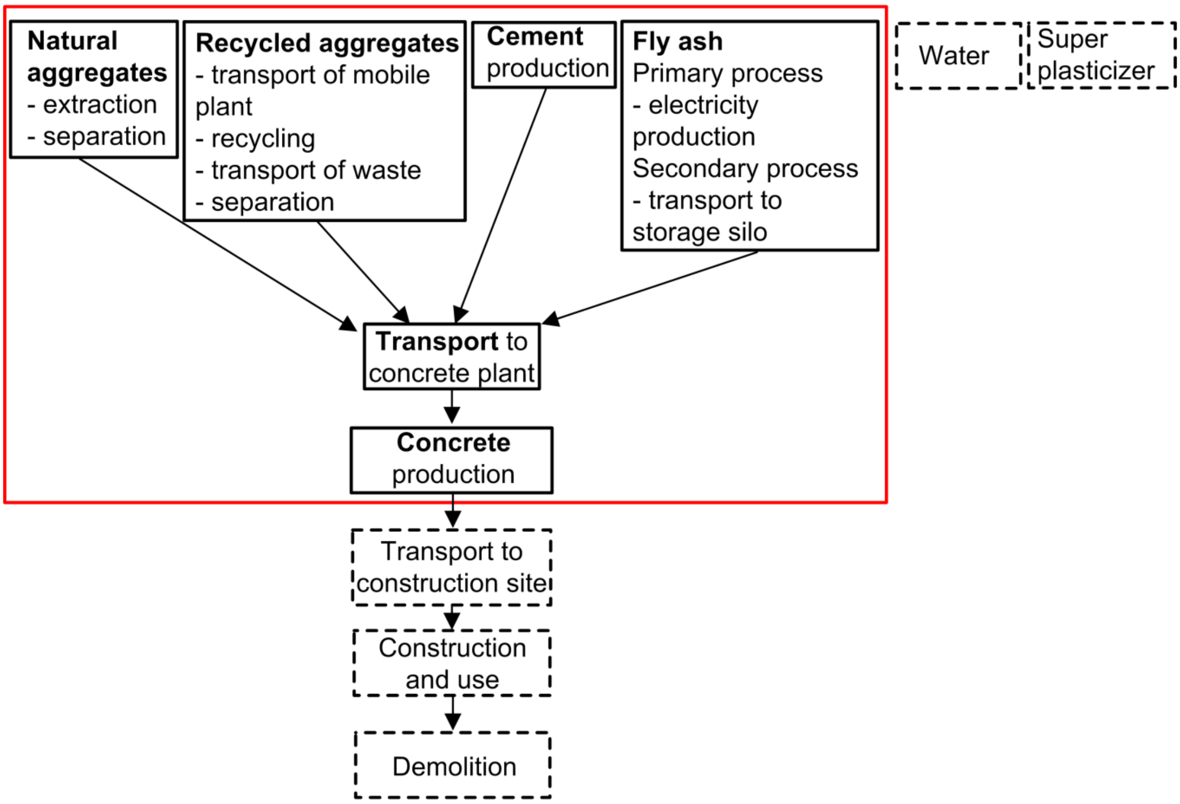

Fig. 1: Life-cycle of a concrete structure and system boundaries in the case study.

4 RESULTS AND DISCUSSION

Calculated impact indicators in the 'no allocation', 'mass allocation' and 'economic allocation' case are shown in Figures 2, 3 and 4. Impact indicators of RAC_FA19 and RAC_FA38 are presented as percentage of RAC_FA0 impact indicators.

It can easily be seen that in the 'no allocation' case all impacts of RAC with fly ash are lower than the impacts of RAC with no fly ash, the decrease being larger with a higher amount of FA. Results are different for other types of allocation since large quantities of airborne pollutants are emitted from coal power plants in the process of electricity production and even a small allocation coefficient can strongly affect FA impact indicators [16].

This is especially the case with 'mass allocation' because a relatively large mass of FA is generated during electricity production. In this case, all impacts of RAC with FA, except ozone layer depletion, are significantly higher than impacts of RAC with no FA, the increase being larger with higher amount of FA.

In the 'economic allocation' case results are more favourable for RAC with FA mostly because of the very low price of FA in Serbia. In this case all calculated impact indicators of RAC_FA38 (except eutrophication where calculated values are approximately the same) are lower than the impact indicators of RAC with no fly ash. This decrease can be considered as significant since it ranges from 3% to 38%, depending on the impact indicator. RAC_FA19 has a somewhat higher (8% - 9%) eutrophication and acidification indicator than RAC_FA0, while other indicators are lower than indicators of RAC with no FA.

5 CONCLUSION

This case study was based on Serbian LCI data and typical conditions in Serbia. Within these limits, and for the chosen impact categories, it was concluded that FA application in recycled aggregate concrete can bring environmental benefits over cement application, but this depends on the applied type of allocation.

If mass allocation is applied, the FA environmental burdens become higher than the burdens of blended Portland cement and this can certainly discourage the producers to implement this material as cement clinker replacement. That's why the economic allocation is recommended since it results in much (several times) lower impacts of FA. Similar conclusions have been made by other researchers [16, 17] regarding the FA environmental impact when used as a mineral addition to concrete.

The important environmental benefit which is not accounted for in the CML methodology is the amount of waste materials used for the production of RAC with FA. Only 40% (35% if water is excluded) of RAC_FA38 is made of natural resources, while 60% (65% if water is excluded) is made of waste – RCA and FA. Yet

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this concrete can be used in structural applications where low-to-middle strength concrete is economically justified (for instance in residential buildings). This certainly contributes to the preservation of natural bulk resources and landfill capacity, both becoming an important and scarce resource nowadays in many countries.

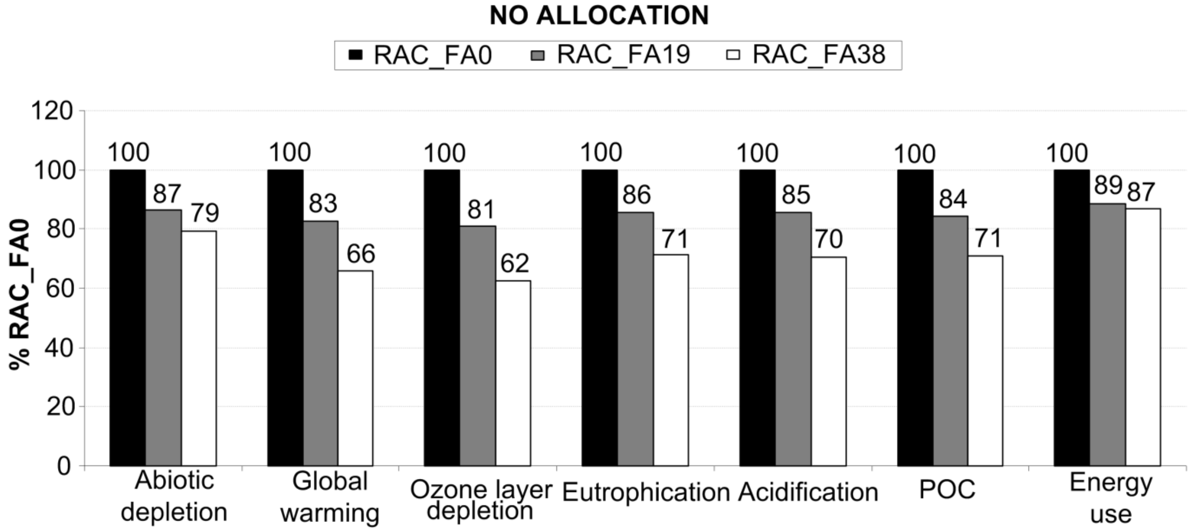

Fig. 2: Impact category indicators in 'no allocation' case.

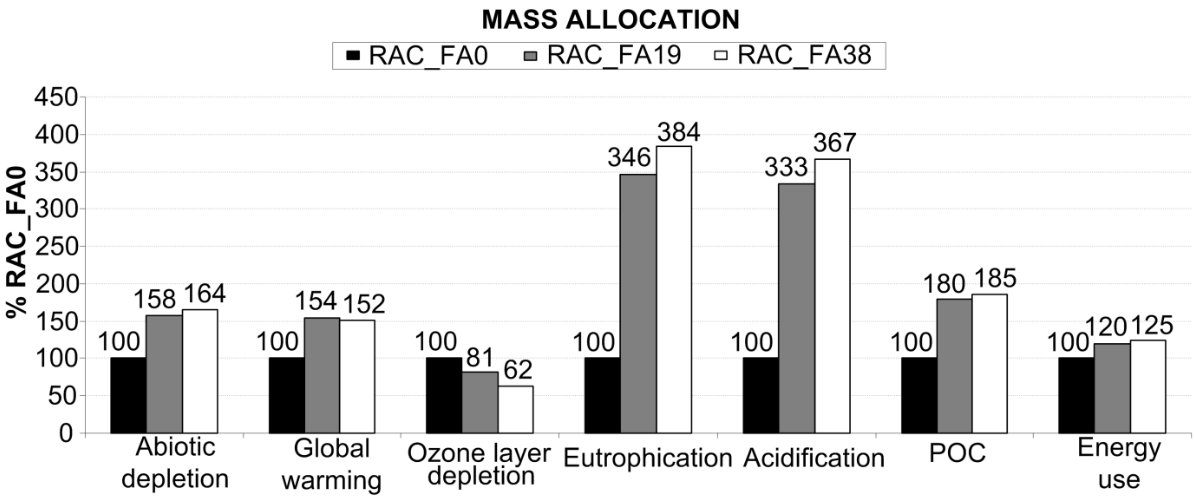

Fig. 3: Impact category indicators in 'mass allocation' case.

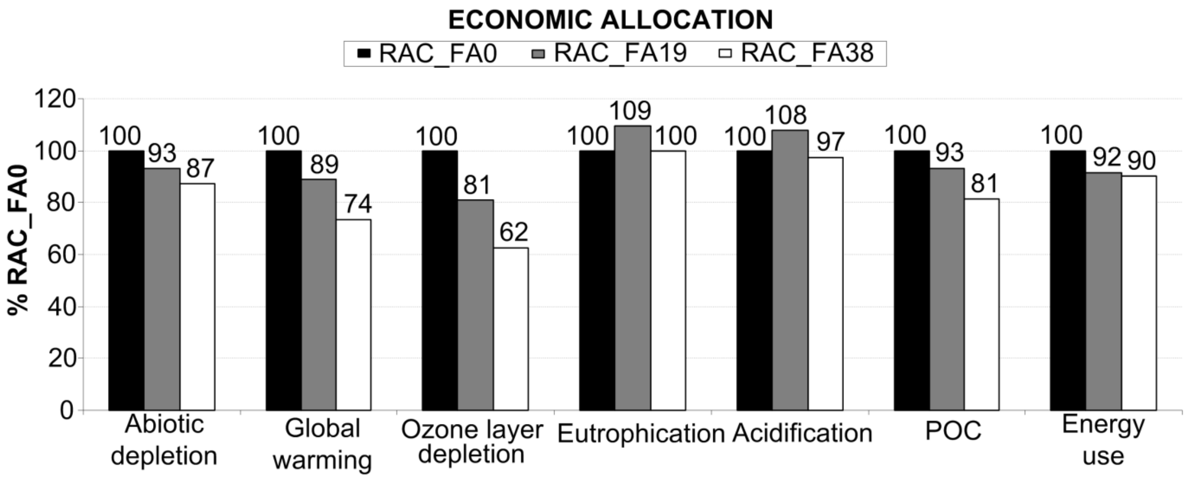

Fig. 4: Impact category indicators in 'economic allocation' case.

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