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Environmental, economic and experimental assessment of the valorization of dredged sediment through sand substitution in concrete

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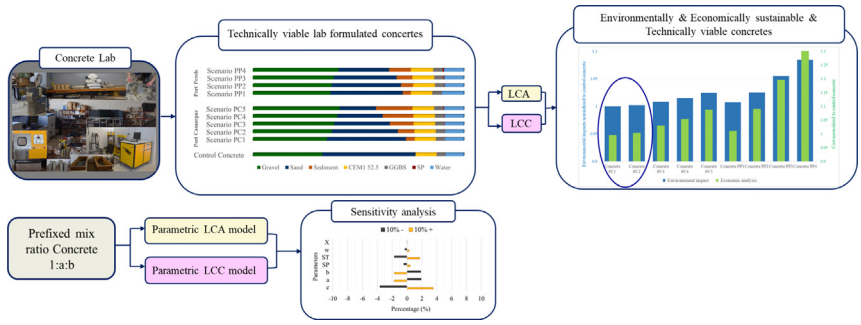
HIGHLIGHTS

- LCA and LCC were integrated into the lab-based valorization scenarios for sediment.
- The threshold of the sustainable rate of sediment incorporation was obtained by LCA & LCC.
- The rate of sand substitution by dredged sediment higher than 20 % was not sustainable.
- Superplasticiser and transport limited the sustainable rate of sediment in concrete.

GRAPHICAL ABSTRACT



ABSTRACT

The integrated life cycle assessment (LCA), life cycle cost assessment (LCC) and laboratory-based experimental assess-ment were applied to provide insight for early stage decision-making on the valorization of the dredged sediments. The objective was to find a viable and sustainable solution for the valorization of the dredged sediment in concrete, holding up a certain level of standard concrete performance without compromising in terms of economy and environment. For the sensitivity analysis, parametric life cycle inventories were developed to assess the sensitivity of environmental and economic costs to the rate of sand substitution by sediment, as well as the variations in the concrete components. The workability of fresh concrete and the compressive strength of hardened concrete at 28 days were assigned as the qual-ity indicators to evaluate the influence of sand substitution by sediment on the concrete performance. The compressive strength evaluation in the laboratory demonstrated that a maximum rate of sand substitution in concrete up to 40 % by predominantly sandy sediment could sustain the concrete strength class. However, LCA and LCC negated the rate of sand substitution by sediment higher than 20 %. The integrated environmental, economic, and experimental assess-ments demonstrated that the substitution of sand by predominantly fine sediment downgrades the strength class of concrete, even in the low rate of incorporation (10 %) and increases the environmental and economic costs. Inferred from the results, the maximum rate of sustainable sand substitution by sediment in concrete could be optimized through a compromise between the expected mechanical strength and workability of the concrete, the economic and environmental impacts of the superplasticiser and the sediment transport. Overall, integrating environmental and economic cost assessments into the laboratory-based assessment of the valorization scenarios would determine the threshold for the sustainable rate of incorporation of sediment in valorization scenarios.

Keywords:
Life cycle assessment
Life cycle cost assessment
Environmental assessment
Economic assessment
Dredged sediment
Valorization
Concrete

1. Introduction

Ports as the nodes of the maritime transport network are vital for local and global economic development. To sustain the operational water

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depth at ports for maritime navigation, dredging operations are necessary on a regular basis. The more than 300 million tons of sediments dredged annually in Europe (Snellings et al., 2016; Amar et al., 2018) are needed to be managed through marine or land disposal. The satisfying the gradually stricter regulatory requirements which imposes considerable burdens on the local and global economy and environment. The change in point of view from focusing on dredged sediment as a challenge may offer an opportunity rather than a threat (Rakshith and Singh, 2016). The valorization of the sediment in the scope of the circular economy could alleviate the environmental, economic and social impacts and even turn the sediment into a beneficial local resource (Brils et al., 2014; Crocetti et al., 2022).

Valorization strategies adapted to the local conditions can be developed through a collaboration between the local actors such as port authorities, academics, and stakeholders (Abriak et al., 2006). The feasibility of incorporating dredged sediments as a fraction of substitute for cementitious matrix and the potential application in the construction materials are proven by several studies. The dredged sediments are promisingly valorized in roads (Junqua et al., 2006; Kasmi et al., 2017; Bellara et al., 2021), fired clay bricks (Samara et al., 2009), partial substitution of sand by the sediment (Beddaa et al., 2020; Kazi Aoual-Benslafa et al., 2012), partial replacement of cement by the calcined sediment in concrete (Laoufi, 2016; Amar et al., 2020; Hadj Sadok et al., 2022) and mortar (Beddaa et al., 2020; Ezzaki and Diouri, 2018; Benslafa et al., 2015; Agostini et al., 2007) as well as self-compacting concrete (Ouédraogo et al., 2021).

Several studies investigated the valorization of untreated dredged sediments. Some of them have investigated the sediment valorization in terms of technical feasibility (Beddaa et al., 2022), some others in terms of economy and environment (Zhao et al., 2018; Achour et al., 2019). For large-scale application of sediment-based products which are technically feasible, economically and environmentally sustainable and are able to compete with the conventional ones in the market is still lacking (Crocetti et al., 2022). In addition, the sustainable threshold of sand substitution by sediment in concrete is not studied through integrating LCA and LCC to the experimental prototyping.

This study presents a part of a comprehensive ongoing project on strategies for feasible and sustainable valorization of large quantities of dredged sediment. The Ports of Camargue (PC) and Perols (PP) are marinas in the south of France in the region of Occitanie, where several million m^3 of sediment has to be dredged annually by the marinas, the harbor regional service and France inland waterways. As the most widely used construction material in the world (Henry and Kato, 2014), concrete promising for the mass valorization of sediment. Accordingly, varied rate of sand substitution in an ordinary concrete was aimed to be assessed in terms of technical feasibility as well as the economic and environmental sustainability.

To assess the sustainability of sediment management strategies and the valorization scenarios, life cycle assessment (LCA) is a common approach. LCA has been applied to evaluate various management options for marine dredged sediment (Svensson et al., 2022; Hossain et al., 2020; Bai et al., 2017; Zhou et al., 2021) as well as the dredged sediment valorization scenarios (Hadj Sadok et al., 2022; Zhou et al., 2021). A series of trial concrete formulations and laboratory evaluation of the workability and strength of the concretes with the orientation of industrial scale application were performed in this study. In parallel, we have applied LCA for comparative environmental impact assessment of the untreated sediment valorization scenarios which arises from the rates of incorporation of dredged sediments in concrete. To assess the sustainability of the valorization scenarios, a complementary life cycle cost assessment (LCC) was implemented based on the current French market. The consistency in both economic and environmental inventories enabled to conduct reliable comparative assessment between the valorization scenarios. To determine the sensitivity of environmental impacts and the cost of concrete to the quantity of materials and processes involved in its production, parametric inventories based on a prefixed mix ratio concrete were applied.

The aim of this study as a collaborative partnership between the port authorities, the academic researchers, and the regional concrete plant was to find a viable and sustainable solution for the valorization of the dredged sediment in concrete. The viable valorization scenarios were obtained from the laboratory-based trials for sand substitution by sediment in concrete, directly applicable in concrete plants. To distinguish the sustainable scenarios, LCA and LCC were integrated into the laboratory-based trials to determine the consensual threshold for the practical and sustainable rate of sand substitution by sediment in concrete.

2. Materials and methods

2.1. Life cycle assessment

Life cycle assessment (LCA) is the most popular and recognized analytical framework to assess holistically the environmental impacts associated with the entire life cycle of a product or process (Guinee, 2002). It identifies hotspots that have a high contribution to the environmental impacts. The comparative LCA was performed under the four standard phases of goal and scope definition, inventory analysis, impact assessment and interpretation as outlined in ISO 14040, 2006 and ISO 14044, 2006. The life cycle inventories of the scenarios (LCIs) were developed for the experimental scenarios in openLCA v. 1.11.0, using the inventories from the database ecoinvent, v. 3.5 with allocation at the point of substitution and modifications based on the data from the field.

The Recipe midpoint (H), a state-of-the-art and harmonized life cycle impact assessment method at the midpoint and endpoint level (Huijbregts et al., 2017; Mehmeti et al., 2018) was applied in this study to assess environmental impacts in 18 categories yet 8 conventional local and global environmental impact categories in concrete LCA studies were adopted for visual presentation including: global warming potential (GWP: kg CO_2eq), freshwater eutrophication potential (FEP: kgPeq), human toxicity potential (HTP: kg dichlorobenzene (1,4-DCBeq), marine eutrophication potential (MEP: kg N eq), terrestrial ecotoxicity (TETP: 1,4-DCBeq), photochemical oxidant formation (POFP: 9.47273E-5 kg NMVOC), ozone depletion (ODP: kg CFC-11 eq), and terrestrial acidification potential (TAP: kg SO_2eq).

To be able to track the economic and environmental variations between the scenarios the impacts of $1m^3$ of an ordinary concrete was assigned as the control concrete for the comparative assessment. In addition, the impacts of the control concrete were applied for the normalization to convert the impact indicator values with varied units into a unitless score by dividing the impact values to the corresponding of control concrete. This normalization facilitates the comparison between impact categories as well as the scenarios.

2.2. Goal and functional unit of the LCA

The goal and scope definition provide a description of the production system in terms of system boundary and a functional unit. The functional unit represents the quantified performance of a product system for use as a reference unit for the LCA study. It relates all the incoming and outgoing flows of the production system and ensures comparable product quantities to have reliable LCA results. Among the most common types of functional units applied for concrete production, including volume ($1m^3$), mass (1 t) and the performance of compressive strength, volume is the most common functional unit used in concrete LCAs (Panesar et al., 2017). Accordingly, the functional unit used in this study is one cubic meter ($1m^3$) of concrete at the gate of the concrete plant. All input of energy and materials, the emissions of pollutants, and transportation distance are defined based on this functional unit. All the processes in the concrete production chain were considered in the cradle-to-gate system boundary such as the production of cement (CEM I, 52.5), ground granulated blast-furnace slag (GGBS), aggregates (sand, gravel), water, energy, concrete mixing factory, transport of materials to the concrete plant, and the manufacture of concrete in the plant (Fig. 1). The whole environmental impacts of sediment dredging up to end of dewatering on land were allocated (cut off) to the dredging operation and the sediment was considered to be recyclable material with zero environmental impacts. The use stage and the end-of-life phase of the products were not considered in the study. It is assumed that the organic, inorganic and the heavy metals content of the sediment are completely

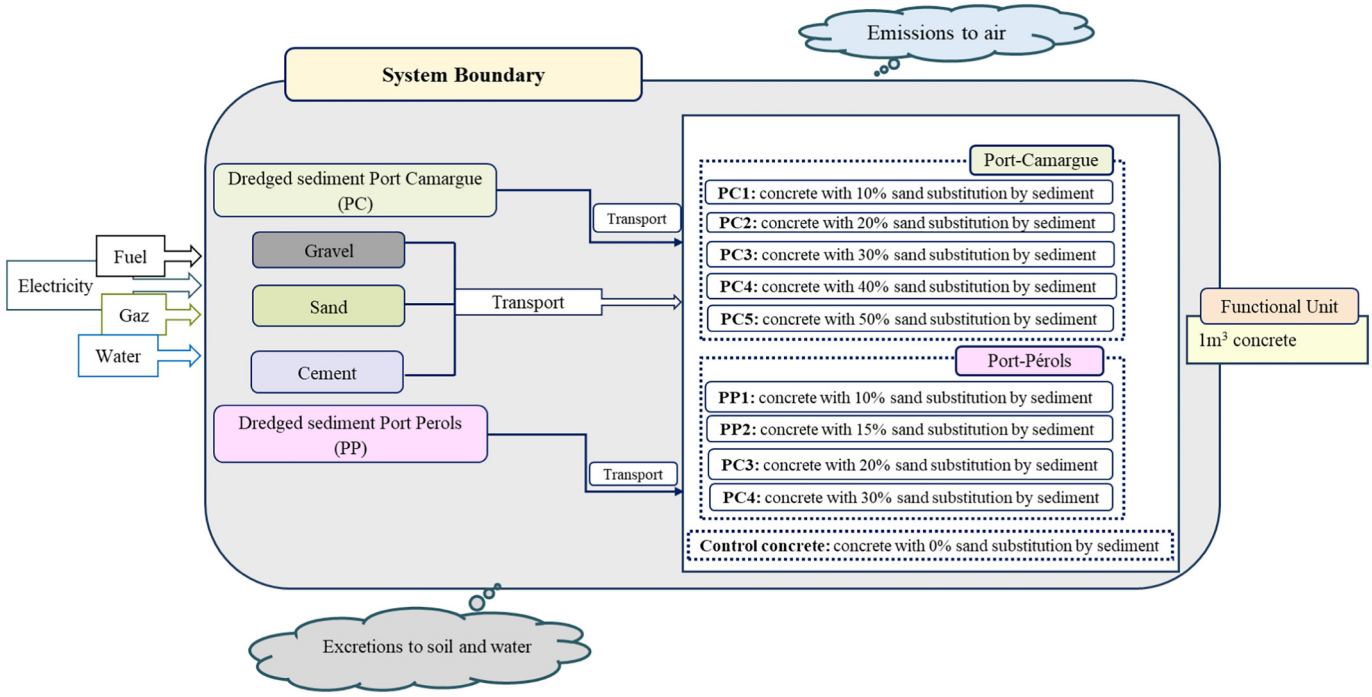

Fig. 1. Scheme of the system boundary, which includes the production of cement, ground granulated blast-furnace slag (GGBS), aggregates (sand, gravel), superplasticiser, water, energy, concrete mixing factory, transport of materials to the concrete plant, and the manufacture of concrete in the plant.

immobilized and solidified in the concrete production. As the complementary information to provide more insight into the sensitive parameters, the hotspot contributed materials and processes, and the interval of variations in the impacts, the results of sensitivity analysis, contribution analysis, and uncertainty analysis are presented in this study. For the reliability of the comparative assessments, the model, the inventories, the method, the system boundary and the unit prices of the market were consistent for all the concrete scenarios.

2.3. Data

The LCI for concrete production were adopted from background inventory data in ecoinvent database v.3.5 in openLCA including energy, materials and transportation. To perform a comparative attributional LCA, the mean values of the inputs and outputs of the system boundary were adopted from the project internal data. The physico-chemical and geotechnical qualification parameters of the sediment samples of the ports (PC: port Camargue; PP: port Perols) as well as the heavy metals, exogenous organic matters including polychlorobiphenyls (PCBs), polycyclic aromatic hydrocarbon (PAHs), total organic carbon (TOC), total nitrogen (TN) and total phosphorus (TP), is characterized by the CISMA environment laboratory in France (Table S1; S: supplementary material). The chemical analysis of the PC and PP sediments showed that these are non-hazardous sediments and can be incorporated into concrete without the need for treatment. According to the laser granulometry analysis, the sediments PC are formed mainly by fine sands (49 %) with an average diameter of 177.49 μm while those of PP are mainly formed of silt (70 %) with an average diameter of 44.27 μm (Table S1). The transports of input materials for all the scenarios were estimated from the origin to the destination (concrete plant) using Google Maps. The sediment samples were collected from different locations in the ports, illustrated on the map (Fig. S1).

2.4. Experimental lab derived scenarios

The composition of the concretes with sand substitution by two types of sediments were obtained applying the modified Dreux-Gorisse method (Dreux, 1981; Dreux and Festa, 1998). In this method, the proportions of the composition of the concrete could be determined based on the granulometric analysis. The optimal component quantities of one cubic meter of an ordinary concrete of grade C30/37 with slump class S4 (16–21 cm), the minimum binder content of 330 kg/m^3 and a water/cement ratio not higher than 0.55, were obtained from this method for one cubic meter of concrete. The concretes were formulated based on constant quantities of binder composed of 70 % CEMI 52.5 N and 30 % ground granulated blast-furnace slag (GGBS), and partially substitution of sand by the untreated sediment. Two quality indexes of workability for the fresh concrete (the slump level) and the compressive strength for hardened concrete (3, 7 & 28 days) were assigned to evaluate the impacts of sand substitution by sediment on the concrete practical performances. The objective was the maximum substitution of sand by sediment yet conserving the workability and mechanical resistance of the concrete. To specify the effect of sediment incorporation on the workability of the concrete, a slump cone test (slump of 190 mm ± 25 mm according to NF EN 12350–2 (EN 12350–2, 2019)) was performed for each fresh concrete scenario in the lab. To retain the expected slump level (S4), the required quantity of superplasticizer (MasterSure Hes 1503) was incorporated into the concrete. To investigate the effect of sediment incorporation on the compressive mechanical resistance of the concrete, uniaxial compression tests were implemented on cylindrical specimens at 3, 7 and 28 days. The quantity of the ingredients in one cubic meter of the lab formulated concrete scenarios with the sand substitution by 10 % (PC1), 20 % (PC2), 30 % (PC3), 40 % (PC4) and 50 % (PC5) of sediment from port Camargue and by 10 % (PP1), 15 % (PP2), 20 % (PP3) and 30 % (PP4) of sediment from port Perols are presented in Table 1. The names of scenarios are abbreviated according to the origin port of the sediment (PC: port Camargue; PP: port Pérols) and ordered according to the volume rate of sand substitution by the sediment (%). Since the concretes are derived from the Dreux-Gorisse method, the sand substitutions by sediment are not precisely in compliance with the exact percentage in the concrete scenarios (PC1 ~ approximately 10 % sand substitution by sediment).

2.5. Cost evaluation

To assess the sustainability, a parallel economic assessment is a key factor for decision making about the sediment management and valorization

Table 1
The quantity of the ingredients in $1m^3$ of the lab formulated concrete scenarios.

Materials	Control Concrete	Port Camargue					Port Perols			
		Scenario PC1	Scenario PC2	Scenario PC3	Scenario PC4	Scenario PC5	Scenario PP1	Scenario PP2	Scenario PP3	Scenario PP4
Gravel (16–14)	785.5	835.5	882	901.5	927.5	951	862	864	884.5	917.5
Sand (0–4)	1059.5	894.15	736.8	614.6	503.4	400	802	759.5	688	542
Sediment	0	99.35	184.2	263.4	335.6	400	89.1	133.5	172	232.5
CEM I 52.5	238	238	238	238	238	238	238	238	238	238
GGBS	102	102	102	102	102	102	102	102	102	102
Superplasticiser	0.2475	0.66	1.65	3.3	4.785	6.6	1.815	5.28	9.9	15.18
Water	202	208.5	205.5	208	207.5	212.5	242	205.5	208	207.5

Sand substitution by 10 % sediment (PC1), 20 % (PC2), 30 % (PC3), 40 % (PC4) and 50 % (PC5) and by 10 % (PP1), 15 % (PP2), 20 % (PP3) and 30 % (PP4); PC: Port Camargue, PP: Port Perols.

scenarios. To conduct an LCC in Excel, the costs of energy, raw materials (cement, sand, gravel, superplasticiser, GGBS), transport, labor, equipment, and maintenance, obtained from the French market (Table S2), were applied in this study. The cost of $1m^3$ of concrete for each scenario was calculated according to the rate of incorporation of materials and processes in the concrete production and their market price. The raw sediment of both ports with no treatment (drying, grinding, screening, etc.) was considered with a zero-market value yet the cost of its transport is taken into account.

2.6. Uncertainty analysis

A Monte Carlo (MC) simulation is an approach to quantify the effects of uncertainties of the model parameters on the estimated environmental impacts: by resampling parameter values based on their uncertainties, a confidence interval can be obtained for each impact. Monte Carlo simulations were run (1000 trials) to assess the sensitivity of the impact categories to the uncertainties in the model inventories. The uncertainty analysis unveils the confidence interval in each impact category. The statistical uncertainties are captured via MC analysis embedded in openLCA through random sampling from the probability distributions of the parameters incorporated in the processes. The 5 % percentile and 95 % percentile of the environmental impact values resulting from 1000 MC simulations would be illustrated in the graph of environmental impacts of scenarios as the upper and lower error bars representing the 90 % confidence interval.

2.7. Developing parametric life cycle inventories (LCI) for environmental and economic sensitivity analysis

Sensitivity analysis is the study of the relative importance of different input parameters in the model outputs. To perform a sensitivity analysis, it is necessary to have a parametric model in which all the incorporated parameters are mathematically interlinked together and to the outcome of the model (Soleimani and Gilbert, 2020). In this way, any change in input parameters would affect the related procedures and changes the outcome, an ideal tool for sensitivity analyses on the incorporated parameters in the model. The parametric LCI was developed for environmental assessment in openLCA and for economic assessment in Excel for $1m^3$ concrete production based on a prefixed mix ratio of Cement: Sand: Gravel (c: a: b). The concrete mixing ratio determines the proportional volume of cement, sand and aggregate as the basic constituent materials in concrete. The formulations for calculation of the quantity of concrete components based on c: a: b mix ratio integrated to partial sand substitution by sediment are presented in Table S3. The percentage of sand substitution by sediment on volume was incorporated as the variable of X in the LCIs enabled to analyse the variations in the environmental and economic costs of $1m^3$ concrete corresponding to the X variations. To consider the difference of the sediment's PC and PP in terms of the density and transport, separate LCIs for PC and PP scenarios were developed. To ensure the comparability of results, the methods, inventories, market prices and calculations were kept the same in all the LCIs. A 'one-at-a-time (OAT)' sensitivity analysis, an appropriate approach for non-correlated parameters in a linear model, was applied in our sensitivity analyses. In an OAT sensitivity analysis, all incorporated production parameters will be held constant, but the value of one parameter would be changed by $\pm 2SD$ or a percentage of its mean value. To perform the sensitivity analysis, the percentage of superplasticiser relatively to cement, the water to cement ratio, the rate of sand substitution by sediment, and the transport of sand and cement were changed ± 10 % and the percentage of changes in the environmental impacts and the price of $1m^3$ concrete were calculated.

3. Results and discussion

In this study, we integrated LCA and LCC to laboratory-based trials and errors for incorporation of dredged sediments as a substitute for a fraction of sand in concrete to provide a comprehensive insight from a combined environmental, economic and technical point of views. The results of experimental, environmental and economic assessments of the partially sand substitution by two distinct granulometric dredged sediments are reported. The modifications of the concrete composition proportionally to the increase in the rate of sand substitution by sediment, the challenges and the limitation in terms of technic, environment and economy are discussed.

3.1. Environmental, economic and experimental results of the lab concrete scenarios

3.1.1. Experimental performances of concrete scenarios

The experimental evaluation of the workability of the fresh concrete scenarios demonstrated that the fluidity of the concretes was decreased proportionally to the contribution of sediment in the concrete, despite the addition of excess quantity of water. To maintain the subsidence class of S4 as the quality indicator for the workability of the fresh concrete, an additional amount of superplasticiser was added to the mix. The significantly higher requirement of superplasticiser (15.18 kg) for 1 m^3 concrete with a sediment of port Pérols could be attributed to the higher absorption capacity due to finer particles with greater specific surface area (10,97 $\pm$ 3,14 m^2/g for PP vs. 3.14 $\pm$ 0.82 m^2/g for PC) of sediment (Zhang et al., 2021). The mechanical resistance tests of specimens at 28 days unveiled that in spite of the considerable reduction in the mechanical strength, the concretes with sand substitution up to 40 % by the sediment PC could sustain in the C30/37 concrete class, while the one based on 50 % sediment PC and all those by the supplementing of sediment PP downgraded to the lower concrete classes. (e.g.: class C20/25 for 50 % sediment PC; class C16/20 for 30 % sediment PP). The decline in the concrete strength due to the untreated sediment incorporation could be attributed to the organic and inorganic impurities, additional admixture, fine sediments (clay) and their chemical interactions (Amar et al., 2020; Beddaa et al., 2022).

3.1.2. Comparative environmental and economic impacts of experimental concrete scenarios

To have insight into the overall impacts of each scenario, the economic and environmental impacts of the scenarios normalized to the corresponding impacts of the control concrete were calculated. For environmental impacts, the mean values of the 18 impact categories estimated by method

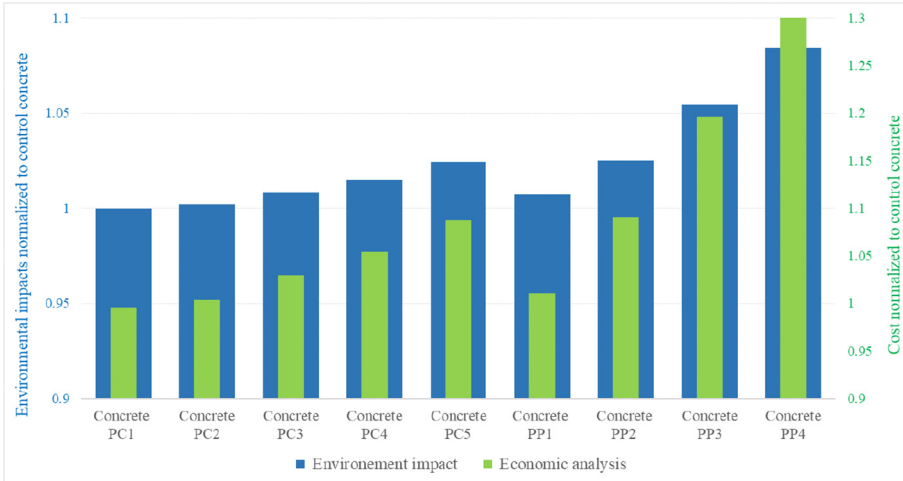

Fig. 2. Single score environmental impacts and costs of the experimental concrete scenarios normalized to the corresponding of control concrete. Sand substitution by 10 % sediment (PC1), 20 % (PC2), 30 % (PC3), 40 % (PC4) and 50 % (PC5) and by 10 % (PP1), 15 % (PP2), 20 % (PP3) and 30 % (PP4); PC: Port Camargue, PP: Port Perols.

Recipe midpoint (H) (Table S4) were normalized to those of the control concrete and were integrated into a single score. The single score of each concrete scenario normalized to the single score of the control concrete, along with the cost of each concrete scenario (Table S5) normalized to the cost of the control concrete are superimposed in a graph to provide visual insight at a glance about the sustainability of the concrete scenarios (Figs. 2, 6). The graph illustrates the impacts of sand substitution by sediment PC up to 10 % (PC1) has lower cost and environmental impacts compared to the control concrete, while up to 20 % (PC2) exhibit approximately the same cost and environmental impacts as the control concrete. For the PC scenarios at 10 % (PC1) the economic and environmental impacts are inferior to those of the control concrete and at 20 % (PC2), the additional impacts of modifications in concrete composition have neutralized the economic and environmental benefits of sand substitution by sediment. In other side, the economic and environmental impacts of all the scenarios with the sand substitution by sediment PP from 10 % (PP1) to 30 % (PP4) outweighed those of the control concrete (Fig. 2).

The percentage of variations of the environmental impacts in eight categories as well as the cost among the scenarios are visualized in Fig. 3. Apparently, the rate of variation in concrete costs is higher than the rate of variation in the environmental impact of concrete scenarios, especially among PP scenarios. The cost of $1m^3$ is increased 23 % from the minimum cost (103.2€) for PC1 to maximum cost (135.6€) for PP4. The terrestrial acidification is the most influenced indicator (18.6 %) and the climate change is the least affected impact category (3.6 %) among all the concrete scenarios including the control concrete, mainly due to the high contribution of superplasticiser. Among PC scenarios the minimum cost and environmental impacts were obtained for PC1 and among PP scenarios the minimum and environmental impacts were obtained for PP1. For all the scenarios plus the control, the least cost was obtained for PC1 and the least POFP is obtained for PP1, while PP4 showed the maximum cost and environmental impacts.

3.2. Contribution analysis

To reveal the economic and environmental hotspots and to track the variations in contribution of the materials and the processes between scenarios, the contribution analysis was performed. The cost contributions of the materials and the processes in the total costs of $1m^3$ concrete based on sand substitution by PC sediment and PP sediment are compared to the cost contributions of the control concrete in Fig. 4.

The increase in the cost contribution of superplasticiser and the decrease in the cost contribution of sand between PP and PC scenarios is evident. The incremental trend of the cost contribution of superplasticiser from PP1 to PP5 and PC1 to PC4 is in comply with the increase of the concrete cost between corresponding scenarios. The increase in the quantity of superplasticiser from 0.247 kg in the control concrete up to 6.6 kg in PC5

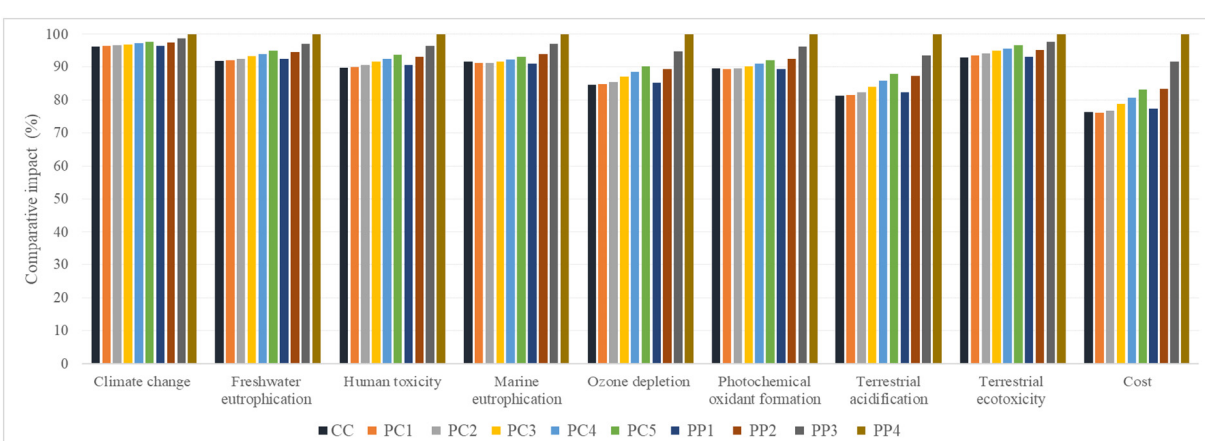

Fig. 3. Comparative environmental impacts and cost for concrete scenarios. Sand substitution by 10 % sediment (PC1), 20 % (PC2), 30 % (PC3), 40 % (PC4) and 50 % (PC5) and by 10 % (PP1), 15 % (PP2), 20 % (PP3) and 30 % (PP4); PC: Port Camargue, PP: Port Perols, CC: control concrete.

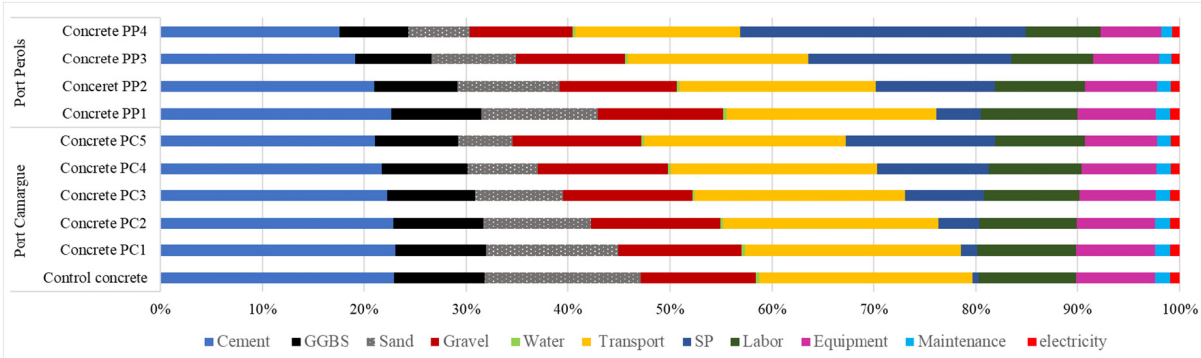

Fig. 4. Comparison between the cost contribution of materials and processes of experimental concrete scenarios. Sand substitution by 10 % sediment (PC1), 20 % (PC2), 30 % (PC3), 40 % (PC4) and 50 % (PC5) and by 10 % (PP1), 15 % (PP2), 20 % (PP3) and 30 % (PP4); PC: Port Camargue, PP: Port Perols.

and up to 15.18 kg in PP4 has increased the cost contribution of superplasticiser from 0.5 % in control concrete to 14 % in PC5 and 27 % in PP4. The const contribution of sand is decreased from 15 % in control concrete to 5 % in PC5 and to 6 % in PP4. The incremental trend in cost contribution of superplasticiser among the scenarios is mainly due to the high price of 2.5 € per litter of superplasticiser as well as its rate of incorporation from 0.075 % in control concrete to 2 % in PC5 and to 4.6 % in PP4. The environmental contributions of the materials and the processes involved in 1m^3 concrete production for the lowest sand substitution of 10 % (PP1, PC1) and the highest sand substitution of 50 % (PC5) and 30 % (PP4) by sediment in each group of scenarios are compared with the corresponding of the control concrete in Fig. 5.

From the environmental contribution graphs of the control concrete it is apparent that the contributions of the binder (cement plus GGBS) and the transport are dominant in all the environmental impact categories, the same for the environmental contributions of the experimental scenarios. The environmental contribution analysis highlighted the contribution of the environmental impacts of superplasticiser in the incremental environmental impacts of the lab concrete scenarios, proportionally to the rate of incorporation of superplasticiser. The contribution percentages (%) of the GWP, FEP, HTP, MEP, ODP, POFP, TAP, TETP impacts of superplasticiser has increased from 0.17, 0.42, 0.39, 0.51, 0.81, 0.60, 1.00, 0.32 in PC1 to 1.17, 4.08, 3.81, 5.02, 7.71, 5.90, 9.35, 3.10 in PC5 respectively. Similarly, the contribution percentages of those impacts of superplasticiser is increased from 0.47, 1.15, 1.07, 1.41, 2.23, 1.66, 2.72, 0.88 in PP1 to 3.85, 8.9, 8.35, 10.8, 16.11, 12.55, 19.14, 6.91 in PP4 respectively.

3.3. Uncertainty analysis

To unveil the uncertainties in the environmental impacts, the MC simulation was carried out on the process parameters of the lab scenarios in openLCA, when all the parameters fluctuated in the range of ±5 %. Due

Fig. 5. Comparison of environmental impacts contributions between the extreme sand substitution by sediment within experimental concrete scenarios. Sand substitution by 10 % sediment (PC1), 50 % (PC5) and by 10 % (PP1), 30 % (PP4); PC: Port Camargue, PP: Port Perols.

to the practical limitations and time-consuming processes, the uncertainties of only four global and local environmental impact categories, resulting from 1000 MC simulations are illustrated as error bars in Fig. S2, representing the respective 5 % percentile and 95 % percentile.

The results of uncertainty analysis determine that considering the variations in all the process parameters in the range of ±5 %, the impacts would fluctuate in a limited range between the upper and lower bands of error bars as the 90 % confidence interval. The results illustrate that some scenarios may outrank other scenarios when the uncertainties in the input parameters are taken into account.

3.4. Sensitivity analysis

The parametric LCIs were developed based on an ordinary concrete with one part of cement, three parts of sand and three parts of aggregate, water cement ratio of 0.55, SP cement ratio of 0.01 and with 30 % GGBS incorporation in cement. The costs and single score environmental impacts of concrete scenarios derived from 10 % to 50 % sand substitution by sediment PC and from 10 % to 30 % sand substitution by sediment PP with the assumption of no change in other components of concrete, normalized to corresponding of the reference concrete are superimposed in Fig. 6.

The graph illustrates that the substitution of sand with the dredged sediment decreases the overall economic and environmental impacts of $1m^3$ of concrete proportional to the rate of substitution when other components of concrete were kept intact. Comparing these results (Fig. 6) to those of the experimental scenarios (Fig. 2) it is apparent that the reduction in the environmental and economic impacts arising from sand substitution by sediment has been offset by the necessary modifications to the composition of the experimental concrete scenarios.

3.4.1. Sensitivity analysis of environmental impacts of $1m^3$ concrete

The sensitivity of parameters was calculated applying an LCI developed in openLCA based on a concrete with the mix ratio of 1:3:3 for cement: sand: aggregate in which 30 % of sand is substituted by sediment. The percentage of variations in the environmental impacts of $1m^3$ concrete arisen from the ±10 % changes in the SP cement ratio, cement mix ratio (c), sand mix ratio (a), gravel mix ratio (b), the water to cement ratio (w), the rate of sand substitution by sediment of PC (X), and the transport of sediment are illustrated in Fig. 7.

The results of sensitivity analysis confirmed the expectation that the environmental impacts of the concrete are highly sensitive to the rate of incorporation of cement in the concrete. The low sensitivity of the environmental impacts to the rate of sand substitution by sediment in concrete could be attributed to the low impacts of the sand and the longer transport of sediments compared to the transport of sand. Therefore, it could be inferred that the variations in the environmental impacts of concrete due to variations in the rate of incorporation of sand and gravel (a, b) could be mainly referred to the variation of cement because of their integrity in the mix ratios (1: a: b). The impacts show low sensitivity to the water cement ratio in most of the impact categories. The sensitivity analysis illustrated that the superplasticiser cement ratio and the transport compete for higher contribution in the environmental impacts. In the impact categories of GWP, FEP, HTP, ODP, and TAP the sensitivities to superplasticiser cement ratio have outranked the sensitivity to sediment transport and vice versa in the rest of impact categories.

3.4.2. Sensitivity analysis of cost of $1m^3$ concrete

The sensitivity of parameters was calculated applying an LCI developed in Excel based on a concrete with the mix ratio of 1:3:3 for cement: sand: aggregate in which 30 % of sand is substituted by sediment. The percentage of variations in the price of $1m^3$ concrete originated from the ±10 % changes in the %superplasticiser cement ratio, cement mix ratio (c), sand mix ratio (a), gravel mix ratio (b), the rate of sand substitution by sediment PC and PP (X), and the transport of sediment are visualized in Fig. 8.

Similar to environmental impacts, the price of $1m^3$ concrete has the highest sensitivity to the cement mix ratio. The sensitivity of the price of concrete to the sand and gravel mix ratios is mainly due to the variation in the cement incorporation in the concrete because of the integrity of the mix ratios (1:3:3). The graph shows that a 10 % increase or decrease in the cement mix ratio would result in an approximately 4 % increase and decrease in the price of $1m^3$. The cost sensitivity analysis shows that in spite of the very low incorporation of superplasticiser in the concrete (1 % of cement) the price of concrete is considerably sensitive to the superplasticiser cement ratio.

4. Discussion

From a technical point of view, in spite of the negative effect of aggregate substitution by sediment on the fluidity behavior (Millrath et al., 2001) as well as the mechanical strength of cementitious materials (Beddaa et al., 2020), the results of compressive resistance test implemented in this study are promising for direct application of raw state sediment of PC into concrete up to 40 % of sand substitute. The laboratory-based experiments demonstrated that the sand substitution for sediment PC with an average diameter of 177.49 μm in concrete can conserve the concrete strength class (C30/37) up to 40 % which is far from 0 % for sediment of PP with an average diameter of 44.27 μm, the best rate of 20 % recommended by Kazi Aoual-Benslafa et al. (2012) and the maximum

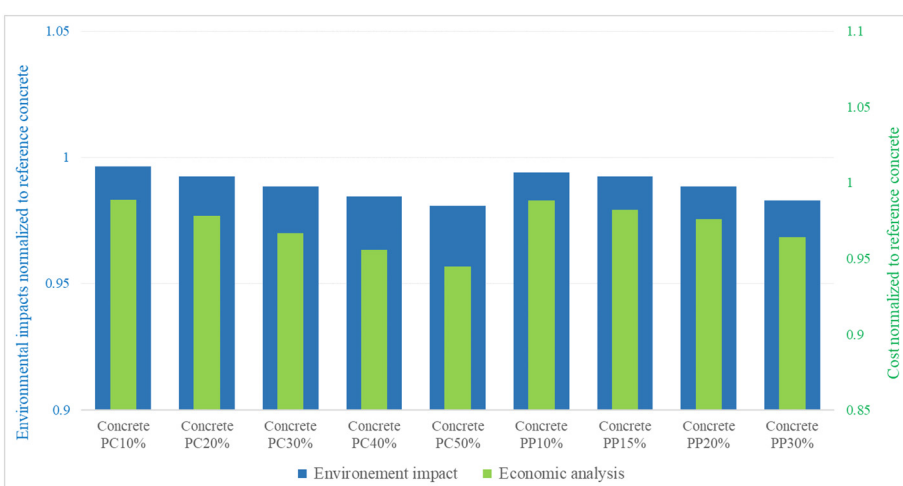

Fig. 6. Single score environmental impacts and costs of the concrete scenarios normalized to the corresponding of the reference concrete. The sand substitution by 10 % sediment (PC1), 20 % (PC2), 30 % (PC3), 40 % (PC4) and 50 % (PC5) and by 10 % (PP1), 15 % (PP2), 20 % (PP3) and 30 % (PP4); PC: Port Camargue, PP: Port Perols.

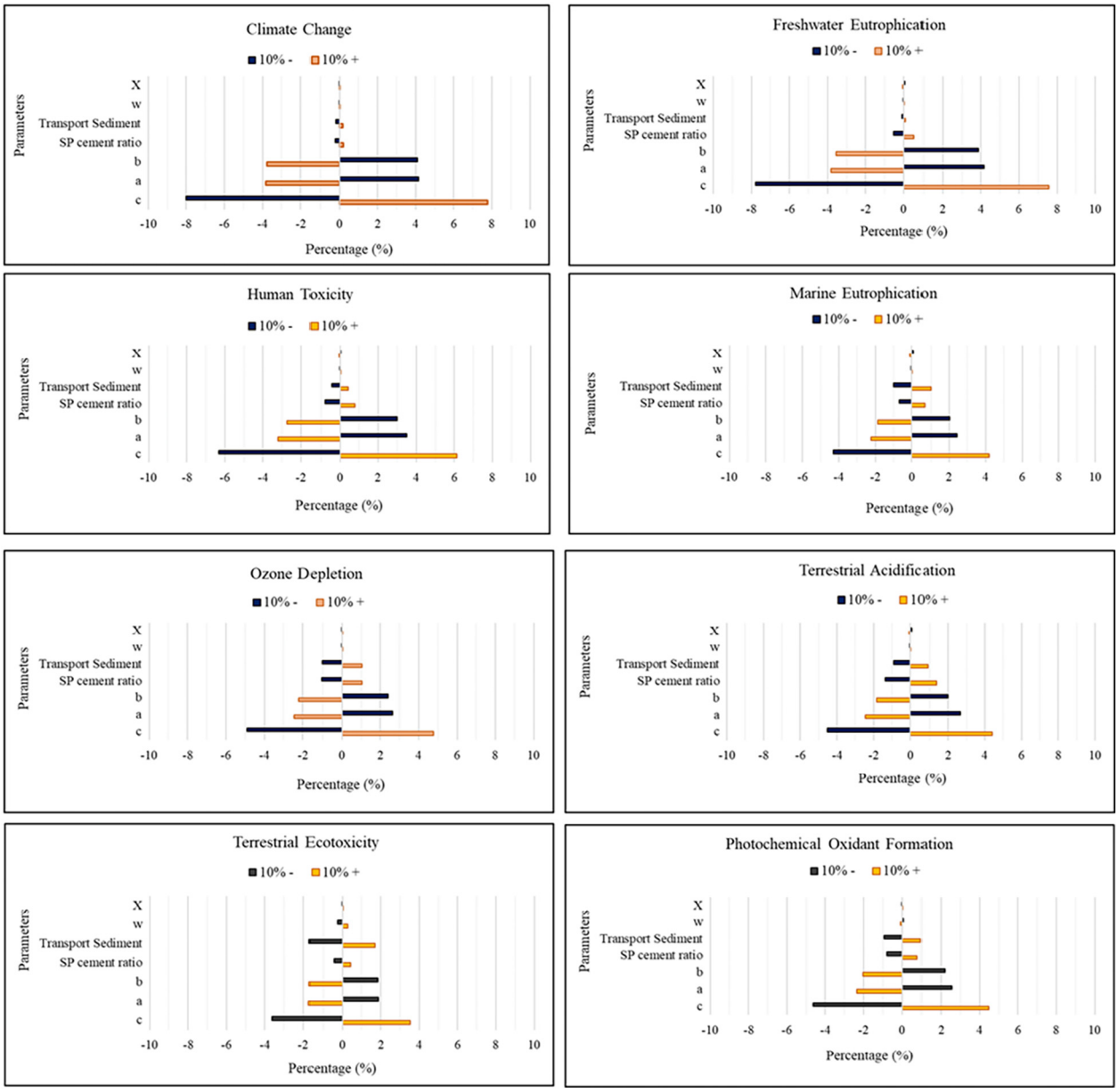

Fig. 7. Percentage changes in the environmental impacts of 1m^3 of concrete with the mix ratio of 1:3:3 and 30 % sand substitution by sediment, when the parameters incorporated in parametric LCI are changed by ±10 % one-at-a-time. Cement (c), sand (a), gravel (b), water cement ratio (w), the rate of sand substitution by sediment of port Camargue (X), and the transport of sediment.

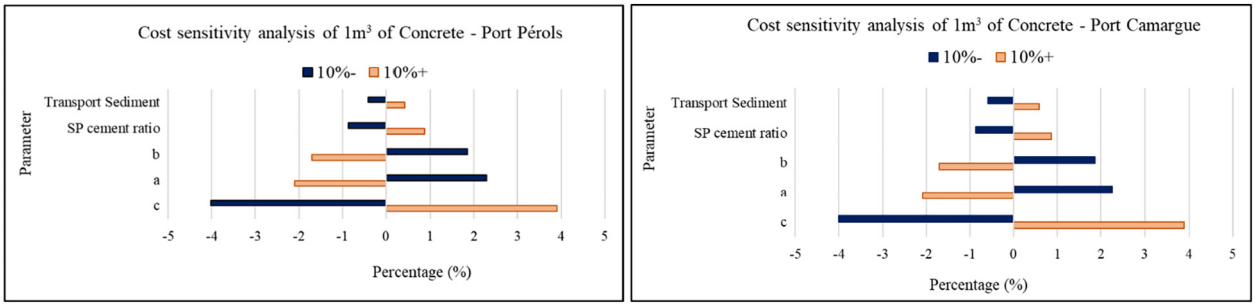

Fig. 8. Percentage changes in the cost of 1m^3 of concrete with the mix ratio of 1:3:3 and 30 % sand substitution by sediment, when the parameters incorporated in parametric LCI are changed by ±10 % one-at-a-time. Cement (c), sand (a), gravel (b), superplasticiser (SP) cement ratio, cement ratio (w), the rate of sand substitution by sediment of port Camargue and port Perols (X), and the transport of sediment.

of 12.5 % recommended by Achour et al. (2019) for concrete durability. It could be inferred that from a technical perspective, the type of the sediment in terms of granulometric composition and the expected application, performance and durability play important roles to determine maximum rate of incorporation of sediment in cementitious matrices. The substitution of sand by untreated sediment in concrete involves with a compromise to additional superplasticiser to compensate for the deteriorative effects on the workability of concrete. The combined environmental and economic results from the assessment of the experimental scenarios, downgraded the 40 % maximum rate of sand substitution by sediment PC from a technical perspective to less than 20 % to compete the control concrete in terms of sustainability. It reminds that an economic and environmental impacts assessment should be carried out parallel to the laboratory-based developments of valorization scenarios to verify their sustainability. The price or environmental impacts higher than those of control concrete is not sustainable and would not be accepted in the market. However, expanding the system boundary to the territory may alter the acceptable rate of sand substitution in concrete, in terms of sustainability. The high economic cost of the sediment landfill of 100€/ton in France market, as well as the environmental costs (Holm et al., 2013; Bates et al., 2015), even the more costly experimental concrete scenarios, conserving the concrete class (PC3 and PC4) could be compromised from an environmental and economic perspective. Besides, inferred from the results, the fluctuations in the market price of the concrete ingredients and their transports would affect the maximum rate of sand substitute for sediment, in terms of economy. The PP scenarios and PP5 could not save the concrete grade and were not sustainable in terms of economy and environment compared to the control concrete. Accordingly, for sediment PP developing further valorization scenarios would be expected.

The contribution analysis demonstrated that the consumption of the superplasticiser to alleviate the side effects of sediment on the workability of concrete has offset the economic and environmental benefits of the sand substitution with PC sediment upper than 20 % as well as all the scenarios for PP sediments. Consequently, it seems that superplasticiser is the key component to enable higher rate of substitution of sand by raw sediment, yet its cost and environmental impacts limits its rate of incorporation from a sustainability point of view. However novel techniques and technologies have emerged promising higher performance superplasticiser with lower economic and environmental burdens (Liu et al., 2021). In case of availability of novel high-performance superplasticiser with lower environmental impacts and cost, higher rate of substitution of sand by sediment up to 40 % could be both technically practical and sustainable. The environmental and economic sensitivity analysis on the parameter incorporated in the parametric LCIs were developed based on a prefixed concrete mix ratio, showed that in case of no need for modification in the concrete composition, the higher rate of sand substitution by sediments PC and PP in concrete, the higher benefit would be expected compared to the reference concrete in terms of economy and environment. The contribution analysis and the sensitivity analysis showed that the transport has a considerable share in all the environmental impact categories as well as the cost of concrete. In addition, it is reported that the transport has a linear relation to the environment impacts (Sabbagh and Esmatloo, 2019). Therefore, decrease in the transport of the raw materials of concrete through local application, would improve the concrete sustainability and facilitate towards the tradeoff for larger rate of sand substitution by sediment in concrete. Inferred from the results, the maximum rate of sustainable sand substitution by sediment in concrete could be optimized through a compromise between the expected mechanical strength and workability of the concrete, the economic and the environmental impacts of the superplasticiser, and the sediment transport.

5. Conclusions

The objective of this study was to evaluate the viability and sustainability of the scenarios to valorize large quantity of sediment through maximum sand substitution in concrete, as a win-win collaboration between civil engineering industry, academics, and the port authorities. The large economic and environmental impacts of the off-site sediment disposal in the landfills, any sustainable valorization strategy would offer a potential opportunity to alleviate the burdens of sediments. By altogether considering the results of LCA, LCC, laboratory-based technical performance analysis, contribution analysis as well as the sensitivity and uncertainty analysis some implications could be inferred:

- Lack of environmental and economic assessments parallel to an experimental development of valorization scenarios may offer non-sustainable valorization strategies, vice versa; lack of experimental trials next to the sustainability assessment may offer impractical valorization strategies.
- Integrating LCA and LCC to the laboratory assessment of valorization scenarios would determine the threshold for the sustainable rate of incorporation of sediment in valorization scenarios.
- The maximum rate of sustainable sand substitution by sediment in concrete could be optimized through a compromise between the expected mechanical strength and workability of the concrete, the economic and the environmental impacts of the superplasticiser as well as the sediment transport.
- Since the application of sediment of port Perols as a fraction of sand in concrete class C30–37 is neither practical nor sustainable, it may be valorized in other applications such as road, cycle track, cement substitution etc.
- The sustainable threshold of 20 % for sand substitution by sediment in concrete was obtained for sediment of port Camargue from integrating environmental and economic cost assessments into the laboratory-based assessment of the valorization scenarios.
- In spite of the low price of sand compared to cement, the large quantity of sand substitution by the sediments would offer an economic benefit due to its zero-market value, in condition that its transport cost does not deteriorate the benefit.
- From a prospective point of view, further application and valorization scenarios for sediment would be expected in this ongoing project to comprehensively evaluate through integrated LCA, LCC and the experiment.
- The system boundary, the territorial resources and needs and the compromise for avoided impacts of sediment disposal could influence the sustainable rate of sand substitution by sediment in valorization scenarios.

CRediT authorship contribution statement

All authors contributed equally to this work.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.159980.

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