Mathematical model for beneficial use of dredged sediments in road construction

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Abstract—In a context of regulatory and economic constraints of increasingly stringent, the sustainability of valorization processes of dredged sediments strongly depends on technical, economic and environmental factors. From the raw material to the final application, an optimization of the different steps of valorization is essential to ensure the sustainable development of secondary raw materials such as sediments and their diffusion in the construction engineering. In this paper, we have specifically studied the environmental constraints on chemical species as well as mechanical constraints on the arrangement of granular skeleton and on organic matter. The objective is to determine an optimal solution for a beneficial use in road construction while taking into account economic criteria. The solution is defined by a non-linear mathematical model with binaries variables. The resolution method is based on a linearization of the constraints in order to solve a simple problem using a solver. This solution has been validated experimentally on laboratory tests performed on marine and river sediments of the Nord-Pas-de-Calais region in the north of France.

Keywords—Dredged sediments, Mathematical model Optimization, Treatment, Valorization.

I. INTRODUCTION

The construction sector is a major consumer of non-renewable natural resources. About 382 million tons of natural aggregates were used for the construction sector in France in 2011 (nearly 55% in road and rail works, driveways and other uses for infrastructure). Currently, almost of aggregates used in this field comes from soft and massive rocks. A very small proportion (only 6.5%) is derived from recycling and demolition materials. In an increased context of preservation of natural resources, management and valorization of waste, industrial by-products and co-products, remain important issues, both financial and environmental and positioned in the center of sustainable development policies. Indeed, the exploration and exploitation of existing and future natural resources are increasingly regulated and difficult to access for economic, social and environmental reasons. In this context, dredged sediments appear to be a major ecological alternative. Large amounts of sediments and sands (marine and river) in harbors and land waterways are dredged annually and stands for a global volume of nearly 600 million cubic meter per year [9]. Solutions of integrated and sustainable managements of these sediments exist: mainly in civil engineering applications, several beneficial use fields have been performed through road foundations, dikes, landscape mounts, concrete or artificial aggregates [3], [5], [12], [14] and [19]. However, in the context of a rational valorization of secondary renewable raw materials in construction engineering, it is essential to contribute to design alternative materials optimized in term of environmental and techno-economic criteria. The multi-criteria optimization can be approximated by operational research [1] [18]. For sediment management, the application of operations research focused primarily on environmental criteria appeared in the late seventies [2], [7]. The consideration of logistics management is also included in several studies [4], [6]. The majority of research works to optimize the management and valorization of sediment are discussed in the context of logistics and transport of sediments. To our knowledge, no previous study of operational research has been realized on the process of valorization of sediment and simultaneous coupling taking into environmental and techno-economic criteria

II. SCIENTIFIC APPROACH FOR CIVIL ENGINEERING APPLICATIONS

Through european research projects, several experiments of valorization of dredged sediment have emerged such as roads of several hundred meters (GPMD project, SETARMS project), concrete blocks and landscape mounds (GPMD project), dikes (PRISMA project), etc. These instrumented scientific achievements give currently promising results but the sustainability of these valorization processes remains subject to the joint optimization of environmental and techno-economic criteria. Indeed, according to the valorization processes involved, various specific treatments such as dewatering, mineralogical and organic pollution, strengthening of bonding agents or granular additions may be needed. In parallel, beneficial use fields face to problems of optimizations of resources available locally and to problems of optimization methods and costs associated treatments. The overall scientific approach used for the beneficial use of dredged sediment in road engineering is presented in Figure 1.

The valorization of dredged sediment is decomposed through six major steps:
1. Zoning: location of potential field to dredged
2. Dredging operation: mechanical or hydraulic
3. Storage: function of the environmental quality of sediment
4. Treatment/Formulation

5. Validation in laboratory
6. Validation on experimental site

Fig. 1. Different steps for beneficial use process

The step 4 about treatment and formulation of a new material based on sediment remains the most problematic in the valorization approach. A complex process of optimization is required to identify different treatments needed to improve the sediment quality in order to respect the criteria and requirements for mechanical, environmental and economic feasibilities. Several treatment techniques exist such as reducing pollution by electro kinetic methods [10], reduction of organic matter by burning [11], reducing the water content by press or natural settling filter [15], etc. The objective of formulations methods mainly targets to reach a level of mechanical performance compatible and sustainable with the target applications fields. These formulations are mainly based on the compactness optimization of granular skeletons [8], on the additions of binders [16], [17] and their interaction with aggregates.

III. MATHEMATICAL MODELING

A. General constraints

The objective of our research is to find a solution that provides a suitable material for road use. This solution is in the form of a mixture of sediment with one or more natural materials (e.g., sand) subject to a set of physical and chemical treatments in order to respect the requirements and normative constraints. The first condition ensures the selection of single sediment. For this we create the constraint (1):

$$\sum_{i=1}^{n} x_{i} = 1. \quad (1)$$

where each binary variable $x_{i}$ is equal to 1 if the sediment $i$ is used and $i = 1, \ldots, n$ ($n$ is the number of sediments).

For the natural materials, we introduce the variables $(S > 0)$ which represents the units number of material $s$ used in the formulation. Then the total quantity $S$ of natural materials used in the formulation is presented by the constraint (2):

$$S = \sum_{s=1}^{m} S_{s}. \quad (2)$$

B. Chemical constraints

The environmental aspect in the field of road construction that uses sub-products or wastes is nowadays strongly constrained by legislation (Guide SETRA\textsuperscript{4}). Each country requires certain limits for contaminants elements in the used material for construction. The acceptable limits constraints for the use of the materials in road application are mainly concerning the concentration of contaminants elements in these materials. For example, France requires limits given in Table 1.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Limit (mg/kg)</th>
<th>Elements</th>
<th>Limit (mg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOC</td>
<td>60000</td>
<td>Mo</td>
<td>10</td>
</tr>
<tr>
<td>BTEX</td>
<td>6</td>
<td>Ni</td>
<td>10</td>
</tr>
<tr>
<td>PCBs</td>
<td>1</td>
<td>Pb</td>
<td>10</td>
</tr>
<tr>
<td>HCT</td>
<td>500</td>
<td>Sb</td>
<td>0.7</td>
</tr>
<tr>
<td>PAHs</td>
<td>50</td>
<td>Se</td>
<td>0.5</td>
</tr>
<tr>
<td>As</td>
<td>2</td>
<td>Zn</td>
<td>50</td>
</tr>
<tr>
<td>Ba</td>
<td>100</td>
<td>Fluoride</td>
<td>150</td>
</tr>
<tr>
<td>Cd</td>
<td>1</td>
<td>chloride</td>
<td>15000</td>
</tr>
<tr>
<td>Cr</td>
<td>10</td>
<td>Sulfate</td>
<td>20000</td>
</tr>
<tr>
<td>Cu</td>
<td>50</td>
<td>Soluble fraction</td>
<td>60000</td>
</tr>
<tr>
<td>Hg</td>
<td>0.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

These limits change from a country to another, but the constraints are always present. In order to make the material (sediment in our case) acceptable for road construction, this must be clean. More precisely, it should be treated using known pretreatment and treatment techniques to reduce the concentration of elements if necessary. We know that each treatment technique has an impact on all polluting elements. For example, electro kinetic treatment can reduce the percentage concentration of some heavy metals such as Zn up to 32% [10] and remediation treatment can reduce it further to 10% [13]. Then the application of the two previous treatments can reduce the concentration of Zn until (32% × 10% = 3.2%) of its initial concentration. Note that in practice rarely are the cases where the sediment requires multiple treatments. In order to model this constraint, we introduce binaries variables $T_{i}$ for $i = 1, \ldots, [7]$ where [7] is the number of possible treatments:

$$T_{i} = \begin{cases} 1 & \text{if the treatment } i \text{ is applied} \\ 0 & \text{else} \end{cases}$$

$q_{i} \in [0]$ is continuous value that indicates the quantity of the contaminant element $j$ in the used sediment $i$ and $q_{j}$ is a permitted limit associated with the element $j$. Denote by $|Q|$ number of contaminants elements. The parameter $\delta_{ij}$ represents the reduction percentage of the concentration of $j$ when treatment $i$ is applied to the sediment $i$. Environmental constraints (3) then can be written as follows:

$$\left(1 - \delta_{ij} T_{i}\right) \leq q_{j} \leq \left(1 - x_{i}\right) M \quad (3)$$

\textsuperscript{4}http://www.setra.equipement.gouv.fr/-Guides-documents-de-reference-.html
With $M$ is a large positive value that helps to relax the constraint when sediment $i$ is not selected ($x_i = 0$). The product $\prod_{i=1}^{n} (1 - \delta_{i}^{j} T_j)$ models the reduction percentage of the concentration. Other constraints concerning the treatments should be respected which indicates the incompatibility of using two or more treatments together. Denote by the set of incompatible combinations of treatments. This condition can be modeled by the constraint (4):

$$\sum_{i=1}^{n} T_i \leq 1 \quad k = 1, \ldots, |C_T|$$

(C. Mechanical constraints)

Constraints in this section are divided into two: the constraints size characteristics and constraints related to the concentration of organic matter in the sediment (source of contamination and degradation of sediment).

1) Granulometric constraints

The granulometric percentage composition of the sediments and natural materials (eg sand) used for road application should satisfy some limits related to Talbot-Fuller-Thomson’s zone. In general, the most reliable materials are those that show an optimized granular arrangement. This means a good compactness of the material and consequently a stronger material. Talbot’s zone is defined by the interval $[u, \frac{u}{1-S}]$ where $u$ is the diameter and $s$ is the maximum diameter of grains. The mathematical formulation of the above constraints can be written as follows:

$$\sum_{i=1}^{n} \frac{d_{i}^{j}}{d_{i}^{0.25}} (1 + S) \leq \sum_{i=1}^{n} \frac{d_{i}^{u}}{d_{i}^{0.25}} + \sum_{i=1}^{[\frac{S}{d_{i}^{0.25}}]} \frac{d_{i}^{u}}{d_{i}^{0.25}} (1 + S) \quad k = 1, \ldots, |I|$$

where $|I|$ is the number of considered diameters and is the grain percentage of diameter $u$ in the sediment $i$ (resp. the natural material $s$). Recall that $S$ is a variable that indicates the units number of natural material added to the sediment. Then $(1 + S)$ is the total quantity of used material: one sediment must be chosen (constraints (1)) represented by the value 1; and natural materials represented by $S$. Then (1 + $S$) represents the used units number (one for sediment and $S$ for natural materials). This added quantity $S$ to the sediment helps to dilute the organic matter. Note that this constraint follows the same logic of constraint (3) in terms of treatment and relaxation of constraint using $M$.

2) Constraints on organic matter

One of the major problems in the valorization process of sediments in road construction is the concentration of organic matter in the sediment. It often contains a significant quantity of contaminant metals. Moreover, it has a considerable influence on the mechanical behavior of the sediment. The quantity of this matter must be limited by $Q^{MO} = 3$. To reduce the organic matter, we need to apply some type of treatments: the first type which is part of the treatments set $T$ and a second one can be done by the mixture with natural materials that have not organic material (eg sand). The constraint (6) ensures the limit of the organic matter in the following way:

$$Q^{MO}_{i} \prod_{i=1}^{n} (1 - \delta_{i}^{j} T_j) \leq Q^{MO} (1 + S) + (1 - x_i) M$$

where $\delta_{i}^{j}$ is the quantity of organic matter in one unit of sediment $i$. $Q^{i} (= 3)$ is the acceptable limit for road use, $\delta_{i}$ is the reduction percentage of the organic matter in the sediment $i$ after applying the treatment $t$ and $(1+S)$ represents the used units number (one for sediment and $S$ for natural materials). This added quantity $S$ to the sediment helps to dilute the organic matter. Note that this constraint follows the same logic of constraint (3) in terms of treatment and relaxation of constraint using $M$.

(D. Objective function)

The objective of our mathematical model is to find an acceptable solution for road use with a minimum cost. These costs are divided into three. The costs of sediment defined by the cost of acquisition and/or dredging denoted by the vector $C_1 = \{c_1, \ldots, c_n\}$, the treatment costs denoted by $C_2 = \{c_2, \ldots, c_m\}$ and the acquisition costs of natural materials $C_3 = \{c_3, \ldots, c_l\}$. The formulation of the objective function is then presented by (7):

$$\text{Min} \sum_{i=1}^{n} c_i^{j} x_i + \sum_{j=1}^{m} c_r^{j} T_j + \sum_{s=1}^{l} c_s^{j} S_s$$

(E. Overall presentation of the mathematical model)

The modelization of the valorization sediments problem for road use is made by the following 0-1 Mixed Integer Programming Model. This model is non-linear because of constraints (3) and (6).
IV. HEURISTIC

A. Linearization of nonlinear constraints (3) and (6)

Constraints (3) and (6) are nonlinear. They pose a particular difficulty to solve our problem. In order to simplify the resolution of the mathematical model, it is necessary to linearize these constraints. This can be done on the quadratic part of constraints (3) and (6) by the enumeration of all possible combinations of variables. This expensive process is justified by the limited number of possible treatments (more or less |\mathcal{T}| = 20). To linearize, we introduce a new variable associated with the combinations of variables denoted by $i(h$ is the index of the combination):

$$y_h = \begin{cases} 
1 & \text{if } \forall t \in C^x_h, T_t = 1 \text{ and } \forall t \notin C^x_h, T_t = 0 \\
0 & \text{else}
\end{cases}$$

The associated cost with $i$ is then calculated by $c^i_h = \sum_{t \in C^x_h} \zeta$ and the coefficients are calculated by $a^i_h = \prod_{t \in C^x_h} (1 - \delta_t)$. For example: the combination of variables $C^x_h = \{2, 3\}$ is replaced by a new binary variable $x_h$ with a cost $c^i_h = (1 - \delta_2)^2 \times (1 - \delta_3)^2 \times (1 - \delta_4)$ and coefficients $a^i_h = (1 - \delta_2)^2 \times (1 - \delta_3)^2 \times (1 - \delta_4)$.

To complete this linearization, we add the constraint (8) to impose the choice of a single combination of treatments at most.

$$\sum_{h=1}^{2^{\left|\mathcal{T}'\right|}} y_h \leq 1$$

(recall that in practice the number of applied treatments to a sediment is very limited, so we will start with small combinations. This means, a combination of two treatments then three and so on. This linearization allows us to eliminate the constraint (4) because it will be taken into account during the generation of the combinations.

The linearization of the previous model is presented below.

$$\text{Min } \sum_{i=1}^{n} c^i x_i + \sum_{h=1}^{2^{\left|\mathcal{T}'\right|}} c^x_h y_h + \sum_{s=1}^{\left|\mathcal{T}\right|} c^S_s S_s$$

s.t. $\sum_{i=1}^{\left|\mathcal{T}\right|} x_i = 1$  \hspace{1cm} (1)

$$S = \sum_{s=1}^{\left|\mathcal{T}\right|} S_s$$

$$q_i \sum_{h=1}^{2^{\left|\mathcal{T}'\right|}} a^i_h y_h \leq Q^i + (1 - x_i)M$$

In fact, the linearization procedure proposed in this section presents the first step of the resolution of our problem. The linearized model can be solved using an optimization solver either commercial solvers (Cplex) or open source solvers (Lpsolve).

B. Validation of the model

In order to validate our mathematical model, tests were done on three different types of sediments. These sediments have a larger concentration of organic matter than the tolerated limit for road application. Moreover, their mechanical properties are less than the bearing capacity needed for the road application. As indicated above, several treatments are available to reduce the organic matter in the sediment (chemical and/or adds granular). On the other hand, to improve the bearing capacity of the sediment and increase the mechanical properties, it is often necessary to make adds granular (eg. sand). From these observations, in the experimental solution, the choice was done to add granular material to reduce the organic matter and to increase at the same time the bearing capacity and the mechanical characteristic of the new mixture. To realize our experimental tests, 3 types of sediment and 3 types of natural sand were used.

![Fig.2. Comparison between experimental and theoretical results](image-url)

These different inputs data were introduced in our model. Figure 2 shows that the obtained results (mixtures) by the model and by lab experiments are very close. The resulting mixtures respect regulatory constraints for road application according to the organic matter percentage (\leq3%). Moreover, obtained mixtures by our model converge to the optimal mixtures obtained in the laboratory.
V. CONCLUSION

In this paper, we study the valorization problem of marine and river sediments in road construction. The main parameters controlling the optimization process, for the road construction, are the environmental and the mechanical aspects. The environmental and the mechanical properties of the optimal formulated material are obtained by improving the compactness and the granular arrangements and by reducing the organic matter and the chemical elements. This problem is modeled in the form of a nonlinear mathematical model with mixed variables. It composed by a linear objective function that represents the costs, two nonlinear constraints modeling the concentration of organic matter and chemical elements, and a linear constraint modeling the granular arrangements of mixtures (sediments and natural materials). The resolution approach for our model is based on a linearization of this model in order to simplify its resolution using a solver. The validation of the mathematical model is made through experimental tests realized in the laboratory. The obtained solutions by the model are very close to those obtained experimentally which proves the feasibility and optimality of the model solutions.

VI. ACKNOWLEDGMENTS

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REFERENCES


