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Methodology for Optimizing Sewage Sludge Treatment, Valorization and Disposal Methods. Application to the Marrakech (Morocco) Wastewater Treatment Plant

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Abstract*: Wastewater treatment leads to a significant production of about 150 to 200 kg of sludge per population equivalent (P.E) per year, with a humidity level higher than 90%. The treatment and discharge of this sludge involves high costs for wastewater treatment plants (WWTPs), which can amount to up to 60% of their total operating cost. The environmental and public health aspect should also be carefully considered during evacuation as sludge may contain harmful elements. Currently, several treatment, valorization and disposal methods are possible for sludge. In order to respect the various constraints on the possibilities of discharging sludge and to minimize its cost, a reasonable approach must be followed to establish an optimal management path according to the WWTP situation. The objective of this work is to develop a methodology for optimizing sludge treatment, valorization and disposal methods for a given WWTP. This method is based on operational research technique. The methodology follows the following six steps: description of the existing situation, identification of possible treatment, valorization and disposal methods for the WWTP and development of a decision tree specific to the WWTP, mathematical formulation and assumptions, mathematical resolution and sensitivity analysis, validation of the solution and application of the solution. After the application of this methodology, a decision support tool is developed to define the optimal method(s) for sludge management in the WWTP. According to the example of the application of this methodology on sludge management of the WWTP of Marrakech (Morocco), the optimal solution, with respect to the data used and keeping the installations in place, is the application of agricultural spreading after the sludge treatments which are: thickening, anaerobic digestion, mechanical dehydration and solar drying. On a 20-year operation, an average gain of about €10 (110 DHs) per ton of dry solid (DS) incoming is generated.

***Keywords*: Optimization methodology, Sludge management, Sludge valorization, Waste water treatment plant.**

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I. INTRODUCTION

Wastewater treatment plant (WWTP) installations have an important role in protecting the environment by depolluting wastewater before it is returned to the natural environment. During this process, a significant and unavoidable amount of by-product, called sludge, is produced. Wastewater treatment processes can be classified as extensive and intensive [1]. Intensive processes treat a high pollutant load per unit area, resulting in a high sludge production in a shorter time compared to extensive processes. The disposal of this produced sludge is one of the major problems faced by WWTP managers, especially in extensive processes, due to the high sludge quantity and cost of disposal. Indeed, after wastewater treatment, a quantity of about 150 to 200 kg of sludge per population equivalent (P.E) per year is produced at the level of WWTPs [2], with a humidity level higher than 90% [3]. The operating cost of the sludge chain can be up to 60% of the total operating cost of the WWTP [4]. In addition to quantity and cost issues, particular attention must be paid to the destinations of sludge because risks to the environment and public health are present due to pollutants, such as heavy metals and pathogens, that sludge can contain. The organic nature of the sludge also gives it a high fermentable power, which is often a source of olfactory nuisance. In order to take this environmental and health aspect into account, directives and regulations are being developed in several countries such as the European economic community directive 86 / 278 [5] and Part 503, title 40 of the Code of Federal Regulations of the United States [6], which include standards for the use or disposal of sewage sludge.

In recent years, several methods of sludge treatment, valorization and disposal have been developed and practiced at the WWTP level. Some of these methods are now considered to have reached a proven development stage, others are still at a research and experimentation stage. In addition, a new approach to sludge management has been developed. Currently, the idea of considering sludge as a resource rather than a waste is widespread enough in the world, this is due to the agronomic, energy and material potential that sludge represents [7].

Faced with this rather complex situation, which involves a multitude of choices on the methods to be used, different costs and constraints, it is necessary to define for each case of WWTP a set or an optimal management method as it is also mentioned in [8]. This management must take into account the financial aspect, ease of evacuation, accessibility to the site, the health of the concerned humans and animals, and the environmental and social aspect [9]. In order to make a decision on the optimal management method(s), a methodology is required.

A direct comparison of possibilities is sometimes possible, as it was done in [9], but the use of the Life Cycle Assessment (LCA) method is often found in the literature to evaluate different sludge management scenarios, as in the work [10], [11] and [12]. This methodology oriented towards environmental impact assessment can be used with an inventory of costs for decision-making, such as the work of [11].

In a complex decision-making area, such as the current sludge management situation, the use of operational research technique is relevant. The objective of this work is to present a methodology for optimizing the treatment, valorization and disposal of WWTP sludge, based on this technique.

First, the main methods of sludge treatment, disposal and valorization are presented, and based on proven and innovative methods and technologies, a general decision tree is developed. The optimization methodology is then presented and explained. Finally, an example of the application of this methodology to the case of sludge management at the WWTP of Marrakech (Morocco) is provided.

II. SLUDGE TREATMENT, VALORIZATION AND DISPOSAL METHODS

After its extraction in the wastewater treatment process, sludge is treated and then valorized and/or disposed of. Treatment methods are steps that result in the modification of the physicochemical and/or microbiological characteristics of the sludge in order to facilitate its valorization and/or elimination. The main objectives of the treatments are to reduce the volume, fermentability and pathogens in the sludge.

Valorization methods refer to methods in which sludge is used for energy production and/or as a source of material or nutrient for another sector.

Disposal methods refer to methods where sludge is not used as a source of energy, material or nutrient for another sector.

In this section we will present the methods of sludge treatment, valorization and disposal that are proven or innovative and that will be used in this work.

A. Sludge treatments

The treatments reduce the negative effects on the environment and the costs of valorization and/or disposal. Some of these treatments stabilize and/or sanitize the sludge. Stabilization means a decrease in the fermentable power, thus a decrease of the olfactory nuisance. Hygienization reduces pathogenic microorganisms in the sludge.

➢ Thickening and mechanical dewatering

The purpose of these operations is to concentrate the sludge by extracting part of the water, often classified as free water, contained in the sludge.

Thickening is an operation applied to liquid sludge, which can be dynamic or gravitational, and allows a dryness of 3 to 10% [7].

Dewatering is an operation often applied to thickened sludge, which consists of mechanical separation of the water by means of a machine and allows a dryness of 15 to 40% [13]. The output dryness depends on the nature of the sludge and the dewatering technology used. Among the techniques used are centrifugation (centrifuge) and filtration (pressure filter, vacuum filter). In order to improve dehydration, chemical conditioning using mineral or organic reagents is often applied with mechanical dewatering.

As a reference on the use of these treatments, we can cite the case of the WWTP of Marrakech (Morocco) which uses gravity thickening to thicken the primary sludge and mechanical dewatering by belt filters to produce sludge dewatered to a dryness level of about 22% [14].

➢ Conventional and solar drying

Drying is an operation applied to the dewatered sludge; it consists of removing water from the sludge by supplying it with energy. Drying is an energy consuming operation. It is said to be conventional when the energy source used is a conventional energy and is solar when the energy used is solar energy.

Drying allows a significant reduction in sludge volume and produces sludge with high dryness. For conventional drying, the final dryness can be higher than 85% [7] and for solar energy around 70% [15], depending on the climate of the installation site and the dryer technology installed.

As the temperature increases during drying, the sludge at the outlet is also hygienized. Hygienization is guaranteed for conventional drying. Solar drying allows hygienization but often not enough to completely eliminate the risk of pathogens [16] [17]. In recent years, the use of solar dryers for sludge drying has become more and more common due to their low operating cost compared to conventional dryers. As a reference on this technology, we can mention the installation of solar sludge drying in the city of Marrakech (Morocco), which currently represents the largest solar installation for sludge drying in the world, with a drying area of 40 320 m². This installation is shown in **Fig. 1** [18].

Fig. 1 : Solar sludge drying installation, Marrakech [18]

➢ Chemical stabilization

Chemical stabilization is

Fig. 2 : Sludge liming installation, MYDIBEL Belgium [20]

achieved by adding a chemical reagent to stabilize the sludge. It can be done by adding lime or nitrite salts.

Liming takes place after dewatering, it consists in adding quicklime (CaO) or hydrated lime (Ca(OH)2) to the sludge, which stabilizes and hygienizes it. Liming also increases the dryness of the sludge by up to 25 to 35% [19].

The addition of nitrite salts is practiced on thickened sludge and is generally used in small WWTPs. It stabilizes and hygienizes the sludge and also increases the dryness by 2 to 5% more [19].

As a reference we can mention the installation of a sludge liming unit (**Fig. 2**) by Sodimate on behalf of the potato products production and marketing industry MYDIBEL in Belgium. The unit has a maximum sludge treatment capacity of 7 m^3/h [20].

➢ Biological stabilization

Aerobic and anaerobic digestion can be distinguished.

Aerobic digestion consists of storage and aeration in a tank or composting of sludge. It allows the organic part of the sludge to be aerobically degraded. Generally, in the case of composting, it is practiced with a dehydrated sludge and a mixture of green waste as a carbonaceous support, therefore a co-composting. This practice promotes the oxygenation of the mixture and increases the carbon/nitrogen ratio, which is generally low for sludge. The compost produced is stabilized and hygienized with an average of about 50% dryness [21].

Anaerobic digestion consists of fermenting the sludge in the absence of oxygen. Depending on the temperature, a distinction is made between psycrophilic (between 15 and 20°C), mesophilic (between 30 and 35°C) and thermophilic (between 50 and 60°C) digestion. Among these operations, mesophilic digestion is the most common [22]. Anaerobic digestion allows a significant reduction in sludge, from about 35 to 40% of the dry matter, and a biogas production that is composed of about 65% methane and 35% carbon dioxide [23]. Digestion stabilizes the sludge by reducing its organic matter. It is also considered as a valorization method because of the possibility of thermal and electrical valorization offered by biogas.

As an example of reference on the use of this method, we can cite the use of a mesophilic anaerobic digester at the WWTP in Marrakech (Morocco) [14].

➢ Wet oxidation (WO)

Wet oxidation is a treatment that is carried out on thickened sludge, with a maximum of about 10% dryness, and consists of heating the sludge to 200 to 250°C, under pressure (up to 50 bar) and in the presence of pure oxygen. This operation destroys up to 95% of the organic matter by transforming it mainly into carbon dioxide and ammonia. At the end of this treatment, technosands with a dryness of about 50% are produced, which are solid mineral residues containing less than 5% organic matter [19].

As a reference, we can cite the Athos™ process (**Fig. 3**) of Veolia water technologies, which was installed to treat sludge in several WWTPs, such as the WWTP in Epernay (France) in 2006, the WWTP in Brussels (Belgium) in 2008 and the WWTP in Rennes Beaurade (France) in 2012 [24].

Fig. 3 : Athos™ process [24]

➢ Thermal hydrolysis

Thermal hydrolysis is a process that consists of decomposing the organic matter in the sludge using heat and at low or absence of oxygen. It is often called pyrolysis or thermolysis.

Thermal hydrolysis can be carried out on dehydrated and dried sludge.

The application on dewatered sludge is coupled with anaerobic digestion to improve biogas production and dry matter reduction compared to conventional digestion. This thermal hydrolysis and anaerobic digestion coupling can produce 25 to 30% less dry matter and 30 to 50% more biogas than conventional anaerobic digestion [25].

The thermal hydrolysis of dried sludge results in the production of synthesis gas and mineral residue. The gases can be recovered later.

The search for references on the practice of OVH on dried sludge was not conclusive, so only the application on dewatered sludge coupled with biogas will be taken into account for the rest of the work.

One example is the Exelys™ process **(Fig. 4)** by Veolia water technologies, which combines thermal hydrolysis with anaerobic digestion.

Fig. 4 : Exelys™ process, [26]

Several installations of this process have been carried out, such as in the WWTP of Versailles (France) in 2015 and in the WWTP of Billund (Denmark) in 2016 [26].

B. Sludge valorization and disposal

These methods are the final steps in sludge management. Depending on the possibilities that WWTPs may have, these methods determine the treatment of the sludge to be sent to them.

➢ Landfill

Landfilling is a disposal method that consists of sending the sludge to landfill. It is generally an inexpensive option for WWTP but should be considered as a last resort and is increasingly being abandoned in several countries such as European countries. For the latter, European Directive 91/271 prohibits the landfilling of waste that is not considered to be final waste or that contains more than 70% water and more than 10 to 20% organic matter, so sludge is prohibited. At the level of the European Union countries, there has been a decline in the application of this method in recent years.

As a reference on the application of this method, we can cite the case of the European Union countries that have eliminated approximately 282 000 tons dry solid (DS) from their sludge, 10% of the total sludge eliminated, at the landfill for the year 2017 [27].

➢ Construction

Recycling in construction mainly consists of technosand, which are solid mineral residues from WO, and ash from incineration. These residues can be used in the public works, ceramics and cement sectors. Technosand can be mixed up to 35% with other materials for road embankments, and for ceramics they can be mixed up to 7% for the manufacture of tiles [28]. For ashes, uses in the manufacture of bricks have been reported in the literature as well as various studies concluding the feasibility of incorporating ashes in cementitious matrices [29].

➢ Agricultural use or application

Agricultural use or application is a valorization method that consists of spreading the sludge on agricultural land and/or forests. This method can be used for liquid, dewatered, dry and co-composed sludge. Due to the agronomic interest of sludge and the simplicity and often low cost of this practice, agricultural use is generally promoted. However, rules must be respected to avoid the negative effects that sludge can have on soil, water and the environment. These effects are due to the possibility of the presence of metallic, organic and biological pollutants or pathogens in the sludge.

As a reference on the application of this method, we can cite the case of the European Union countries that have eliminated more than 776 000 tons DS from their sludge, 28% of the total sludge eliminated, in agricultural use for the year 2017 [27].

➢ Incineration

Incineration is an oxidation operation at a temperature around 850°C and in an oxidizing atmosphere or in excess of air. During this operation, the organic fraction of the sludge is totally oxidized and a significant amount of energy is produced. Incineration allows a reduction of up to 7-10% in the volume of dewatered sludge [30], which can be translated into a mass reduction of up to 30% of the mass of the initial dry matter. The energy produced during the operation can be recovered in thermal or electrical form. In the case of incineration with valorization of the energy produced, incineration is referred to as a valorization method, but in the case where the energy is not recovered, it can be considered as a disposal method or a treatment with the objective of reducing the quantity of sludge produced.

For sludge incineration, a distinction can be made between specific incineration, co-incineration in cement factory and co-incineration with household waste. The specific incinerator is an incinerator that is intended only to incinerate the sludge without mixing it with other materials. Specific incinerators are generally installed in the WWTP. The installation of an incinerator for the incineration of sludge from a set of WWTPs is possible. Sludge co-incineration consists of sending the sludge to incinerators outside the WWTP, which are generally incinerators for household waste or in cement factory.

As a reference on the application of this method, we can cite the case of the European Union countries that have eliminated approximately 491 000 tons DS from their sludge, 18% of the total sludge eliminated, in incineration for the year 2017 [27]. In the case of specific incinerators, mention can be made of Suez's Thermilys™ process **(Fig. 5)**. An installation of this process was carried out in the WWTP of Le Havre (France), which was commissioned in 2011, with a sludge treatment capacity of 10 000 tons per year [31].

Fig. 5 : Thermilys™ process, WWTP Havre, France [31]

Based on the treatment, valorization and disposal methods described above, a decision tree is established, which is presented in **Fig. 6**. The tree includes combinations of treatment, disposal and valorization methods that are technically feasible, based on the physical characteristics of the sludge, as well as the state of development of each possible technology and method. The combinations of methods form the disposal or valorization paths.

III. METHODOLOGY FOR OPTIMIZING SLUDGE TREATMENT, VALORIZATION AND DISPOSAL METHODS

In this section, we present a methodology for optimizing treatment, valorization and disposal methods of WWTP sludge. **Figure 7** presents a synoptic diagram of this methodology for an application to a given WWTP.

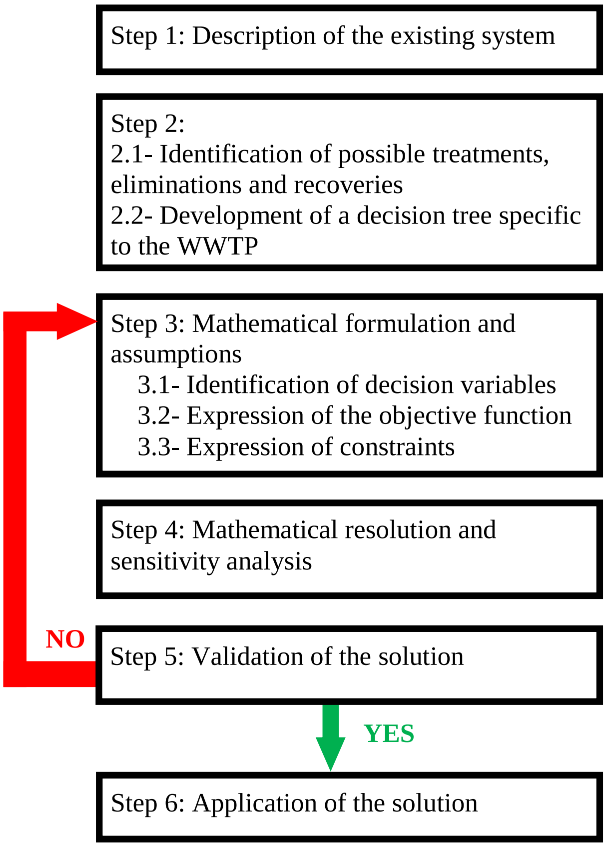

Fig. 7: Synoptic diagram of the methodology for optimizing sewage sludge treatment, valorization and disposal methods.

A. Step 1: Description of the existing

This step is reserved for an already built WWTP and envisages applying the optimization of the sludge process. It consists of describing the methods of treatment, valorization and/or disposal of sludge already applied by the WWTP. The existing path can be used as a baseline situation or a starting point for optimization if the path is not complete and the WWTP does not want to change what is existing.

B. Step 2: Identification of possible methods and development of a decision tree specific to WWTP

➢ **Identification of possible treatment, valorization and disposal methods**

In this step, the technically feasible treatment, disposal and valorization methods applicable in the WWTP situation and not prohibited by regulation are identified. Applicable in the situation of the WWTP means that all the elements necessary for the WWTP to consider a method are present or the WWTP has the possibility to acquire it. For example, WWTP will not be able to consider incineration in cement plants if there is no cement plant in the region where the WWTP is located. This identification must also take into account the state of development of each technology being considered. It is advisable to consider proven technologies and that the maintenance of these technologies will not be a problem for WWTP.

➢ **Development of a decision tree specific to the WWTP**

In order to have a clear visibility on the possible routes that WWTP may consider, a specific decision tree is developed in this step. This tree groups together the treatment, valorization and disposal methods that are possible for WWTP. The development of this tree also facilitates the following steps of the method.

C. Step 3: Mathematical formulation and assumptions

The objective of this step is to develop a mathematical model of the sludge valorization and disposal paths.

At the beginning of the formulation, simplifying assumptions may be made. Among these hypotheses, a linear relationship can be assumed between the quantities of sludge to be treated and the receipts and costs of treatment, valorization or disposal methods.

➢ **Identification of decision variables**

The first sub-step of mathematical formulation begins with the identification of the decision variables, which in this case are the quantities of sludge to be sent to each valorization and disposal paths. These quantities may be notified by:

$$X_n \quad (n = 1,2,\dots,N)$$

n: index representing the method of treatment, valorization or disposal.

➢ **Expression of the objective function**

The second sub-step of mathematical formulation is the expression of the objective function as a function of decision variables. This function will be used to maximize the benefit or minimize the cost of the chosen channel(s). The coefficients of this function are the differences between the revenues and costs of each treatment, disposal and valorization method. This function can be expressed as follows:

$$F = \sum_{n=1}^{N} d_n X_n \quad \text{with } d_n = (R_n - C_n) \tag{1}$$

R: Revenue for the method of treatment, valorization or disposal n.

C: Cost of the treatment, valorization or disposal method n.

➢ **Expression of constraints**

The third sub-step of mathematical formulation is the

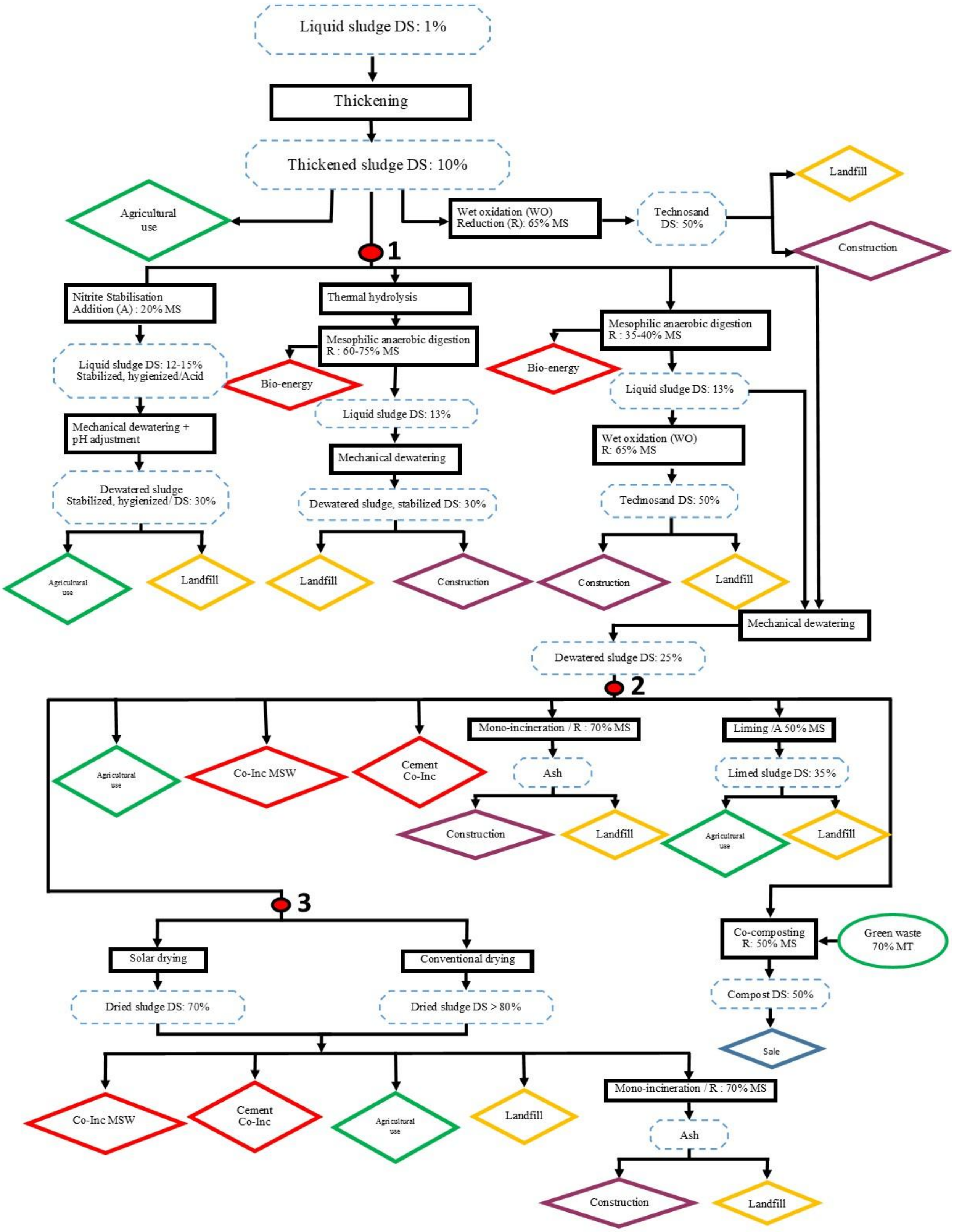

Figure 6 : General decision tree for the treatment, valorization and disposal of WWTP sludge

expression of constraints as a function of decision variables. These constraints represent the conditions that the solutions found must respect. They are of two kinds. The first is the constraints related to material balances, which can be global, dry matter or performance balances of an operation. These constraints are represented by equations.

$$\sum_{n=1}^{N} a_n X_n = 0 \qquad (2)$$

a: Coefficient resulting from material balances.

The second is the constraints related to the amount of material that each treatment, valorization or disposal method can accept. These constraints are often represented by inequalities.

$$\sum_{n=1}^{N} b_n X_n \leq d \qquad (3)$$

b: Coefficient that takes the value 0 if the method is not affected by the constraint in question and takes the value 1 otherwise.
d: Quantity of limiting material to be sent in the method(s) of treatment, valorization or disposal.

D. Step 4: Mathematical resolution and sensitivity analysis

➢ **Mathematical resolution**

The objective function and constraints forming the mathematical model are then programmed in an appropriate computer tool before it is resolved. The Excel software is one of the possibilities. The objective here is to develop a computer tool that makes it easy to carry out the optimization.

The mathematical resolution is now being carried out to find the optimal path.

➢ **Sensitivity analysis**

The sensitivity analysis consists in evaluating the effect of the variation of the coefficients of the objective function as well as the modifiable constraints on the validity of the optimal solution found.

This analysis can be done using appropriate tools such as Excel.

E. Step 5: Validation of the solution

The solution found can be validated in this step depending on the situation of the WWTP. If the solution does not satisfy the manager or the decision maker, a return to the formulation stage can be achieved.

F. Step 6: Application of the solution

Once the solution has been validated, it can be applied.

IV. APPLICATION EXAMPLE: CASE OF THE MARRAKECH (MOROCCO) WWTP

In this section we will use the Marrakech WWTP as an example of the application of the methodology presented above. The WWTP is located in the north of the city of Marrakech, it started treating the city's wastewater in 2008. It is a biological WWTP with an intensive activated sludge type process. The treatment capacity of the WWTP is 1 300 000 P.E with a daily treated wastewater flow of about 120 000 m^3. [14, 32]

A. Step 1: Description of the existing

At the end of the wastewater treatment, the sludge with a dryness of about 1% undergoes thickening, mesophilic anaerobic digestion and mechanical dewatering by means of a belt filter. The current sludge production of the WWTP is about 140 tons of raw sludge (R.S) a day with an average dryness of 22% [14]. Before 2018, the dewatered sludge is limed and then sent to the landfill. From August 2018, sludge drying greenhouses were put into service to take back and treat the dewatered sludge. These greenhouses have a capacity to treat about 75,000 t R.S/y, from a dryness of 22% to about 80% on a surface area of 40,320 m² [33]. Dried sludge is currently stored at the drying platform because no disposal or valorization route is currently defined [14].

B. Step 2: Identification of possible methods and development of a decision tree specific to WWTP

Using the general tree presented in **Fig. 6** and the current sludge management situation at the WWTP level, the following options are possible after solar drying of the sludge: agricultural use, landfill, co-incineration with household waste, co-incineration in cement works and mono-incineration. Since the household waste incinerator is non-existent for the city, this option is eliminated. For the other routes, we assume that from a technical, environmental and regulatory point of view, they are feasible.

The tree specific to the Marrakech WWTP is shown in **Fig. 8**.

C. Step 3: Mathematical formulation and assumptions

As an assumption in this study, we assume a linear relationship between the quantities to be treated as well as the revenues and costs of treatments, recoveries or disposals methods.

➢ **Identification of decision variables**

Decision variables are the quantities of sludge to be sent to each treatment, valorization and disposal method. These variables are reported in **Table I**.

➢ **Expression of the objective function**

The objective function to be maximized is as follows:

$$\begin{aligned} F = & -0.3X_0 - 5X_{1_{Ep}} - 39X_{2_{Dg}} + 4550X_{2_{Bg}} \\ & -38X_{3_{DshM}} + 0X_{4_{Sec}} - 230X_{5_{CoInCim}} - 14X_{6_{Epd}} \\ & -240X_{7_{Dech}} - 560X_{8_{MonInc}} + 0X_{80_{Cd}} \\ & +1000X_{81_{CdVt}} - 35X_{82\_CdDech} \end{aligned} \qquad (4)$$

The values of the coefficients of the objective function **dn** are calculated from the data presented in **Table II** for an operating life of 20 years. The currency unit used for the example is the Moroccan Dirham (1€ ≈ 11 DHs). These values are given as an indication, they are based on bibliographic research, information obtained from certain suppliers and estimation made on the basis of the situation of the case studied.

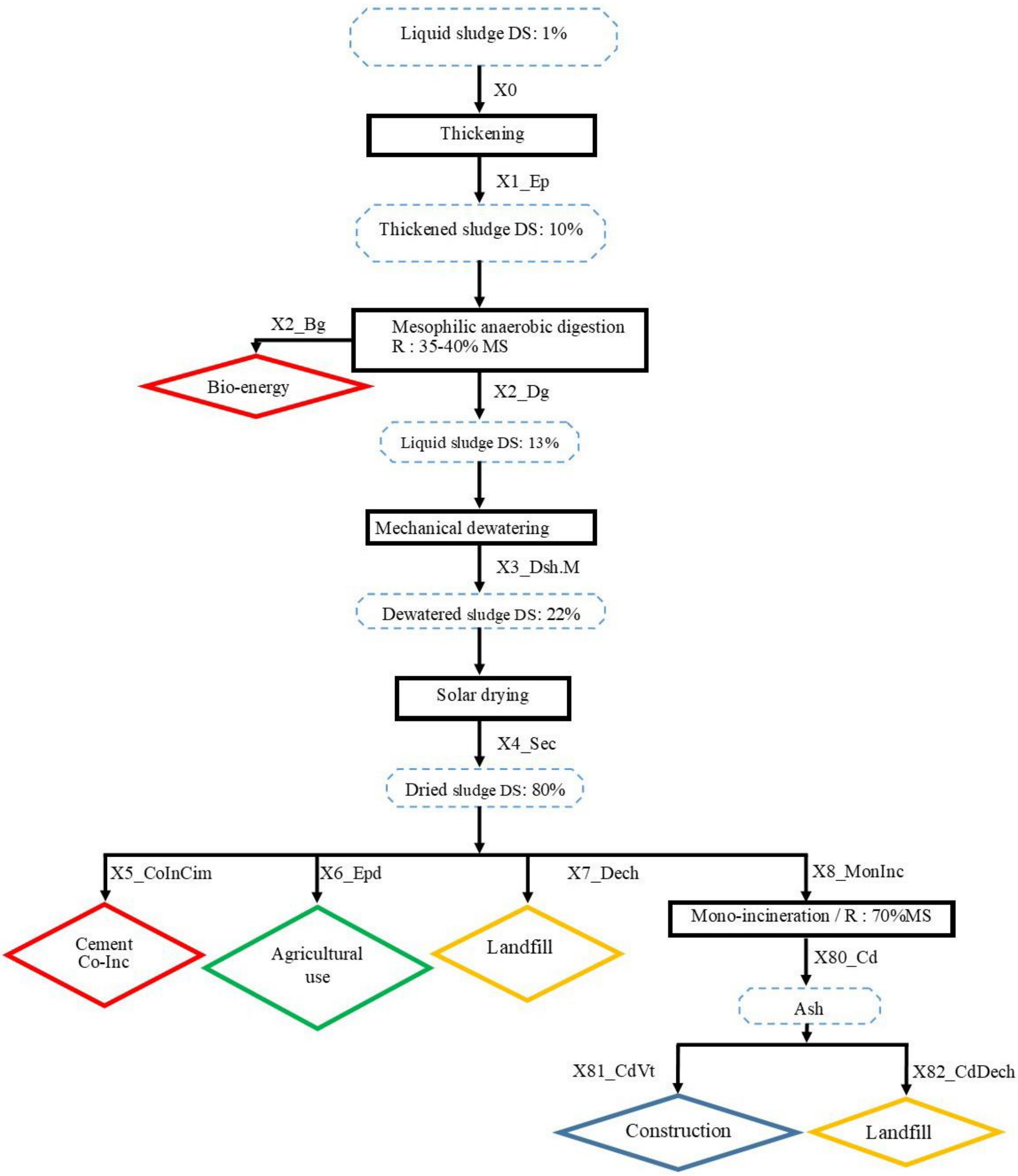

Figure 7 : Specific decision tree for the valorization and disposal paths of the Marrakech WWTP

Table I: Decision variables for the Marrakech WWTP

Variable	Quantity represented	Variable	Quantity represented
X0	Initial liquid sludge	X6_Epd	Sludge to be sent to agriculturale use
X1_Ep	Sludge after thickening	X7_Dech	Sludge to be sent to the landfill
X2_Dg	Sludge after anaerobic digestion	X8_MonInc	Sludge to be incinerated in mono-incineration
X2_Bg	Quantity of D.S transformed into biogas	X80_Cd	Ash produced
X3_DshM	Sludge after mechanical dewatering	X81_CdVt	Ash for sale to construction or cement plant
X4_Sec	Sludge after drying	X82_CdDech	Ash to be sent to landfill
X5_CoInCim	Sludge to be sent to the cement plant		

Table II : Data used to calculate the coefficients of the objective function (dn)

Coefficient	Rn	Cn (Inv.)	Cn (Op.)	Description	Source
Thickening	-	180 €/t D.S/y	30 €/t D.S	-	Estimation
Anaerobic digestion	-	110 €/t D.S/y	5 €/t D.S	-	[34]
Biogas	0.07 €/kWh	-	-	Selling price of the heat produced	[35]
Mechanical dewatering	-	120 €/t D.S/y	30 €/t D.S	-	[34]
Solar drying	-	860 €/t D.S/y	15 €/t D.S	-	[36]
Transportation	-	-	0.3 €/t R.S/km	5.5 tons dump truck, reference cost Morocco	[37]
Co-incineration in cement factory	-	-	15 €/t D.S	Cost of the deposit at the cement factory	Estimation
Landfill	-	-	10 €/t R.S	Cost of landfill disposal	[38]
Mono-incineration	-	420 €/t D.S/y	80 €/t D.S	-	[34, 38]
Ashes	100 €/t	-	-	Revenue for sale of ashes	Estimation

Inv.: Investment. **Op.**: Operating.

➢ **Expression of constraints**

First, the constraints related to material balances can be written on the different steps of the selected paths. The data summarized in **Table III** were used to find the coefficients of these constraints.

The constraints are as follows:

- Thickening: dry matter balance **(Constraint 01)**

$$0.1X_{1\_Ep} - 0.01X_0 = 0 \qquad (5)$$

- Anaerobic digestion: dry matter performance balance **(Constraint 02)**

$$0.13X_{2\_Dg} - 0.065X_{1\_Ep} = 0 \qquad (6)$$

- Quantity of dry matter transformed into biogas **(Constraint 03)**

$$-0.035X_{1_{Ep}} + X_{2_{Bg}} = 0 \qquad (7)$$

- Mechanical dewatering: dry matter balance **(Constraint 04)**

$$0.22X_{3\_DshM} - 0.13X_{2\_Dg} = 0 \qquad (8)$$

- Solar drying: dry matter balance **(Constraint 05)**

$$0.8X_{4\_Sec} - 0.22X_{3\_DshM} = 0 \qquad (9)$$

- Overall material balance after solar drying **(Constraint 06)**

$$X_{4\_Sec} - X_{5\_CoIncim} - X_{6\_Epd} - X_{7\_Dech} - X_{8\_MonInc} = 0 \qquad (10)$$

- Mono-incineration: dry matter performance balance **(Constraint 07)**

$$X_{80\_Cd} - 0.24X_{8\_MonInc} = 0 \qquad (11)$$

- Overall material balance after single incineration **(Constraint 08)**

$$X_{80\_Cd} - X_{81\_CdVt} - X_{82\_CdDech} = 0 \qquad (12)$$

Second, the constraints related to the amount of material that disposal and valorization methods can receive are necessary. In this case, these are the quantities of sludge that could be accepted by cement plants, agricultural application and landfill. For the moment, sending sludge to cement plants is not a practice in Morocco, but we hypothesize its possibility in our study. In the Marrakech area, a cement factory has been identified. It is a cement plant of the Moroccan Cement Company located in the municipality of Mzoudia, with an annual production capacity of 1.4 million tons of cement [39]. The cement plant is located at 75 km from the drying greenhouses and 60 km from the WWTP. With this capacity, the cement plant could have the possibility to absorb all the dried sludge by using it as fuel in the pre-cooking stages and/or by mixing with the raw material, provided that the addition will not affect the quality of the cement and is accepted by the cement plant. For our study we will assume that the cement plant accepts to receive 10% of its maximum capacity which is 140 000 tons a year.

Regarding agricultural applications, the Marrakech-Safi region holds about 22% of Morocco's useful agricultural area with a total area of 1 904 363 hectares as well as a forest area of about 721 876 hectares. In addition to this, Marrakech has about 12 000 hectares of palm groves [40]. In this study we consider that sludge can be spread on 10% of all surfaces. Furthermore, we also retain a limit of 3 kg of D.S/m² over 10 years of spreading [41].

For landfilling, it is important to note that the solar greenhouses are located on the same site as the controlled landfill of the Wilaya of Marrakech, in the commune of Mnabha. A storage capacity of 20 531 tons of dried sludge has been planned at the greenhouses, which will allow the sludge to be stored for one year pending a decision on the way forward [14]. In our study, we consider that a surface of 3 hectares is available to receive the sludge and that it will be stored up to 10 m high.

Table III: Data used for constraint coefficients from material balances

Step	Output dryness (t D.S/t BB)	D.S reduction (%)
Thickening	0.1	-
Anaerobic digestion	0.13	35
Mechanical dewatering	0.25	-
Solar drying	0.8	-
Mono-incineration	1	70

From these data, the constraints related to the quantity of material that valorization and disposal methods can receive in tons per day are as follows:

- Cement factory **(Constraint 09)**

$$X_{5\_CoInCim} + X_{81\_CdVt} \leq 380 \qquad (13)$$

- Agricultural application **(Constraint 10)**

$$X_{6\_Epd} \leq 2\ 700 \qquad (14)$$

- Landfill **(Constraint 11)**

$$X_{7\_Dech} + X_{82\_CdDech} \leq 50 \qquad (15)$$

D. Step 4: Mathematical resolution and sensitivity analysis

➢ Mathematical resolution

The objective function and constraints forming the mathematical model were then programmed into the Excel software.

The quantity X0 at the inlet of the thickening is **5 500 tons** of sludge at a dryness of 1% per day. The result of the optimization is given in **Table IV**. The optimal way found after solar drying under the given conditions is agricultural with a gain of about 10 € (110 DHs) per ton of incoming D.S. This gain is generated by the use of biogas.

➢ Sensitivity analysis

Table V presents the result of the sensitivity analysis on the coefficients of the objective function. The allowable increase and decrease columns represent the values of possible increase or decrease in the coefficients of the objective function so that the path found remains the optimal solution. For the first six variables, from X_0 to X_{4_Sec}, which corresponds to the thickening treatment until drying, the increase or decrease values can go to infinity without affecting the optimal path. This is because these are the existing steps. After drying, several options are possible. For the present solution, an interpretation is given for the variable X_{6_Epd}. Here the allowable increase in the coefficient of this variable tends towards infinity, which is logical because an increase in the variable will further increase the value of the objective function. On the other hand, in order for the path found to remain the optimal solution, the permissible reduction in the coefficient of this variable is 216 units, which means that it must not be less than – 230.

Table IV : Result of the optimization

Variable	Final value
X0	5500
X1_Ep	550
X2_Bg	19
X2_Dg	275
X3_DshM	143
X4_Sec	51
X6_Epd	51
X8_MonInc	0
X80_Cd	0
X81_CdVt	0
X5_CoInCim	0
X7_Dech	0
X82_CdDech	0

For variables whose final values are equal to zero, which means that they are not part of the current optimal solution, their allowable reduction is infinite because their decrease further reduces their potential to be part of the optimal solution. On the other hand, their allowable increase presents the possible maximum values increase of the coefficients so that the result found remains the optimal solution. If we take an example of interpretation on the variable $X_{5\_CoInCim}$, which represents the quantity of sludge to be sent to cement plant co-incineration, an increase in the coefficient of the variable by more than 216 units will change the optimal solution.

The reduced cost represents the decrease in profit or increase in cost in the case where a quantity of one unit (ton) of sludge is processed by the corresponding method. In the case of X_{7_Dch}, sending one ton of sludge to the landfill will increase the cost by 226 units.

The result of the constraint sensitivity analysis is given in **Table VI**. The shadow price represents the variation in the value of the optimal solution when the right-hand side (RHS) value of the corresponding constraint is increased by one unit. For constraints related to material balances, the increase in the RHS terms cannot be achieved, so the interpretation of shadow prices is not relevant except in the case of an increase in processing capacity. For constraints related to valorization and disposal methods, the results can be interpreted as described below. The allowable reduction and increase give the value interval in which the shadow price remains the same. For example, in the case of the constraint related to the quantity to be sent for agricultural application (Constraint 10), the variation in the value of the objective function is zero as long as the right-hand term of the constraint remains between 51 and infinite.

E. Step 5: Validation of the solution

In this step, it is up to the managers or decision-makers of the WWTP to validate the solution found.

In this study, with respect to the data used, the optimal way to

Table V: Result of the sensitivity analysis on the coefficients of the objective function

Variable	Final value	Reduced cost	Objective coefficient	Allowable increase	Allowable decrease
X0	5500	0	-0,3	Infini	Infini
X1_Ep	550	0	-5	Infini	Infini
X2_Bg	19	0	4550	Infini	Infini
X2_Dg	275	0	-39	Infini	Infini
X3_DshM	143	0	-38	Infini	Infini
X4_Sec	51	0	0	Infini	Infini
X6_Epd	51	0	-14	Infini	216
X5_CoInCim	0	-216	-230	216	Infini
X7_Dch	0	-226	-240	226	Infini
X8_MonInc	0	0	-560	336	Infini
X80.1_Cd	0	0	0	1601	Infini
X81_CdVt	0	-1601	1000	1601	Infini
X82_CdDch	0	-2636	-35	2636	Infini

Table VI: Result of the sensitivity analysis on constraints

Contrainte	Final value	Shadow	Constraint RHS	Allowable increase	Allowable decrease
Constraint 05	0	-20	0	1861	36
Constraint 06	0	14	0	51	2659
Constraint 02	0	472	0	36	1861
Constraint 03	0	4550	0	Infini	19
X0	5500	12	5500	286402	5500
Constraint 01	0	-1235	0	55	2864
Constraint 10	51	0	2710	Infini	2659
Constraint 09	0	0	383	Infini	383
Constraint 04	0	-171	0	1861	36
Constraint 07	0	2601	0	0	10
Constraint 08	0	-2601	0	10	0
Constraint 11	0	0	49	Infini	49

manage dried sludge in the case of the Marrakech WWTP is agricultural application. The adaptation of this optimal path will allow a gain of about 10 € (100 DHs) per ton of incoming D.S, which comes from the valorization of biogas.

F. Step 6: Application of the solution

This found solution can be applied if it is validated by WWTP managers.

V. CONCLUSION

At the end of this work, which aims to present a methodology for optimizing WWTP sludge treatment, disposal and valorization methods and which can be a decision-making tool for their managers, it was first pointed out that given the multitude of choices and the different constraints on sludge management, optimization is necessary. Before discharging the sludge, treatments must be carried out to reduce the volume and the risks that this sludge may present to the environment and public health. These treatments are closely linked to the method of disposal and/or valorization to be adopted. Different methods of treatment, disposal and valorization have been described, methods that are considered proven and innovative have been used to develop a general decision tree for the different sludge management options. This general tree can be used for WWTPs that do not yet have a sludge management method in place, WWTPs that are not yet built or do not have a complete idea of the steps involved in their sludge management method. Then the methodology for optimizing the treatment, valorization and disposal methods for WWTP sludge is presented. This methodology follows the following six (6) steps: description of the existing system, identification of possible treatment, disposal and valorization methods for the WWTP and development of a decision tree specific to the WWTP, mathematical formulation and assumptions, mathematical resolution and sensitivity analysis, validation of the solution and application of the solution. During the mathematical resolution phase, a computer tool is developed to assist managers in their decision-making. Finally, an example of an application was made using the case of sludge management at the WWTP in the city of Marrakech (Morocco). As a result of this example, the optimal methods identified, with respect to the data used, consist of the existing treatment methods which are: thickening, anaerobic digestion, mechanical dewatering and solar drying, as well as the use of dried sludge in agricultural application. A gain of about €10 (110 DHs) per ton of incoming D.S was found.

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During his research career, Professor Hajji worked on various aspects of thermal engineering such as heat and mass transfer, process simulation and optimization of processes. During the last ten years his work was mainly in the field of applied solar energy. He lead numerous engineering design and construction of solar thermal and photovoltaic projects: solar space heating, power production, solar water pumping etc.

Professor Hajji had an extensive experience in the field of energy and production management consulting. He lead numerous audits and design work in various industries. This included efficiency assessment, identification of cost saving opportunities and cost-benefit analysis of projects. He also wrote technical manuals and organized several training seminars in the fields of energy management, quantitative management techniques and industrial computer applications.

Professor Hajji's latest articles dealt with various aspects of solar energy application such as solar cooking, solar drying, solar water desalination, and remote areas electrification.

Some latest publications:

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