Automated decisional process for material and equipment selection: Application to the selection of material for water pipes

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Abstract

In this paper, we are interested in the material selection process as one of the essential steps in the design of products or projects. This task is very complex due to the multitude and heterogeneity of criteria involved and the specificities of each project. The selection process can be very time consuming, especially if it is a repetitive operation. This type of process also requires the use of all the knowledge already available to guarantee the reliability of the decisions. This article proposes a methodology for selecting equipment and material based on an automated model that integrates Multiple-Criteria Decision Analysis (MCDA) methods and knowledge management principles. This model is particularly relevant in situations where the selection process is repetitive but should be reviewed according to the specific conditions of each case. Using this model will allow decision-makers to save time and benefit from the knowledge created during selection processes. A practical application to water pipe material selection is proposed to illustrate practical contribution of the model. It is also applicable to other cases where the selection process is repetitive and depends each time on specific conditions.

Keywords
Material selection, Equipment selection, Multiple-Criteria Decision Analysis, Knowledge management, Water pipe material

1. Introduction
Material and Equipment Selection (MES) is a decision that is permanently taken depending on the specifications of the project at hand and many other reasons developed in (Edwards 2004). The most common ones are the improvement of products or services performance, meeting new legal requirements and reducing cost of environmental issues.
The process of selecting the "best" material for a particular project is complex because of the need to satisfy a set of generally contradictory requirements. Properties and characteristics of materials are difficult to reconcile when looking for an ideal solution to an operational problem (Jahan et al. 2016). However, priorities must be set and working rules

need to be defined for the selection process to be relevant. Many researchers worked on frameworks to structure and facilitate selection processes. We note the work (Albiñana and Vila 2012) which proposes a six steps process and placed the Multiple-Criteria Decision Analysis (MCDA) on the fifth stage as the key of the process.
MCDA is a sub-discipline of operational research that explicitly consider multiple criteria or objectives in decision making. Many methods are proposed in the literature (Schärlig 1985) and can be used to support the selection of materials and equipment by allowing the simultaneous consideration of design requirements, material properties and characteristics, and product features and uses (Jahan et al. 2010). MCDA methods are very effective, in particular in MES. As detailed in section 2.2, several studies have applied MCDA methods to decide on the appropriate material or equipment.
Besides, several studies have highlighted the importance of knowledge management in decision-making in general and in MES in particular (see section 2.5).
Here, we are interested in cases where the MES is a recurring operation with constant parameters and other variables that depends on the conditions of the project. In these cases, there is need to optimize the time allocated to the execution of the selection process. Besides, in order to be effective we need to capitalize on the knowledge available and created during past selection processes. Thus, we propose a selection model adapted to the field of MES based on multi-criteria methods and integrating the principles of knowledge management. The contribution of this paper is to automate the decision-making process in order to save time and ensure reliability and consistency of the results.
The following section provides the theoretical and practical framework which served as the basis for our work. Indeed, we will start with a quick description of the MCDA discipline. We will then review decision-making in the MES field and its biggest challenges, namely, the screening of alternatives, the definition of criteria and knowledge management. Section 3 presents the main contribution of this article, which is an automated decisional process for material and equipment selection. An application of this process to the selection of the best material for water pipes in a water treatment company is proposed in Section 4.
For simplicity, and throughout the rest of the article, the acronym MES will be used to denote the material and equipment selection.

2. MCDA methods and MES

2.1 MCDA methods

MCDA is concerned with structuring and solving decision making problems explicitly involving many criteria. Generally, there is no unique optimal solution for such problems and it is necessary to use decision-maker's preferences to differentiate between solutions.
In (Schärlig 1985), four common steps to all MCDA methods are presented:

- Definition of the alternatives: it consists on selecting a subset, as small as possible, of alternatives Ai, i = 1…n. These alternatives or actions will be analyzed and evaluated during the decision process.
- Construction of criteria: this phase is very important and decisive for all multiple criteria methods. Weights are often affected to criteria. To model their relative importance, values between 0 and 1 whose sum equals 1, can be set freely by the decision maker or a decision aid method.
- Performance matrix: each action is judged according to each criterion. All assessments can be presented in a double-entry table, called a performance matrix. Other parameters relate to the criteria are also mentioned in the performance matrix depending on the chosen aggregation method. Such as the weights of the criteria, which are used in almost all the methods, thresholds, vetoes ...
- Aggregation phase: it consists in aggregating the performances to designate the action that has the best evaluation.

In (Guitouni and Martel 1998), the authors rely on 99 references to develop guidelines to choose the adequate MCDA method for each situation. They list 29 methods of multiple-criteria decision analysis methods and compare them regarding the guidelines.

2.2 Decision making in MES

The selection of materials is part of the basic decisions when designing a product (Crane et al. 1997). The same approach applies to construction, engineering, infrastructure...
This choice has first a direct impact on economic parameters and then has a large influence on environmental and safety results (Jalham 2006; Van Kesteren et al. 2007). Several researchers have studied the material and equipment selection processes. In (Chiner 1988), Chiner was one of the first experts to work on the subject by considering material selection as a problem-solving situation and proposes a methodology based on 5 steps.

Few years later, (Ashby et al. 2004) reviewed the main work done in this field (Ashby et al. 2001; Ashby and Cebon 1993, 1996; Crane et al. 1997; Farag 1990; Lampman and Dieter 1997) and identified three basic steps to achieve material selection: screening to reduce number of alternatives, ranking to evaluate performance of remaining alternatives and supporting information to finalize selection regarding to specific information. In 2010, Jahan also studied the various phases proposed by the literature and concluded that they differ slightly (Jahan et al. 2010).
All these studies have focused on structuring the material selection process to simplify it and improve its efficiency. Further research has focused on tools that can support the material selection decision and many have used multi-criteria decision analysis methods and approaches to achieve their goal.
(Jahan et al. 2010) reviewed 95 published research studies up to the year 2009 on material screening and choosing methods and found that MCDM (Multi Criteria Decision Methods), especially TOPSIS, ELECTRE and AHP, are much more widely used than optimization methods. Indeed, the literature offers many applications of MCDA methods for equipment and material selection. Most of them use the Analytic Hierarchy Process (AHP), as a primary tool (Chakraborty and Banik 2006a; Samanta et al. 2002; Shapira and Goldenberg 2005), or in combination with other methods when a deep analysis is needed (Bhattacharya et al. 2005; Dağdeviren 2008; Hodgett 2016; Paramasivam et al. 2011; Rao and Davim 2008; Yazdani-Chamzini 2014). However, other outranking and utility function methods were used in (Ashby 2000; Dehghan-Manshadi et al. 2007; Rao 2006; Shanian and Savadogo 2006; Sharma et al. 1993; Ulubeyli and Kazaz 2009; Wade 1995).
All the studies presented above provide evidence that MCDA methods are very useful and effective in a material and equipment selection process.

2.3. Screening of alternatives in MES
In most of the selection processes cited in Section 2.2, we find the phase of screening of alternatives. Authors in (Jahan et al. 2010) were interested in this stage and presented eight methods to help screening materials that are inspired from previous research. In a more basic way, (Ashby et al. 2004) proposed three strategies to support and guide material selection processes: "free searching", based on quantitative analysis, "the questionnaire strategy", based on expertise capture and "inductive reasoning and analogy" (see Figure 1).

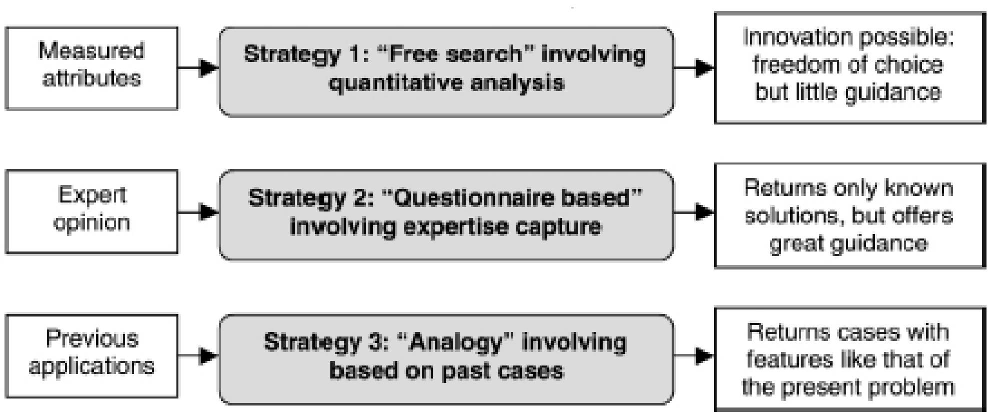

Figure. 1 Ashby's material selection strategies (Ashby et al. 2004)

To guide the use of these strategies, (Ashby et al. 2004) gives two different applications and admits the possibility to use them individually or together. In the model that we propose, we combine the three strategies in order to add up their benefits and go beyond the limits of each one (see Section 2.3)

2.4 Definition of criteria in MES
Several studies have focused on the criteria definition phase and have shown that the selection of materials and equipment is based on many conflicting parameters (Brechet et al. 2001; Farag 1979; Jalham 2006; Karana 2006; Karana et al. 2008; Shapira and Goldenberg 2005; Van Kesteren et al. 2007)
(Karana 2006) noted the difficulty to deal with technical functions of products as well as the user experience. (Van Kesteren et al. 2007) have developed a Material Selection Activity Model that takes into account a number of external factors that were previously neglected. The choice of the material should be made regarding the environment in which

the product will operate (Chen et al. 1994; Kutz 2002). (Deng and Edwards 2007) listed other requirements on material selection for more details on this subject.
Concerning guidelines to choose the right criteria, several studies that give general recommendations are available in literature. (Roy 1985) proposes three conditions for the set of criteria to be relevant for a multiple-criteria analysis: completeness, consistency and non-redundancy. More specifically to material selection, (Ashby et al. 2004) proposes a material selection strategy in which the criteria can be drawn from a detailed exploration and formulation of the constraints that must be satisfied if the material is to fill the desired function.

2.5. Knowledge Management in MES

As we mentioned before, in a MES decision process, the data is not always readily available and needs to be inferred. (Ashby et al. 2004) has already raised types of knowledge useful in decision-making in the field of materials. He distinguished between "structured data" and "stuff that is not in data sheets". Hierarchical structures seem effective to organize the first type of data but there is a difficulty to manage the second type of knowledge. (Ashby et al. 2004) highlighted the need to store and retrieve expertise in the engineering field. This need has also been reported by other works (Chakraborty and Banik 2006b; Rao and Patel 2010).
In a more global context, (Molina et al. 2007) underlined that the large amount of information produced in companies is very necessary for the various decision-making processes to promote employee autonomy. He also demonstrated through a literature study a close relationship between decision-making and knowledge transfer in companies. (Kogut and Zander 1992) had previously argued that poor knowledge transfer could lead to a highly inefficient decision-making process. Therefore, to ensure the efficiency of the decision-making process, it is important to integrate the largest amount of knowledge (coded or not) scattered across all levels of the organization (Hoopes and Postrel 1999; Lessard and Zaheer 1996; Nicolas 2004).
In this sense, (Molina et al. 2007) and (Ashby et al. 2004) made the same recommendation regarding the need to identify, code, summarize and share the company's knowledge to effectively feed into decision-making processes.
More specifically to material and equipment selection, it is natural to be concerned about the result of the knowledge that will be created and applied in this type of processes and to refer to expertise that have taken place in the past (Chiner 1988).
Knowledge management discipline proposes several tools to effectively manage each tacit and explicit knowledge. The objective is to convert all tacit knowledge to an explicit one so it can be stored and shared for further use. We can mention Return of Experience (REX) systems that are very useful to avoid data loss by storing and sharing knowledge acquired from previous experienced. This tool may offer a rich database for the creation of new knowledge by feeding and improving the decision-making process (Prax 2000).

2.6. Summary

From the literature review presented in this section 2, we retain the following points:

- Material and equipment selection is a very complex task that must be carried out carefully. Depending on the project, the choice of a bad material or equipment may have a serious impact on the final product or service (cost, quality, service life, maintenance, environment, safety, etc.)
- Faced with the multitude of criteria, MCDA methods are very useful and effective to support the selection of materials and equipment.
- Material and equipment selection, consumes a lot of coded knowledge and expertise. The use of tools to capture, store and share this knowledge will ensure completeness and save time and money.

3. Automated decisional process for material and equipment selection

In this work, we are interested in repetitive MES decisions. These are situations where decision about a material or equipment selection needs to be taken regularly, each time depending on the specific conditions of the project at hand. These situations are encountered for example in construction companies that have to choose construction materials for each new project taking into account the environmental conditions such as humidity, temperature, geological conditions...
Another example concerns the packaging industry where the choice of material's components depends each time on the product to be packaged, its storage conditions, its use, the logistical conditions it will have to follow...
The process of MES is long and expensive. Indeed, data collection for example is time and effort consuming, as it must be exhaustive to ensure the reliability of the results. If the decision is repetitive, this step will be repeated each time a decision situation arises. It is therefore interesting to optimize the process, especially if the data does not change much.

A great dispersion of data and expertise has also been observed in practice and relayed by many authors (see section 2.5). This phenomenon can also have negative consequences on the selection process, whether in terms of time, effort or accuracy.
In this paper, we introduce a material and equipment selection process adapted to such situations. It is based on Multi Criteria Decision Analysis (MCDA) approach and integrates knowledge and learnings from past experiences.
The originality of this model is that it "automates" a part of the decisional process that does not depend on the specific conditions of the decision at hand.
This way, time and effort are saved while benefiting from past experiences.
The model developed is organized through two major steps as follows:

1. Construction of the prefilled performance matrix: It should be done through three phases:
    a. Definition of the alternatives: it's important to list all materials or equipment that can meet the specific needs of the project. All alternatives must be comparable regarding to the selection criteria. To do this, we suggest to follow guidance that Ashby proposes in (Ashby et al. 2004) and apply strategies 1 and 3 to capture as much information about alternatives as possible. At this stage, no decision to eliminate an alternative will be taken even if there is not enough information to evaluate it. This step is carried out once and for all so as not to repeat a new search about alternatives at the launch of each project. The list of materials can be updated regarding to available materials, but this will be done occasionally. (see illustration in Section 4.2.1)
    b. Construction of the criteria: to succeed this stage, decision-makers should take into consideration theoretical and empirical recommendations in this field (see Section 2.4). In the MES field, criteria are generally derived from the requirements and specifications of the project (functional, process, cost, reliability, resistance to service conditions, environmental characteristics...). This step is also done once and for all. (see illustration in Section 4.2.2)
    c. Development of the performance matrix: this phase contains our major contribution. We evaluate the alternatives regarding to criteria using all explicit knowledge available as discussed previously. All this data is used to obtain a prefilled version of the performance matrix. (see illustration in Section 4.2.3)

   This prefilled performance matrix is done once and for all and can be occasionally updated as needed. It is, essentially the automation of this phase, that will allow the model to gain time and efficiency compared to a classical model. This action must allow codified storage of existing data for simple sharing and it must also offer the possibility of codifying the tacit knowledge that will be created during each workshop session around specific conditions.
2. Integration of the specific conditions: It consists on updating the prefilled performance matrix with new knowledge concerning the specific conditions of the project under study. This can be weights of existing criteria, new alternatives or other missing parameters. This results on a final performance matrix that should be codified and stored in a unique database. Once the performance matrix complete, the aggregation phase can be executed (see illustration in Section 4.3). The analyst can choose, depending on the case under study, to work with the method of his choice. In the material and equipment field, the multitude of criteria and their heterogeneity make decision making a complex task. This difference in the nature of the criteria may be accompanied by a difference in compensatory approaches.
   Indeed, in (van Kesteren et al. 2008) the authors supported that in material selection it can be interesting to combine different methods. Some methods are more used then others in the MES field, such as TOPSIS, ELECTRE and AHP. Analysts may find more guidance to choose the appropriate method for each case in reviews proposed by (Guitouni and Martel 1998) or (Jahan et al. 2010).

The proposed framework recommends the use of a REX system to capture and save the new knowledge created during the two phases of the process. Indeed, the decision-makers should, after each session, feed the database with the results of their work. This operation will complete the database after each selection process.
A schematic of the integrated framework that we propose is presented in Figure 2.

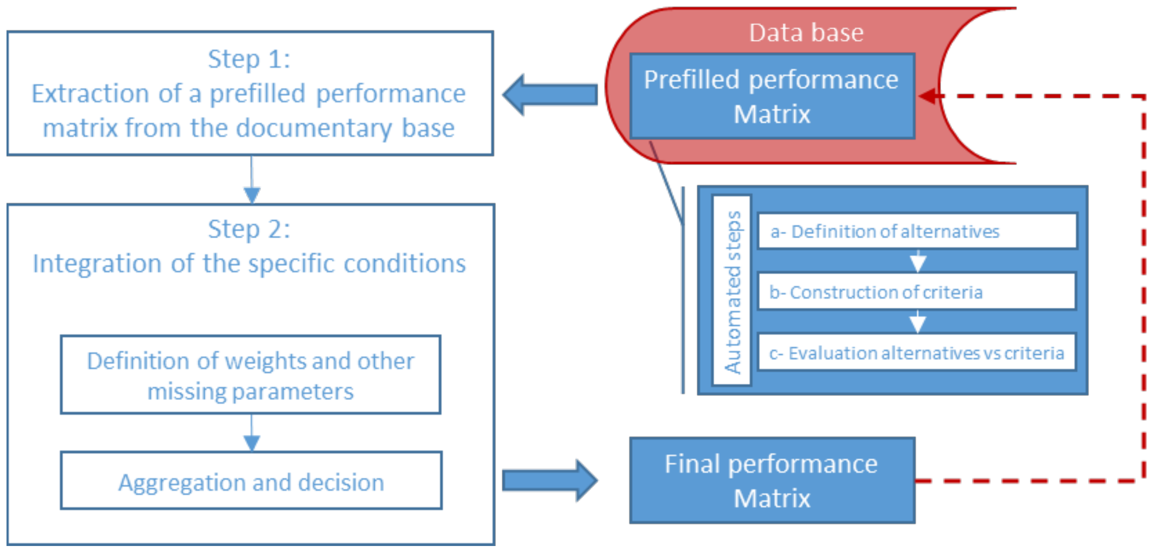

Figure. 2 Our automated decisional process for material and equipment selection
The figure represents the process explained in Section 3. A material or equipment selection process is executed on 2 steps: extraction of a prefilled performance matrix from a database which saves the history of previous decision-making; and integration of specific conditions to allow aggregation and decision. The current decision process should also be captured to update the database. The automated steps under the prefilled performance matrix describes the three steps traditionally followed by a classical decision process. In this model, these steps are executed only during the first decision processes.

To illustrate our decisional process, we share an application to a case study concerning the selection of the best material for water pipes in a water treatment company. This is presented in next section.

4. Case study: selection of a water pipe material

4.1. Context

The case study concerns the Moroccan subsidiary of a multinational company which manages the distribution of water and electricity, the collection of wastewater and rainwater and street lighting for 4.2 million inhabitants. The water distribution systems are, in general, very complex and there is a lot of uncertainty in their design and management processes (TANY1MBOH and Templeman 2000). This makes decisions difficult regarding to the complexity of the situation.
The company of our study needs to take decisions about its pipes material each time the pipe network needs an extension or a repair. The selection of the material depends on technical characteristics of the materials as well as on the conditions of the environment where the implementation is planned.
The company has found that the life span of its pipes is well below their theoretical life, resulting in an increase in the annual rate of renewal of installed pipes. A throughout study exhibited two main explanations:

- The first one is that the materials of the pipes are generally not adapted to the external conditions.
- The second is that the recommendations concerning the procedure of installation of the pipes are often not respected.

While analyzing the current process of pipes materials selection, we discovered that this material decision falls in the category described in Section 3. Indeed, the decision need to be taken regularly and the characteristics of the materials are invariable. Moreover, each particular project depends on the location and environmental conditions.
For example, it is unthinkable to use "concrete" for an industrial drinking water pipeline project or to use "smooth PVC-U" for a gravity sewer pipeline project where depth is greater than 4m. We have assisted the company in automating its process by applying the decisional process presented in Section 3.

4.2 Construction of the prefilled performance matrix

As explained in section 3, this stage should be done once and updated if needed. A complete data collection will make the automation of this phase more reliable and avoid repeating it for each project. This consists on three phases as illustrated in figure 2.

4.2.1 Definition of the alternatives:

Water management is a service regulated by international standards and national and local laws. The equipment on the market is fairly standardized and well-studied. However, several possible materials are available and a selection is needed to decide of the appropriate material for each project.
This case deals with the distribution of drinking water or collection of waste water. The company can choose between the following materials:

- a1: PVC-U
- a2: PEHD 100
- a3: Ductile iron
- a4: Prestressed concrete
- a5: PRV
- a6: PVC-BO

Each one has hard and soft characteristics which constitute an identity card that will be explored during the evaluation phase. In our application we use strategies proposed in (Ashby et al. 2004) and described in section 2.3 to collect as much data as possible on the materials listed above.

- Strategy 1: technical data is directly extracted from the characteristics and recommendations provided by the producers.
- Strategy 3: qualitative performances are captured from previous experiences while selecting a material pipe for a similar situation.

4.2.2 Construction of the criteria

Together, with the company experts, we have identified eight criteria to consider when selecting the pipe material.

- C1: Hydraulic capacity, represented by the range of standardized minimum and maximum diameters possible for this material, in mm.
- C2: The maximum pressure supported, in bars.
- C3: Charge loss. This criterion represents the capacity of the material to preserve the energy of the fluid during its flow. It depends on the nature of the inner wall. This criterion does not influence the survival time of the pipe, but represents the financial aspect. Indeed, when the charge losses are high, the operating costs of the pipe are also high.
- C4: Mechanical resistance to rolling loads. It represents the ability of the material to resist the mechanical forces exerted by rolling loads (cars, trucks, ...) on the road and which are transmitted to buried collectors. These charges are greater in the case of main roads, where traffic is high and loaded trucks are frequent.
- C5: Resistance to soil aggression. This criterion represents the ability of the outer wall of the material to cope with chemical reactions with soil containing industrial waste or chemicals that can react with this material. This criterion is important in industrial zones.
- C6: Resistance to the aggressiveness of the fluid. This criterion represents the ability of the inner wall of the material to cope with chemical reactions with the fluid. This criterion is particularly important in waste water collection projects.
- C7: Resistance to stray currents. This criterion represents the resistance of the material to cathodic corrosion by electrolysis which is caused by the proximity to a railway for example. The corrosion leads to a degradation of the pipe which decreases its survival time.
- C8: Ease and speed of installation. This criterion represents the degree of ease for the material to be laid without any accidents or fractures. It should be noted that this installation problem is critical, since the non-compliance with the standards developed by the standardization department for laying pipes is one of the major causes of the limited survival time of the pipe network.

4.2.3 Evaluation of the alternatives with the criteria

All the evaluations of the alternatives with respect to criteria C1 and C2 are available. However, a team of eight technical experts of the company was asked to evaluate the six alternatives against criteria C3 to C8 using an ascending scale from 1 to 4. All these data are added to the performance matrix to obtain a first version of the prefilled version (see Table 1).

Table 1 First version of the Prefilled performance matrix

	C1	C2	C3	C4	C5	C6	C7	C8
a1	[75;315]	16	3	1	4	4	3	3
a2	[25;315]	20	3	1	3	4	3	1
a3	[60;2000]	40	2	4	1	4	2	2
a4	[400;2000]	40	1	4	1	4	1	2
a5	[400;3000]	30	3	3	3	4	3	2
a6	[80;400]	25	3	2	3	4	3	3

This table consolidates the performance of alternatives regarding to criteria. Some of these values are extracted from technical documentation but most of this data has been evaluated by the experts called upon. Saving this data in a specific database and automating it would prevent the company from having to call in experts again each time a decision of this kind has to be made.

4.3 Integration of the specific conditions

The relative importance of each criterion changes from one project to another. Assigning weights to the criteria is a critical step. Several methods are available. AHP is the most used (Belton and Stewart 2002; Saaty 2008). Delphi can also be used in cases where experts' opinions are necessary (Linstone et al. 1975).
In our case study we use a weighting matrix where the criteria are compared two by two to obtain the relative weight of each criterion.
It is a square matrix A of size equal to the number of criteria m, where each element ajl is given by

- ajl = 1 if criterion j is more important than criterion l,
- ajl = 0 otherwise.

The weight of a criterion j is then given by

$$w_j = \frac{\sum_{l=1}^{m} a_{jl}}{\sum_{l=1,k=1}^{m} a_{kl}}$$

For reasons that we will explain later (see Section 4.4), we will only need to determine the relative weights of criteria C4 to C8. The resulting weights, for the project at hand, are given in Table 2.

Table 2 Weighting matrix

	C4	C5	C6	C7	C8	Weights (w)
C4	0	1	0	1	1	0,3
C5	0	0	0	1	1	0,2
C6	1	1	0	1	1	0,4
C7	0	0	0	0	1	0,1
C8	0	0	0	0	0	0

This table shows the relative importance of each criterion. C8 is definitely the most influent criterion on the material selection.
The integration of weights leads to the final performance matrix shown in Table 3.

Table 3 Pre-filled performance matrix

	C1	C2	C3	C4	C5	C6	C7	C8
a1	[75;315]	16	3	1	4	4	3	3
a2	[25;315]	20	3	1	3	4	3	1
a3	[60;2000]	40	2	4	1	4	2	2
a4	[400;2000]	40	1	4	1	4	1	2
a5	[400;3000]	30	3	3	3	4	3	2
a6	[80;400]	25	3	2	3	4	3	3
Weights (w)	--	--	--	0,3	0,2	0,4	0,1	0

Weights attributed to criteria are specific to this project. They may be different in other situations. Saving and automating this data will prevent decision makers to redo the calculations in a similar case.
According to the model proposed, this prefilled performance matrix should also feed the data base of the decision process and go to the aggregation phase. Currently, the analyze is still under process. Results of this stage will be the subject of another publication.

5. Conclusion

This paper is concerned with material and equipment selection processes. It focused on cases where the MES is a repetitive action which depends on both fixed parameters and specific conditions. An automated decisional process for material and equipment selection was proposed to deal with such situations. This model is based on an MCDA approach and integrates a knowledge management tool which enables expertise related to projects to be recovered.
The main contribution of this model is to automate once and for all the stages for which the data is fixed and available. And for each new case, decision-makers will only have to produce data related to specific conditions. This data must then be stored in a database for further projects. A case study was presented in this paper to illustrate the proposed model. It concerns the selection of a water pipe material for the Moroccan subsidiary of a multinational company which manages the distribution of water and electricity.

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