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Determination of Requirements for the Improvement of Occupational Safety in the Cleaning of Vertical Tanks of Petroleum Products

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Abstract: Since the beginning of the second industrial revolution, the use of tanks for the storage of petroleum products ensured the permanent supply of equipment that depended on fossil fuel derived from petroleum, either for direct consumption or as an element for power generation. For correct operation, periodic cleaning of these confined spaces was required, being a common practice for the direct exposure of operators to explosive atmospheres. Currently, there are many industries that keep this kind of deposit, and cleaning works are considered of high occupational risk. In this context, the question arises as to whether human–machine collaboration thanks to the technologies that compose Industry 5.0 can mitigate these risks while generating a sustainable balance by optimizing costs and protecting the environment. In the present work, the analytic hierarchy process (AHP) method is used to prioritize the requirements that should be compiled to establish safe protocols in tank cleaning works, solving the multi-criteria problem. Results prove that a couple of alternatives improve the working conditions of the people involved in this process: the chemical cleaning and the robotic cleaning, which approximately accounts for two thirds of the decision. These requirements are aligned with the Industry 5.0 paradigm, encouraging the use of robots for high-risk processes, and influencing human behavior. In addition, cost reduction is achieved without compromising on quality of service or delivery schedule, thus enabling a circular economy that promotes occupational safety in company policies.

Keywords: occupational safety; safety requirements; tank cleaning; AHP; Industry 5.0; robotic cleaning

1. Introduction

The Technological Revolution, as the Second Industrial Revolution was called, introduced new technological systems, the most significant of which was electric power [1]. However, advances in manufacturing and production technology allowed the widespread adoption of technological systems, even in the petroleum industry [2]. These developments necessitated the use of storage tanks that, either for direct consumption or for power generation, ensured the supply of petroleum products for equipment that depended on them [3].

For proper operation, periodic cleaning of these confined spaces is required [4], either due to production needs or maintenance work. In this context, direct exposure of operators to explosive atmospheres is a common and risky practice [5]. Currently, many industries maintain this type of tank, which leads to considering these cleaning works as a high occupational hazard [6]. Since these spaces are not designed for the permanent occupation of workers, it is necessary to consider the special measures to be taken in the case of specific tasks, because of they are characterized by a lack of oxygen [7], as well as by the presence of flammable substances and chemical contaminants [8]. Statistical data on fatal accidents in this sector in the period between 1980 and 1990 indicated a ratio of 0.69 deaths per 100,000 workers per year in the United States [9]. By 2011, these data had not improved, with four out of five incidents involving multiple fatalities [10]. This was due to the fact that, on most occasions, the rescue personnel involved were not trained in the risks associated with entering these spaces [11], given that, for each person requiring rescue, up to three rescuers are required [12]. The high occupational hazard involving industrial cleaning is present in different project stages: in the study phase, during execution and commissioning, and also in the facilities that are in service (maintenance, repair, and periodic inspections, among others), affecting different sectors such as the industrial [13], petrochemical [14], and naval [15].

Integration of enabling technologies reduces risks and increases safety and production levels [16]. However, the singularity of many industrial cleaning processes requires a combination of the resourcefulness of human expertise in collaboration with efficient, intelligent, and accurate machines, to obtain reliable solutions [17,18]. In this context, the new paradigm of Industry 5.0 becomes essential [19] to consider safety, environmental, quality, and cost-optimal issues, placing the wellbeing of the industrial worker at the center of the production process [20]. These new concerns have been taken into account in other industrial cleaning processes, such as in food production [21], manufacturing [22], or coating and painting [23].

Tank cleaning includes the association of hazardous work, as stated in Spain in Annex I of Royal Decree 39/97 [24]. These activities include work in explosive risk environments, work with fuel transfers, work in confined spaces and work with chemical substances, and work with machines and electrical and/or mechanical tools, among other jobs. These cleaning tasks consist of the removal of residues formed by the storage of oil over time. Therefore, cleaning must be carried out inside the tank, once the tank is free of gas and ensuring the entry of the operators [25]. The removal of these sludges and sediments can be performed using manual methods or various technologies, with the help of chemicals, mechanical devices, and/or water [26]. Figure 1 shows a classification of the different methodologies that can be used.

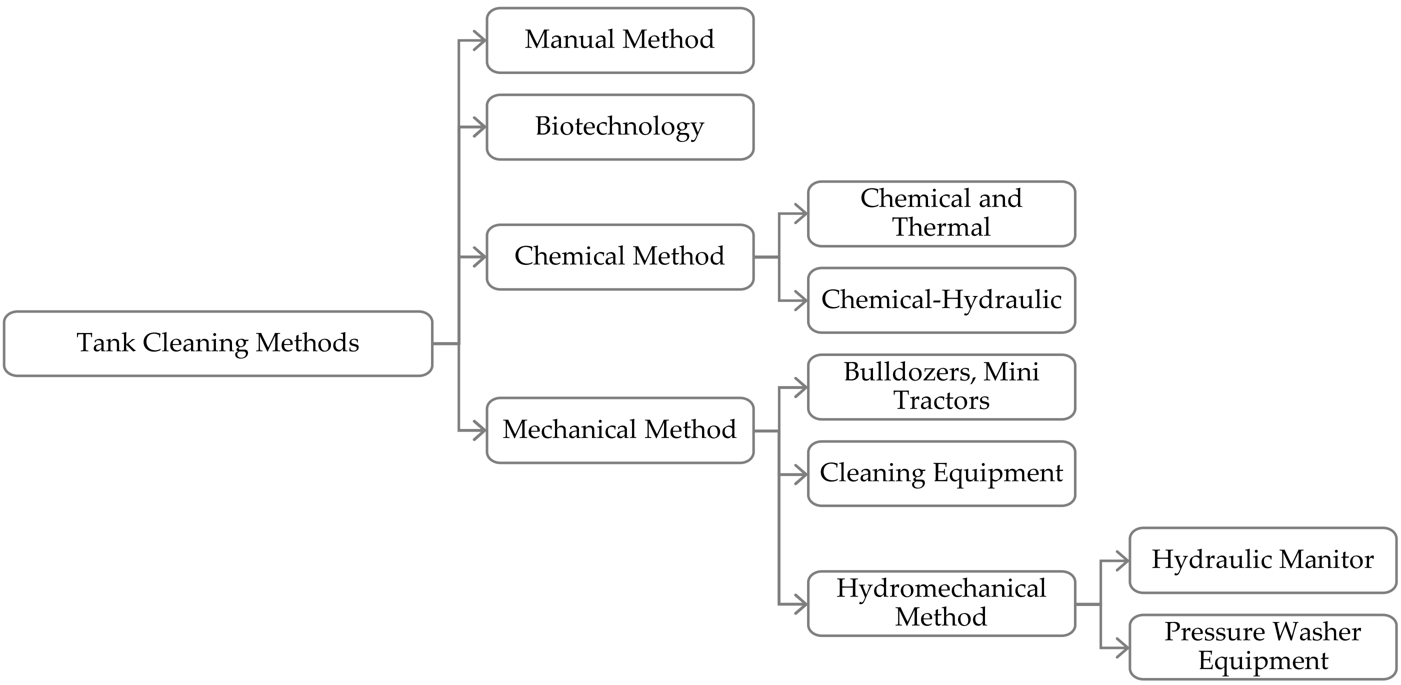

Figure 1. Tank cleaning methods. Adapted from [26].

First, manual cleaning, which consists of an intervention methodology based on the manual removal of the residues removed with hand tools (usually shovels), once specialized technicians have certified the absence of gas and the fluids have been removed by means of vacuum trucks or pneumatic or volumetric pumps, electrically or hydraulically operated but with explosion protection. This procedure requires access to the tank by qualified personnel with appropriate protection and the use of tools and equipment that are not capable of producing sparks. Fortunately, this type of cleaning is being used today in more and more specific cases where the characteristics of the tank or other external conditions do not allow the use of another methodology, due to the time needed to complete the entire procedure and the exposure of the operators to carry it out [27,28].

Next, the cleaning of deposits by biotechnological methods, based on the use of microorganisms fed by hydrocarbons, which decompose the oil. In this way, it is also possible to use these oil wastes as food for the plant world [29], while at the same time controlling pollution [30]. However, these are very time-consuming (although environmentally friendly) processes, so their applicability is very limited.

Then, chemical cleaning, which consists of adding chemical reagents to the waste to be removed, with the intention of oxidizing the organic compounds present in the waste [28]. However, these can deteriorate the tank coating, reducing its useful life or adding (costly) activities to recover its functionality. In addition, they generate enormous amounts of noxious water. Therefore, most current studies focus on optimizing the cleaning parameters to increase their efficiency [31], while improving their sustainability [32], reducing water consumption and/or using more innocuous products.

Finally, mechanical cleaning, which can be performed with purely mechanical equipment or using hydromechanical solutions, which in turn can include chemical products [33] or not [34]. These processes have evolved with technological advances up to the incorporation of robotic systems [35–37]. It should be noted that these methods manage to eliminate the entry of people into the tanks to be cleaned, making these cleaning operations safer tasks.

Based on these methods that can be applied to the cleaning of petroleum tanks, this article aims to:

- Define and prioritize the requirements that should be used to establish (safer) protocols for cleaning petroleum product tanks.
- Select a case study (defining the type of substance to be stored, the type of storage tank, etc.), in which to perform the methods selected.
- Assess two types of alternative cleaning procedures to conventional (manual) tank cleaning, with the potential to minimize worker exposure to rarefied and/or explosive atmospheres: chemical cleaning and mechanical (robotic) cleaning.

The case study begins with the sizing of an integral system for degassing, degreasing, and cleaning of such storage tanks. For the efficient storage of products such as crude oil and its derivatives, different types of storage tanks, usually metallic, are required. In addition, if large volumes are stored, cylindrical tanks with a vertical axis at atmospheric pressure are usually used. In addition, these tanks require a self-supporting fixed roof that can absorb the loads generated by the live loads plus their weight, in accordance with API 650 standard [38] and the complementary technical instruction MI IP-02 [39].

The evaluation of alternative cleaning procedures is realized using the multi-criteria decision method analytic hierarchy process (AHP). In this way, it will be possible to reflect by applying structured reasoning until a reliable result is reached for the establishment of the cleaning protocol. Both alternatives perform the cleaning of vertical shaft tanks for the storage of petroleum products with the purpose of minimizing the risks inherent to the activity, from the entry into confined spaces [40] to the projection of particles [41] and even musculoskeletal disorders [42], increasing the safety and health of the workers in the different actions involved with respect to manual cleaning.

2. Materials and Methods

2.1. Case Study

This research has opted for a case study because it enables the selection of the object of the study and the real scenario [43]. The case study is a research method that has been used by many authors [44–47]. When only limited theoretical knowledge exists, an inductive research strategy leading to emerging theory from a case study constitutes a good starting point [48]. This is based on multiple sources of evidence to study contemporary events in their real context when the phenomenon and the context are difficult to separate [49], which can replace experiments and analysis of archival information [50]. Building theory from a case study is a research strategy that involves using the case to create theoretical constructs, propositions, and/or midrange theory empirical evidence [51]. A theoretical sampling of single cases is straightforward. Cases are chosen because they are unusually revelatory, extremely exemplary, or because they represent unique opportunities for gaining research insights [52]. For the interested reader, Eisenhardt and Graebner provided the keys to building a solid case study [53].

The study will focus on the cleaning of a vertical shaft tank, with the dimensions compiled in Table 1.

Table 1. Tank characteristics.

Feature	Value
Inner diameter	28 m
Height	18 m
Internal floor area	615.75 m^2
Internal area ferrules	1582 m^2
Total area to be cleaned	2197 m^2
Effective capacity	10,000 m^3
Ferrules	9 units
Ground manhole	2 units
Roof manhole	1 unit

The type of cleaning taken as a reference is manual cleaning. The first alternative to be analyzed is chemical cleaning. This procedure is based on the recirculation of preheated chemical solutions, which accelerates and improves their chemical attack which, added to the mechanical attack produced by the physical impact caused by the projected solution, irrigates, and falls down the surface (walls) of the tank to the drainage well, from where it is collected by pumping it to the decantation tank, as shown in Figure 2.

In detail, the aim is to eliminate the remains of fuel oil/gas oil, degreasing and cleaning the walls, floor, and roof of the storage tank. This is achieved by recirculation of water solution with marine dispersant [54], through impact with hot water at low pressure (10 bar), and high flow (42 m^3/h), projected by a rotating head with 360° impact coverage [55], whose movement is shown in Figure 3, as a result of a simulation performed with Scanjet Tank Cleaning Simulator software.

This type of cleaning method differs significantly from the manual method in several respects. Firstly, with respect to the use of a marine dispersant instead of the usual chemical products. Products such as caustic soda, sodium carbonate or trisodium phosphate have been replaced by a marine dispersant, composed of aliphatic solvents and surfactants. In this way, toxicity is reduced by providing bio-degradability [54]. Moreover, the use of the injector eliminates the entry of operators into the confined space, while considerably reducing cleaning time, reducing energy costs, and simplifying the wastewater treatment process.

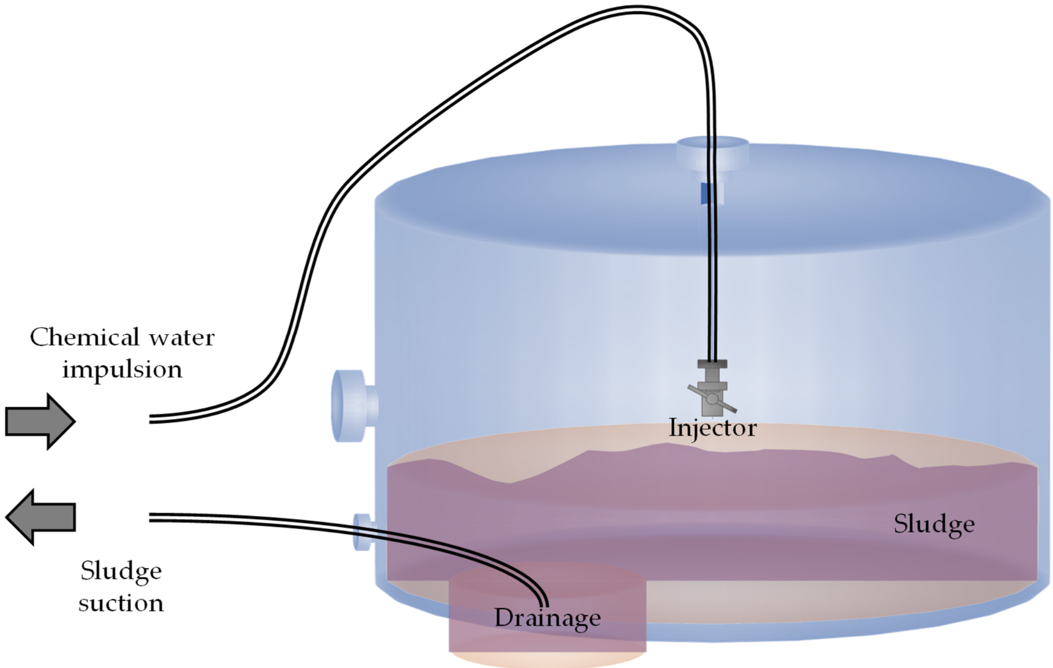

Figure 2. Chemical cleaning process.

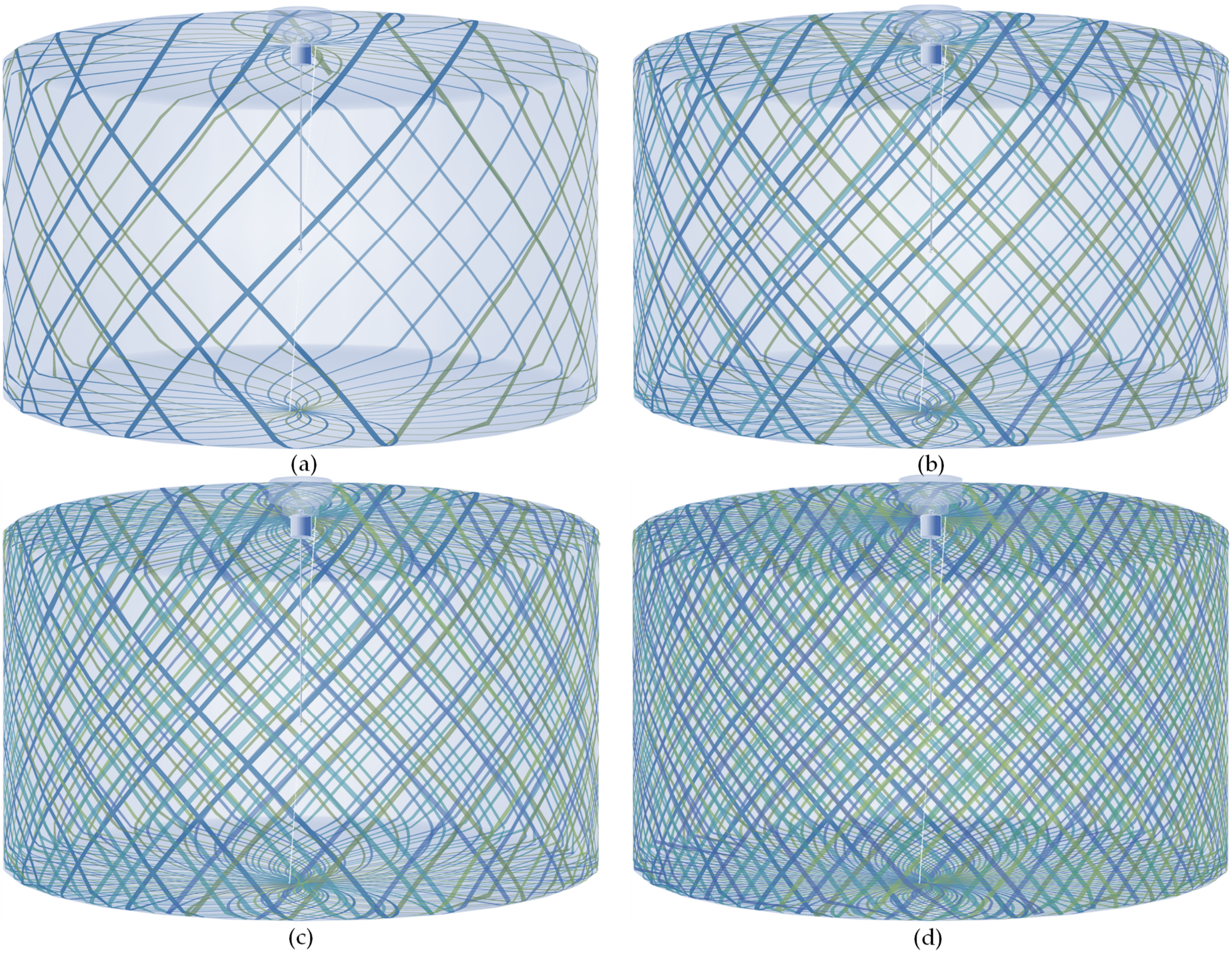

Figure 3. Rotary head: (**a**) after 8 min, (**b**) after 16 min, (**c**) after 24 min, (**d**) after 32 min.

The second cleaning alternative to consider is to apply a solution of water plus degreasing product by means of a magnetic robot directed from the outside, as shown in Figure 4. This robot, like the one shown in Figure 5, operates at high pressure, between 120–140 kg/cm^2, and projects at 1 cm from the nets, forming 1 m sweeping columns, as shown in Figure 5. In this way, both chemical (described above) and mechanical cleaning is achieved, thanks to the impact of the jet of aqueous solution at a short distance, so that the tank can be emptied from the tank's drainage well.

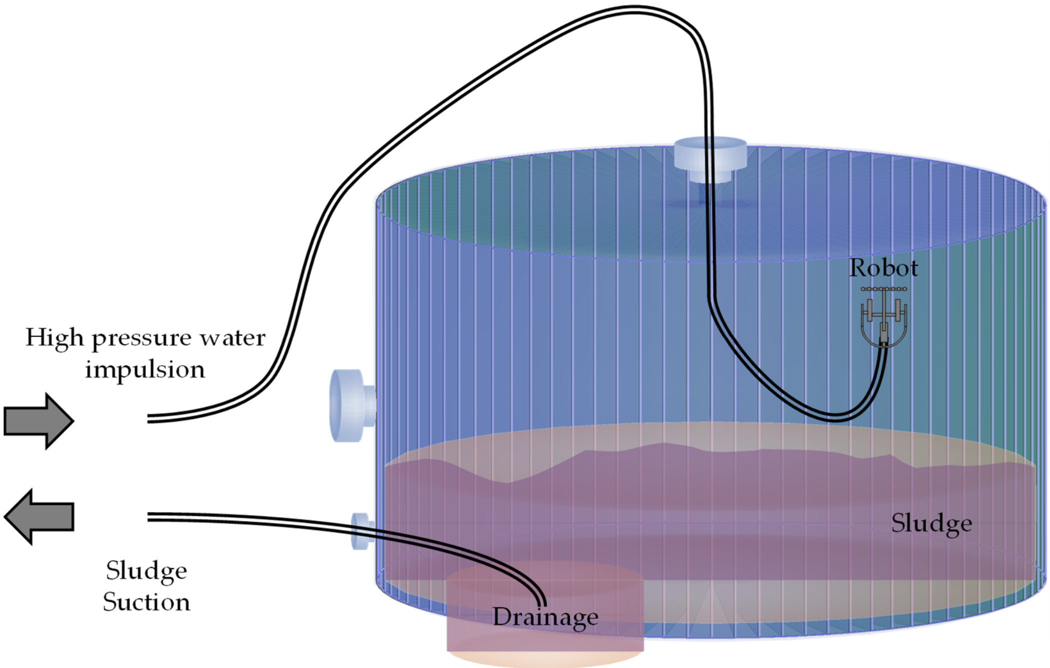

Figure 4. Robotic cleaning process.

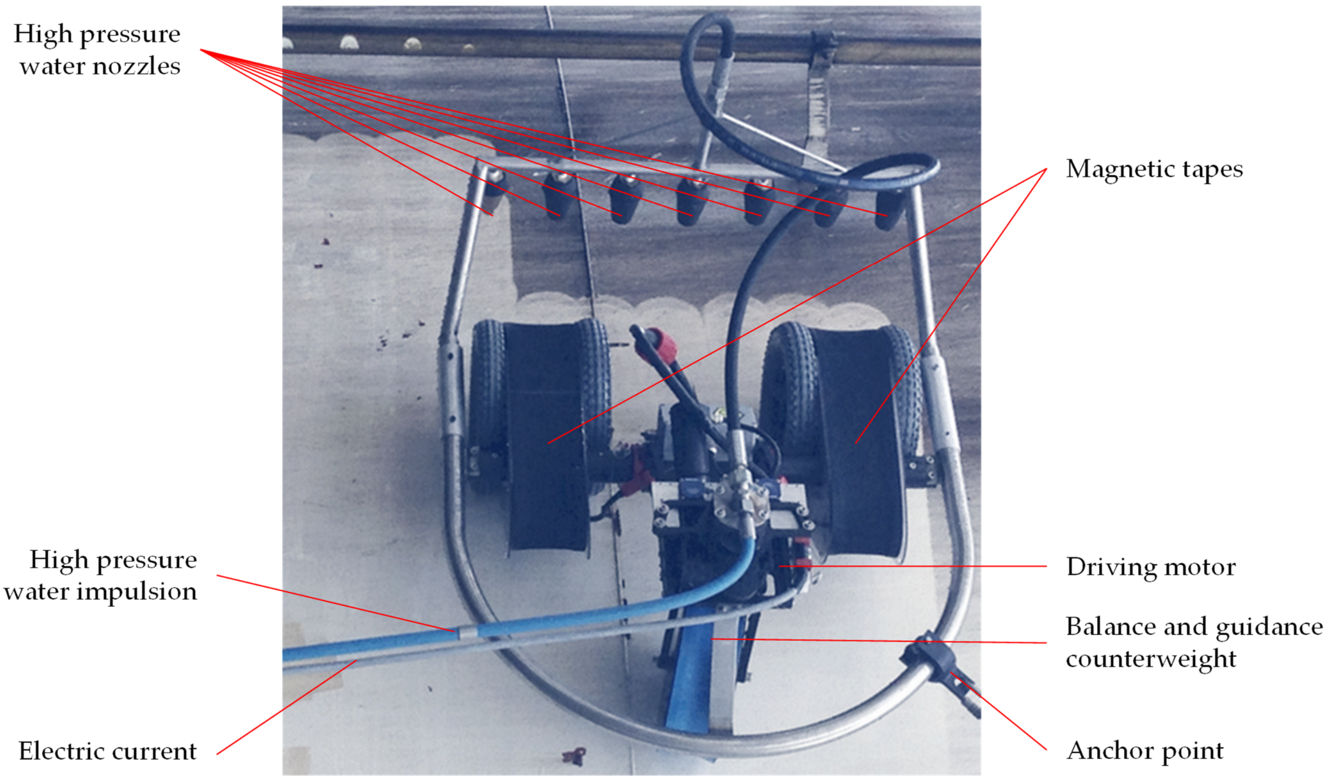

Figure 5. Detail of magnetic robot in operation.

In this case, the daily work output using this process can be estimated at 200 m^2/day. In addition, to this competitive advantage, together with those previously mentioned related to mechanical cleaning, must be added the possibility of being able to carry out occasional reworking, as opposed to the need to repeat a complete washing cycle in the case of chemical cleaning.

2.2. Multicriteria Decision

The choice of a safe protocol that meets the proposed objectives is made by analyzing two alternatives (chemical cleaning and robotic cleaning) to manual cleaning. To make an informed decision, a multi-criteria decision tool is selected. In this context, the analytical hierarchy process (AHP) method is a very popular discrete multi-criteria decision tool [56,57]. The AHP is applied through the construction of hierarchical structures, in which the first hierarchical level consists of the problem goal, the next hierarchical levels encompass the decision criteria and subcriteria, and, finally, the last level contains the alternatives. For allocating weights to the decision criteria and subcriteria, paired comparisons are made (criterion vs. criterion) by knowledgeable members of a panel. In addition, the method allows measuring the degree of inconsistency, thus providing confidence in the resolution of the method [58,59]. Therefore, the AHP tool will be used to prioritize decision making in which there may be multiple objectives, criteria, participants, and different alternatives of any kind. This method has been successfully tested to resolve and prioritize issues related to worker safety and health in different sectors [60,61]. Figure 6 shows the phases into which this process is divided.

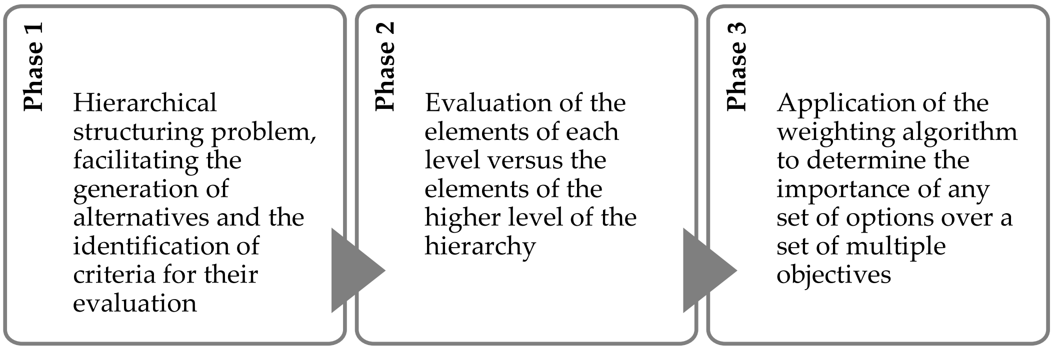

Figure 6. Phases of the AHP method.

The process for applying the AHP method begins with the definition of the problem to be addressed. In this research, the goal is to determine the requirements to improve safety in the cleaning of (vertical) storage tanks for petroleum products. Once the problem has been defined, and to apply the AHP method, it is necessary to disaggregate the problem into multiple and different criteria to help explore the decisions that matter and to discover when there may be conflict between criteria or between stakeholders on these criteria, until a hierarchical order is established, as shown in Figure 7.

To do this, the first step is to apply the principle of hierarchical construction, establishing the different levels required. In this way, level 1 will focus on the objective, level 2 will be composed of the criteria and subcriteria necessary for the evaluation of the problem, and level 3 will present the possible alternatives. Levels 1 and 2 are composed of the criteria and subcriteria listed in Table 2. In this regard, although the AHP method can accept an unlimited number of entries at the criteria and subcriteria levels, only a limited number of analyzed criteria and alternatives can assure an appropriate precision of obtained results [62,63]. This number can be defined as 7 +/− 2 (which means 9 maximum) [64], commonly referred to as Miller's law. If a higher number of items are compiled, an analytical method (eliminating less important criteria based on expert evaluations) or a deductive one (eliminating less important criteria accordingly to the particularity of the analyzed subject and the evaluation of criteria variability in time) can be applied [65].

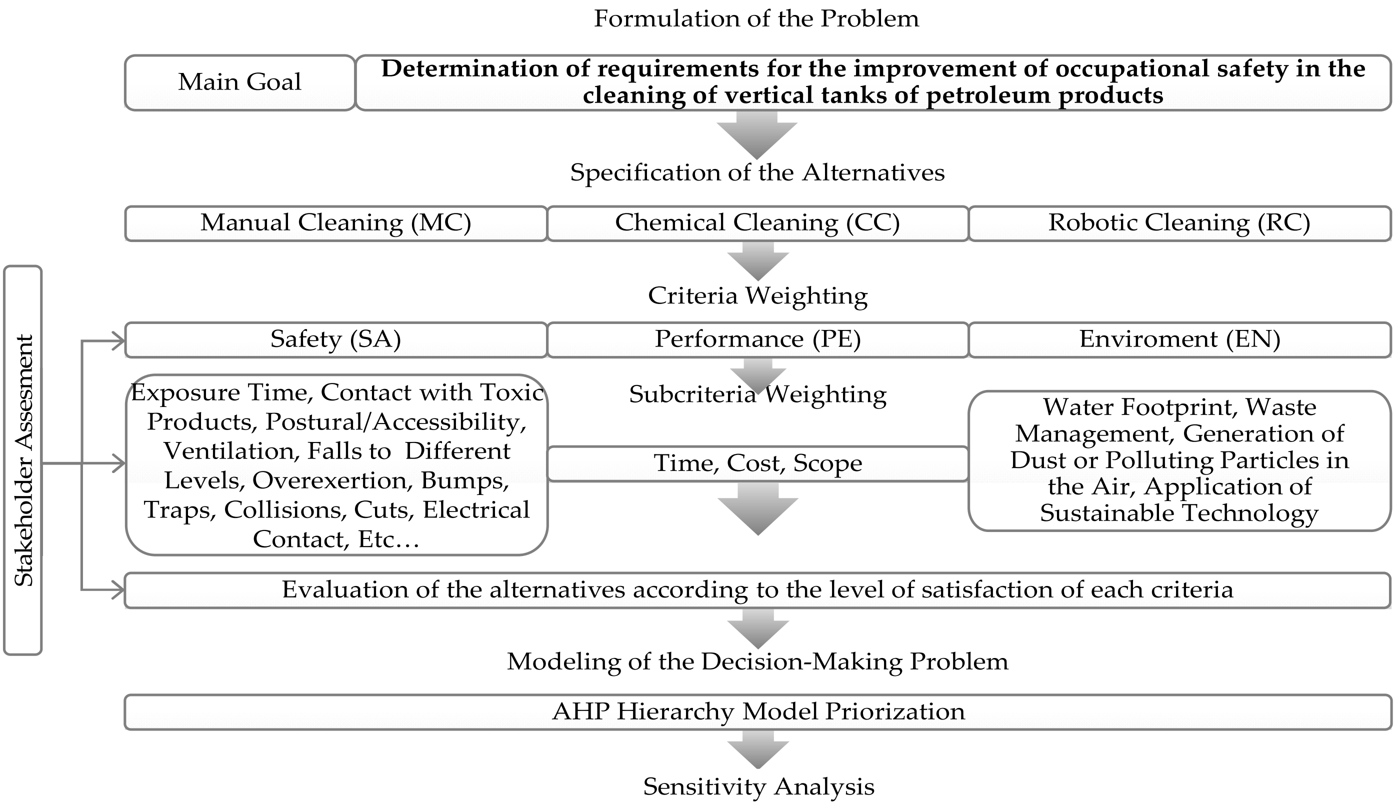

Figure 7. Decision-making process.

Table 2. Identification of criteria and subcriteria.

Id	Criteria	Id	Subcriteria
SA	Safety	SA1	Worker exposure time
		SA2	Contact with toxic products
		SA3	Postural/accessibility
		SA4	Ventilation
		SA5	Falls to different levels
		SA6	Overexertion
		SA7	Bumps
		SA8	Traps, collisions, cuts, etc.…
		SA9	Electrical contact
PE	Performance	PE1	Time
		PE2	Cost
		PE3	Scope
EN	Environment	EN1	Water footprint
		EN2	Waste management
		EN3	Generation of dust/polluting particles in the air
		EN4	Application of sustainable technology

When establishing the criteria, in accordance with the purpose of the study, safety appears as the first criterion, broken down into nine subcriteria ranging from exposure (focus) to the associated risks to which the worker is exposed when working in confined spaces. However, although safety is the main criterion for the definition of a tank cleaning protocol that improves the safety of the people involved, the consideration of factors such as collaboration between people and machines, the delegation of mechanical, dangerous, and routine tasks, speed and quality or environmental respect, typical of applying the principles of Industry 5.0, means that the decision must consider other points of view.

Therefore, the second criterion is performance (of the cleanup operation), supported by the subcriteria associated with the most basic constraints of an undertaking, such as cost, time, and scope [66], defined as the tasks necessary to perform each of the alternatives. As a third criterion, the environment is included, evaluating different sub-criteria associated with the development of the objective of the study. Water footprint is considered necessary to be included because it has an important weight in the development of the three alternatives to be evaluated, as well as regulatory waste management, which includes both the amount of waste and the ease of its removal (recycling, treatment, etc.), the generation of dust or particles in the air, which goes beyond that which the workers themselves could be affected, and, finally, the application of sustainable technology. In this sense, both the EMAS regulation [67] and the international standard UNE-EN ISO 14001 [68], encourage the use of the most advanced existing technology that is appropriate for the objective of organizations to establish a correct environmental policy, thus demonstrating a commitment to the continuous improvement of environmental performance, provided that it is feasible and economically viable.

Once the criteria have been defined, these criteria and their corresponding subcriteria can be weighted to determine how they will influence the interest of each of the alternatives. These subcriteria are the requirements that the selected protocol must incorporate. For this purpose, the role of decision-maker corresponds to a panel of experts. This panel is represented by a multidisciplinary team composed of experts from each area involved. Prioritization begins with pairwise comparisons of elements at the same level. Each criterion, subcriteria, or alternative i is compared with each criterion, subcriteria, or alternative j following a decision scale called the Saaty scale [69], shown in Table 3, although a national scale can also be used if a quantitative variable is being assessed. The assessments are made by taking a value of the decision-making team reached by consensus.

Table 3. Saaty Scale for AHP method.

Intensity	Definition	Explanation
1	Equal importance	Equal contribution to the objective
3	Moderate importance	Experience and judgement slightly favor one over another
5	Strong importance	Experience and judgement strongly favor one over another
7	Very strong importance	One is favored very strongly over another
9	Extreme importance	The evidence favoring one over another is the highest
2, 4, 6, 8	Intermediate values	Judgements between defined prior intensities
Reciprocals	For reverse comparison	Opposite judgments on previously defined intensities

The consensus values compose the pairwise matrix shown in Equation (1). They must meet three conditions: homogeneity (the elements of the main diagonal are equal to 1), reciprocity ($a_{ij} \times a_{ji} = 1$), and transitivity ($a_{ij} \times a_{jk} = a_{ik}$).

$$A_w = \begin{bmatrix} a_{11} & \cdots & a_{1j} & \cdots & a_{1n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ a_{j1} & \cdots & a_{ji} & \cdots & a_{jn} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ a_{n1} & \cdots & a_{ni} & \cdots & a_{nn} \end{bmatrix} \quad (1)$$

Once the pairwise matrices for criteria, subcriteria and alternatives have been compiled, the columns of each matrix are summed, and their values normalized. Then, the average of the rows is calculated to obtain the eigenvector representing the relative importance of the criteria compared in each of the pairwise comparison matrices, resulting in the best approach [70]. However, the principle of logical consistency must be applied to validate these results. The AHP method measures the consistency of each judgment by means of the consistency ratio (CR), which is the ratio between the consistency index (CI) shown in Equation (2) and the consistency index of a random matrix (RI) shown in Table 4.

$$CI = \frac{\lambda \max - n}{n - 1} \quad (2)$$

where λ represents the average of the eigenvector values of each matrix and n the dimension of the matrix.

Table 4. Index ratio values based on the order of the comparison matrix.

n	1	2	3	4	5	6	7	8	9
RI	0	0	0.525	0.882	1.115	1.252	1.341	1.404	1.452

Once this value is obtained, it is related with respect to the random consistency index shown in Table 4, resulting in the consistency ratio, as shown in Equation (3).

$$CR = \frac{CI}{RI} \quad (3)$$

Based on the results obtained, it will be assessed whether or not to accept them, according to the maximum percentages shown in Table 5. If CR exceeds these threshold values then the judgments should be reviewed [71].

Table 5. Maximum percentages of the consistency ratio CR.

n	**CR_{max}**
2	0%
3	5%
4	8%
≥5	10%

Where n represents the dimension of the matrix. Once the consistency has been verified, the weights are then calculated. These weights represent the relative importance of each criterion (also defined as the priorities of the different alternatives with respect to a given criterion), which is calculated by solving Equation (4).

$$\lambda_{max} \times w_i = \sum_{j=1}^{n} a_{ij}\, w_j \quad (4)$$

where w represents the criteria weights (eigenvectors) and λmax the principal eigenvector. The weights of each level are then calculated using the geometric mean. In order to unify the priorities to achieve a global calculation of them, all the answers of the respondents are synthesized after agreement, according to Equation (5) where G represents the geometric mean of each factor in the hierarchy, a represents the weight achieved by the expert panel and n the order of each pairwise comparison matrix.

$$G = \begin{bmatrix} (1 \times \cdots \times a_{1i} \times \cdots a_{1n})^{1/n} \\ (a_{j1} \times \cdots \times a_{ji} \times \cdots a_{j1n})^{1/n} \\ (a_{nj} \times \cdots \times a_{ni} \times \cdots 1)^{1/n} \end{bmatrix} \quad (5)$$

Finally, all that remains is to calculate the global priority weight of each parameter (W_P) by applying Equation (6), where i indicates the level of the hierarchy, W_f indicates the local priority weighting of the factor and W_c of the category.

$$W_{pi} = W_{fi} \times W_{ci} \quad (6)$$

3. Results and Discussion

In order to validate what was stated in the previous section, the first step is the selection of experts, which will be made up of people with extensive experience in the field of industrial cleaning from different perspectives. Therefore, a group of experts has been considered, made up of six people from different disciplines: mechanical engineer, chemical engineer, environmentalist, site manager, site contractor, and technician in occupational risk prevention, with the condition that they have at least a master's degree in occupational risk prevention and experience in industrial tank cleaning of more than ten years. As stated before, agreements are reached by consensus, for which a meeting is organized, in which the researchers have no voice or vote but lead the session.

This panel of experts receives the problem by the researchers, as shown in Figure 8: a summary of the structure followed in the method composed of the criteria, subcriteria, and alternatives that will be evaluated below. They will be responsible for making decisions based on the value judgments made on the pairwise comparisons of the problem shown. To do so, the six experts meet, moderated by the researchers. At the meeting, the researchers explain the process and the experts discuss each of the comparisons until a consensus is reached, at all three levels.

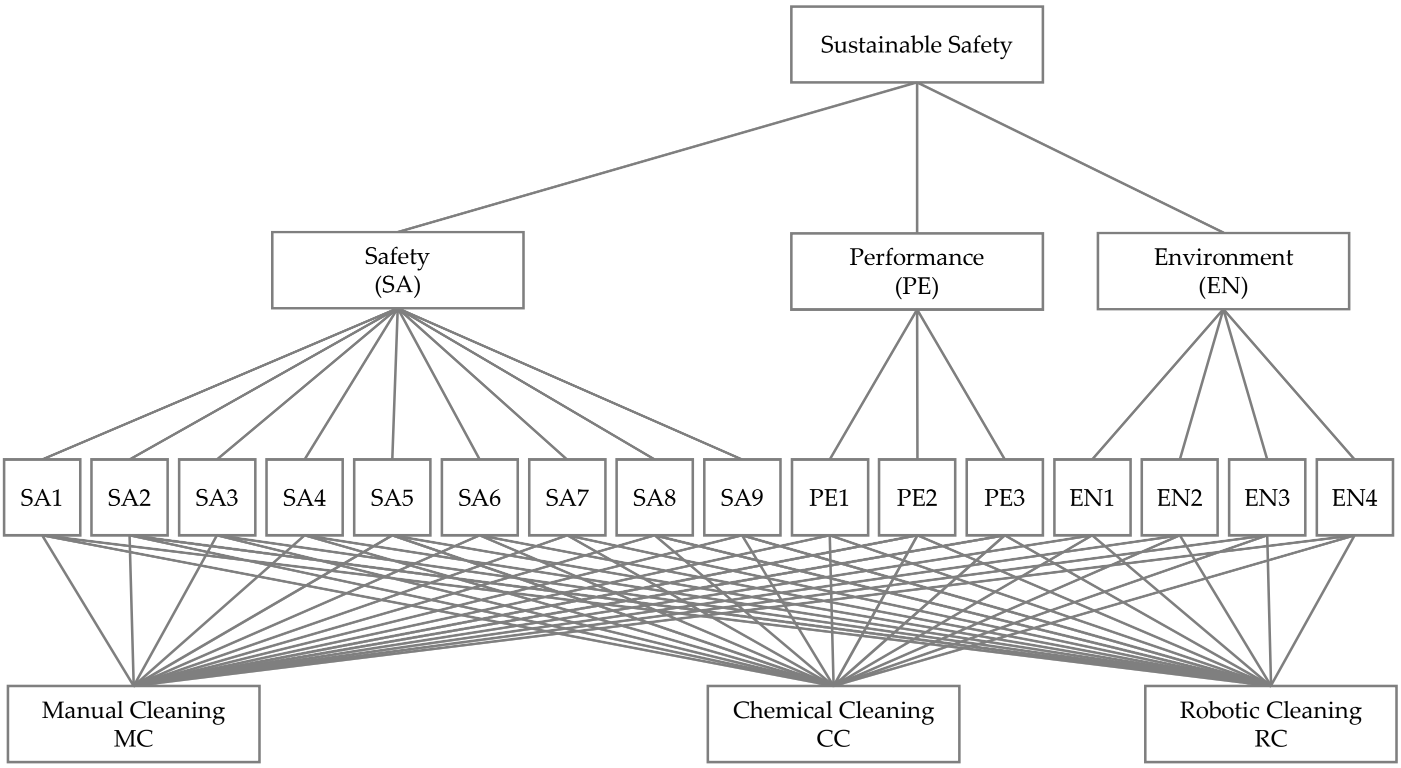

Figure 8. Structure of the problem to be solved by AHP.

The criteria are then compared in pairs. Table 6 shows the results obtained by consensus after one round of discussion for this comparison, which also reflects the scale chosen, as well as the consistency of the comparison. Further details are provided in Appendix A (Table A1). This table shows how, among the three criteria established, safety stands out above the others (72%), due to the fact that the weighting given by the experts considers safety as a key factor to be considered in relation to the type of work researched [60,61]. The second order of weighting established by the experts is the environment (19%), with performance in last place (9%), broken down into time, cost, and scope. As expected, waste disposal, the water footprint, and the generation of dust and/or particles polluting the environment are issues on which society is working to improve every day, as reflected in the opinion of the experts [29,72].

Table 6. Criteria comparison matrix (dimensions).

Criteria	SA	PE	EN	Eigenvector	Weight
SA	1	8	4	3.175	0.727
PE	1/8	1	1/2	0.397	0.091
EN	1/4	2	1	0.794	0.187

CR = 0.00%.

Likewise, all the results of the pairwise comparisons between the subcriteria (set of potential requirements into which each criterion is broken down), together with the scale chosen and the corresponding consistency, are shown in Appendix A (Tables A2–A4). Consensus for subcriteria comparisons is reached after two rounds of discussion. As a summary, Table 7 shows the weights of these two levels decided by the panel of experts.

Table 7. Criteria and subcriteria local weighting summary.

ID	Criteria	ID	Subcriteria	Subcriteria Weight	Criteria Weight
SA	Safety	SA1	Work exposure time	35%	72%
		SA2	Contac with toxic products	12%	
		SA3	Postural/accessibility	8%	
		SA4	Ventilation	5%	
		SA5	Falls to different level	19%	
		SA6	Overexertion	3%	
		SA7	Bumps	3%	
		SA8	Traps, collisions, cuts, etc.…	3%	
		SA9	Electrical contact	11%	
PE	Performance	PE1	Time	14%	9%
		PE2	Cost	14%	
		PE3	Scope	72%	
EN	Environmental	EN1	Water footprint	30%	19%
		EN2	Waste management	54%	
		EN3	Dust generation/particulate air pollutants	12%	
		EN4	Application of sustainable technology	4%	

Finally, after the expert pairwise comparison of the alternatives for each of the subcriteria by the panel of experts, the final decision is made. These comparisons are also shown in Appendix A (Tables A5–A20). Consensus for alternative comparisons is reached after four rounds of discussion. As a result, Figure 9 shows the degree of adequacy of each alternative to the set of subcriteria and criteria (requirements), based on the objective set.

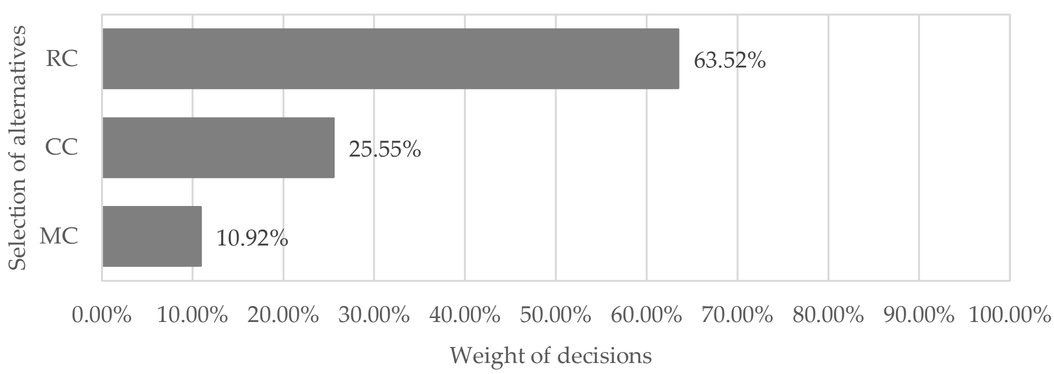

Figure 9. Hierarchical alternatives.

Regarding the alternatives to choose from, robotic cleaning was the best rated by the panel, according to the result obtained (approximately 63% of the decision). Therefore, it is the first option in the hierarchical decision. Among the advantages of robotic cleaning, the reduction in personnel, equipment, and water consumption must be stressed. On the contrary, although it takes longer to perform the tasks than chemical cleaning, spot repairs can be undertaken if any areas are not properly cleaned, whereas chemical cleaning would have to be repeated in full. However, the advantages outweigh the disadvantages, ranking it as the best option [35–37]. Furthermore, these advantages are aligned with the environmental criterion. In fact, it is the alternative that best reflects the common objective of international environmental standards regarding the promotion of the most advanced technology as long as it is appropriate, feasible, and economically viable for the implementing organization [67,68].

The alternative of chemical cleaning was the second rated (approximately 26%), quite distant from the previous one, but it also greatly reduces the hazard [73], and the total cleaning work time, although it requires a greater supply of water, generates a greater amount of residues, and requires repeating the entire process if it is not perfectly clean at first instance (which cannot be determined until the work is completed). However, these parameters are still under study, in order to achieve greater efficiency [31,32]. Finally, manual cleaning was the worst rated by the panel (approximately 11%), endorsing the current trend that reserves it for certain jobs when it is not possible to use any of the previous procedures [27]. These results add to those that advocate Industry 5.0 as a solution to reduce occupational hazards in industrial processes, replacing routine, monotonous, and dangerous jobs by other more skilled ones [74].

According to the weighting of criteria and subcriteria compiled in Table 6, the use of robotic cleaning completely eliminates worker exposure time. This subcriterion is the one with the highest weighting (approximately 25% of the global weight). It also directly affects others, such as falls to different levels (approximately 14% of the global weight), which is the second most important one, contact with toxic products (approximately 9% of the global weight), and contact with electric current (approximately 8% of the global weight), among others. On the other hand, waste management is another subcriterion to be considered (approximately 10% of the global weight), which is the most important environmental issue. Regarding the performance criterion, the scope is the most important factor (approximately 7% of the global weight), over and above time and cost, given the importance of properly performing the task, so as not to have to repeat the process, not to reduce the quality of the stored product and not to shorten the useful life of the tanks.

4. Conclusions

The industrial cleaning of petroleum tanks is placed in the group of dangerous activities, which can endanger the safety and health of the workers involved, including potential rescuers. Therefore, it is necessary to study the risks involved in such industrial cleaning operations and to evaluate the different alternatives available on the market that enables the hazard (exposure to occurrence, consequence of occurrence, and probability of occurrence) to be reduced to a minimum, while also providing compliance with environmental regulations without losing sight of the performance (in terms of cost, time, quality, and/or scope) that the activity entails.

In order to deal with this demanding situation, the intervention of experts in the field who can contribute from each area involved (promoters, contractors, clients, prevention services, labor inspectors, etc.), is unavoidable. Because they have different interests, their viewpoints may conflict. In this context, resorting to the methodology of analytical hierarchies means that these conflicts can be resolved on the basis of the procedures required to perform them. The AHP method provides the weighted selection of the alternatives proposed to improve the occupational safety of those involved without undermining the paradigm that Industry 5.0 represents.

In addition, based on a bibliographic search of different potential alternatives, three of them stand out: manual cleaning, which is taken as a base reference for comparison, chemical cleaning with marine dispersant, and mechanical cleaning with magnetic robots. These alternatives have been studied from three criteria: the safety of the parties involved, the performance of the operation, and the degree of environmental impact. From the result of the application of the multi-criteria decision process, it has been concluded that mechanical cleaning using robots is the best option, standing out from the others in all the criteria and subcriteria established to improve the health and safety of workers, rescuers, and other people involved. This is followed by chemical cleaning as the second choice, leaving manual cleaning in last place, which, as has been shown, would only be used in cases where the other two options are impossible to be applied.

It can be noted that the proposed approach faces each requirement independently, so it does not consider the different interrelations among activity needs. In addition, although this research provides several inputs to define safer protocols that take into account performance goals and environmental affairs, future research faces several challenges and constraints because of the heterogeneity of the tanks to be cleaned and the regulatory framework to be applied. Although the proposed framework was designed for the case of the model and methods of vertical shaft tank cleaning, future research should focus on the development and study of autonomous technology for operations in other areas, such as ship tank cleaning, using the study carried out in this article as a basis.

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Appendix A

Table A1. Criteria comparison matrix.

Criteria	SA	PE	EN	Eigenvector	Weight (Wt)
SA	1	8	4	3.175	0.727
PE	1/7	1	1/2	0.397	0.091
EN	1/4	2	1	0.794	0.182

CR = 0.00% < 5%.

Table A2. Safety subcriteria comparison matrix.

Criteria	SA1	SA2	SA3	SA4	SA6	SA7	SA8	SA9	SA10	Eigenvector	Local Wt	Global Wt
SA1	1	4	5	6	3	7	7	7	4	4.292	0.348	0.253
SA2	1/4	1	2	3	1/2	4	4	4	1	1.537	0.125	0.091
SA3	1/5	1/2	1	2	1/3	3	3	3	1/2	0.988	0.080	0.058
SA4	1/6	1/3	1/2	1	1/4	2	2	2	1/3	0.642	0.052	0.038

SA6	1/3	2	3	4	1	5	5	5	2	0.406	0.033	0.024
SA7	1/7	1/4	1/3	1/2	1/5	1	1	1	1/4	0.406	0.033	0.024
SA8	1/7	1/4	1/3	1/2	1/5	1	1	1	1/4	0.406	0.033	0.024
SA9	1/7	1/4	1/3	1/2	1/5	1	1	1	1/4	1.318	0.107	0.078
SA10	1/4	1	2	3	1/2	1	4	4	1	4.292	0.348	0.253

CR = 5.00% < 10%.

Table A3. Performance subcriteria comparison matrix.

Criteria	PE1	PE2	PE3	Eigenvector	Local Wt	Global Wt
PE1	1	1	1/5	0.585	0.143	0.010
PE2	1	1	1/5	0.585	0.143	0.010
PE3	5	5	1	2.924	0.714	0.050

CR = 0.00% < 5%.

Table A4. Environment subcriteria comparison matrix.

Criteria	EN1	EN2	EN3	EN4	Eigenvector	Local Wt	Global Wt
EN1	1	1/2	3	7	1.800	0.301	0.056
EN2	2	1	6	9	3.224	0.538	0.101
EN3	1/3	1/6	1	5	0.726	0.121	0.023
EN4	1/7	1/9	1/5	1	0.237	0.040	0.007

CR = 0.13% < 8%.

Table A5. Comparison of alternatives matrix for subcriterion SA1.

Option	MC	CC	RC	Eigenvector	Local Wt	Global Wt
MC	1	1/4	1/9	0.303	0.066	0.014
CC	4	1	1/4	1.000	0.217	0.045
RC	9	4	1	3.302	0.717	0.149

CR = 3.51% < 5%.

Table A6. Comparison of alternatives matrix for subcriterion SA2.

Option	MC	CC	RC	Eigenvector	Local Wt	Global Wt
MC	1	1/6	1/9	0.265	0.061	0.005
CC	6	1	1/2	1.442	0.333	0.029
RC	9	2	1	2.621	0.606	0.052

CR = 0.88% < 5%.

Table A7. Comparison of alternatives matrix for subcriterion SA3.

Option	MC	CC	RC	Eigenvector	Local Wt	Global Wt
MC	1	1/6	1/9	0.265	0.061	0.004
CC	6	1	1/2	1.442	0.333	0.020
RC	9	2	1	2.621	0.606	0.036

CR = 0.88% < 5%.

Table A8. Comparison of alternatives matrix for subcriterion SA4.

Option	MC	CC	RC	Eigenvector	Local Wt	Global Wt
MC	1	1/6	1/9	0.265	0.061	0.002
CC	6	1	1/2	1.442	0.333	0.013
RC	9	2	1	2.621	0.606	0.024

CR = 0.88% < 5%.

Table A9. Comparison of alternatives matrix for subcriterion SA5.

Option	MC	CC	RC	Eigenvector	Local Wt	Global Wt
MC	1	1/5	1/9	0.281	0.063	0.008
CC	5	1	1/3	1.186	0.265	0.033
RC	9	3	1	3.000	0.672	0.082

CR = 2.77% < 5%.

Table A10. Comparison of alternatives matrix for subcriterion SA6.

Option	MC	CC	RC	Eigenvector	Local Wt	Global Wt
MC	1	1/2	1/9	0.382	0.076	0.002
CC	2	1	1/7	0.659	0.131	0.003
RC	9	7	1	3.979	0.793	0.021

CR = 2.07% < 5%.

Table A11. Comparison of alternatives matrix for subcriterion SA7.

Option	MC	CC	RC	Eigenvector	Local Wt	Global Wt
MC	1	1/8	1/9	0.240	0.054	0.001
CC	8	1	1/2	1.587	0.357	0.009
RC	9	2	1	2.621	0.589	0.015

CR = 3.51% < 5%.

Table A12. Comparison of alternatives matrix for subcriterion SA8.

Option	MC	CC	RC	Eigenvector	Local Wt	Global Wt
MC	1	1/4	1/9	0.303	0.066	0.002
CC	4	1	1/4	1.000	0.217	0.006
RC	9	4	1	3.302	0.717	0.019

CR = 3.51% < 5%.

Table A13. Comparison of alternatives matrix for subcriterion SA9.

Option	MC	CC	RC	Eigenvector	Local Wt	Global Wt
MC	1	2	7	2.410	0.592	0.045
CC	1/2	1	5	1.357	0.333	0.026
RC	1/7	1/5	1	0.306	0.075	0.006

CR = 1.35% < 5%.

Table A14. Comparison of alternatives matrix for subcriterion PE1.

Option	MC	CC	RC	Eigenvector	Local Wt	Global Wt
MC	1	1/4	1/9	0.303	0.066	0.0009
CC	4	1	1/4	1.000	0.217	0.0030
RC	9	4	1	3.302	0.717	0.0100

CR = 3.51% < 5%.

Table A15. Comparison of alternatives matrix for subcriterion PE2.

Option	MC	CC	RC	Eigenvector	Local Wt	Global Wt
MC	1	1/4	1/9	0.303	0.066	0.0009
CC	4	1	1/4	1.000	0.217	0.0030
RC	9	4	1	3.302	0.717	0.0100

CR = 3.51% < 5%.

Table A16. Comparison of alternatives matrix for subcriterion PE3.

Option	MC	CC	RC	Eigenvector	Local Wt	Global Wt
MC	1	1/7	1/9	0.251	0.057	0.0040
CC	7	1	1/2	1.518	0.346	0.0241
RC	9	2	1	2.621	0.597	0.0417

CR = 2.07% < 5%.

Table A17. Comparison of alternatives matrix for subcriterion EN1.

Option	MC	CC	RC	Eigenvector	Local Wt	Global Wt
MC	1	2	1/6	0.693	0.143	0.0080
CC	1/2	1	1/9	0.382	0.079	0.0044
RC	6	9	1	3.780	0.779	0.0438

CR = 0.88% < 5%.

Table A18. Comparison of alternatives matrix for subcriterion EN2.

Option	MC	CC	RC	Eigenvector	Local Wt	Global Wt
MC	1	1/4	1/9	0.303	0.066	0.0066
CC	4	1	1/4	1.000	0.217	0.0219
RC	9	4	1	3.302	0.717	0.0722

CR = 3.51% < 5%.

Table A19. Comparison of alternatives matrix for subcriterion EN3.

Option	MC	CC	RC	Eigenvector	Local Wt	Global Wt
MC	1	1/2	1/9	0.382	0.076	0.0017
CC	2	1	1/7	0.659	0.131	0.0030
RC	9	7	1	3.979	0.793	0.0180

CR = 2.07% < 5%.

Table A20. Comparison of alternatives matrix for subcriterion EN4.

Option	MC	CC	RC	Eigenvector	Local Wt	Global Wt
MC	1	1/6	1/9	0.265	0.061	0.0005
CC	6	1	1/2	1.442	0.333	0.0025
RC	9	2	1	2.621	0.606	0.0045

CR = 0.88% < 5%.

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