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A Monte Carlo Simulation for the Improvement of Drinking Water and Sewerage Services in a Northern Settlement in Peru

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Abstract Clean water and sewerage systems are essential for global and local development. In Perú, even though most of its urban population has access to these services, it does not mean that those services are enough for the population's necessities. Moreover, they usually do not have acceptable quality. Consequently, it is necessary to invest public funds to provide clean water and sewerage systems to the possible people. However, it does not mean spending money carelessly on projects that might not fulfill people's demands. Then, the current research applied a Monte Carlo-based risk analysis for a public investment project seeking to improve those services in a poor human settlement on the northern coast of Peru. Hence, the Monte Carlo simulation was employed along with its sensitivity analysis. The research found that the project had an excellent chance of being sustainable. Still, it was necessary to make real improvements in the service to meet the population's needs, for instance, by improving the water quality or expanding the hours of clean water supply. Also, due to the investment's quantity, the project's sustainability depends on population growth and public expense efficiency. Finally, the importance of correctly maintaining the works to keep and improve those services was highlighted.

Keywords Monte Carlo Simulation, Risk Analysis, Sanitization, Waterworks, Sewerage Works

1. Introduction

Water is necessary for all kinds of life on the earth. This resource is difficult to get and manage for humankind because their natural sources are far away from most people [1]. Of course, some places face this problem heterogeneously. In arid areas where there is not even rain, it is compulsory to perform activities like moving, treating, and distributing water at high costs [2]. On the other hand, there are places with plenty of water sources, but due to the lack of proper sewerage construction population pollutes them [3]. However, its use value is low against its importance [1]. Therefore, the population pays little for them, making it difficult for governments to establish a fair pay scheme [2].

Water and sanitization are essential for global and local development [4]. Therefore, the sixth sustainable goal established that by 2030 the world must ensure sustainable management of water and sanitization [5]. Around the world, it is estimated that one out of three people lives lacking clean water and appropriate sewerage [6]. This situation is hazardous for spreading fatal diseases like cholera and other infectious diseases [7]. Also, those problems have a significant impact on the economic performance of the countries because a sick population is not going to perform economically as well as a healthy one [8]

The Peruvian situation is far away from the United Nation's sixth goal. Although more than 90% of the Peruvian urban population has access to clean water, the coverage in the rural area falls to 76.3% [3]. Analogously, about 26% of the Peruvian rural population does not have access to the public sewerage system, while in the urban area, it was about 10% [3]. It is essential to add that even though many houses have access to clean water, it does not mean they have 24-hour access to this resource. The Peruvian average full-day access to this resource is only 56.6% [3]. The most affected areas are ones with a lack of water sources, like the coastal regions, and regions with plenty of water sources but poor infrastructures, like the jungle and impoverished Andean places. Consequently, it is not only the availability of water sources but also the infrastructure to provide a water service of good quality.

A particular region, Lambayeque, is surrounded by an arid scene, but its soil is very productive [9]. People compensated for the lack of rain in most of the months by constructing aqueducts transporting water from its highlands to their main urban and agricultural centers on the arid coast [10]. The prosperous economic activities of this region have attracted migrants from Andean and jungle areas. Then, due to the lack of urban planning, they have established "human settlements" which lack essential urban services such as potable water and sanitization [11].

Recently, though, there has been a massive quantity of work to bring clean water to most people in this region. Therefore, more than 95% of the total population has clean water, but only 79% have access to the public sewerage system [3]. Moreover, more than half of the population does not have 24-hour access to this source, which is highly worrying that only 13% of the population has access to an excellent clean water system [3].

In consequence, although clean water coverage is high, there are deficiencies in the sewerage public system coverage and the quality of the service. Also, it is essential to state that many public drinking water works, not only in this area but also in others, present deficiencies in their files. Then, they do not consider factors that might affect the sustainability of the projects. Luckily, statistical methods can forecast the effects on sustainability due to internal and external factors. The most valuable and popular in this field is the Monte Carlo simulation. Therefore, the following research will apply the Monte Carlo simulation to a water and sanitization improvement project in Lambayeque.

2. Literature Review

2.1. Previous Studies

There are few studies about applying the Monte Carlo simulation to analyze drinking water and sanitization projects worldwide. For instance, [12] analyzed through the Monte Carlo simulation the sensibility of a drinking water project in the Peruvian Andes. Hence, he employed input variables: investment, operation, maintenance, and social benefits costs. Also, the researchers harnessed the project's Net Present Value and Internal Rate of Return as output variables. After applying the Monte Carlo simulation, the research found the probability that the project had a good chance of becoming a sustainable project.

Furthermore, the sensitivity analysis showed that the most critical variable was the initial investment project, with a weight of 87.3%; operation and maintenance costs had no effect. Another study was conducted by [13], who studied the economic viability of a drinking water project in the largest Peruvian city. This analysis also employed similar variables as [12]. However, it aimed to estimate the cost/benefit ratio probability by applying the Monte Carlos simulation. Hence, [13] obtained a chance of 52.3% to get a positive project's Net Present Value. Also, [14] applied the Monte Carlo simulation in a project on drinking water in Andean indigenous communities. Furthermore, this study employed the same variables as the two previous studies.

The results obtained after the Monte Carlo simulation were more than 97% to get a positive Net Present Value. Additionally, [14] obtained that familiar benefit was the most sensitive input, followed by the initial investment and operation and maintenance costs. The weight percentages were 44.4%, 15.6%, and 0.5% respectively. In Colombia, [15] studied the viability of a project to give drinking water to indigenous communities in El Cauca Valley. Hence, it was employed the Monte Carlo simulation to have a better perception of the project's risk. Therefore, the mentioned study employed input variables: inflation, maintenance costs, population growth rate, population death risk rate, and future risks. After the risk analysis, the study encountered a probability of 90% that the project would be sustainable.

Also, some studies approach the research's scope. In Colombia, a study by [16] found that the construction of 248 toilets in a housing building had a 95% probability of reporting positive revenues after applying the Monte Carlo Simulation. [17] built a social network-based water supply network to predict economic and operational benefits for water projects. The research employed a mix of the Short Run Economic Leakage Level concept, non-deterministic optimization method based on Genetic Algorithms, and the Monte Carlo method to build the model in a 246 km water pipeline with a profit of more than seventy thousand dollars. This research stated that reducing reported and unreported leaks, repairing pipes, and domestic consumption is possible to get crucial savings for the project.

[18] employed the Monte Carlo simulation to determine the optimal placement and operation of sewer mining units in urban surroundings located in Greece. It was necessary

to join the Environmental Protection Agency's Storm Water Management Model with the Monte Carlo model to meet the research's primary objective. Similarly, [19] employed the Monte Carlo method and the Environmental Protection Agency's Storm Water Management Model to model a Peruvian city's drinking water distribution network. [20] also employed the Monte Carlo analysis to probabilistically model the optimal flow rate of a sewage treatment plant. The other use of the Fourier series and Lognormal function was necessary here. Besides, [21] employed the Monte Carlo simulation to model the optimum water balance of a Colombian dam. They harnessed as inputs the variables of precipitation, runoff, transportation, and the subsurface flow and extraction flow. The forecasted years for the whole model were 40 years. A summary of these studies can be found in Table 1.

Due to the analysis of the previous studies, it became clear that the current research would be necessary to identify the variables correctly.

2.2. Theoretical Basis

2.2.1. Risk Analysis

Both private and public projects need a risk analysis [22]. Every risk analysis is necessary to identify the possible situations and how they can impact the project's outcome. The definition of outcome might be heterogeneous among the projects. Most of the time, private projects seek the economic profit that can be obtained. On the other hand, public projects look after the population's welfare at an efficient cost.

Nonetheless, the risks can affect this outcome when they become real. They will be different according to the project's sector. Then, it is necessary to know the empirical evidence of the sector's risk [23]. Although avoiding all threats is impossible, it is possible to estimate their consequences on the project's outcome [24]. Therefore, it is mandatory to decompose the project to get its inputs and outputs. In other words, it is essential to know the critical factors of the project.

Table 1. Previous studies

Author	Title	Results
12	Benefits calculation and risk analysis in public education projects	It was found that this project had an excellent chance of becoming sustainable after using the Monte Carlo analysis
13	Social profitability in a waterworks project	The research encountered that the most critical variable was the initial investment, while operation and maintenance had no cost effect
14	Social evaluation of the drinking water network in Conduriri	It was encountered that this project had more than a 90% probability of being sustainable
15	A social profitability risk analysis for a water drinking system in La Rivera	The analysis obtained that the most sensitive input was the familiar benefit. The other inputs, ranked by importance, were initial investment and operation and maintenance costs
16	Financial risk analysis for the improvement of a housing project in Colombia	In this project for an indigenous community, it was discovered that it had an excellent chance to be socially sustainable
17	Social-network-based water supply network sectorization methodology uses Monte Carlo simulation to predict economic and operational benefits	This research encountered that in a housing building project, the Monte Carlo simulation suggested that this project had high odds of being sustainable. Also, the reduction of leaks, the excellent repairment of pipes, and the control of domestic consumption had a crucial impact on the project's future profitability
18	A Monte-Carlo-based method for optimizing sewer mining units' placement and operation scheduling in an urban wastewater network	This research found the Monte Carlo simulation functional to place the sanitization project's pipelines
19	A fuzzy Monte Carlo analysis for the modeling of a probabilistic network in a drinking water project	Alongside the Monte Carlo simulation, this research employed the Environmental Protection Agency's Storm Water Management to design an urban drinking water distribution network
20	Probabilistic modeling and estimation of the flow rate of sewage treatment plant using monte Carlo hybrid method	This analysis employed the Monte Carlo analysis to obtain the flow rate of the sewerage plant treatment
21	Methodological design for the simulation of a dam hydric balance	In this study, the Monte Carlo analysis helped to detect the riskiest variables and set the optimum water balance for a Colombian barrier

Consequently, it is essential to get accurate information to decrease risk and uncertainty. In this process, the experts' suggestions and points of view must be taken carefully. On one side, they can provide valuable information about the sector, but at the same time, the provided information can be biased. Once the critical factors and their risk are estimated, it is imperative to classify them according to their probability of occurrence. Therefore, they can be classified into three scenarios: optimistic, pessimistic, and conservative [25]. Although uncertainty can be tricky, the correct anticipation of harmful future changes is essential for the project's survival [26]. Hence, the probability assignation is the only way to anticipate possible future risks. Since the current research applies a risk estimation model in a public project, it becomes essential to know the official Peruvian guidelines about this issue. According to the Peruvian guides, sensitivity analysis belongs to the risk study [27]. It is possible to employ the terms sensitivity and risk as synonyms. Still, for the Peruvian guidelines, sensitivity analysis is the risk analysis component that involves the deliberate manipulation of variables to see their relation and effect on the project's outcome. The risk analyzer makes the manipulation magnitude decision based on his criteria. Also, the probability of occurrence is managed in the same way. Therefore, as stated before, depending solely on expert knowledge can damage the analysis. Fortunately, probabilistic-based methods like Monte Carlo complement the expert suggestion by providing unbiased probabilities of risks.

2.2.2. Monte Carlo Simulation

As written before, Monte Carlo is a statistical model which provides probabilities of occurrence [25]. The name is after Monte Carlo's casinos because of the scenarios' randomness. The Monte Carlo method offers random numbers which simulate the future's uncertainty [26]. Because of its statistical methodology, this model is beneficial when forecasting a project's risk occurrence [28]. The risk analyzer can set the simulation number, also called iterations. The model stops when no more proof can be performed [29]. After that, the probability distribution is provided along with the sensitivity analysis and descriptive statistical information [30].

Therefore, this model is widely employed by risk analyzers because of its unbiased information [24]. Nonetheless, this technique is not engaged in public projects in Peru, which is the reason for this research.

3. Method

The previous studies in the literature review first identified the components of the project. Then, it is necessary to establish what will be the outcome and which ones will be their inputs. In a study of drinking water projects, the authors found the Net Present Value and the Internal Rate of Return as outputs. Of course, some studies did not choose those indicators as outputs since their primary objectives were optimal flow volumes. Therefore, in this study, the outcomes will be the Net Present Value and Internal Rate of Return. Those outputs are based on the project's financial information. However, it is essential to understand the dynamics of this information to get the critical factors.

A typical financial cash flow is divided into two: income and expenses. Since this project is public, it will not be possible to get any economic revenues. However, any public project aims to provide the population with a social benefit [31]. Consequently, the Peruvian public project methodology states that the benefits should be quantified in social terms. Hence, it is crucial to estimate the help of the project economically. Hence, according to the project's profile, the benefits were the users' value to the drinking water and sewerage services. This value depended on the improvement of the population's quality of life, the diminution of infectious diseases, the reduction of expenses on medical attention, and the savings of eliminating sewerage.

On the other hand, the project's expenses were classified in the following way: investment and operation and maintenance costs. For both of them, the prices expressed on the project's financial information were not the real ones. The Peruvian guidelines state that the costs must be expressed in social ones [27]. The conversion from private to social prices is done through a conversion provided by the Peruvian guidelines. The purpose of those conversion factors is to eliminate market distortions [31]. However, it is necessary to add that drinking water flow is essential to maintain a good service [32]. Additionally, the project's financial information costs differ from the existing and new costs. They are called incremental costs.

Once the project's cash flow is fully understood, it is possible to choose the critical factors that can become risky for the project's sustainability. In this research, thanks to an expert, the essential elements were: former users' benefit, new users' benefit, sewerage works investment, drinking water works investment, population growth, inflation, sewerage operation, and maintenance costs, and drinking water operation and maintenance works. Of course, this is a simplified model since, for drinking water works, other elements, as stated by [33], are necessary. After that, the distribution of the variable was selected depending on the variables' data nature. Then, the triangular distribution was assigned to variables with numeric data.

In contrast, variables with rates as data were given with the Pert distribution. Therefore, all variables but inflation and population growth were assigned with the triangular data. Only inflation and population growth had Pert distributions. The number of iterations chosen was seven thousand. After that, the model provided the project's Net Present Value and the Internal Rate of Return risk analysis, the analysis of sensitivity, and their descriptive statistics.

Table 2. Descriptive statistics for the Net Present Value simulation

Statistic	Values
Iteration	7,000
Base Case*	10,123.32
Mean*	9,768.71
Median*	9,765.92
Standard Deviation*	1,144.62
Bias	0.01
Kurtosis	2.73
Coefficient of variation	0.12
Min*	6,337.76
Max*	13,402.20

*in thousands of United States dollars

Table 3. Descriptive statistics for Internatl Rate of Return simulation

Statistic	Values
Iteration	7,000
Base Case	77%
Mean	66%
Median	66%
Standard Deviation	6%
Bias	0.08
Kurtosis	2.68
Coefficient of variation	0.09
Min	45%
Max	86%

Table 4. Distribution of the project's Net Present Value odds

Rank*	Probability	Accumulated
< 7,000	0.27%	0.27%
[7,000-8,000>	4.71%	4.98%
[8,000-9,000>	20.37%	25.35%
[9,000-10,000>	31.87%	57.22%
[10,000-11,000>	26.85%	84.07%
[11,000-12,000>	13.10%	97.17%
>12,000	2.82%	99.99%
*in thousands of United States dollars		

Table 5. Distribution of the project's Internal Rate of Return odds

Rank	Probability	Accumulated
<50%	0.09%	0.09%
[50%-55%>	3.02%	3.11%
[55%-60%>	14.61%	17.72%
[60%-65%>	24.47%	42.19%
[65%-70%>	29.82%	72.01%
[70%-75%>	20.57%	92.58%
[75%-80%>	6.44%	99.02%
>80%	0.86%	99.88%

Table 6. Project's Net Present Value sensitivity analysis data

Rank	Variance contribution	Ranks correlation
Population growth	71.50%	0.84
Former users' benefits	27.20%	0.52
New users' benefits	0.70%	0.08
Sewerage works investment	0.60%	-0.07
Inflation	0.10%	-0.03
Drinking water works investment	0.00%	-0.02
Drinking water operation and maintenance costs	0.00%	0.00
Sewerage operation and maintenance costs	0.00%	0.00

Table 7. Project's Internal Interest Rate sensitivity analysis data

Rank	Variance contribution	Ranks correlation
Sewerage work investment	53.70%	-0.72
Former users' benefits	33.90%	0.57
Drinking water works investment	9.60%	-0.30
Population growth	2.60%	0.16
Sewerage operation and maintenance costs	0.10%	0.03
Drinking water operation and maintenance costs	0.10%	-0.03
New users' benefits	0.10%	0.03
Inflation	0.00%	-0.02

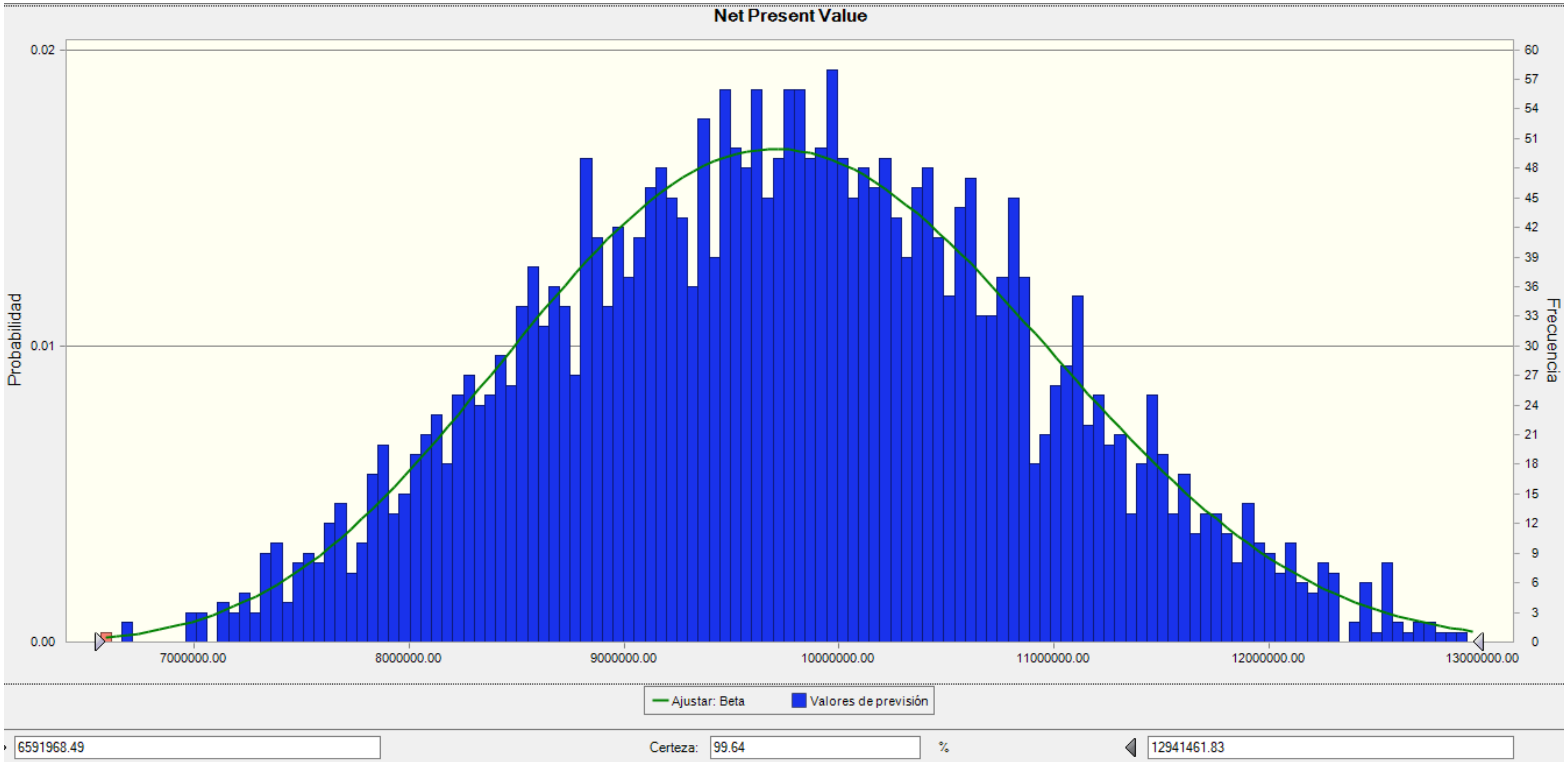

Figure 1. Monte Carlo simulation for the project's Net Present Value

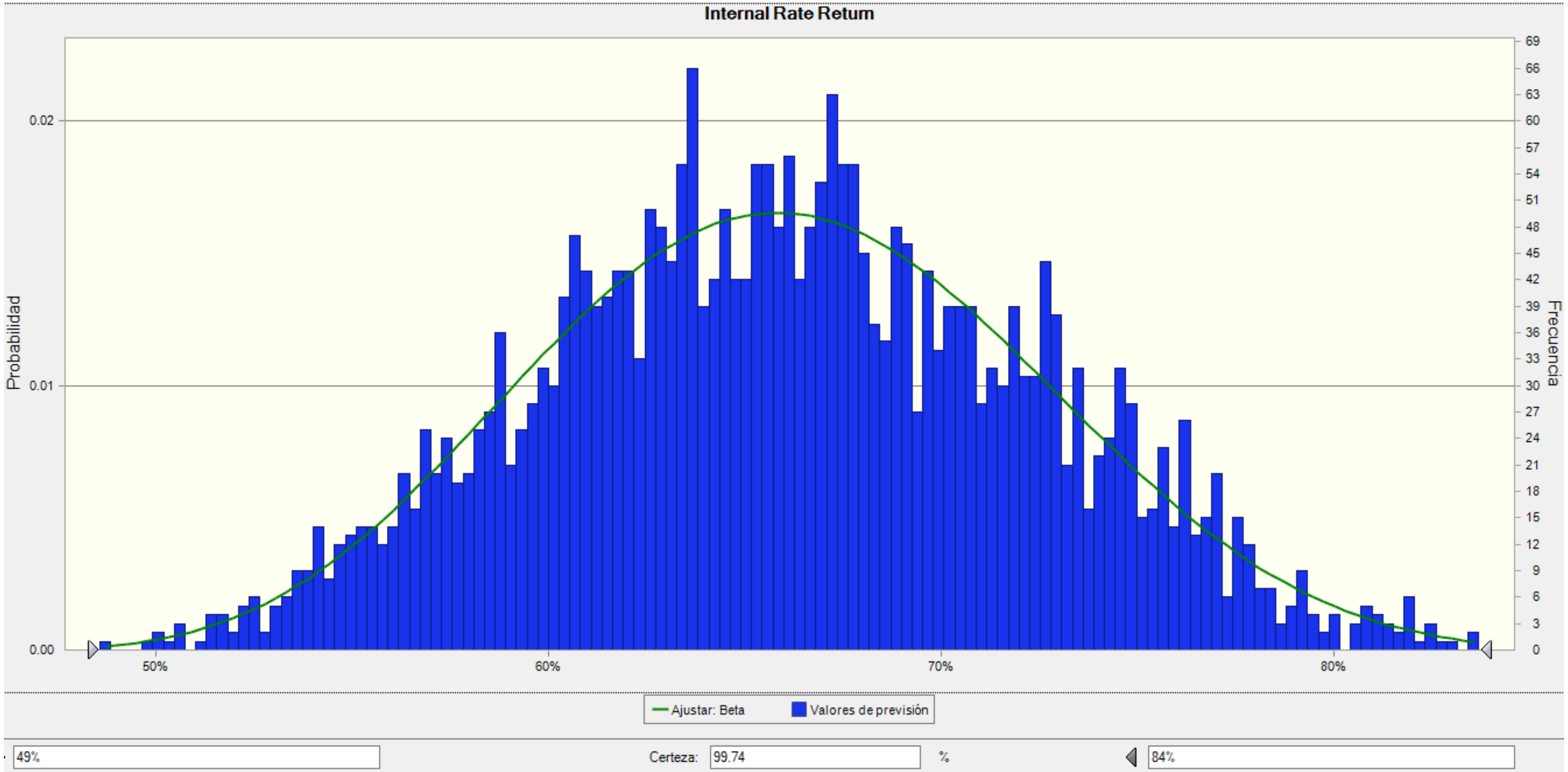

Figure 2. Monte Carlo simulation for the project's Internal Rate of Return

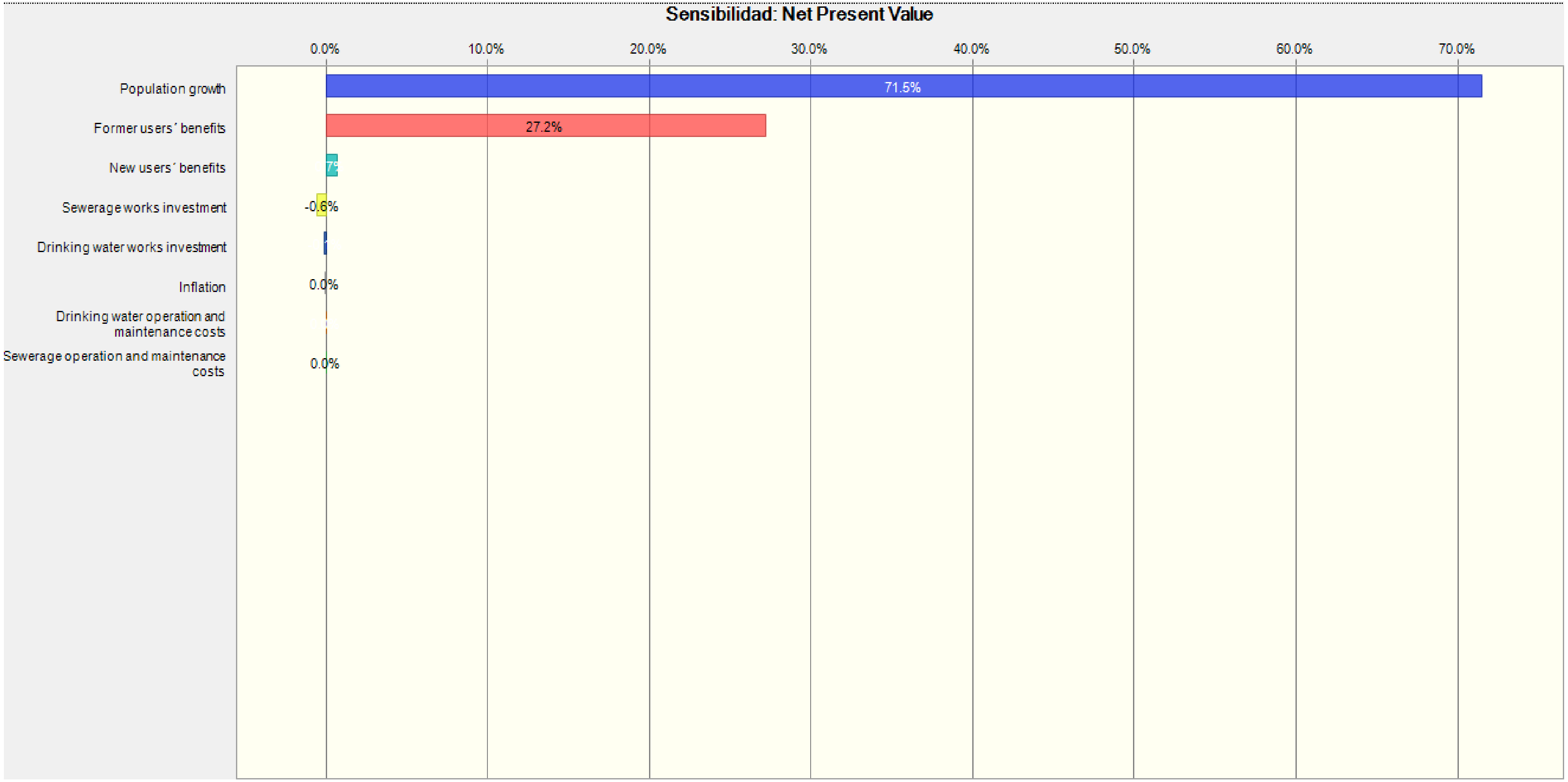

Figure 3. Project's Net Present Value sensitivity analysis

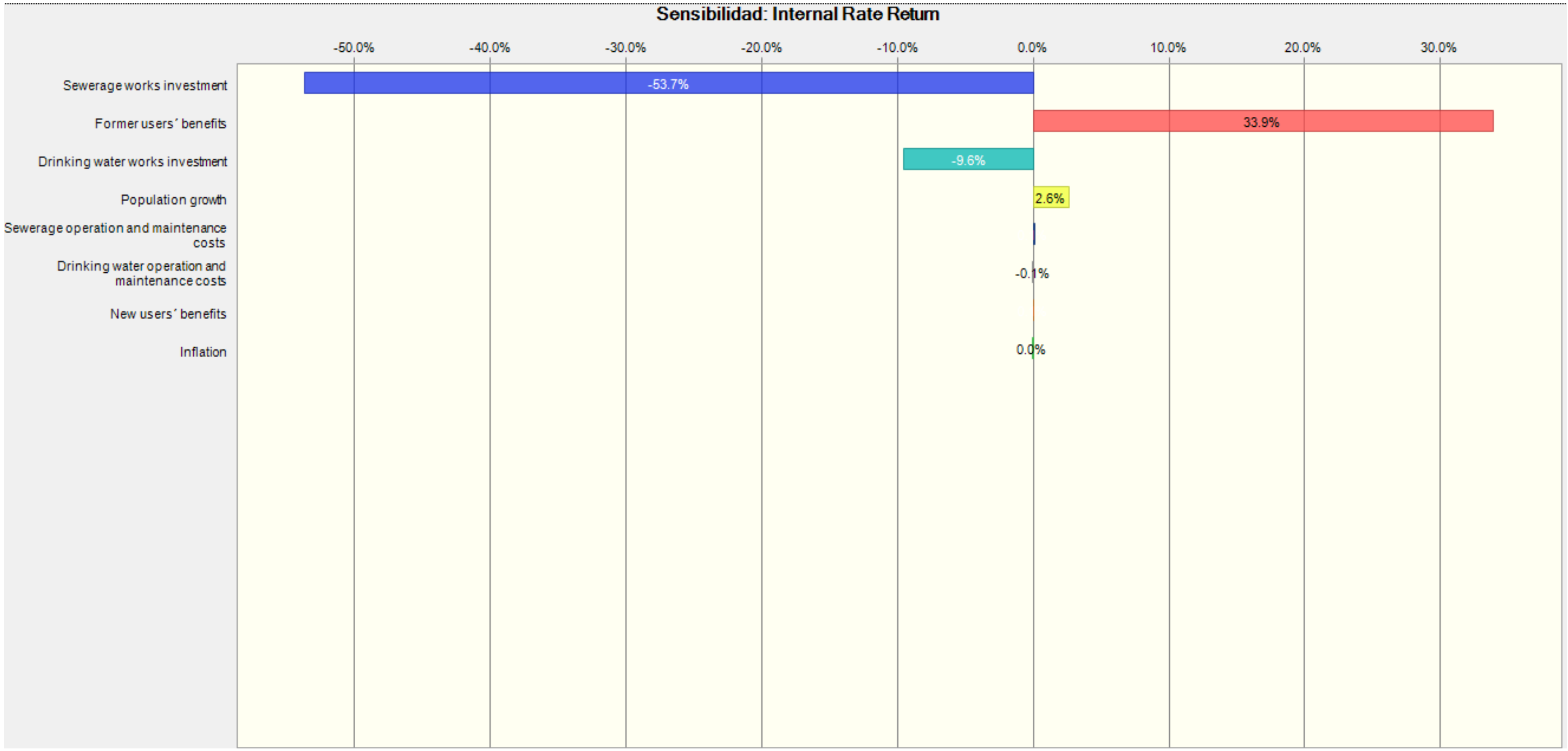

Figure 4. Project's Internal Rate of Return sensitivity analysis

4. Results

4.1. Overall Risk Analysis

Table 2 shows the descriptive statistics of the Net Present Value simulation. It can be seen that the minimum value estimated was about six million dollars, while the maximum value was thirteen million dollars. Table 3 shows similar information, but for the Internal Rate of Return, this table shows that the Internal Rate of Return ranged from 45% to 86%.

Figure 1 and Figure 2 depict the Monte Carlo simulation for the project's Net Present Value and Internal Rate of Return, respectively. In Figure 1, it can be observed that there was a certainty of 99.64% that the Net Present Value ranged from 6 million to twelve million dollars. Moreover, Figure 2 showed that with a confidence of 99.74%, the Internal Rate of Return values was from 49% to 84%. Table 4 shows the project's Net Present Value odds distribution. Hence, the probability of occurrence of values lower than seven million dollars is only about 0.27%. Also, there is a probability of 2.82% that the Net Present Value exceeds twelve million dollars. Among the ranks, the significant likelihood is that the Net Present Value goes from eight to eleven million dollars. According to that table, the probability is almost 79%. Table 5 shows similar information but for the project's Internal Rate of Return, then, the most significant likelihood is that the final project's Internal Rate of Return ranks from 60% to 75%. This probability is almost 75%. On the other hand, there is a tiny probability of less than one percent that the final Internal Rate of Return value becomes lower than 50% or more than 80%.

4.2. Sensitivity Analysis

Table 6 and Table 7 show the sensitivity analysis data of the project's Net Present Value and Internal Rate of Return, respectively. Hence, it can be observed that in Table 6, the variable that contributed the most to the dependent variable was population growth, followed by former users' benefits. Their contribution to the variance was 71.50% and 27.20%, respectively. Moreover, Table 6 shows that population growth and former users' and new users' benefits positively correlated with the project's Net Present Value. Meanwhile, sewerage works investment, inflation, and drinking water investment were negatively correlated with the project's Net Present Value. The same information is portrayed graphically in Figure 3.

Table 7 portrays that sewerage works investment is the most relevant variable. This variable contributes to the project's Internal Rate of Return of 53.70%. In importance, it is followed by former users' benefits, drinking water works investment, and population growth with variance contributions of 33.90%, 9.60%, and 2.60%, respectively. Also, sewerage and maintenance costs, drinking water operations and maintenance costs, and new users' benefits contribute 0.10% each. The rank correlation showed that the investment in sewerage and drinking water works, operation and maintenance costs, and inflation negatively affected the project's Internal Rate of Return. Meanwhile, the dependent variable positively correlated with former users' benefits, population growth, sewerage operation, maintenance costs, and new users' benefits. Figure 4 portrays the information mentioned above.

5. Discussion

The current analysis found that the project had an excellent chance of being sustainable. Both project's Net Present Value and Internal Rate of Return showed that the project would be socially profitable and benefit the population. In terms of odds, it was found that the project had a 79% of probability that its Net Present Value would be between eight and eleven million dollars. Likely, there was a chance of 75% that the project's Internal Rate of Return would be between 60% and 75%. Hence, these results match with the findings of [12-15]. Those studies found that water and sanitization projects had a good chance of being sustainable and beneficial to the population correctly. It is important to add that study [13] also found that a critical value was the initial investment for the project's sustainability. In the study [15], it was discovered that the benefit to the population was critical in the sensibility analysis. Likely, the current research encountered that population growth was the most important variable for the project's Net Present Value, followed by former users' and new users' benefits.

Additionally, the information given by the sensitivity analysis of the project's Internal Rate of Return showed that the most critical variable was the investment in sewerage works, followed by former users' benefits, drinking water works investment and population growth. The three mentioned variables in the project's Net Present Value positively affected the output. However, in the project's Internal Rate of Return, only former users benefit, and population growth positively impacts production. Then, those results do not match with the results of [12,14,15] because those studies stated that other factors impacted the Internal Rate of Return. The differences might be related to how the previous studies analyzed the financial information about their projects. All of them explored the benefits, but in this research, we disaggregated it to get a better panorama of the situation. In all ways, the importance of public service is to generate shared value. Hence, if the project does not provide the population with the required service, the project's benefit will be endangered.

Financially, a drinking water and sewerage project had an excellent chance to impact the state's economy and the population. Also, this result was found by [16] in Colombia, which has similar characteristics to the people of Lambayeque. In terms of maintenance, proper attention to the pipelines are very probable to be essential, as suggested by [17], which stated that it could be the difference between a sustainable project and not. Moreover, those pipelines should be strategically placed to avoid unnecessary installation costs for the state and population, as claimed in [18]. Similarly, [19] highlighted a similar suggestion for putting drinking water pipelines. Those factors will be crucial for the estimation of the maintenance costs of the project. Finally, [20] and [21] recommend estimating the flow volume of both drinking water and sewerage to avoid the overestimation of investment and maintenance costs which were found critical for both the Internal Rate of Return and Net Present Value of the project.

6. Conclusions

It is a human right and a universal need for more people to have access to clean water and sewerage systems to prevent infectious diseases and improve their quality of life. Therefore, improving the drinking water and sewerage services in a poor human settlement on the northern Peruvian coast is significant to improving the living conditions of its impoverished people. The Monte Carlo analysis found that the project had an excellent chance to become sustainable and report enormous benefits for the population. Also, the sensitivity analysis pictured that the population growth was vital for a good result in the project's Net Present Value. Indeed, the expected increase in the habitants in this settlement will prevent that project from becoming a white elephant.

Additionally, the results showed that service should be appropriate in terms of time availability and water quality to boost the perceived benefits of the project. It is also necessary to take preventive measures in the investment expenses since it can make the task even unfeasible. Consequently, the local government should take steps to avoid addends to the expected investment that would harm the public treasury and the quality of the project.

Finally, where drinking water and sewerage services exist, it is mandatory to improve those services to benefit the population. It is inconceivable that people only get a few hours of drinking water despite the installed infrastructure. Moreover, it is necessary to improve the sewerage treatment to avoid more contamination of water sources in all places, especially in locations where water is severely scarce.

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