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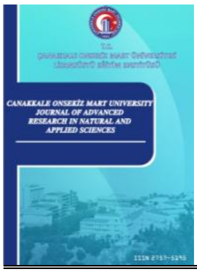

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Development of Small Hydroelectric Power Plant Maintenance Costs using Chaos Embedded Adaptive Particle Swarm Optimization

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Research Article

Abstract − In this study, a new equation model is proposed to improve the maintenance costs of Small Scale Hydroelectric Power Plants (SHPP). The proposed equation model consists of 4 terms and 7 parameters using the Chaos Embedded Adaptive Particle Swarm Optimization (CEAPSO). The MATLAB program was used to calculate the parameters in the proposed equation model. In this study, the main error value for 14 maintenance items required for a SHPP is calculated as 17.4819%. The maintenance cost of a SHPP to be installed in this way can be predicted with high accuracy using the proposed equation model. In the study, the sensitivity analysis of the proposed equation model is also performed, and maintenance cost changes are expressed in different parameter values. In the study, corrected data from 8 SHPP in India are used. These data cover the maintenance costs of all components for the years 2015-2016. In the study, unlike the literature, the flow parameter is added to the power and head parameters. In this way, a more sensitive equation model is developed for SHPP data. In addition, realistic results are obtained by applying constraints to the parameters. Considering the 14 different maintenance cost parameters examined in the study, a correlation model is proposed to give better results than the literature for other maintenance costs except the power channel and penstock cost.

Keywords − *Chaos embedded adaptive particle swarm optimization, Correlation model, Sensitivity analysis, Small hydroelectric power plants, Maintenance cost estimation*

1. Introduction

The need for energy is increasing rapidly with developing technology and increasing world population. This increasing need for energy is usually provided by fossil resources. Considering the damage caused by this situation to the environment, the importance of renewable energy sources increases (Dincer, 2012; Uzar, 2020; Karmendra K. A. et al.,2022). Renewable energy sources consist of hydroelectric, wind, solar, geothermal and biomass energy sources.

Hydroelectric energy resources have a great potential for the world. It is important to use this potential efficiently as well as to evaluate it. Cost information is important for evaluating the current potential and converting it into investment. Therefore, cost analysis and estimation is a topic addressed by researchers (Ogayar and Vidal 2009; Aggidis et al. 2010; Cavazzini et al. 2016; Celikdemir, Yildirim, and Ozdemir 2017; Filho, Santos, and Barros 2017;). After the investment decision is taken for a new power plant installation, techno-economic cost information is analyzed. This analysis information influences cost planning. The parameters for installation cost of Small Scale Hydroelectric Power Plant (SHPP) projects are analyzed in three main sections. These are respectively; civil works, hydromechanical and electromechanical equipment. In the studies, cost correlations based on the installed power and head parameters of electromechanical equipment

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have been developed (Mishra et al., 2011). In addition to these parameters, the flow parameter has been added to the equation model as a new approach for cost estimation (Cavazzini et al., 2016; Çelikdemir and Özdemir, 2022). In such a way, the smallest mean error values with the best performance were obtained. In later studies, better results were obtained by developing equation model parameters. Optimization methods were used to determine equation model parameters (Çelikdemir, S. and Ozdemir 2021; Çelikdemir and Özdemir 2022). Further, cost estimates were obtained with less error rate. In the studies examined, head, flow and turbine types parameters were used in the equation models developed by the researchers.

Another issue addressed by researchers is maintenance costs. As result of that, it is seen that increased operating and maintenance costs increase the unit production cost of energy. This increase in the production cost of energy decreased the net profit of the projects. In the studies, different maintenance costs were analyzed and correlations based on power and head parameters were developed (Kumar, Singal, Dwivedi, and Shukla, 2020).

Motivation of the Study;

In this study, the maintenance costs of SHPPs, which are not often addressed by researchers, were examined. For this, the previously examined SHPPs in India are addressed. There are two main sources of motivation for this study. First, the flow parameters were also added to the correlation models created by the researchers based on only power and head parameters. In such a way, a more sensitive and comprehensive correlation model was obtained. While developing this correlation model, corrected current data of SHPPs were also used. The second, while the correlation models were being developed, some coefficients were found to be negative because there was no limit on the coefficients of power, head and flow parameters. Such a situation would not reflect reality. Because with increasing flow, power and head parameters, the cost value will decrease. For this, a limitation has been applied to the coefficients of the parameters in the proposed equation model. Thus, these two main issues ignored by the researchers constitute the main motivation of the study.

In this study was carried out in three different stages. First, the error rates of the correlation model developed in the literature were recalculated using the corrected SHPP data. In the second stage, new coefficients were obtained by adding the flow parameter to the correlation equation model. These calculated error values were compared with the error rates in the existing studies. In the last stage, sensitivity analysis was performed. For the sensitivity analysis, the effects of the parameters in the proposed equation model were examined respectively. As a result, the maintenance costs of the equation model proposed in the study were calculated with less errors.

2. Materials and methods

In the literature, optimization methods developed in the literature are generally developed for the most appropriate solution to a problem. There are many different optimization algorithms in the literature. Commonly used algorithms; bee algorithm, genetic algorithm, Particle Swarm Algorithm (PSO). The most preferred among these is the PSO. It is an algorithm developed in 1995 (Elbatran et al., 2015). This method imitates the swarming behavior of some living things that live in flocks. These behaviors are both to reach food sources and to be protected from external dangers. This is achieved by communicating with all living things in the swarm. Living things in the swarm consist of N particles living in an n-dimensional space. Here $x_i(t)$ represents the position of particle “i" in iteration “t”. This expression is used to evaluate the state of the particle. PSO needs information sharing among the living things in the swarm to solve problems. Each individual updates its position towards the best position in the swarm to avoid danger and forage. He also uses his previous experiences for this. Particles in the swarm set their best position to the personal best position (X_{pbest}) and the best position in the whole swarm (X_{gbest}). The following equation is used for the next velocity and position of each particle (Alatas et al., 2009; Özdemir, 2021a);

$$v_i(t+1) = wv_{i,j}(t) + c_1 r_1(t)\left(X_{pbest} - x_{i,j}(t)\right) + c_2 r_2(t)\left(X_{gbest} - x_{i,j}(t)\right) \tag{2.1}$$

$$x_i(t+1) = x_i(t) + v_i(t+1) \tag{2.2}$$

Where c_1 and c_2 X_{gbest} are velocity factors, v_i is the velocity of the particles, x_i is the position of the particle and w is the inertia coefficient. The flow diagram of the developed CEAPSO algorithm is given in Figure 1 (Alatas et al., 2009). The velocity expression for CEAPSO is given in Equation (2.3).

$$v_i(t+1) = CM1v_{i,j}(t) + c_1 CM2\,(t)\left(X_{pbest} - x_{i,j}(t)\right) + c_2 CM3(t)\left(X_{gbest} - x_{i,j}(t)\right) \tag{2.3}$$

Where, CM1, CM2, and CM3 are the results of the determined chaotic maps with values between 0-1. There are many CMs used in the literature (Alatas et al., 2009). However, in this study, Chebyshev CM is preferred as the velocity function. In this situation (Özdemir, 2021);

$$CM1{,}2{,}3 = CM_{t+1} = cos(n * arccos(CM_t)) \tag{2.4}$$

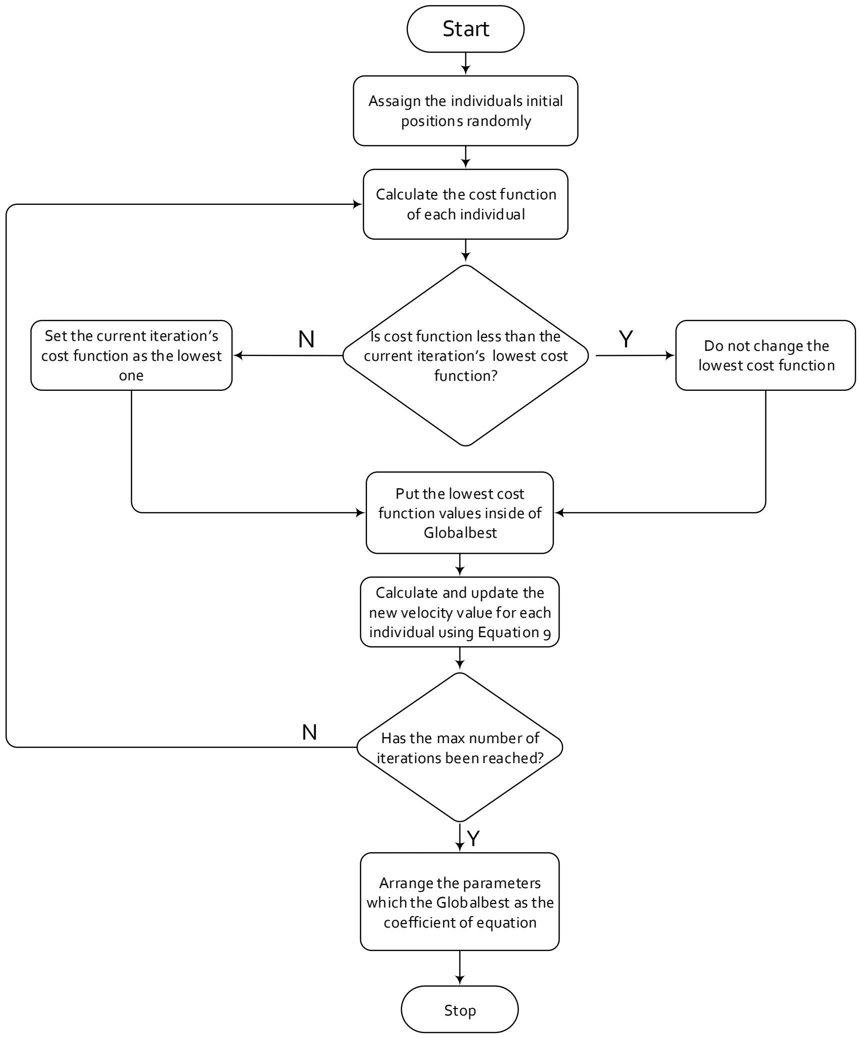

Figure 1. CEAPSO flowchart

The work of CEAPSO, on the other hand, first begins with the determination of the initial positions of the individuals. Then, cost values are calculated for each individual using the cost function. As a result of the calculations, the cycle continues until the lowest cost is calculated. The lowest cost value is assigned as globalbest. The new velocity value is calculated using the velocity equation and the calculations are updated. This process continues until the maximum number of iterations is reached. At the end of the process, the coefficients in globalbest are given as a result. The position and speed values of individuals are determined from the chaotic map. For this, the studies of Alataş et al. were taken as reference. Where, the initial value of CMs was determined as 0.6. In addition, as the other parameter in the CEAPSO algorithm, the number of iterations is 1200, the inertia coefficient is 0.8, c_1= 0.12, c_2= 1.2 and the herd size is 150. It is seen that the best mean error values for the data applied to the heuristic swarm algorithms are CEAPSO. Therefore, CEAPSO was preferred in subsequent studies.

2.1. Classification of hydropower plant

SHPPs are classified according to different criteria. These criteria differ from country to country. The differences in the economic and hydraulic potentials of the countries cause this situation. In many countries, the classification of SHPPs is made according to the installed power of the plant. The classification determined by the United Nations Industrial Development Organization (UNIDO) for different countries is given in Table 1.

Table 1
Worldwide HPP classification

Country	**UK**	**UNIDO**	**Sweden**	**Colombia**	**Australia**	**India**	**China**	**Philippi-nes**	**New Zealand**
Capacity	< 5	< 10	< 15	< 20	< 20	< 25	< 25	< 50	< 50

In addition, different classifications are made according to the head, flow rate, turbine type and structures of SHPPs. SHPPs according to their structures; It is classified as river structure, water storage, channel structure and pump structure.

2.2. Small hydropower plant and components

Energy production in river type SHPP's, which is one of the types of hydroelectric power plants, is proportional to the flow of water. Although the unit costs of small SHPPs are high, they have a long life. In addition, the negative effects on humans and the environment are negligible. A river type SHPP consists of main inlet valve, penstock, power channel, gates, desilting tank. In addition, it consists of turbines, generators, transformer, switchyard, governor, thrust bearing, oil pressure unit, control panel and station auxiliary.

A SHPP consists of construction, electromechanical and hydromechanical equipment and their subcomponents. These components are given in detail in Figure 2 (Kumar et al., 2020).

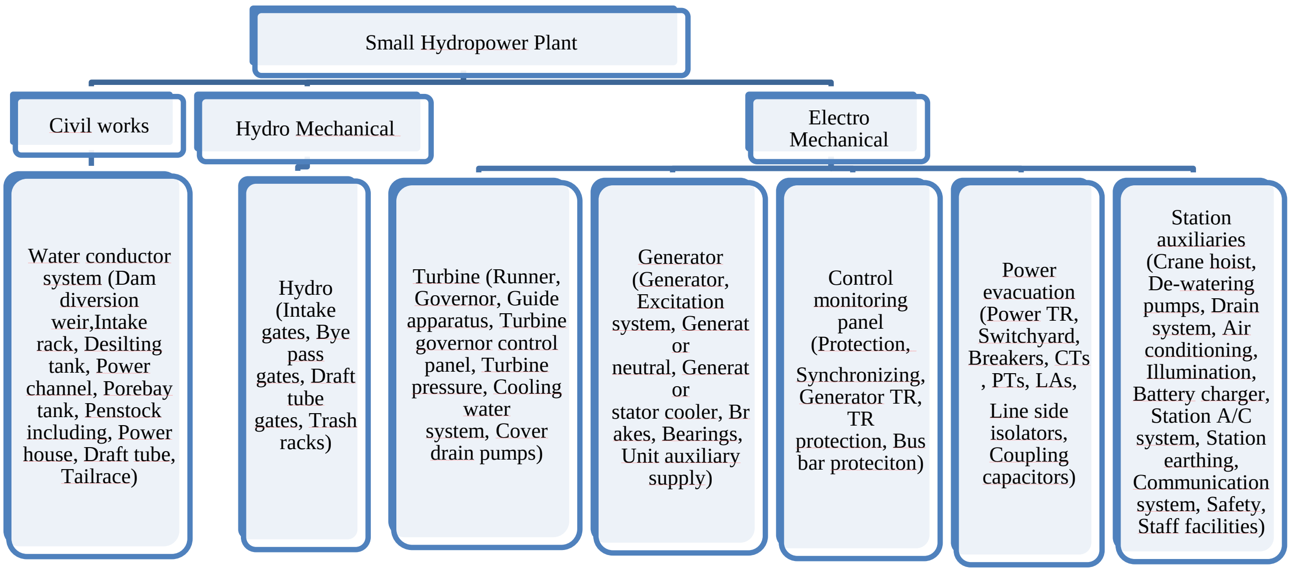

Figure 2. Detail of SHPP components

Repair and maintenance at SHPP directly affect the operating life of the system. Therefore, maintenance work includes regular and systematic work. Effective operation and maintenance is one of the most cost-effective approaches to achieving high energy efficiency. Insufficient maintenance of power plants causes an increase in unit energy costs.

2.3. Data collection

In this study, data from 8 SHPP in India were used. These data cover the maintenance costs of all components for the years 2015-2016. The power plant data for SHPP are given in Figure 3 (*United Nations Framework Convention on Climate Change*, n.d.).

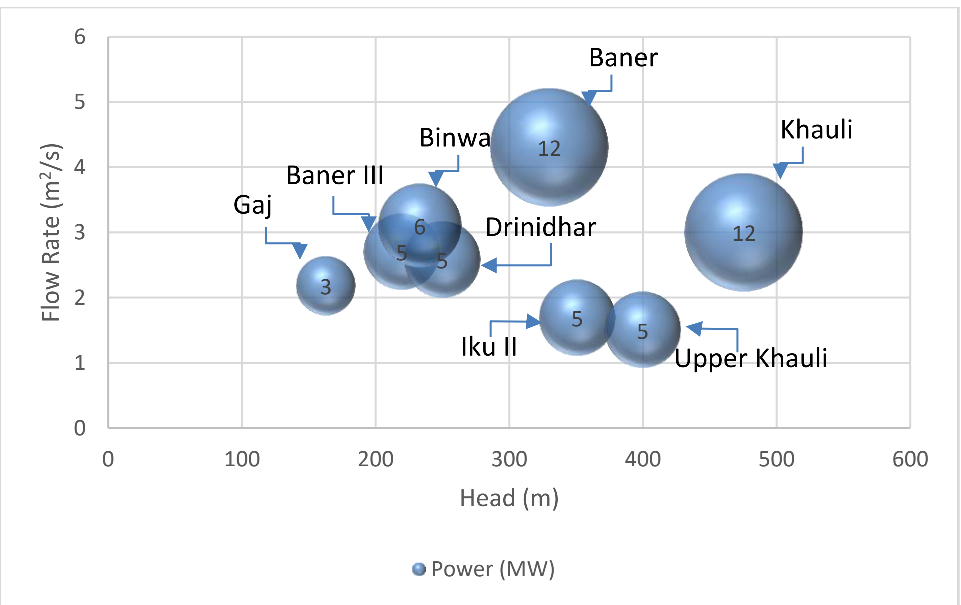

Figure 3. SHPP data diagram

Where, data for 8 SHPPs in India referenced in the study are given. Horizontal axis in Figure 3, the head (m) information of the SHPPs, the vertical axis, the flow rate (m^2/s) information of the SHPPs and the sizes of the figures on the graph give the installed power (MW) values of the SHPPs.

Table 2
SHPP data

Plant Name	Power (MW)	Head (m)	Flow (m^3/s)	Turbine	Date
Baner III	5	219.8	2.7	Pelton	2009
Iku II	5	351	1.69	Pelton	2009
Drinidhar	5	250	2.58	Pelton	2010
Upper Khauli	5	400	1.5	Pelton	2010
Binwa	6	233.2	3.1	Pelton	1984
Baner	12	330.1	4.3	-	1996
Gaj	3	163	2.18	Pelton	1996
Khauli	12	475.7	3	-	2007

In addition, the adjusted data of 8 hydroelectric power plants used in the study are given in Table 3.

2.4. Developed equation model

The power expression of SHPPs is generally expressed as the conversion of potential energy of water into kinetic energy. Flow and head parameters are used in the calculation of power. The expression of the work performed in SHPPs is given in Equation (2.5).

$$dW = \rho \text{ g dV H} \tag{2.5}$$

Where ρ is the water density (kg/m^3), dW is the work, g is the gravity constant (m/s^2), dV is the volume of the water and H is the head (m). Equation (2.6) is used for volume information of water (Celikdemir et al., 2017).

$$dq = \frac{dV}{dt} \tag{2.6}$$

Where t is time (s) and q is flow rate (m^3/s). The definition of power is given Equation (2.7);

$$dP = \frac{dW}{dt} \tag{2.7}$$

The arranged form of the equations is given in Equation (2.8) and Equation (2.9).

$$dP = \frac{\rho \text{ g dq dt H}}{dt} \tag{2.8}$$

$$P = \rho\ g\ q\ h\ \eta \tag{2.9}$$

Where P is the power (Watt) converted from the turbine shaft and η the turbine efficiency (%).

In the literature, three basic models are mostly used in proposing cost equations. These models are Sigma, Linest and Logest equation models. Linest equation model is preferred as the most preferred equation model, which is accepted to give correct results by researchers. As this preference factor, Linest equation model was preferred in this study. Many equation models have been proposed in the literature for electromechanical equipment cost estimation of SHPPs. These proposed equation models are given in Equation (2.10).

$$Cost\ [\$] = a.P^b + c.H^d + e.Q^f + g \tag{2.10}$$

In Equation (3.10), “a and b” are the expression of power P (kW), “c and d” are the expression of head H (m), and “e and f” are the expression of flow Q (m^3/s). Where the coefficients are constrained to be positive for them. In this situation, more realistic results are obtained.

In the study, the maintenance costs of SHPPs, which are not often addressed by researchers, were examined. For this, few data available in the literature with the SHPPs in India belonging to the study were examined.

One of the motivation sources of the study was to propose an equation model with less mean. While doing this, it is aimed to obtain a more general expression and realistic results. The calculated results were compared with the literature results. (Kumar et al., 2020).

3. Result and discussion

The cost data used in the calculations were calculated in dollars over the exchange rate of the maintenance year using the Central Bank data. The coefficients in Equation 2.10 have been developed for the estimation of electromechanical equipment cost calculation of SHPPs. CEAPSO was used to calculate these values. MATLAB program was used to calculate the parameters of the proposed equation model. The calculated coefficients are given in Table 2 (Wang et al., 2022). The corrected data of 8 hydropower plants used in the study are given in Table 3. Corrected data are from Clean Development Mechanism (CDM).

Table 3
Calculated coefficient parameters

Component	a	b	c	d	e	f	g
Turbine	0.698557	4.294794	32.72562	0.562217	2081.046	1.714907	144.5411
Main inlet valve (MIV)	851.2471	0.791228	7.01079	0.791732	3.874605	4.081728	-264.658
Generator	1047.519	1.107083	10.67688	0.132195	74.67233	2.901739	96.94424
Thrust bearing	0.393331	3.707275	8.8809	0.816154	0.190436	5.783192	6.051182
Governor	678.0206	1.023596	0.464932	0.452947	124.7796	2.193964	-25.8276
Oil pressure unit (OPU)	107.4133	1.462108	12.2603	0.462201	196.0348	1.633853	794.357
Control panel	27.75594	2.568188	2.860927	0.718667	4112.165	0.762245	-5344.14
Transformer	3.517244	2.530749	0.742108	1.258029	0.555896	4.256665	897.8485
Switchyard	1.857732	2.49357	10.71817	0.915983	4.046528	4.305202	4758.941
Desilting tank	0.997891	2.811734	359.8555	0.429108	0.487902	4.863487	-1.93133
Power channel	0.001008	0.286092	11139.34	1.07E-06	14.14716	9.72E-06	-653.26
Penstock	1.68E-05	0.079193	419.7806	0.386657	39.57226	0.00281	-8.27214
Gates	11.21851	2.729121	0.006329	0.361564	2818.363	0.683863	-3780.71
Station auxiliaries	46.02745	0.562321	2.91556	1.229814	515.1306	1.538834	1297.404

In this section, 14 different maintenance cost data for 8 hydroelectric power plants are analyzed. The cost and error rates calculated as a result of the analysis are given in Table 4. For this, the 4 term 7 parameter equation model in the proposed Equation 3.10 was used.

Table 4
Costs and error rates of hydroelectric power plants

Component	Plant Name	Actual Maintenance	(Kumar et al., 2020) Cost	(Kumar et al., 2020) Error	(Kumar et al., 2020) Cost (Corrected)	(Kumar et al., 2020) Error (Corrected)	Analysed Maintenance	Analysed Error
Turbine	**Baner III**	3311.26	3564.35	-7.64	4888.34	-47.63	4289.54	-29.54
	Iku II	2317.88	2554.27	-10.20	2849.53	-22.94	2267.20	2.19
	Drinidhar	4966.89	4341.34	12.59	4419.04	11.03	4022.55	19.01
	Upper Khauli	1490.07	1458.72	2.10	2088.08	-40.13	1976.03	-32.61
	Binwa	6622.52	6796.33	-2.62	6796.33	-2.62	5584.94	15.67
	Baner	17935.98	17987.88	-0.29	17987.88	-0.29	18715.07	-4.34
	Gaj	16556.29	16634.80	-0.47	1538.55	90.71	2886.08	82.57
	Khauli	15866.45	15725.30	0.89	15725.30	0.89	14907.12	6.05
Main inlet valve (MIV)	**Baner III**	1158.94	1189.75	−2.66	1241.92	-7.16	1159.43	-0.04
	Iku II	1192.05	1149.96	3.53	1161.59	2.56	1170.85	1.78
	Drinidhar	1158.94	1220.37	−5.30	1223.43	-5.56	1164.71	-0.50
	Upper Khauli	1192.05	1106.79	7.15	1131.59	5.07	1192.85	-0.07
	Binwa	1379.69	1430.60	−3.69	1430.60	-3.69	1379.70	0.00
	Baner	2649.01	2552.60	3.64	2552.60	3.64	2648.92	0.00
	Gaj	8278.15	2329.02	1.53	882.92	89.33	746.53	90.98
	Khauli	2345.47	2463.45	−5.03	2463.45	-5.03	2345.27	0.01
Generator	**Baner III**	2317.88	2472.20	−6.66	2821.75	-21.74	2541.24	-9.64
	Iku II	2384.11	2205.53	7.49	2283.48	4.22	2213.62	7.15
	Drinidhar	2483.44	2677.33	−7.81	2697.85	-8.63	2486.81	-0.14
	Upper Khauli	2152.32	1916.29	10.97	2082.45	3.25	2180.60	-1.31
	Binwa	3311.26	3424.39	−3.42	3424.39	-3.42	3219.83	2.76
	Baner	7174.39	6972.54	2.81	6972.54	2.81	7174.33	0.00
	Gaj	23178.81	6466.94	2.35	1739.55	92.50	1446.81	93.76
	Khauli	6070.64	6375.19	−5.02	6375.19	-5.02	6070.61	0.00

Table 4
Costs and error rates of hydroelectric power plants (continued)

Thurst bearing	**Baner III**	0.00	41.14	0.00	0.00	0.00	0.00	0.00
	Iku II	0.00	-16.78	0.00	0.00	0.00	0.00	0.00
	Drinidhar	0.00	85.69	0.00	0.00	0.00	0.00	0.00
	Upper Khauli	0.00	-79.60	0.00	0.00	0.00	0.00	0.00
	Binwa	397.35	382.67	3.70	382.67	3.70	397.39	-0.01
	Baner	1931.57	1961.62	−1.56	1961.62	-1.56	1931.67	-0.01
	Gaj	6070.64	1649.73	4.89	-387.43	106.38	203.27	96.65
	Khauli	1793.60	1831.88	−2.13	1831.88	-2.13	1793.48	0.01
Governor	**Baner III**	1324.50	1441.22	−8.81	1623.58	-22.58	1524.42	-15.09
	Iku II	1324.50	1302.09	1.69	1342.76	-1.38	1290.29	2.58
	Drinidhar	1490.07	1548.24	−3.90	1558.94	-4.62	1489.86	0.01
	Upper Khauli	1258.28	1151.19	8.51	1237.88	1.62	1260.34	-0.16
	Binwa	1986.75	19309917.8	2.81	1930.99	2.81	1893.00	4.72
	Baner	3863.14	3.74	3.18	3740.14	3.18	3864.17	-0.03
	Gaj	12130.79	3.49	−0.60	1072.97	91.15	912.61	92.48
	Khauli	3311.26	3.43	−3.54	3428.50	-3.54	3310.95	0.01
Oil pressure unit (OPU)	**Baner III**	927.15	957.51	−3.27	1056.28	-13.93	1015.19	-9.50
	Iku II	927.15	882.16	4.85	904.19	2.48	851.09	8.20
	Drinidhar	993.38	1015.48	−2.22	1021.27	-2.81	994.65	-0.13
	Upper Khauli	827.81	800.43	3.31	847.38	-2.36	827.80	0.00
	Binwa	1214.13	1237.24	−1.90	1237.24	-1.90	1214.13	0.00
	Baner	2373.07	2303.85	2.92	2303.85	2.92	2371.51	0.07
	Gaj	7505.52	2144.98	−0.03	729.15	90.29	714.97	90.47
	Khauli	2069.54	2135.06	−3.17	2135.06	-3.17	2069.54	0.00
Control panel	**Baner III**	1324.50	1420.35	−7.24	1891.77	-42.83	1752.60	-32.32
	Iku II	1059.60	1060.70	−0.10	1165.82	-10.02	899.00	15.16
	Drinidhar	1655.63	1697.00	−2.50	1724.67	-4.17	1658.15	-0.15
	Upper Khauli	728.48	670.61	7.94	894.70	-22.82	728.78	-0.04
	Binwa	2759.38	2719.28	1.45	2719.28	1.45	2419.38	12.32
	Baner	7312.36	7593.06	−3.84	7593.06	-3.84	7861.95	-7.52
	Gaj	24834.44	6889.05	2.91	402.74	98.38	888.00	96.42
	Khauli	6898.45	6787.43	1.61	6787.43	1.61	6886.99	0.17

Table 4
Costs and error rates of hydroelectric power plants (continued)

Transformer	**Baner III**	596.03	636.99	−6.87	532.63	10.64	595.50	0.09
	Iku II	761.59	716.60	5.91	693.33	8.96	758.75	0.37
	Drinidhar	529.80	575.74	−8.67	569.62	-7.52	631.46	-19.19
	Upper Khauli	827.81	802.95	3.00	753.34	9.00	827.99	-0.02
	Binwa	662.25	649.54	1.92	649.54	1.92	662.50	-0.04
	Baner	1379.69	1371.21	0.62	1371.21	0.62	1378.13	0.11
	Gaj	3863.14	1076.91	2.43	262.07	93.22	470.25	87.83
	Khauli	1517.66	1549.54	−2.10	1549.54	-2.10	1517.78	-0.01
Switchyard	**Baner III**	2317.88	2313.08	0.21	2283.20	1.50	2202.14	4.99
	Iku II	2384.11	2335.87	2.02	2329.21	2.30	2384.00	0.00
	Drinidhar	2185.43	2295.54	−5.04	2293.79	-4.96	2247.06	-2.82
	Upper Khauli	2483.44	2360.59	4.95	2346.39	5.52	2475.66	0.31
	Binwa	2317.88	2408.00	−3.89	2408.00	-3.89	2327.71	-0.42
	Baner	3311.26	3162.57	4.49	3162.57	4.49	3312.46	-0.04
	Gaj	10485.65	2941.33	1.82	2023.09	80.71	2000.80	80.92
	Khauli	3035.32	3213.63	−5.87	3213.63	-5.87	3035.35	0.00
Desilting tank	**Baner III**	1456.95	1411.05	3.15	1289.29	11.51	1255.43	13.83
	Iku II	1655.63	1503.95	9.16	1476.79	10.80	1505.38	9.08
	Drinidhar	1192.05	1339.60	-12.38	1332.45	-11.78	1319.88	-10.72
	Upper Khauli	1589.40	1604.70	-0.96	1546.82	2.68	1589.45	0.00
	Binwa	1324.50	1379.57	-4.16	1379.57	-4.16	1326.25	-0.13
	Baner	1986.75	1944.81	2.11	1944.81	2.11	1986.75	0.00
	Gaj	6070.64	1670.62	3.68	1065.86	82.44	1073.97	82.31
	Khauli	2069.54	2152.89	-4.03	2152.89	-4.03	2069.54	0.00
Power channel	**Baner III**	3642.38	3884.60	-6.65	3424.75	5.98	3476.92	4.54
	Iku II	4304.64	4.24	1.61	4132.88	3.99	3476.92	19.23
	Drinidhar	3476.82	3614.74	-3.97	3587.75	-3.19	3476.92	0.00
	Upper Khauli	4768.21	4615.94	3.19	4397.35	7.78	3476.92	27.08
	Binwa	3311.26	3130.85	5.45	3130.85	5.45	3476.92	-5.00
	Baner	1490.07	1456.50	2.25	1456.50	2.25	3476.92	-133.34
	Gaj	4966.89	1373.27	3.23	3850.63	22.47	3476.92	30.00
	Khauli	2152.32	2242.35	-4.18	2242.35	-4.18	3476.92	-61.54

Table 4
Costs and error rates of hydroelectric power plants (continued)

Pentstock	**Baner III**	1324.50	1369.87	-343.00	1119.29	15.49	1128.75	14.78
	Iku II	1655.63	1561.04	5.71	1505.16	9.09	1350.61	18.42
	Drinidhar	1125.83	1222.82	-8.61	1208.11	-7.31	1185.83	-5.33
	Upper Khauli	1821.19	1768.38	2.90	1649.27	9.44	1420.06	22.03
	Binwa	1103.75	1121.62	-1.62	1121.62	-1.62	1154.64	-4.61
	Baner	1241.72	1184.09	4.64	1184.09	4.64	1319.20	-6.24
	Gaj	3311.26	895.03	5.40	1026.41	69.00	1006.66	69.60
	Khauli	1517.66	1612.31	-6.24	1612.31	-6.24	1517.80	-0.01
Gates	**Baner III**	662.25	697.43	-5.31	1034.57	-56.22	889.09	-34.25
	Iku II	450.33	440.23	2.24	515.41	-14.45	384.47	14.62
	Drinidhar	827.81	895.28	-8.15	915.07	-10.54	832.74	-0.60
	Upper Khauli	165.56	161.27	2.59	321.52	-94.20	279.83	-69.02
	Binwa	1655.63	1548.43	6.47	1548.43	6.47	1265.06	23.59
	Baner	4552.98	4566.33	-0.29	4566.33	-0.29	4553.06	0.00
	Gaj	14569.54	4179.75	-0.41	125.55	99.14	412.79	97.17
	Khauli	4001.10	3990.19	0.27	3990.20	0.27	4000.84	0.01
Station auxilia-ries	**Baner III**	1986.75	2140.10	-7.72	2104.01	-5.90	1986.58	0.01
	Iku II	2152.32	2167.63	-0.71	2159.58	-0.34	2152.82	-0.02
	Drinidhar	1986.75	2118.92	-6.65	2116.80	-6.55	2059.14	-3.64
	Upper Khauli	2317.88	2197.48	5.19	2180.33	5.93	2315.88	0.09
	Binwa	2483.44	2273.07	8.47	2273.07	8.47	2232.27	10.11
	Baner	3311.26	3294.37	0.51	3294.37	0.51	3309.14	0.06
	Gaj	10485.65	2999.67	−0.13	1753.20	83.28	1531.11	85.40
	Khauli	3311.26	3356.03	−1.35	3356.03	-1.35	3310.01	0.04

In this study, a correlation model was developed by examining the maintenance costs of 8 river type SHPPs in India. For this, realistic maintenance costs and adjusted plant data for the years 2015-2016 were used. Developed and literature correlation model mean error results are given in Table 5.

Table 5
Error rates of maintenance costs

	Max. Error (%)		**Min. Error (%)**		**Standart Deviation**		**Mean Error**	
Parameters	**(Kumar et al., 2020)**	**Proposed Model**	**(Kumar et al., 2020)**	**Proposed Model**	**(Kumar et al., 2020)**	**Proposed Model**	**(Kumar et al., 2020)**	**Proposed Model**
Turbine	11.030	19.013	-47.628	-32.614	19.508	12.203	27.030	23.998
MIV	5.072	1.779	-7.160	-0.498	1.516	0.658	15.256	11.672
Generator	4.221	7.151	-21.738	-9.636	6.782	3.881	17.698	14.345
Thrust B.	3.695	0.006	-2.135	-0.011	1.106	0.003	14.221	12.084
Governor	3.184	4.719	-22.580	-15.094	7.536	5.534	16.361	14.386
OPU	2.917	8.203	-13.928	-9.495	4.299	4.315	14.981	13.546
Control P.	1.609	15.157	-42.829	-32.321	15.370	11.751	23.140	20.513
Tr.	10.637	0.373	-7.516	-19.189	4.127	7.213	16.745	13.457
Switchyard	5.519	4.993	-5.875	-2.820	1.638	1.942	13.654	11.189
D. Tank	11.508	13.832	-11.778	-10.723	4.407	6.135	16.188	14.509
Power C.	7.778	27.081	-4.183	-133.340	1.857	47.844	6.911	35.092
Penstock	15.493	22.026	-7.309	-6.240	4.365	8.195	15.354	17.627
Gates	6.475	23.590	-94.200	-69.016	35.686	25.242	35.199	29.907
Station A.	8.471	10.114	-6.546	-3.644	3.324	3.822	14.042	12.422
Mean Error of Absolute Values							17.62	17.48

Considering the 14 different maintenance cost parameters examined in the study, the correlation model was carried out to give better results than the literature for 12 maintenance costs except the power channel and penstock cost. In addition, the best error values are shown in green in Table 5. The reason why the correlation model developed for these two maintenance costs gave worse results is that there is no limitation to the head, flow and power parameters, which are not discussed in the literature. On the other hand, the developed correlation model gives more realistic results. Although the correlation model developed for the power channel and penstock cost gives worse results, the total mean error still gives better results than the literature. The main error results of the correlation model developed and in the literature are given in Figure 4.

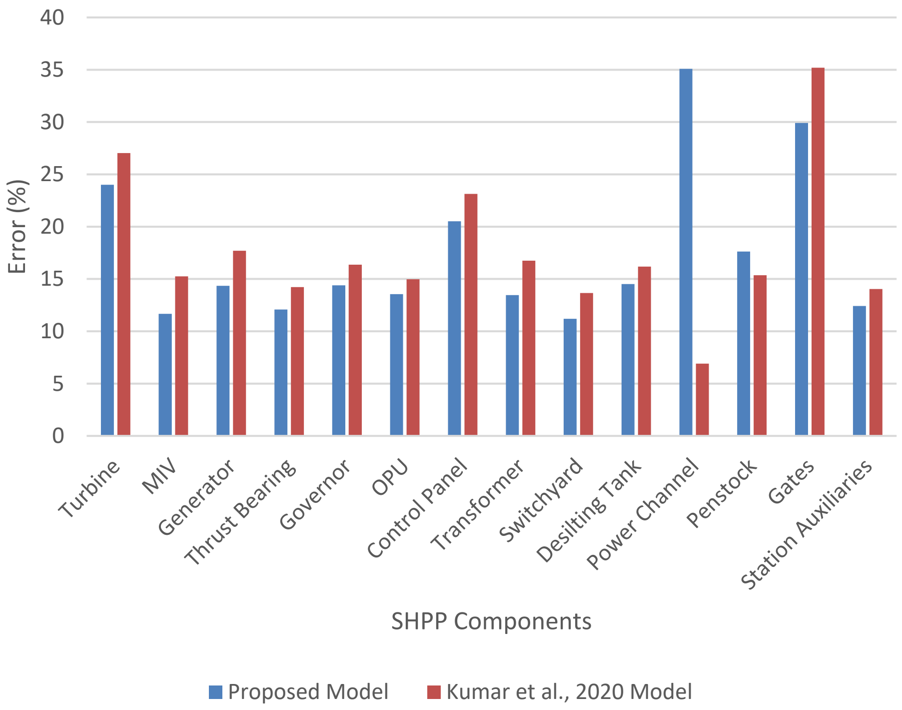

Figure 4. Literature and proposed equation model mean error values

The standard deviation results of the correlation model developed in the literature are given in Figure 5.

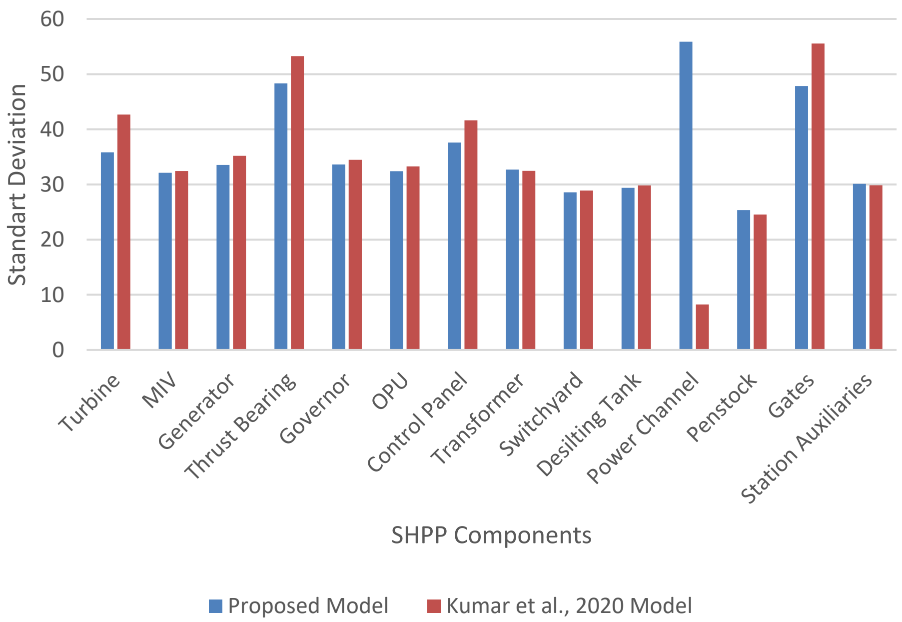

Figure 5. Literature and proposed equation model standard deviation error values

Similarly, when the results of the developed and literature correlation model are examined, the biggest error rate belongs to Gaj SHPP. Since this error rate is not within the acceptable range, it can be assumed that there is an error in the data and maintenance costs of this plant.

In this section, a sensitivity analysis was performed. The effect of the parameters in the equation model proposed for the sensitivity analysis was examined. For this, the changes of the parameters in the proposed equation model were examined respectively. In this way, the effect of the parameters on the cost can be seen clearly. In the proposed equation model, sensitivity analyses for some maintenance costs were examined using the coefficients in Table 2.

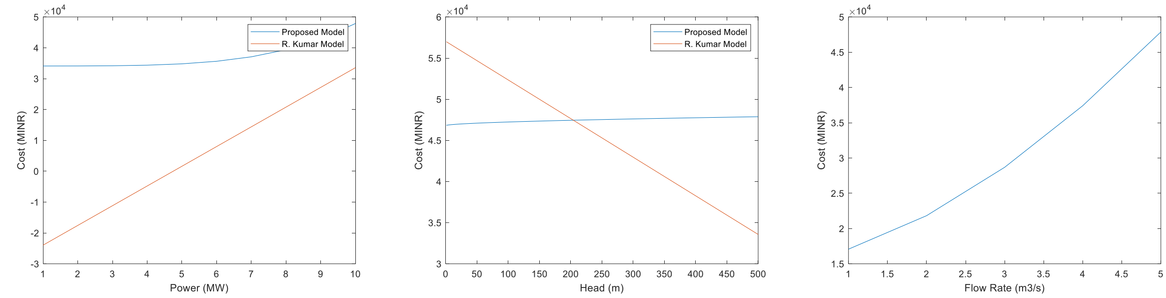

Figure 6. Sensitivity analysis for turbine cost

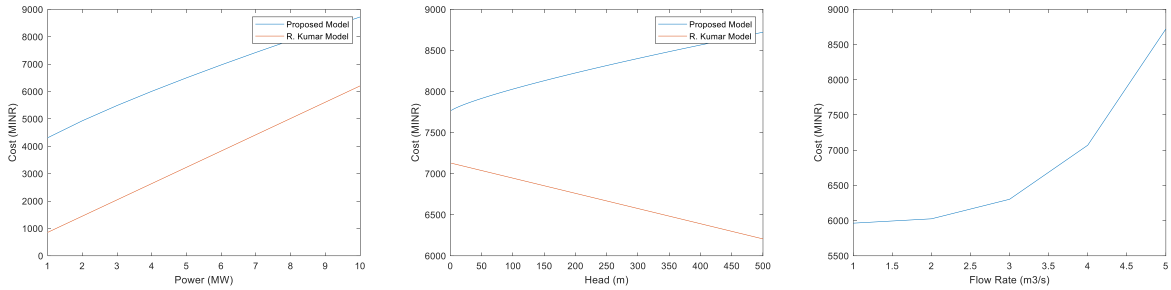

Figure 7. Sensitivity analysis for MIV cost

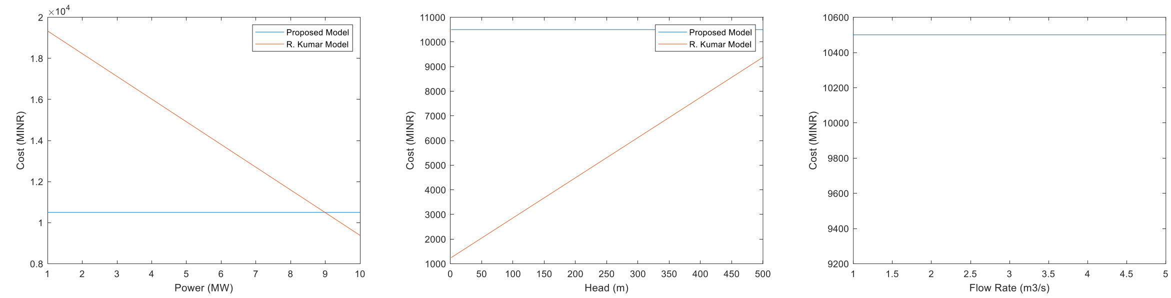

Figure 8. Sensitivity analysis for power channel cost

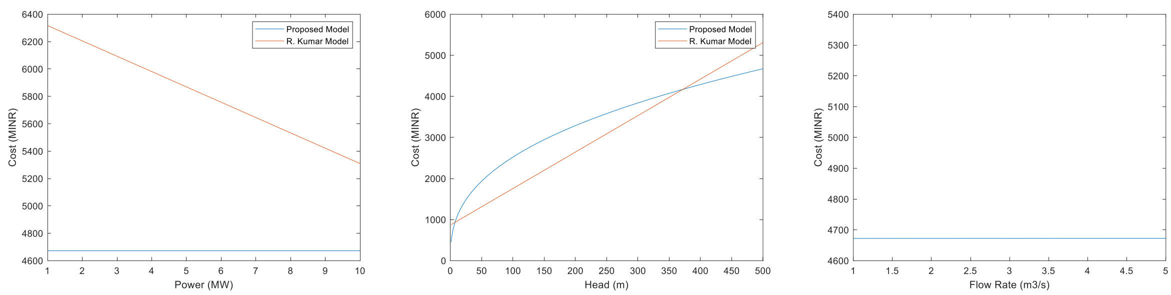

Figure 9. Sensitivity analysis for penstock cost

Sensitivity analysis of turbine maintenance costs is given in Figure 6. According to this; in the literature correlation, it is seen that the maintenance cost decreases with the increasing flow parameter, but the maintenance cost increases in the developed correlation. Similarly, the sensitivity analysis of main inlet valve maintenance costs is given in Figure 7. According to this; In the literature correlation, it is seen that the maintenance cost decreases with the increasing flow parameter, but the maintenance cost increases in the developed correlation. Sensitivity analysis of power channel maintenance costs is given in Figure 8. According to this; in the literature correlation, it is seen that the maintenance cost decreases with the increasing power parameter, but the maintenance cost increases in the developed correlation. Similarly, the sensitivity analysis of penstock maintenance costs is given in Figure 9. According to this; in the literature correlation, it is seen that the maintenance cost decreases with the increasing power parameter, but the maintenance cost increases in the developed correlation.

4. Conclusions

Maintenance costs of power plants have a direct impact on the unit production cost of energy. Therefore, it is important to carry out regular and periodic maintenance in order to reduce the unit cost of energy and increase the operating life of the power plant. In this study, a realistic correlation model is proposed for investment costs. The correlation model is proposed with 4 terms and 7 parameters. In the study, model parameters were determined by using the CEAPSO, which was developed because it has many advantages.

Considering the 14 different maintenance cost parameters examined in the study, a correlation model was proposed to give better results than the literature for other maintenance costs except the power channel and penstock cost. With this study, the cost of a SHPP to be maintained can be predicted with high accuracy using the proposed equation model. Also, in the future, its accuracy can be further improved by adding new SHPP data to the proposed equation model. The equation model proposed in this study can be improved by adding different parameters.

The literature of this study;

- ✓ Suggesting a more sensitive equation model by adding a new parameter to the correlation model,
- ✓ Obtaining more realistic results by limiting head, flow and power parameters in the correlation model,
- ✓ Suggesting a CEAPSO algorithm to estimate of cost equation parameters

contributions have been made.

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Author contributions

The authors declared that they contributed equally to the article.

Conflicts of interest

The authors declare no conflict of interest.

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