Non-Smooth Pollution Less Economic Dispatch Solution using Grasshopper Optimization Algorithm

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Abstract - **Economic load dispatch is the process of distributing the necessary energy load to the accessible generating unit at low cost. Pollution Less Economic Dispatch (PLED) is the advancing method which combines the problem of fuel cost minimization and emission minimization as a single entity. Price penalty factor is a blending factor required for PLED calculation and in this article eight different price penalty factors are tested on three different test systems such as 6 unit system considering transmission loss, IEEE 30 bus system and 40 unit system considering valve point effects. This article adapts Grasshopper Optimization Algorithm (GOA) to compute optimal solution for PLED problem. The final outcome of the GOA based PLED approach has a determined solution which ultimately minimizes both the cost and emission. The obtained result in comparison with other optimization algorithms confirms that the proposed method can serve as a potential tool for solving PLED problems.**

Keywords – emission, grasshopper optimization algorithm, pollution less economic dispatch, price penalty factor, transmission loss, valve point effects

I. INTRODUCTION

1.1 Pollution Less Economic Dispatch (PLED)

In past few decades, the problem of Economic Dispatch (ED) has received much attention by many utilities and it has been marked as one of the most important optimization problem in power system operation. A classical economic dispatch problem is to distribute instant and/or dynamic energy demand among online available energy resources economically while satisfying various system and operational constraints. However, with the growing public cognizance of the environmental pollution caused by fossil fuel fired thermal power plants, this single objective can no longer be considered alone. Limiting emission of pollutants becomes another crucial objective in the power dispatch. In recent days, Pollution Less Economic Dispatch (PLED) is becoming more and more desirable which not only resulting in great economic benefit, but also reducing the pollutants emission.

1.2 Literature Survey

Over the past decades, many optimization methods have been used to solve PLED problem. These methods can be classified into three categories: (i) conventional methods, (ii) non-conventional methods and (iii) hybrid Methods. Previously mathematical programming based conventional methods such as Lagrange relaxation, lambda iteration, Newton-Raphson, interior point method and quadratic programming [1] had been used to solve ED and PLED problems. Classical methods have some advantages like they don't have any problem-specific parameters to specify and their optimality is mathematically proven. They have some major disadvantages like they can immaturely converge into local optimum, sensitivity to the initial starting points, many of the them are not applicable to some types of cost function i.e. non-smooth, non-convex, non-monotonically increasing cost functions etc.

Artificial intelligence-based non-conventional methods have been frequently used to solve PLED problems which include Genetic Algorithm (GA) [2], Particle Swarm Optimization (PSO) [3], Harmony Search (HS) [4], Gravitational Search Algorithm (GSA) [5], Backtracking Search Algorithm (BSA) [6], Spiral Optimization Algorithm (SOA) [7] and some nature inspired advanced methods like Artificial Bee Colony (ABC) [8], Flower Pollination Algorithm (9) and Cuckoo Search (CS) [10]. These advanced optimization methods play a pivotal role in alleviating the problems found in the classical approaches in solving PLED problem, for example, they can enable us to solve nonlinear and non-convex cost functions and can achieve nearly global/global solutions. However, some of these methods suffer from many problem specific parameter selections and high computational time.

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In order to combine the best features of different algorithm and thereby achieve superior performance than the stand-alone methods researchers have developed many hybrid methods [11-14] by combining two or more algorithms to solve PLED problems. But hybrid algorithm usually suffer from long computational time, as two or more algorithms operated (either in parallel) to solve PLED problem, where each of the algorithms perform individually into the problem.

1.2.1 Recent Rivals

A multi objective economic emission dispatch problem can be converted into single objective by introducing price penalty factor 'h' which blends the emission with fuel cost. The recent articles examining the PLED no longer considers single price penalty factor. The impact of various price penalty factors such as $h_{Min\text{-}Maxi}$, $h_{Max\text{-}Mini}$, $h_{Max\text{-}Maxi}$, $h_{Min\text{-}Mini}$, h_{Avgi}, h_{Common} which are available in the literature are considered together in [16-18] for the multi-objective dispatch problem and their impact on fuel cost, emission and total cost are found.

1.3 Research Gap and Motivation

In past the only objective is to minimize cost while generation of power whereas now a big concern is about saving environment from pollution and hence two more additional price penalty factors h_{Avg1}= ((h_{maxi}/h_{maxi}) + ($h_{min,i}+h_{mini}$))/ 2 ($/kg) and h_{Avg2} = ((h_{maxi}/h_{mini}) + ($h_{mini}+h_{maxi}$))/ 2 ($/kg) are introduced as a maiden attempt in addition to the above price penalty factors, in this article and the impact of various price penalty factors on the dispatch solution is carried out. This study uncovers the aspects of various price penalty factors which will benefit the policy maker to implement more economical and environmental friendly power generation system. Often the researchers apply various price penalty factors to optimize PLED problem and this study will help to choose more suitable penalty factor among various price penalty factors for PLED problems.

1.4 Objectives

Although several optimization methodologies have been developed for the PLED problem, the complexity of the task reveals the necessity for development of efficient algorithms to accurately locate the optimum solution. In this perspective, the objective of this work is to demonstrate a new approach for solving PLED problems considering various penalty factors, aiming to provide a practical alternative for conventional methods.

1.5 Article Organization

The overview of PLED problems is discussed initially followed by its earlier and recent literature survey reports. Section 2 presents the mathematical formulation of PLED problem. The methodology of GOA and its implementation on PLED problem is presented in section 3. In section 4, the test systems are outlined and its results are examined in terms of cost and emission and compared with other rival approaches. Finally section 5 draws the conclusion from the results.

II. POLLUTION LESS ECONOMIC DISPATCH FORMULATION

The main objective of PLED problem is to minimize the two incompatible objective functions fuel cost and emission simultaneously satisfying the equality and inequality constraints. The problem formulation is as follows:

2.1 *Fuel Cost (F) Function*

$$F_i(P_i) = \sum_{i=1}^{N} \left[\left(a_i P_i^2 + b_i P_i + c_i\right) + \left| d_i \sin(e_i(P_i^{\min} - P_i)) \right| \right] \left(\frac{\$}{h}\right) \tag{2.1}$$

where $F_i(P_i)$ is the fuel cost of the ith generator, P_i is the real power generation of unit i, a_i, b_i, c_i are the cost coefficients of ith generating unit, d_i, e_i are the valve point effect coefficients of unit i, N denotes number of generating units.

2.2 Emission (E) Function

$$E_i(P_i) = \sum_{i=1}^{N} \left[\left(\alpha_i P_i^2 + \beta_i P_i + \gamma_i\right) + \eta_i \exp(\delta_i P_i) \right] \left(\frac{kg}{h}\right) \tag{2.2}$$

where $E_i(P_i)$ is the total emission of the ith generator, α_i, β_i, γ_i are the emission coefficients of generators in Kg/MW^2, Kg/MW, Kg respectively. η_i, δ, are the emission coefficients in Tons and MW^{-1} respectively.

2.3 Pollution Less Emission Dispatch

A nonlinear multi-objective optimization problem consisting of the fuel cost and the emission as competing objectives can be converted into a single objective minimization problem by introducing a price penalty factor *h* as follows

$$Minimize\ F_T = \sum_{i=1}^{N} \{F_i(P_i), E_i(P_i)\} \tag{2.3}$$

$$Minimize\ F_T = F_i(P_i) + h_i E_i(P_i) \left(\frac{\$}{h}\right) \tag{2.4}$$

where F_T is the total operating cost of the system.

2.4 Various Price Penalty Factors for PLED Problem

The conflicting issues, cost and emission are converted to a single objective by introducing price penalty factor, which is the ratio between the fuel cost and emission for different power capacities of the plant. The various price penalty factors such as max-max, min-max, max-min, min-min, average and common which are already available in the existing literatures and the two proposed penalty factors such as h_{Avg1}= ((h_{maxi}/h_{maxi}) + ($h_{min,i}+h_{mini}$))/ 2 ($/kg) and h_{Avg2} = ((h_{maxi}/h_{mini}) + ($h_{mini}+h_{maxi}$))/ 2 ($/kg) are chosen to solve PLED problem. The above mentioned price penalty factors are formulated in detail and presented in Appendix.

2.5 Equality and Inequality Constraints

The PLED problem is subject to the following constraints

2.5.1 Real Power Balance Constraint

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The total generated power should be the same as the total load demand (P_D) plus the line loss (P_{LOSS}). Thus, the real power balance operation can be modeled as in Eqn. (2.5)

$$\sum_{i=1}^{N} P_i = P_D + P_{LOSS} \quad (MW) \tag{2.5}$$

The transmission loss is a function of active power generation of each generating unit for a given load demand. The same may realized as in Eqn. (2.6)

$$P_{LOSS} = \sum_{i=1}^{N}\sum_{j=1}^{N} P_i B_{ij} P_j + \sum_{i=1}^{N} B_{0i} P_i + B_{00} \quad (MW) \tag{2.6}$$

Where B_{ij} is the (i-j)th element of the symmetric loss coefficient matrix(B); B_{0i} is the ith element of the loss coefficient vector and B_{00} is the constant loss coefficient.

2.5.2 Generation Capacity Constraints

The power output of each generator should be within minimum and maximum limits. The generating capacity constraint is shown in Eqn. (2.7)

$$P_i^{\min} \le P_i \le P_i^{\max} \tag{2.7}$$

where P_i^{min} and P_i^{max} are the minimum and the maximum outputs of the ith generator, respectively.

III. Grasshopper Optimization Algorithm (GOA)

GOA was developed by Seyedali Mirjalili in 2017 [15] inspiring the behavior of grasshopper swarms in nature for solving optimization problems. It has been adopted in this article to solve the PLED problems. Like evolutionary algorithms, GOA conducts search using a population of grasshopper. In GOA, grasshoppers change their positions by flying around in a multi-dimensional search space until an objective has been encountered, or until the computational limitations are exploded.

The most common insects found in the meadows and agricultural fields are Grasshoppers and it is herbivorous in nature. It is considered as a great hindrance to the farmers as it destroys the growing crops. Fig. 1 exhibits the life cycle of grasshopper. The swarming behavior of the grasshopper is procured to solve the optimization problems. The two main stage of grasshopper are nymph and adulthood. In the nymph stage the insect jump and move like a spinning cylinder and in the adulthood the grasshopper begins to swarm in air. In this way it travels from one place to another place for its basic needs.

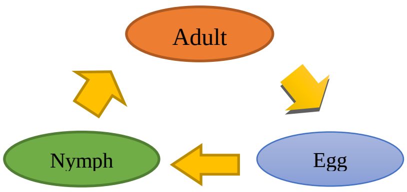

Fig. 1. Life cycle of grasshoppers

Food searching through swarming is the main objective of grasshopper in its living world. Intellectually grasshopper has two inviting habits. One is by exploring the food and another is by exploiting the food. The grasshopper move instinctively in exploration and move locally in exploitation. This technique of exploration and exploitation is main searching aspects in GOA. With this natural behavior one can design the mathematical model and which is recorded as follows.

The mathematical model employed as

$$X_i = S_i + G_i + A_i \tag{3.1}$$

where X_i is the position of the ith grasshopper, S_i denotes Social interaction, G_i denotes Gravity force of the ith grasshopper, A_i denotes Wind advection

$$S_i = \sum_{\substack{j=1 \\ j\neq i}}^{N} s\left(d_{ij}\right) \hat{d}_{ij} \tag{3.2}$$

where $\hat{d}_{ij}$ denotes distance between the ith and jth grasshopper, S function is the social forces, is calculated as follows

$$s(r) = f_i e^{\frac{-r}{l}} - e^{-r} \tag{3.3}$$

where f denotes intensity of attraction, denote attractive length scale.

One another important features in swarming behavior is the social attraction which involves attraction and repulsion of grasshopper, when they move together and apart in the searching space. The parameters l and f changes the comfort zone, attraction region, and repulsion region significantly.

The function S will explicitly segregate the space between repulsion region, comfort zone, and attraction region. This function returns the values close to zero with distances greater than 10.

$$G_i = -g\hat{e}_g \tag{3.4}$$

where g denotes gravitational constant, $\hat{e}_g$ denotes unity vector towards the centre of earth.

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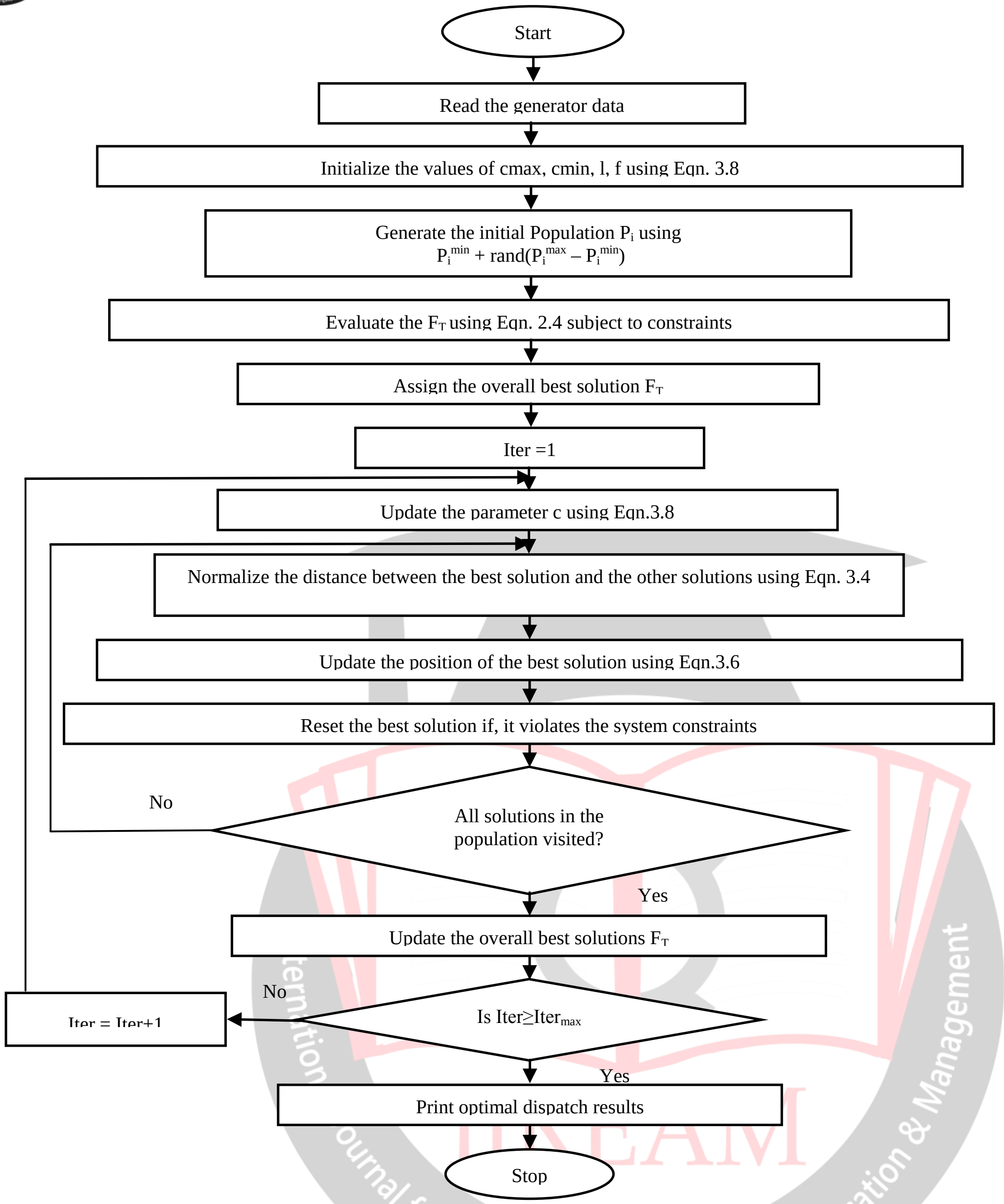

Fig. 2 Implementation of GOA for PLED problem

$$A_i = u\hat{e}_w \tag{3.5}$$

where u denotes constant drift, $\hat{e}_w$ denotes unity vector in the direction of wind.

$$X_i = \sum_{\substack{j=1 \\ j\neq i}}^{N} s\left(\left|x_j - x_i\right|\right)\frac{x_j - x_i}{d_{ij}} - g\hat{e}_g + u\hat{e}_w \tag{3.6}$$

Mathematically the model cannot be used directly because either the grasshoppers swiftly reach the comfort zone or the swarm does not move towards specified point. Further a modified version of this equation is implied as follows to solve the optimization problem.

$$X_i^d = c\left(\sum_{\substack{j=1 \\ j\neq i}}^{N} c\frac{ub_d - lb_d}{2} s\left(\left|x_j^d - x_i^d\right|\right)\frac{x_j - x_i}{di_j}\right) + \hat{T}_d \tag{3.7}$$

where ub_d denotes the upper bound in the D^{th} dimension, lb_d denotes the lower bound in the D^{th} dimension, $s(r) = f_i e^{\frac{-r}{l}} - e^{-r}, \hat{T}_d$ denotes the value of the D^{th} dimension in the target, c denotes a decreasing coefficient to shrink the comfort zone, repulsion zone and attraction zone.

The coefficient c reduces the comfort zone proportional to the number of iterations and is calculated as follows

$$c = c\max - l\frac{c\max - c\min}{L} \tag{3.8}$$

where cmax denotes maximum value, cmin denotes minimum value, l denotes current iteration, L denotes maximum number of iterations.

In GOA it is assumed that the fittest grasshopper during optimization is the target. This will assist GOA to save the

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most promising target in the search space during each iteration and requires grasshoppers to move towards it. This is done with the hope of finding a better and more accurate target as the best approximation for the real global optimum in the search space. The above discussions demonstrate the effectiveness of the GOA algorithm in finding the global optimum in a search space. The implementation of GOA algorithm for PLED problem is illustrated in Fig. 2.

IV. Numerical Case Studies and Discussion

4.1 Description of Test Systems

A simulation study is performed to validate the feasibility and effectiveness of the proposed GOA algorithm for the solution of PLED problem through the analysis of following three test cases.

Test Case 1: 6-unit system considering transmission loss.
Test Case 2: IEEE 30 bus system with valve point effects.
Test Case 3: 40-unit system with valve point effects.

The test cases 1and 2 considers the total transmission loss and the test case three excludes this consideration. Additionally, the emission equation for the first case is slightly different from Eqn. (2.2). The detailed data of above three test cases are extracted from [16], [18] and [3] respectively. The PLED problem is being analyzed by 100 iterations on a Core i5, 2.65GHz PC with 4 GB RAM. The Matlab 7.10 platform is used for the implementation of the proposed GOA code.

To achieve the optimal total cost, PLED problem is tested with eight different price penalty factors and their effect on cost minimization process is analyzed to fetch the most optimal 'h' parameter for all the above test case studies. Further, the performance of GOA is compared with various optimization algorithms.

4.1.1 Test Case 1: 6-unit system considering transmission loss.

This case studies a six unit thermal generating system considering transmission loss. The data related to the fuel cost coefficients, emission coefficients, loss coefficients, power generation limits of units are data taken from [16].

Table: 1 PLED results for the 6 - unit test system considering various price penalty factors.

P_D (MW)	Price penalty factor	P_1 (MW)	P_2 (MW)	P_3 (MW)	P_4 (MW)	P_5 (MW)	P_6 (MW)	F ($/h)	E (kg/h)	F_T ($/h)	P_L (MW)
150	Min - Max	77.44	27.73	15.00	10.00	10.00	12.00	372.38	182.75	451.8638	2.14
	Max - Max	77.98	27.19	15.00	10.00	10.00	12.00	372.40	180.79	738.9863	2.12
	Max- Min	50.00	28.99	21.62	10.00	28.76	12.00	404.12	192.23	1995.8359	1.38
	Min - min	50.00	35.19	21.34	16.87	14.68	13.45	391.73	188.42	714.4282	1.49
	Avg.1	51.38	36.32	19.60	16.48	14.25	13.54	389.61	187.26	745.5607	1.56
	Avg.2	50.00	26.47	18.41	20.59	19.50	16.49	397.99	188.55	1233.6498	1.55
	Average	50.00	30.03	19.11	19.30	17.49	15.56	398.39	186.75	989.3524	1.53
	Common	77.84	27.33	15.00	10.00	10.00	12.00	379.14	185.55	454.2685	2.24
200	Min - Max	113.32	40.4	18.68	10.00	10.00	12.00	517.85	255.97	619.8846	4.36
	Max - Max	100.67	38.03	18.92	17.21	14.67	14.25	526.25	240.68	994.4294	3.74
	Max- Min	50.00	32.98	32.51	34.99	29.99	21.71	596.31	256.17	2530.4984	2.17
	Min - min	50.00	48.05	28.11	29.65	24.34	22.24	579.56	253.66	981.4583	2.37
	Avg.1	58.07	48.55	25.50	26.98	22.31	21.18	566.45	246.13	1032.6821	2.57
	Avg.2	50.00	37.11	25.51	33.68	30.00	26.09	589.16	254.14	1611.9343	2.40
	Average	50.00	41.82	26.11	31.73	27.95	24.77	584.41	252.55	1330.3579	2.39
	Common	110.68	39.27	18.97	13.31	10.00	12.00	528.00	255.53	621.464	4.34
250	Min - Max	139.89	49.94	22.16	18.23	13.24	13.25	677.39	344.14	808.9897	6.60
	Max - Max	120.20	47.38	23.22	24.61	20.40	19.78	679.29	308.54	1269.8255	5.35
	Max- Min	51.00	57.34	40.25	35.00	30.00	40.00	802.40	343.61	3333.1927	3.60
	Min - min	52.36	65.13	37.09	35.00	30.00	34.13	790.62	344.52	1313.8534	3.64
	Avg.1	65.41	61.95	32.01	35.00	30.00	29.56	749.7	325.85	1383.1979	3.92
	Avg.2	50.08	58.78	39.82	35.00	30.00	40.00	802.09	345.82	2158.5759	3.69
	Average	53.02	59.88	36.74	35.00	30.00	39.13	793.4	340.85	1782.5083	3.73
	Common	131.63	47.22	22.30	22.88	15.92	16.22	688.94	330.75	822.8555	6.09

Table: 2 Comparison of PLED results for various price penalty factors of 6 unit system for a demand, P_D=250 MW

ED Solution	Min - Max	Max - Max	Max- Min	Min - Min	Avg.1	Avg.2	Average	Common
Fuel cost ($/h)	100 %	100.28%	118.96%	116.71%	110.67%	118.40%	117.12%	101.70%
Emission (kg/h)	100 %	89.65%	100.16%	100.11%	94.68%	100.48%	99.04%	96.10%
Total cost ($/h)	100 %	156.96%	413.26%	162.40%	170.97%	266.82%	220.33%	101.71%
Loss (MW)	100 %	81.061%	54.54%	55.15%	59.39%	55.90%	56.51%	92.27%

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The PLED for load demands of 150 MW, 200 MW, and 250 MW using GOA is carried out considering eight different penalty factors such as $h_{min\text{-}max}$, $h_{max\text{-}min}$, $h_{min\text{-}min}$, $h_{max\text{-}max}$, $h_{avg.1}$, $h_{avg.2}$, $h_{average}$ and h_{common} and the results are outlined in Table 1.

For each penalty factor, real power output of the generating units, fuel cost, emission, total cost and transmission losses are achieved using the proposed algorithm. In the PLED minimization process considering various penalty factors, the minimum total cost achieved for the demand of 250 MW is 808.9897 $/h while considering Min-Max penalty factor for blending the emission with the fuel cost. The corresponding fuel cost, emission and losses yielded by the GOA are 677.39 ($/h), 344.14 (kg/h) and 6.6 MW respectively. Similarly for other two demands, 150 MW and 200 MW, the minimum total cost of 451.8638 $/h and 619.8846 $/h is achieved while considering Min-Max penalty factor.

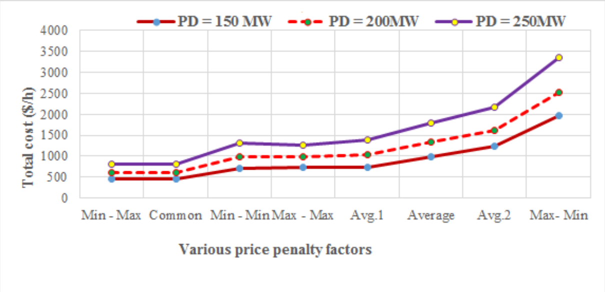

Fig. 3 Total cost versus various price penalty factors of 6 unit system

The Table 2 shows the simulation results of PLED problem considering various penalty factors taking the values obtained from Min-Max penalty factor for a basis of 100%. It is observed that the proposed GOA while considering Min-Max factor gives minimum optimum results in terms of Total cost and fuel cost. Further in PLED minimization problem, the minimized emission value is achieved while considering the Max-Max penalty factor. The Fig. 3 shows the total cost obtained considering various price penalty factors in three different load demands of 6 unit test system which clearly depicts the suitability of Min-Max price penalty factor while blending fuel cost and emission in PLED problem for achieving minimum total cost.

4.1.2 Test Case 2: IEEE 30 bus system with valve point effects.

In this case, IEEE 30 bus system considering transmission loss is studied. Fuel cost coefficients, emission coefficients, loss coefficients and generator constraints are obtained from [18].The PLED is carried out for a load demand of 2.834p.u.

The simulation results of the PLED with and without transmission loss, considering the 8 different penalty factors are listed in Table 3 for the demand of 2.834 p.u. Table 3 shows power output of the 6 generating units, fuel cost, emission value, total cost and losses. In the PLED minimization process considering transmission loss, the various penalty factors are analyzed and the minimum total cost of 606.3602 ($/h) is attained in the Min-Max penalty factor method. The corresponding fuel cost, emission and loss obtained by the GOA are 605.0985 ($/h), 0.2052 (kg/h) and 0.0256 MW respectively.

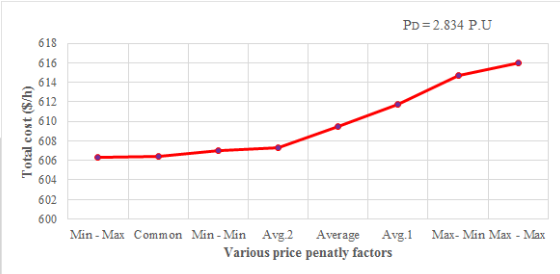

Fig. 4 Total cost versus various price penalty factors of IEEE 30 bus system with valve point with loss

In the PLED minimization process of IEEE 30 bus system neglecting the transmission loss the minimum total cost of 599.5977($/h) is attained in the Min-Max penalty factor. The corresponding fuel cost and emission generated by the GOA are 598.3376 ($/h) and 0.2059 (kg/h) respectively. The Table 4 express the simulation results of PLED with loss considering various penalty factors taking the values obtained from Min-Max penalty factor for a basis of 100%. It is observed that the proposed GOA while considering Min-Max factor gives minimum optimum results in terms of total cost and fuel cost. Further, the minimized emission value is achieved while considering the Max-Max penalty factor. The Fig. 4 illustrates the total cost obtained while considering various price penalty factors for the demand 2.834p.u.

4.1.3. Test Case 3: 40-unit system with valve point effects.

A Taiwan power system of 40-unit system with non-convex fuel cost function incorporating valve point loading effects is considered in this case study. The required load demand to be met by all the 40 generating units is 10,500 MW. Transmission loss has not been considered here. This case study has a larger & more complex solution space than all the previous case studies and so then suitability of GOA for large scale system over other renowned algorithms is revealed in this test case. The fuel cost coefficients, generators constraints, emission coefficients are adopted from [3].

Table: 3 PLED results for the IEEE 30 bus test system with valve point considering various price penalty factors for the demand of P_D=2.834p.u

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Price penalty factor	Min - Max	Max - Max	Max- Min	Min - Min	Avg.1	Avg.2	Average	Common
Considering transmission loss								
P_1 (p.u)	0.1238	0.1261	0.131	0.125	0.1234	0.1248	0.1237	0.1194
P_2 (p.u)	0.288	0.3028	0.2882	0.284	0.2963	0.2905	0.2905	0.2899
P_3 (p.u)	0.5791	0.577	0.5847	0.5916	0.5785	0.5842	0.5825	0.579
P_4 (p.u)	0.9899	0.9811	0.9809	0.991	0.9863	0.9676	0.9888	0.9927
P_5 (p.u)	0.5269	0.5191	0.5291	0.5153	0.5238	0.5247	0.5218	0.526
P_6 (p.u)	0.3519	0.3536	0.3454	0.3525	0.3514	0.3676	0.3524	0.3527
F ($/h)	605.0985	605.5972	606.0265	606.0082	606.0158	606.0682	606.0028	606.0018
E (kg/h)	0.2052	0.2043	0.2046	0.2052	0.2047	0.2045	0.2049	0.2052
Loss (p.u)	0.0256	0.0257	0.0253	0.0254	0.0258	0.0254	0.0256	0.0257
F_T ($/h)	606.3602	615.9905	614.7428	607.0287	611.7391	607.3245	609.5013	606.368
Without transmission loss								
P_1 (p.u)	0.1104	0.1234	0.1222	0.1279	0.1127	0.1121	0.114	0.1106
P_2 (p.u)	0.3022	0.3143	0.3079	0.303	0.3087	0.3069	0.3042	0.2997
P_3 (p.u)	0.5238	0.5082	0.5181	0.5172	0.5225	0.5251	0.5241	0.5345
P_4 (p.u)	1.0149	0.9764	0.9773	1.0035	1.0088	1.0097	1.0087	1.0154
P_5 (p.u)	0.5229	0.5354	0.5311	0.5208	0.5213	0.52	0.5228	0.514
P_6 (p.u)	0.3598	0.3764	0.3773	0.3615	0.3601	0.3602	0.3602	0.3597
F ($/h)	598.3376	600.2938	600.26	600.1583	600.1256	600.1213	600.1191	600.1199
E (kg/h)	0.2059	0.2035	0.2037	0.2048	0.2054	0.2055	0.2055	0.206
F_T ($/h)	599.5977	610.6316	608.938	601.175	605.8469	605.1214	605.4836	600.654

Table: 4 Comparison of PLED results for various price penalty factors of IEEE 30 bus system with loss

ED Solution	Min - Max	Max - Max	Max- Min	Min - Min	Avg.1	Avg.2	Average	Common
Fuel cost ($/h)	100%	100.08%	100.15%	100.15%	100.15%	100.16%	100.15%	100.14%
Emission (kg/h)	100%	99.56%	99.71%	100%	99.77%	99.66%	99.85%	100%
Total cost ($/h)	100%	101.59%	101.14%	100.11%	100.89%	100.16%	100.52%	100.01%
Loss (p.u)	100%	100.39%	98.83%	99.22%	100.78%	99.22%	100%	100.39%

The simulation results of the PLED for the considered 8 penalty factors such as Min-Max, Max-Min, Min-Min, Max-Max, Average, Common, Avg.1, and Avg.2 are shown in Table 5. In the PLED minimization process considering various penalty factors, the minimum total cost of 150586.043 $/h is attained while considering Min-Max penalty factor for blending the emission with the fuel cost. The corresponding fuel cost and emission yielded by the GOA are 128674.52($/h) and 228551.13(kg/h).

The Table 6 shows the simulation results of PLED problem considering various penalty factors taking the values obtained from min-max penalty factor for a basis of 100%. It is observed that the proposed GOA while considering Min-Max factor gives minimum optimum results in terms of total cost and fuel cost. Further in PLED minimization problem, the minimized emission value is achieved while considering the Max-Max penalty factor. The Fig. 5 shows the variation of total cost for various price penalty factors for the load demand of 10,500 MW.

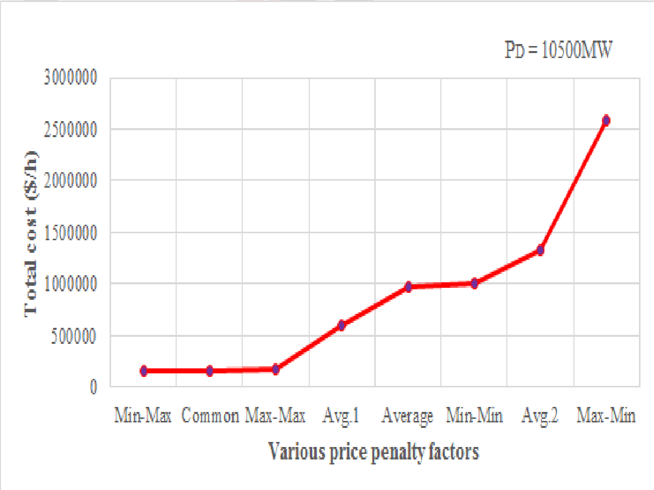

Fig. 5 Total cost versus various price penalty factors of 40 unit system with valve point effects

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Table: 5 PLED results of 40-unit test system with valve point effects considering various price penalty factors (P_D=10500MW)

h factor	Min-Max	Max-Max	Max-Min	Min-Min	Avg.1	Avg.2	Average	Common
P_1(MW)	103.25	98.78	114	114	101.54	114	110.73	110.8
P_2(MW)	99.11	102.19	102.09	114	114	114	114	105.13
P_3(MW)	112.89	109.63	120	120	120	120	120	115.6
P_4(MW)	161.85	166.98	163.19	171.09	190	173.67	171.55	167.38
P_5(MW)	91.73	84.03	97	97	97	97	93.22	91.54
P_6(MW)	121.21	121.09	140	140	140	132.73	135.32	140
P_7(MW)	258.18	259.68	229.61	264.13	254.05	254.23	220.88	260.27
P_8(MW)	262.59	274.89	300	268.74	261.54	300	258.88	293.37
P_9(MW)	278	259.96	300	300	273.72	300	300	285
P_{10}(MW)	204.44	235.11	300	300	299.96	300	300	271.74
P_{11}(MW)	297.53	304.13	235.45	220.46	226.7	206.55	253.08	245.47
P_{12}(MW)	306.05	300.6	221.45	258.4	251.72	224.8	235.08	236.16
P_{13}(MW)	407.11	395.5	414.65	400.54	393.3	364.34	380.57	374.94
P_{14}(MW)	398.17	393.14	400.87	442.73	430.72	454.72	362.94	440.1
P_{15}(MW)	394.28	394.28	465.91	403.42	456.24	442.64	435.16	447.98
P_{16}(MW)	410.08	421.35	425.76	429.82	434.17	431.06	466.49	393.22
P_{17}(MW)	390.97	437.29	457.55	421.77	407.96	420.49	421.32	405.26
P_{18}(MW)	459.43	420.11	413.55	409.16	440.67	432.69	416.77	429.74
P_{19}(MW)	493.99	476.24	472.36	446.01	438.21	459.03	462.97	467.75
P_{20}(MW)	472.16	484.36	456.75	437.97	437.83	473	468.1	455.72
P_{21}(MW)	448.18	482.54	461.48	460.17	457.1	457.9	465.36	475.34
P_{22}(MW)	458.79	477.7	462.02	447.56	451.08	468.96	477.45	473.36
P_{23}(MW)	457.03	492.81	462.84	451.91	446.18	468.38	471.94	510.64
P_{24}(MW)	501.02	478.26	467.9	451.46	441.19	469.05	476.76	487.09
P_{25}(MW)	468	468.3	459.96	446.21	464.46	465.61	466.17	483.81
P_{26}(MW)	502.13	468.17	460.51	450.35	452.71	466.23	464.2	478.82
P_{27}(MW)	16.27	17.14	21.7	84.96	73.77	40.45	28.56	19.4
P_{28}(MW)	16.27	17.14	28.15	63.88	62.13	21.63	28.83	20.63
P_{29}(MW)	16.27	17.14	23.92	101.5	54.25	21.49	35.27	19.42
P_{30}(MW)	91.41	88.91	97	97	97	93.3	97	89.78
P_{31}(MW)	158.82	160.87	125.77	118.29	123.92	126.64	132.54	126.35
P_{32}(MW)	167.92	160.78	132.61	120.55	128.79	127.2	149.28	154.98
P_{33}(MW)	166.09	153.67	138.03	118.86	116.07	137.05	132.8	139.77
P_{34}(MW)	183.18	177.64	188.32	200	200	200	200	165.73
P_{35}(MW)	186.34	176.22	200	200	200	200	200	175.67
P_{36}(MW)	168.5	181.02	175.26	185.55	200	200	179.5	177.13
P_{37}(MW)	95.23	92.34	98.34	103.76	110	46.92	110	96.13
P_{38}(MW)	80.84	90.78	99.29	87.49	110	108.24	90.77	110
P_{39}(MW)	97.26	93.86	105.76	110	110	90.54	104.43	93.22
P_{40}(MW)	497.44	465.36	460.95	441.26	432	475.47	462.06	465.57
F ($/h)	128674.52	129598.66	131285.95	139184.45	135071.74	131876.6	131668.25	129444.03
E (kg/h)	228551.13	224405.29	243534.3	241372.51	233094.04	236296.68	234645.21	242708.97
F_T ($/h)	150586.043	180455.25	2485928.43	1010960.57	601581.87	1313121	967750.18	152136.45

Table: 6 Comparison of PLED results for various price penalty factors of 40 unit system

ED Solution	Min - Max	Max - Max	Max - Min	Min - Min	Avg.1	Avg.2	Average	Common
Fuel cost ($/h)	100 %	101.29%	102.61%	108.78%	105.56%	103.38%	102.78%	101.04%
Emission (kg/h)	100 %	91.77%	94.60%	98.71%	95.32%	93.30%	93.64%	106.24%
Total cost ($/h)	100 %	120.14%	1654.97%	673.03%	400.5%	888.73%	664.61%	101.46%

Table 7: Comparison of simulation results for three test systems

	Min -Max	Max - Max	Max- Min	Min - Min	Avg.1	Avg.2	Average	Common
Test system - 1: 6 unit system with loss								
GOA	808.989	1269.826	3343.26	1313.853	1383.198	2158.576	1782.508	822.856
WOA[17]	810.291	1272.589	3349.473	1315.221	-	-	1783.397	946.869
MF [16]	823.809	1304.869	3347.61	1317.20	-	-	-	-
Test system - 2: IEEE 30 bus system with transmission loss considering valve point effects								
GOA	606.360	615.991	614.743	607.029	611.739	607.325	609.501	607.268
WOA[18]	606.54	616.21	633.687	614.246	-	-	618.532	616.542
Test system - 2: IEEE 30 bus system neglecting transmission loss considering valve point effects								
GOA	599.598	610.632	608.938	601.175	605.847	605.121	605.484	600.654
WOA[18]	599.758	610.717	621.281	603.979	-	-	616.280	602.458
Test system - 3: 40 unit system with effect of valve point								
GOA	150586.04	180455.24	2583167.62	1010960.57	601581.869	1334953.721	998309.108	152403.844
WOA	150701.77	180572.24	2485928.43	1019375.31	-	-	998508.306	152503.844

4.2. Comparative Study of GOA

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To show the superiority of the proposed GOA over other renowned algorithms a comparative study has been carried out for all the cases and presented in Table 7. In case study 1, among eight price penalty factors the minimum total cost is obtained while considering Min-Max price penalty for blending fuel cost and emission. The total cost is relatively less when compared with Moth Flame (MF) [16] and WOA [17] method. In case 2, the PLED is carried out considering 8 different price penalty factors and the results obtained proves that the Min-Max penalty factor fetches minimum total cost of 606.360 $/h considering loss and 599.598 $/h without loss, which is much less than the cost reported by WOA [18]. Further in large scale 40 unit system with valve point effects, the total cost found is also more economical than the cost fetched by WOA while using Min-Max price penalty factor.

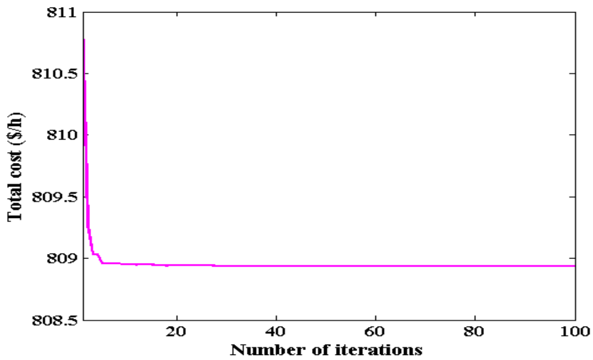

Fig. 6 Convergence characteristics of 6 unit system

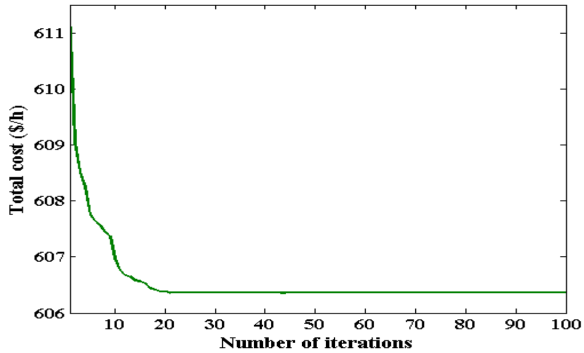

Fig. 7 Convergence characteristics of IEEE 30 bus system with valve point effects

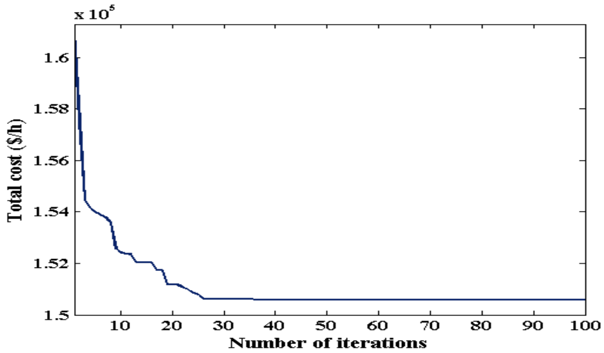

Fig. 8 Convergence characteristics of 40 unit system with valve point effects

From Table 7 it is explicit that in all the test cases, the minimum total cost is acquired while using Min-Max price penalty factor among the chosen eight different price penalty factors. Further, the minimum total cost obtained is proven to be best when compared to reported results in recent literature.

4.3. *Convergence Characteristics*

The convergence profiles of the best total cost yielded in 100 iterations by the proposed GOA considering Min-Max penalty factor for all the aforesaid cases are illustrated in Fig. 6, Fig. 7 and Fig. 8. The convergence characteristic of all the test cases possesses better convergence characteristics which confirm the higher convergence rate of the algorithm.

4.4. *Robustness Test*

Randomness is the inherent property of the stochastic simulation techniques and hence the performance of those algorithms is judged out of a number of trials.

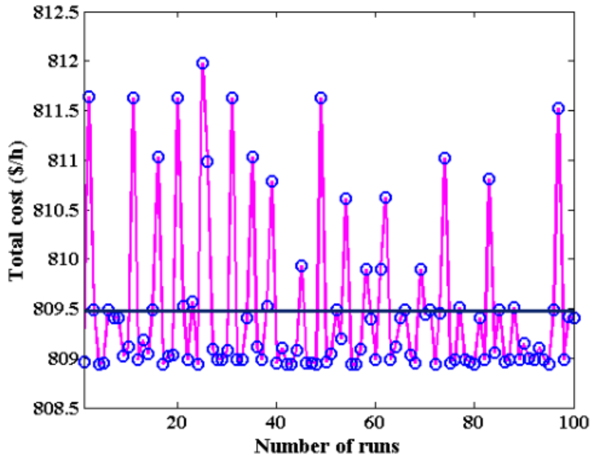

Fig. 9 Robustness characteristics of 6 unit system

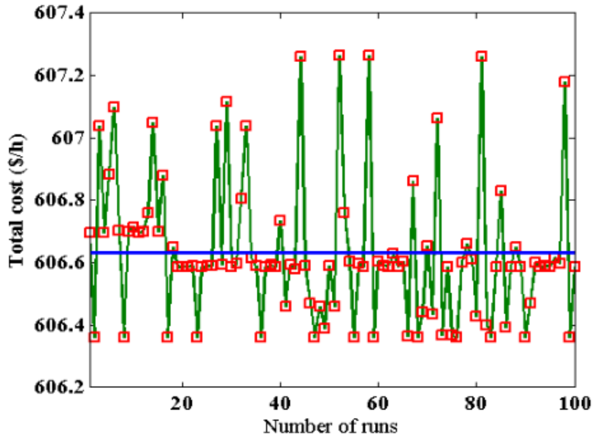

Fig. 10 Robustness characteristics of IEEE 30 bus system with valve point effects

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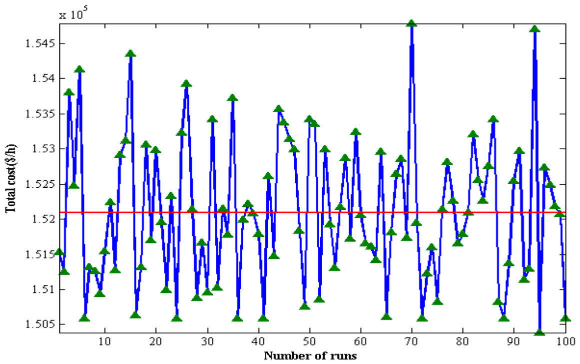

Fig. 11 Robustness characteristics of 40 unit system with valve point effects

The 100 independent trials with different initial population have been carried out to test the reliability of the GOA algorithm for the 6 unit system, IEEE 30 bus system and Taiwan 40 unit system.

To inspect the solutions obtained in test case 1, 2 and 3, the variations of the total cost for 100 independent runs of the algorithm are illustrated in Fig. 9, Fig. 10 and Fig. 11 respectively, which clearly proves the excellent success rate by yielding very small deviation in the evaluation values in all the aforesaid three cases. The best, worst and mean cost of 100 independent trials is listed in Table 8. Solution iteration is the iteration at which the optimal solution is achieved in the evolution of iterations. The solution iteration for all the cases are relatively very small, which shows the fast convergence characteristics of GOA based PLED problem. Comparing the best solution, solution iteration and success rate, it is inferred that GOA is a most powerful algorithm in PLED solution methods.

Table 8: Performance analysis of GOA for 3 different test systems

S. no		Test Case 1	Test Case 2	Test Case 3
1.	Demand	250 MW	2.834 P.U	10500 MW
2.	Optimal h parameter	Min-Max	Min-Max	Min-Max
3.	Solution iteration	16	21	24
4.	Best cost ($/h)	808.9363	606.3602	150586.042
5.	Worst cost ($/h)	811.9833	607.2633	154026.464
6.	Mean cost ($/h)	809.4818	606.6328	152089.974
7.	Success rate	76	73	67

V. Conclusion

This paper has employed Grasshopper Optimization Algorithm for solving PLED problem using eight different penalty factors and their effect is analyzed on three different test systems having non-smooth cost function. The obtained results imply that the "Max-Max" price penalty factor is good to yield minimum emission for quadratic functions compared to other penalty factors. Further the total cost and fuel cost is less when using "Min-Max" penalty factor compared to other penalty factors. The above implications suggest the suitable choice of penalty factor not only reduces the total cost but also keeps a balance between cost and pollutant emissions. From the results, it is found that the proposed GOA method is capable of finding a desirable best solution than the recent optimization algorithms.

Appendix

Various price penalty factors models

1. Max/Max Price penalty factor is

$$h_{Max/Maxi} = \frac{F_i(P_i^{\max})}{E_i(P_i^{\max})}\left(\frac{\$}{kg}\right)$$

2. Min/Max Price penalty factor is

$$h_{Min/Maxi} = \frac{F_i(P_i^{\min})}{E_i(P_i^{\max})}\left(\frac{\$}{kg}\right)$$

3. Max/Min Price penalty factor is

$$h_{Max/Mini} = \frac{F_i(P_i^{\max})}{E_i(P_i^{\min})}\left(\frac{\$}{kg}\right)$$

4. Min/Min Price penalty factor is

$$h_{Min/Mini} = \frac{F_i(P_i^{\min})}{E_i(P_i^{\min})}\left(\frac{\$}{kg}\right)$$

5. Average Price penalty factor is

$$h_{Avg\,i} = \frac{\left(h_{Max/Max\ i}\right)+\left(h_{Min/Min\ i}\right)+\left(h_{Max/Min\ i}\right)+\left(h_{Min/Max\ i}\right)}{4}\left(\frac{\$}{kg}\right)$$

6. Common Price penalty factor is

$$h_{Commoni} = \frac{\sum_{i=1}^{N} h_{Avg\,i}}{n}\left(\frac{\$}{kg}\right)$$

7. Avg.1 Price penalty factor is

$$h_{Avg\,1i} = \frac{\left(h_{Max/Maxi}\right)+\left(h_{Min/Mini}\right)}{2}\left(\frac{\$}{kg}\right)$$

8. Avg.2 Price penalty factor is

$$h_{Avg\,2i} = \frac{\left(h_{Max/Mini}\right)+\left(h_{Min/Maxi}\right)}{2}\left(\frac{\$}{kg}\right)$$

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