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Combined heat and power dispatch with renewable energy sources using a new metaheuristic algorithm

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To our dear professors who we will have the honor of discussing this research withLet them, thank You all

Thank You all

DEDICATION

I dedicate this humble work to...

To every great soul that longs for wisdom and knowledge, he said to it: My Lord, the Great, the Great.

** and save them the wing of humiliation out of mercy, and say, Lord, have mercy on them as they raised me when I was young **

For the one who instilled hope in me, to you, the one with a good heart, my beloved mother.

To the miserable dear in order to provide the means of life for me and my brothers, my father, may allah protect him.

The most precious thing I own and the branches of the noble tree, my dear brothers and my sisters "Maroua. DJamal. Safa. Aissa. Raed. Sajid. Soudjoud".

And my friends who supported me from near or far, to the companion of time, the coincidence of a lifetime" Meriam Achour".

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DEDICATION

To the one who encouraged me to persevere all my life, to the most prominent man in my life (my dear father)

To whom I rise, and upon whom I rest, to the giving heart (my beloved mother)

To those who made an effort to help me and were the best support (brothers and sisters)

To my family, to my friends, to my colleagues, each in his name

To everyone who contributed even with a letter in my academic life, and I prayed for good

To all of those previously mentioned: I dedicate this humble work, which I ask allah

*AHMED-SALMI

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LIST OF SYMBOLS AND ABBREVIATIONS

Abbreviations

CCS	carbon capture system
P2G	Power -to-gas
CHP	combined heat and power
IES	integrated energy system
EPHD	Economic Power and Heat Dispatch
CES	Cogénération Energy Systems
CSO	civilized swarm optimization
ELD	Economic load dispatch
CHPED	Combined Heat and Power Economic Dispatch
CHPEED	Combined Heat and Power Economic Emission Dispatch
CEED	Combined Economic Emission Dispatch
ASO	Atom search optimization
EO	Equilibrium optimizer
LA	Lichtenberg optimization algorithm
MAO	Mexican Axolotl Variable Optimization
DELD	Dynamic Economic load dispatch
DEnD	Dynamice Emission dispatch
DEED	Dynamic Economic Emission dispatch

Symbols

$\boldsymbol{\alpha_i ; b_i ; c_i}$	positive fuel cost coefficients of generator i respectively
$\boldsymbol{e_i ; f_i}$	fuel cost coefficients representing valve point effects of generator i, respectively
$\boldsymbol{P_{i,t}^{TU}}$	power generated from thermal unit i at time t

List of symbols and abbreviations

$\boldsymbol{P_{i,\min}^{TU}}$	minimum capacity of thermal unit i
$\boldsymbol{c_i\left(P_{i,t}^{TU}\right)}$	fuel cost of producing $P_{i,t}^{TU}$
$\boldsymbol{\alpha i, \beta i, \gamma i, \eta i}$	emission function coefficients of generator i
$\boldsymbol{E_i^{TU}}$	total emissions to produce $P_{i,t}^{TU}$
$\boldsymbol{a_k; b_k; c_k; e_k;}$ $\boldsymbol{f_k}$	fuel cost coefficients of CHP generator l respectively
$\boldsymbol{C_k^{CHP}\left(P_{k,t}^{CHP}, H_{k,t}^{CHP}\right)}$	fuel cost for CHP generator l to produce heat and power
$\boldsymbol{\alpha_k; \beta_k}$	emission function coefficients
$\boldsymbol{\alpha_1; \beta_1}$	emissions coefficients of heat units l
$\boldsymbol{F(C)}$	total fuel cost of generations ð$=$h$Þ
$\boldsymbol{E}$	total amount of emissions ð$Kg = h$
$\boldsymbol{F1, F2, F3}$	total operation costs ($\$$), emissions (lbs) and heat (MWt), respectively.

الملخص

يعد القلق بشـأن انبعاثات الغازات الملوثة من أكثر المشـكلات تحديًا في أنظمة الطاقة الكهربائية والتي تفرض ضـغوطًا مفرطة على مختلف المشـاركين في أسـواق الكهرباء. إن الدافع نحو دمج مصـادر الطاقة المتجددة وتطبيق الحرارة والطاقة المشـتركة في محطات الطاقة الحرارية التي يتم تطبيقها من قبل مشـغلي النظام له العديد من المزايا ، مثل تقليل انبعاثات غازات الاحتباس الحراري. يقترح هذا العمل نموذجًا كهربائيًا متعدد الأهداف لدمج التوليد الحراري مع مراعاة توزيع الحرارة والطاقة. تشـمل الوظائف الموضـوعية للإطار متعدد الأهداف المقترح التقليل المتزامن للتكلفة والانبعاثات بالإضافة إلى تعظيم توليد الحرارة. تم تطوير خوارزمية تحسين الكشف عن مجريات الأمور المستوحاة من الفيزياء ، تحسين البحث الذري (ASO) ، لمعالجة مجموعة متنوعة من مشـاكل التحسين. يقوم ASO رياضيًا بنمذجة ومحاكاة الحركة الذرية في الطبيعة ، حيث تتفاعل الذرات من خلال قوى التفاعل التي تسـببها إمكانات ليونارد جونز وتحد من القوى بواسـطة إمكانات طول الرابطة. الخوارزمية المقترحة بسيطة وسهلة التنفيذ. يتم اختبار ASO على مجموعة من الوظائف القياسية للتحقق من صحتها ، من الناحيتين النوعية والكمية ، ثم يتم تطبيقها بنجاح على مشـكلة تقدير المعلمات الهيدروجيولوجية. توضح النتائج أن ASO يتفوق على بعض الخوارزميات الكلاسـيكية والناشـئة حديثًا في الأدبيات وهو حل واعد لمشاكل الهندسة في العالم الحقيقي.

الكلمات المفتاحية: التوليد المشترك للحرارة والطاقة ؛ عدم اليقين في طاقة الرياح؛تحسين البحث عن ذرة الوحدة الكهروضوئية

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ABSTRACT

Concern about emissions of polluting gases is one of the most challenging problems in electric power systems which put excessive pressure on the various participants in the electricity markets. Prompting towards incorporation of renewable energy sources and application of combined heat and energy in thermal power plants that are applied by system operators has many advantages, such as reducing greenhouse gas emissions. This work proposes a multi-objective electrical model for The Combined Heat and Power Economic dispatch (CHPED) and Combined Heat and Power Economic Emission Dispatch (CHPEED) Combined Economic-Emission Dispatch (CEED) with integration of renewable energy source RES. The objective functions of the proposed multi-objective framework include simultaneous minimization of cost and emissions as well as maximization of heat generation. This problems are solved by using a physics-inspired Metaheuristic optimization algorithm, Atomic Search Optimization (ASO), was developed to address a variety of optimization problems. ASO mathematically models and simulates atomic motion in nature, in which atoms interact through interaction forces caused by the Leonard-Jones potential and limiting forces by bond length potentials. The constrains considered in this work is limited to power & head balance constraints, minimum & maximum limits of electrical generators, CHP units and heat generator units. However, this proposed ASO can be extended to solve CHPEED problem in the presence of renewable energy sources, for cost benefit analysis with related constraints.

Keywords: Cogeneration; Combined Heat and Power; wind power uncertainty; PV unit; atom search optimization.

RESUME

Les unités de production combinée de chaleur et d'électricité (CHP) sont populaires en raison de leur capacité à produire simultanément de l'énergie électrique et thermique, à fournir des avantages économiques et à réduire les émissions environnementales.
La présente recherche est étudié et modélisé le problème de dispatching économique combiné de chaleur et d'électricité (CHPED) et le dispatching économique combiné de chaleur et d'électricité (CHPEED) Le dispatching économique combiné d'émissions (CEED) avec intégration des ressources des énergies renouvelable (Photovoltaïque et éolienne) été construit et illustré.

Un algorithme d'optimisation méta-heuristique inspiré de la physique « Atomic Search Optimization » (ASO), a été développé pour résoudre le problème CHPEED. L'ASO modélise et simule mathématiquement le mouvement atomique dans la nature.

On peut constater que l'ASO proposé surpasse mieux pour fournir une bonne qualité de solution de compromis et s'avère être une meilleure méthode d'optimisation pour résoudre le problème des contraintes dures. Cette étude se limite à résoudre le problème multi-objectif de distribution économique des émissions de chaleur et d'électricité (CHPEED) avec l'intégration de RES et ASO consistant en des générateurs thermiques, des unités de cogénération et des unités de chaleur avec des contraintes limitées. Les contraintes considérées dans ce travail se limitent aux contraintes d'équilibre de puissance et de tête, aux limites minimales et maximales des générateurs électriques, des unités de cogénération et des unités de génération de chaleur. Cependant, cet ASO proposé peut être étendu pour résoudre le problème CHPEED en présence de sources d'énergie renouvelables, pour une analyse coûts-avantages avec les contraintes associées.

Mots clés : Cogénération Production combinée de chaleur et d'électricité, l'énergie éolienne, Optimisation de la recherche d'atomes, PV.

GENERAL INTRODUCTIO

GENERAL INTRODUCTION

Combined Heat and Power (CHP) units are being popular because of its capability to simultaneously produce electrical and thermal energy, provide economic benefits and reduce environmental emission.

This CHP system has higher efficiency in the range of 80 to 85% with respect to thermal plants and boilers units. Because of this, the overall efficiency is of the system increased by utilizing the waste heat generated. Keeping in view all the benefits of CHP system, it is important to properly schedule these CHP units. This is due to the optimal scheduling of CHP system with thermal and boiler units are demanding, called as Combined Heat and Power Economic dispatch (CHPED) and Combined Heat and Power Economic Emission Dispatch (CHPEED). The objective of the CHPED problem is to minimize the cost, whereas the objective of CHPEED problem is to minimize the cost as well as simultaneously minimize the emission, respectively. These two objectives are conflicting in nature and when non convexity, nonlinearity and other practical constraints are considered then this multi-objective problem becomes complex. Therefore, for solving this complex problem with various related constraint, a power optimization technique is needed which is capable to provide best compromise solution [1].

However, recently renewable energy sources have been used widely in power system due to their cost and environmental benefits in comparison with the conventional generators. Whereas, the energy storage resources used in the power system include batteries, flywheels and pumped storage. In addition, the power system connected different types of loads such as agriculture, industrial, commercial and residential.

In last years, many different methods have been implemented to solve CHPEED problem with incorporation of renewable energy source RES. According to the Atomic Research Improvement (ASO) model, this brings the economic benefits contributed by multiple renewable energy generation sources and provides practical guidance for its reliable operation.

The present research is organized in the following sequence: The Combined Heat and Power Economic dispatch (CHPED) and Combined Heat and Power Economic Emission Dispatch (CHPEED) Combined Economic-Emission Dispatch (CEED) with integration of renewable energy source RES model was built and illustrated.

Secondly, the metaheuristic algorithms are demonstrated. Third. Furthermore, numerical examples and analysis of simulation results are presented. Finally, some conclusions and possible future work are given.

CHAPTRE I

I-1-INTRODUCTION

With the increasing energy crisis and environmental issues, combined heat and power (CHP) generation, also called cogeneration, has attracted ever-growing concerns in recent years and it has also proven to be an effective way for addressing these challenges [2]. In traditional thermal power plants, a lot of thermal energy is wasted without conversion into electricity during power generation. Even in terms of the most advanced combined cycle power plant, the energy conversion efficiency is by far only in the range from 50% to 60% [3]. The central and most fundamental principle of cogeneration is to improve the total energy conversion efficiency by recovering and reutilizing the waste heats in the energy conversion process, and thereby the fuel utilization efficiency of CHP units can achieve 90% and above. At the same time, compared with traditional power-only units and heat-only units, CHP units can save 10%~40% of the cost of generation, which means that less fuels are needed to produce equal amounts of heat and electricity. Furthermore, recent research suggest that CHP units are considered as an environmentally friendly system, since the greenhouse gas emissions can be reduced by nearly 13%~18% by making use of cogenerations .7CHP economic dispatch (CHPED) has been recognized as an important means to achieve optimal operation for CHP systems, since it is able to significantly reduce the unit energy consumption of coal-fired power plants through optimizing the allocation of thermal and electrical load instructions. In general, the primary goal of CHPED is to minimize of the economic costs like fuel costs. With growing concerns about air pollution and other serious environmental issues, the conventional CHPED has already been unable to meet the diversified demands for energy conservation and environmental protection. For this purpose, CHP economic emission dispatch (CHPEED) has been a hot topic since it can take into account environmental protection while pursuing economic benefits. Essentially, a CHPEED problem is to find the optimal heat-power operating point with reasonable fuel costs and emissions, while satisfying a set of various equality and inequality constraints related to heat/electricity demands. However, CHPEED with incorporation of Renewable Energy Source (RES) poses challenges in terms of computational complexity due to its inherent non-linear, non-convex, and non-smooth characteristic, which is hard to solve directly [4].

I-2-MATHEMATICAL MODEL AND PROBLEM FORMULATION

First for a single objective CHP Economic Dispatch, then a single objective CHP Emission Dispatch problem and, finally, combining them into a CHPEED problem with incorporation of Renewable Energy Source (RES).

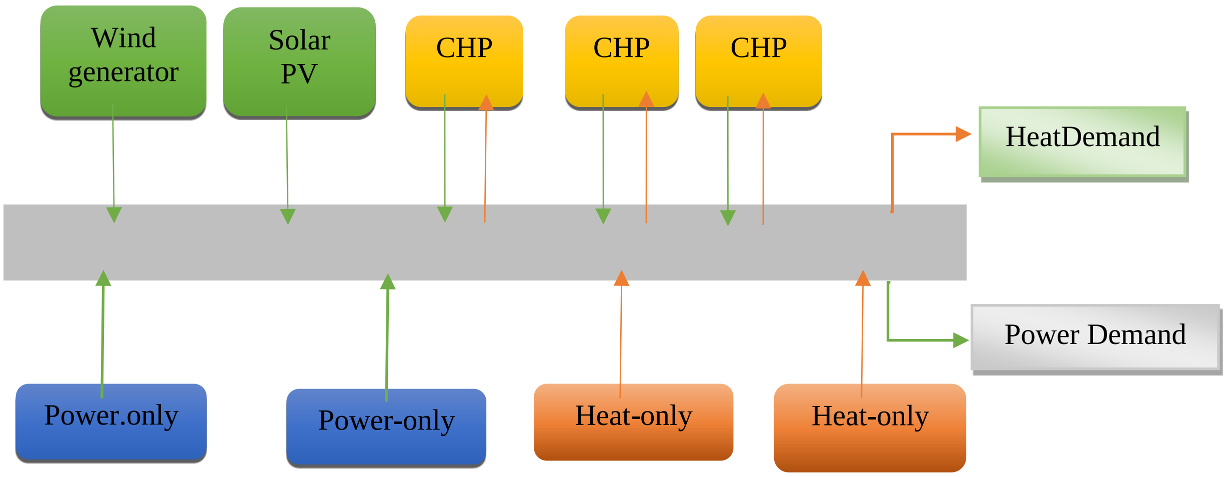

Figure-I-1.The CHEED system.

I-3 Combined Heat Power Economic Load Dispatch

The Dynamic Combined Heat Power Economic Load Dispatch (CHPELD) speculates the objective of sharing the load of a power system among the various generation units in such a way as to minimize the fuel costs of the conventional generators satisfying the various constraints and fulfilling the load demand of the system[6].

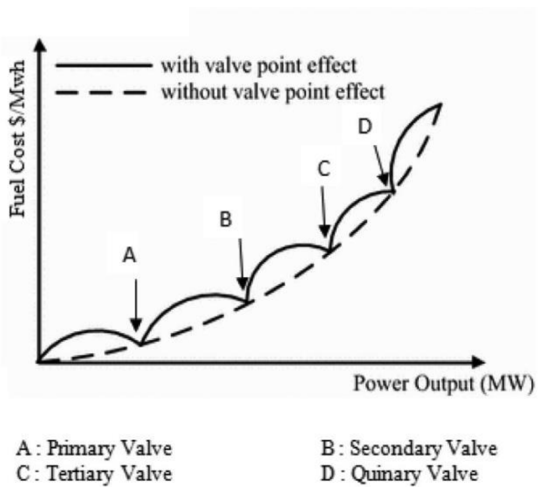

Figure.I-2.Valve point loading effect.

- The fuel costs of the conventional generators which are a non-convexly nominal with valve point loading effect can be mathematically expressed as:

$$F(P_i) = \sum_{t=1}^{24} \sum_{i=1}^{g} \left\{ u_i P_i^2(t) + v_i P_i(t) + w_i + e_i \sin\left(f_i\left(P_{i,min} - P_i(t)\right)\right)\right\} \quad \text{(I-1)}$$

Where:

'g' is the number of conventional generators in the system, $P_i$is the output power of the generation unit i and $u_i, v_i$and $w_i$are thecost coefficients of the i^{th} generate$F(P)$ is in $\$/hr$ [6].

$P_{i,min}$: Represents the minimum capacity of thermal unit$i$;

- The CHP unit produces both power and heat. Thus, the fuel cost is a product of both outputs. Thus is usually representation as a convex cost function given as:

$$C_k^{CHP}\left(P_{k,t}^{CHP}, H_{k,t}^{CHP}\right) = a_k + b_k P_{k,t}^{CHP} + c_k\left(P_{k,t}^{CHP}\right)^2 + d_k H_{k,t}^{CHP} + e_k\left(H_{k,t}^{CHP}\right)^2 + f_k(P_{k,t}^{CHP}, H_{k,t}^{CHP}) \quad \text{(I-2)}$$

Where:

a_k, b_k, c_k, d_k, e_k and f_k are the cost coefficients of the kth CHP unit.

- These units produce only heat and the fuel cost function is depicted by:

$$C_l^H\left(H_{l,t}^H\right) = a_l + b_l H_{l,t}^H + c_l\left(P_{l,t}^H\right)^2 \quad \text{(I-3)}$$

Where:

a_l, b_l and $c_l$are the cost coefficients of the lth heat only units.

I-4-Dynamic Combined Heat Power Emission Dispatch Dispatch

The Dynamic Combined Heat Power Emission Dispatch Dispatch minimizes the release of these harmful gases in the atmosphere.

- The emission dispatch function for thermal units is also a non-convex polynomial by valve point effects can be written as:

$$E_i^{TU}\left(P_{i,t}^{TU}\right) = \sum_{t=1}^{24} \sum_{i=1}^{g} \left\{\alpha_i + \beta_i P_{i,t}^{TU} + \gamma_i\left(P_{i,t}^{TU}\right)^2 + \eta_i exp(\delta_i P_{i,t}^{TU})\right\} \quad \text{(I-4)}$$

Where:

The unit of $E(P_t^{TU})$ is kg/hr[6].

α_i ,β_i ,γ_i , η_i and δ_i are the emission function coefficients of generator$i$ and $Ei(P_{i,t}^{TU})$ represents the total emission to produce $P_{i,t}^{TU}$.

- The total CHP unit emission is solely a function of the power generated and is given as:

$$E_k^{CHP}\left(P_{k,t}^{CHP}\right) = (\alpha_k + \beta_k)P_{k,t}^{CHP} \qquad \textit{(I-5)}$$

- The emission function only heat similarly is given by[5]:

$$H_l^{H}\left(H_{l,t}^{H}\right) = (\alpha_l + \beta_l)H_{l,t}^{H} \qquad \textit{(I-6)}$$

I-5-Combined Economic-Emission Dispatch (CEED)

As discussed above it can be seen that the economic load dispatch and emission dispatch are complete two different objectives. The former deals with the minimization of the fuel costs of the conventional generators and the latter minimizes the emission of harmful and toxic pollutants in the atmosphere. Hence it is necessary to arrive at a compromised solution which can attain both minimized fuel cost emitting least amount of pollutants in the atmosphere. This is done by creating multi-objective problem combining (1) and (2) with the help of parameter called ‘‘Penalty factor”. The penalty factor acts as an intermediate to reform the emission criteria into an equivalent fuel cost for the emission. Mathematically, the price penalty factor or simply penalty factor is a multiplication factor associated with each of the emission coefficients which transforms two differently aimed single objective function to a CEED problem. Needless to say, lower the value of the penalty factor, lesser the value of the CEED problem. The various types of penalty factors are formulated and calculated in later section of this paper.

The multi-objective economic-emission dispatch problem can thus be mathematically stated as:

$$C(P) = \sum_{t=1}^{24} \sum_{i=1}^{g} \left[\left\{a_i P_i^2(t) + b_i P_i(t) + c_i + e_i \sin\left(f_i\left(P_{i,min} - P_i(t)\right)\right)\right\} + h_i \times \{\alpha_i P_i^2(t) + \beta_i P_i(t) + \gamma_i + \eta_i \exp(\delta_i P_i)\,(t)\}\right] \qquad \textit{(I-7)}$$

Where:

h_i is the penalty factor of the i^{th} generating unit. The units of$C(P)$ is $\$/hr$ and $h_i$is$\$/kg$[6].

I-6-Combined Economic-Emission-Heat Dispatch

The CHPEED problem has two conflicting objectives. Obtaining the optimal heat generation and power generation schedule from a list of available power generating unit, CHP units, and heat only units is the foremost objective. The secondary objective is to minimize air pollution from these units. The optimal schedule obtained should reduce the total production cost and must also satisfy the heat demand, the power demand of the system, several operational and physical constraints. Operating the system with minimum fuel cost results in increased emission, and it is not feasible to only minimize the emission from the plants since it increases fuel cost. These two conflicting objectives must be simultaneously minimized, taking into account the FOR of the cogeneration units. This section describes the mathematical formulation of the CHPEED problem. The objective of this paper is to find the diverse set of PO solutions of the CHPEED problem, which minimize the two conflicting objectives and also to satisfy the constraints [6].

I-7-Renewable Energy source Integration

Furthermore, both the fuel costs and the pollutants emission can be reduced by the inclusion of available renewable resources for the generation of power.

The renewable energy resources are clean sources of energy which neither incurs any fuel cost nor does it emits harmful toxic gases in the atmosphere. Although these renewable energy sources do include some installation or maintenance cost whose cost function can be calculated as below [7]:

$$F(P_{RES}) = P_{RES}(AC.I^P + G^E) \quad \text{(I-8)}$$

Where P_{RES} the output power of the renewable energy resources is, AC is the annuitization coefficient, I^P is the ratio of investment cost to established power in $\$/kW$ and G^E is the operational and maintenance cost in$\$/kW$. Annuitization coefficient can be calculated with the formula:

$$AC = \frac{r}{1-(1+r)^{-N}} \quad \text{(I-9)}$$

Where $r$the interest is scale and N is the investment duration in years.

This work on an islanded micro grid uses wind farms and photovoltaic (PV) system as the available RES for the minimization of fuel and emission costs and also to increase the efficiency and maintain an uninterrupted power supply. The operational and maintenance cost for the wind farm and PV system is $0.016\$/kW$invested at 9% interest scale for 20 years. The ratio of investment cost to establish power is $5000\$/kW$for PV system and

$1400\$/kW$ for wind farm. So the cost function of PV becomes $F_{PV} = 547.7483 * P_{PV}$ and the cost function of wind is $F_{WIND} = 153.3810 * P_{WIND}$.

Hence with the inclusion of RES the economic load dispatch function becomes:

$$DELD(P_i(t)) = \sum_{t=1}^{24} \sum_{i=1}^{g} \left\{ a_i P_i^2(t) + b_i P_i(t) + c_i + e_i \sin\left(f_i\left(P_{i,min} - P_i(t)\right)\right)\right\} + 547.7483 * P(t)_{PV} + 153.3810 * P(t)_{\text{WIND}} \quad \textit{(I-10)}$$

And the inclusion of RES in the emission dispatch function turns it into:

$$DED\ (P_i(t)) = \sum_{t=1}^{24} \sum_{i=1}^{g} \{\alpha_i P_i^2(t) + \beta_i P_i(t) + \gamma_i + \eta_i \exp(\delta_i P_i)\ (t)\} + 547.7483 * P(t)_{PV} + 153.3810 * P(t)_{WIND} \quad \textit{(I-11)}$$

The multi-objective dynamic combined economic-emission dispatch problem (DEED) with PV and wind energy can thus be mathematically stated as:

$$DCEED\left(P_i(t)\right) = DELD\left(P_i(t)\right) + DED(P_i(t)) \quad \textit{(I-12)}$$

The above objective functions (I-10) and (I-11) are subject to constraints such as:

i. Generation constraints: The power generated by the conventional generators as well as the RES must lie between a maximum and minimum limit. Mathematically:

$$P_{i,\,min} \leqslant P_i \leqslant P_{i,\,max}$$
$$P_{RES,min} \leqslant P_{RES} \leqslant P_{RES,max} \quad \textit{(I-13)}$$

ii. Power supply-demand balance constraint: the power generated at any instant of time by all the conventional generators and the RES should satisfy the total desired load of the system. This can be mathematically stated as:

$$P_{LOAD} = P_i + P_{RES}, i = 1,2,3, \dots g \quad \textit{(I-14)}$$

This work focuses on minimizing (I-13) and (I-14) separately using various optimization techniques and a comparative study among the techniques as well as the minimized costs of DELD and DEED. [6]

I-8-CONSTRAINTS OF CHPEED PROBLEM:

I-8-1Constraints for Power equilibrium

The production of real power for each generating unit as well as co-generation unit is required to be equal which is expressed as below:

$$\sum_{j=1}^{N_m} \boldsymbol{P}_{tij} + \sum_{j=1}^{N_{ci}} \boldsymbol{P}_{cij} = \boldsymbol{P}_{Di} + \sum_{k,k\neq i} \boldsymbol{T}_{ik} i \in \boldsymbol{N}_A \quad \textit{(I-15)}$$

Represents the transmission of real power interconnection between the two sections i and k. T_{ik} is taken as positive if energy transfers from section i to section k while T_{ik} is negative if the flow is in the reverse way.

capacity constraints Transmission of power through inter connection, i.e. T from section x to must be in the limit of interconnection real power flow range.

$$-T_{xy}^{max} \leq T_{xy} \leq T_{xy}^{max} \qquad (I\text{-}16)$$

Here T_{ik}^{max} denotes the active power flow limit from region i to region k whereas -T_{ik}^{max} is the same from region k to region i.

Restricted effective region of coal fired generating units:

The feasible functional part of j^{th}generation unit in area i with minimal obtainable region can be taken as:

$$\begin{aligned} &P_{tij}^{min} \leq P_{tij} \leq P_{tij,1}^{l} \\ &P_{tij,m-1}^{u} \leq P_{tij} \leq P_{tij,m}^{l}, m = 2,3,\ldots,n_{ij} \\ &P_{tij,n_{ij}}^{u} \leq P_{tij} \leq P_{tij}^{max} \end{aligned} \qquad (I\text{-}17)$$

Here 'm' denotes the magnitude of minimal obtainable regionP_{tijm}^{u} is the highest limit of $(m-1)^{th}$ prohibited workable area of j^{th} thermal generator in region$i$. Denotes lowest limit of m^{th} prohibited workable area of j^{th}thermal unit in region i. Hence the total number of prohibit ted workable areas of j^{th}thermal generator in region $i$is n^{ij}[8].

I-8-2Constraints for heat equilibrium

$$\sum_{j=1}^{N_{di}} H_{cij} + \sum_{j=1}^{N_{hi}} H_{hij} = H_{Di} + \sum_{k,k\neq i} H_{ik} i \in N_A \qquad (I\text{-}18)$$

Here H_{ik} represents the transfer of temperature through interconnection from section $i$to k .

H_{ik} is positive if temperature transfers from section i to k and $H_{ik}$is negative for the reverse way transfer.

I-8-3-Constraints for tie line heat capacity

Temperature flow through interconnection H_{ik} from area i to k must lie within the tie line heat flow limits.

$$-H_{ik}^{max} \leq H_{ik} \leq H_{ik}^{max} \qquad (I\text{-}19)$$

Here H_{ik}^{max} denotes the capability of heat flow between section i to k and -H_{ik}^{max}represents the capability of heat transfer between region k to i [8].

I-9-HEAT POWER (CHP)

I-9-1constraints

I-9-1-1-power balance equality constraint

The power balance equality constraint given by (I-20), balances the power produced by N_p power only units and N_c CHP units with the sum of the total power demand Pdin the system and the total transmission power loss Pl in the system.$Pl$is the transmission power loss represented by the B-loss coefficients, as shown in (I-21) [9].

$$h_1(x) = \sum_{i=1}^{Np} P_i + \sum_{i=1}^{Nc} O_i - Pd - Pl = 0 \qquad (I\text{-}20)$$

The calculation of active power loss Pl for the power network integrated with CHP plants is by using B-loss coefficients given by:

$$Pl = \sum_{i=1}^{Np} \sum_{j=1}^{Np} P_i B_{ij} P_j + \sum_{i=1}^{Np} \sum_{j=1}^{Nc} P_i B_{ij} O_j + \sum_{i=1}^{Nc} \sum_{j=1}^{Nc} O_i B_{ij} O_j + \sum_{i=1}^{Np} B_{0i} P_i + \sum_{i=1}^{Nc} B_{0i} O_i + B_{00} \qquad (I\text{-}21)$$

B_{ij} is the transmission loss coefficients of the transmission lines connecting the buses i and j

I-9-1-2- heat balance equality constraint

The heat balance equality constraint given by (I-22) balances the heat produced by N_c CHP units and Nh heat only units with the total heat demand Hd of the system.

$$h_2(x) = \sum_{i=1}^{Nc} H_i + \sum_{i=1}^{Nh} T_i - Hd = 0 \qquad (I\text{-}22)$$

I-9-1-3-Inequality constraint of CHP units

The modelling of the interdependency between the power and heat produced by the cogeneration units as inequality constraints is given by (I-23). These inequality constraints are satisfied by the constraint handling mechanism proposed in section III.

$$\begin{aligned} g_1(x) &= P_i - P_i^{max}(H_i) \le 0; i \in 1,2,\cdots,Nc \\ g_2(x) &= P_i^{min}(H_i) - P_i \le 0; i \in 1,2,\cdots,Nc \\ g_3(x) &= H_i - H_i^{max}(P_i) \le 0; i \in 1,2,\cdots,Nc \\ g_4(x) &= H_i^{min}(P_i) - H_i \le 0; i \in 1,2,\cdots,Nc \end{aligned} \qquad (I\text{-}23)$$

I-9-1-4-Bounds of variables P and H

$$\begin{aligned} P_i^{min} \le P_i \le P_i^{max}; i \in 1,2,\cdots,Np \\ H_i^{min} \le H_i \le H_i^{max}; i \in 1,2,\cdots,Nh \end{aligned} \qquad (I\text{-}24)$$

The power generated by each unit i should lie within limits given by the minimum limit $P_i^{\min}$ and maximum limit$P_i^{\max}$, as shown in (I-24). The heat output of the i^{th} heat only unit should lie within its limits given by the minimum limit $H_i^{\min}$ and maximum limit H_i^{max} , as shown in (I-24). The next section describes how to fix the bounds for CHP units [10].

I-10-CONCLUSION

In this chapter treat the formulation of Combined Heat and Power Economic dispatch (CHPED) and Combined Heat and Power Economic Emission Dispatch (CHPEED) with incorporation of renewable energy source (RES). The objective of the CHPED problem is to minimize the cost, whereas the objective of CHPEED problem is to minimize the cost as well as simultaneously minimize the emission, respectively. These two objectives are conflicting in nature and when non convexity, non-linearity and other practical constraints are considered then this multi-objective problem becomes complex. Therefore, for solving this complex problem with various related constraint, a power optimization technique is needed which is capable to provide best compromise solution.

CHAPTRE II

II-1-INTRODUCTION

In recent years, several methods of metaheuristic optimization have been proposed in the scientific and engineering fields. In this study, a physics-inspired metaheuristic optimization algorithm is developed, Metaheuristic optimization algorithms are increasingly popular in intelligent computing and widely applied to a large number of real-world engineering problems. Their popularity derives from the following aspects. Firstly, all of these optimization techniques have some fundamental theories and mathematical models proven to be reasonable, which come from the real world and are inspired by all kinds of physical phenomena or biological behaviors. The theories are simple and easy to understand. Secondly, these optimization algorithms can be considered as a black box[12]. It means that given a set of inputs, these algorithms can easily provide a set of outputs for any optimization problem. They are very flexible and versatile since one can change the structures and parameters of algorithms to obtain better solutions. Thirdly, metaheuristic algorithms can effectively avoid local optima, which is very valuable for addressing engineering problems as many engineering problems are considered as multimodal functions. In addition, one can develop their variants by absorbing the merits of other algorithms to improve the accuracy of solutions within a reasonable time. Fourthly, metaheuristic optimization algorithms can tackle different types of problems including, but not limited to, single-objective and multi-objective problems.

II-2-BASIC CONCEPTS

II-2-1Heuristic

A heuristic algorithm is one that is designed to solve a problem in a faster and more efficient fashion than traditional methods by sacrificing optimality, accuracy, precision, or completeness for speed. Heuristic algorithms often times used to solve NP-complete problems, a class of decision problems. In these problems, there is no known efficient way to find a solution quickly and accurately although solutions can be verified when given. Heuristics can produce a solution individually or be used to provide a good baseline and are supplemented with optimization algorithms. Heuristic algorithms are most often employed when approximate solutions are sufficient and exact solutions are necessarily computationally expensive [11].

II-2-2Metaheuristics

Compared to optimization algorithms and iterative methods, meta heuristics do not guarantee that a globally optimal solution can be found on some class of problems. Many meta heuristics implement some form of stochastic optimization, so that the solution found is dependent on the set of random variables generated. In combinatorial optimization, by searching over a large set of feasible solutions, meta heuristics can often find good solutions with less computational effort than optimization algorithms, iterative methods, or simple heuristics. As such, they are useful approaches for optimization problems. Several books and survey papers have been published on the subject [12].

Most literature on Meta heuristics is experimental in nature, describing empirical results based on computer experiments with the algorithms. But some formal theoretical results are also available, often on convergence and the possibility of finding the global optimum. Many meta heuristic methods have been published with claims of novelty and practical efficacy [13]. While the field also features high-quality research, many of the publications have been of poor quality; flaws include vagueness, lack of conceptual elaboration, poor experiments, and ignorance of previous literature.

II-3-Lichtenberg optimization algorithm (LA)

Optimization can be defined as a process of searching for the best solution within a set of possible solutions (Alexandrino et al., 2019). Optimization objectives can be diverse, such as minimizing energy consumption and costs, and maximizing profit, production[13], performance and efficiency. But real-world optimization problems almost always deal with functions where the analytical solution is impractical because the function may not be

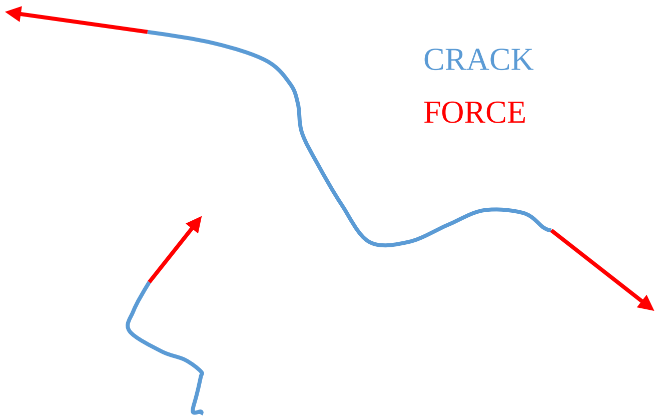

Figure-II-1. Crack propagation model in thin plates

continuous, may have no gradient, may be multimodal and not linear and may have many variables and constraints, becoming a very complex problem. To solve them [13], numerical tools such as metaheuristic optimization algorithms become very important.

The LA is a new hybrid metaheuristic that has trajectory and population algorithm behaviors in its iteration process. Inspired by the physical phenomenal of thunderstorms and more precisely radial intra-cloud lightning, where the Lichtenberg figures and the power of fractals Can be applied [13], the LA has great potential for exploring the search space and enhancing solutions already found. It also presented results with excellent precision in test functions found in the literature.

The algorithm creates Lichtenberg using the diffusion-limited aggregation theory (developed by Niemeyer et al., 1984) in the search space with random scales and rotations at each iteration. Points of this structure are selected for evaluation of the objective function, and the lowest value point of each iteration is the trigger point of the next figure. Thus, the population is distributed according to the size of the figure, which can reduce or enlarge the search space in approaches of almost 0%– 100% of its size, giving the algorithm great exploitability and enhancement of its solutions. Figure 2 illustrates some iterations of algorithm execution in optimizing two-dimensional functions. Also, this same figure can be plotted with an identical but smaller one (ranging from 0% to 100% of its size) to increase the refinement of the search. Thus, we have local (red) and global (blue) figures. This optimizer has seven parameters [14]:

1. Figure creation radius (Rc);
2. number of particles used in its construction (Np);
3. adhesion coefficient (S) that determines the density of the cluster;
4. Local search refinement (ref);
5. small print or not to improve result refinement (ref);
6. construction or not of a new Lichtenberg figure at each iteration (M), remembering that even if it is the same figure, it is always printed in different rotations; and
7. scale and the number of iterations (N_{iter}).

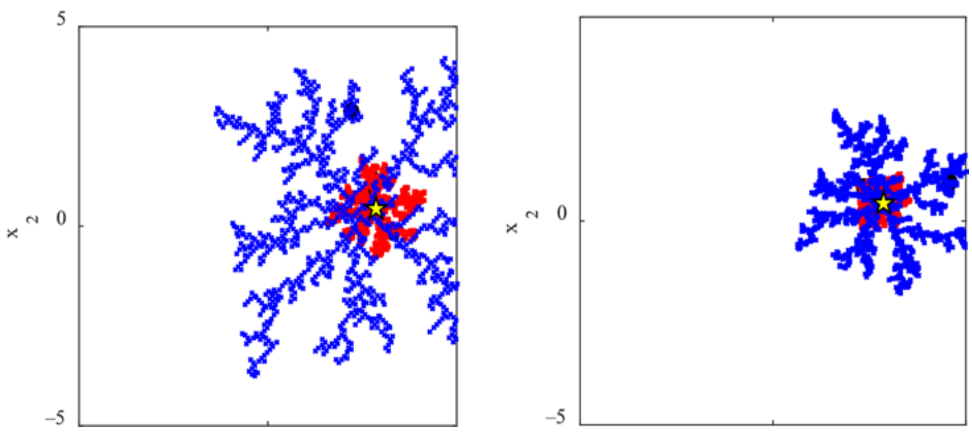

Figure-II-2. Local figure with 30% of global size figure and some iterations

II-3-1Methodology and numerical modeling

The SHM methodology applied in this work consists of the use of two computational programs [14]:

Finite element method (FEM) modeling;

Numerical calculations and optimizer execution, where the LA works.

In the direct problem modeling using finite element analysis, a numerical structure is constructed considering the same parameters of the damaged (cracked) plate. The LA is designed and formulated to generate variables in this model that indicate or the presence, or lack, of the crack. If the crack exists, its direction of propagation and intensity are identified.

II-3-2-Lichtenberg optimization algorithm

Algorithm 1 – Main
Set objective function and search space –, upper and lower bounds
Set number of iteration and population– N_{iter}, POP (common to all optimizers)
Set Refinement and Parameter for changing the $LF - Ref, M$(LA routine parameters)
Set LF Parameters – R_c, N_p, S
if $\boldsymbol{M} = 2$, load LF, end if
if $\boldsymbol{M} = 0$,Greate a LF, end if
While ($iter$<N_{iter}) do
if $\boldsymbol{M} = 1$,Greate a LF, end if
$X_{trigger}$= search space center (trigger point of the firstLF)
if$ref = 0$
Apply random scale and rotation
Initialize random population through $LF, X_i(i = 1, 2, \dots, 0.4 * Pop)$
else
Copy $LF$to create a second $LF$of size $ref * LF(local)$
Apply the same random scale and rotation to both
Initialize global random population throughLF, $Xglobal_i$ $(i = 1, 2, \dots, 0.4 * Pop)$
Initialize local random population throughLF, $Xlocal_j$ $(i = 1, 2, \dots, 0.6 * Pop)$
X_i=$Xglobal_i$+$Xlocal_j$
end if
Calculate the fitness of each X_i
X_{best} = the lowest X_i value found
$X_{trigger} = X_{best}$
$Iter = iter + 1$
Algorithm 2– Creation of *LF*
Great an matrix of R_c - sized zeros
Place a unitary particle in its center
While($I < N_p$)do
Randomly place a unitary particle in the matrix
if the plotted unitary particle t is next to another unitary particle
if $rand < S$
This new unitary particle is placed in the matrix
$i = i + 1$
else
The plotted unitary particle is eliminated
end if
end if
if the cluster of unitary particle reachesR_c
The simulation is finished
end if
end while
X = coordinates of all unitary for Cartesian space in the size of the search space.

Figure-II-3. Pseudo code of the Lichtenberg algorithm[13].

II-4-ATOM SEARCH OPTIMIZATION(ASO)

II-4-1-Basic molecular dynamics

ASO is inspired by basic molecular dynamics. From the micro perspective, a definition of "matter", based on its physical and chemical structure, is thus: matter is made up of molecules. A molecule is the smallest unit of a chemical compound, and it exhibits the same chemical properties as those of that specific compound. A molecule is composed of atoms held together by covalent bonds that vary greatly in terms of complexity and size. So all substances are made of atoms and all atoms have mass and volume. Fig. 4shows the composition of water molecules, each of which is made up of two hydrogen atoms and one oxygen atom, jointly held by two covalent bonds. For an

atomic system, all the atoms interact and are in constant motion, whether in the state of gas, liquid or solid. They are very complex in terms of their structure and microscopic interactions. Because an atomic system is typically composed of numerous atoms, it is analytically impossible to determine their properties that are affected by factors such as temperature, pressure, and so on. With the development of computer technology, molecular dynamics (MD) has rapidly developed in recent years. It circumvents this problem with the use of a computer simulation method to examine the physical movements of atoms and molecules.

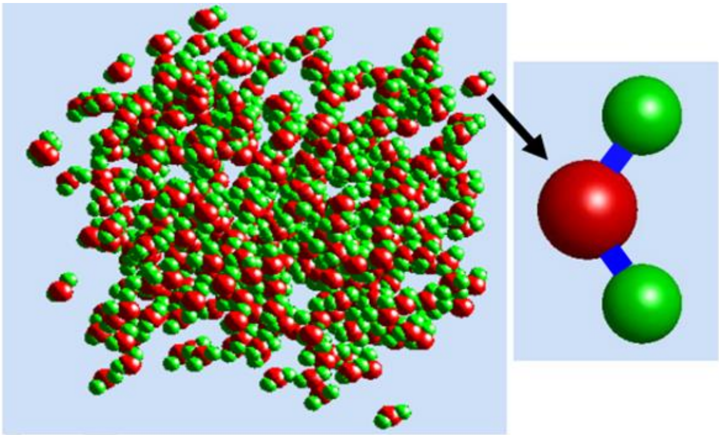

Figure-II-4. Water molecules and their composition

MD was initially conceived in the field of theoretical physics but its use has been extended to computational chemistry, materials science, and biology. Atomic motion follows the classical mechanics. The interaction force among the atoms has two principal characteristics in an atom system. The first is the repulsion to compression, which repels at a close range of crowdedness. The second is the attraction that binds atoms together such as in solid and liquid states. Atoms attract each other over a further range of separation. The potential energy of atoms can well account for these two characteristics, and there are a wide variety of pair-wise formulas in the literature used to express the potential energy [15]. The Lennard-Jones (L-J) potential, initially proposed for liquid, is a simple mathematical model that approximates the interaction force between a pair of atoms. The L-J potential between the ith and the jth atoms is commonly expressed as

$$U(r_{ij}) = 4\varepsilon\left[\left(\frac{\sigma}{r_{ij}}\right)^{12} - \left(\frac{\sigma}{r_{ij}}\right)^{6}\right] \qquad (II\text{-}1)$$

Where: ε is the depth of the potential well that represents the strength of the interaction, σ is the length scale that denotes the collision diameter, $r_{ij} = x_j - x_i$ and $x_i = (x_{i1}, x_{i2}, x_{i3})$ is the position of the $i$thatom in a 3-D space, so the Euclidian distance between the ith and j_th atoms is:

$$r_{ij} = \|x_j - x_i\| = \sqrt{(x_{i1} - x_{j1})^2 + (x_{i2} - x_{j2})^2 + (x_{i3} - x_{j3})^2} \qquad (II\text{-}2)$$

In equation (1), $(\sigma/r)^{12}$ and $(\sigma/r)^{6}$ represent the repulsive and attractive interactions, respectively. The L-Jpotential curve is illustrated in Fig. 4, in which the attraction and repulsion regions are shown. In there pulsion region, the repulsion of the atoms rapidly increases as the

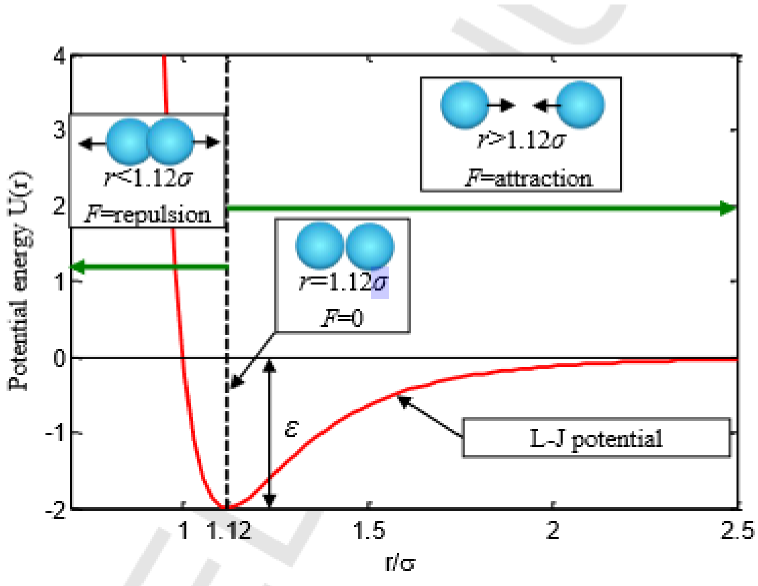

Figure-II-5. L-J potentiel curve

distance between two atoms decreases.

In the attraction region, as the distance between two atoms increases towards a certain further separation, the attraction gradually drops to zero. When two atoms reach an equilibration distance (r=1.12σ), their minimum bonding potential energy is reached. At this point, the interaction force. between the atoms is equal to zero.

Having specified the potential energy function, the interaction force that the j^{th} atom exerts on the i^{th}atom is

$$F_{ij} = -\nabla U(r_{ij}) = \frac{24\varepsilon}{\sigma^2}\left[2\left(\frac{\sigma}{r_{ij}}\right)^{14} - \left(\frac{\sigma}{r_{ij}}\right)^{8}\right] r_{ij} \qquad \textit{(II-3)}$$

So the total interaction force exerted on the ith *atom is simply given as*

$$F_i = \sum_{\substack{j=1 \\ j\neq i}}^{N} F_{ij} \qquad \textit{(II-4)}$$

Where N is the total number of atoms in an atomic system.

To study more complex molecules, a molecular dynamics method with geometric constraints is proposed in, in which a combination of geometrical constraints and internal motion of atoms is considered. In polyatomic molecules, the highest-frequency internal vibrations are usually decoupled from rotational and translational motions. Thus, a certain number of rigid bonds are introduced in the skeleton of the molecules. Consider the case in which the structure of amolecule is subject to one or more geometries[15]. A constraint needs to be introduced to fix the distance between any two atoms with covalent bonds, and the mode can be expressed as:

$$|x_i - x_i|^2 = b_{ij}^2 \qquad \textit{(II-5)}$$

Whereb_{ij} is the fixed bond length between the ith and jth atoms. Suppose that there are a total of $l$constraints influencing a particular molecule, and if the kth constraint for a bond works between the $ikth$and $jkth$ atoms, then the kth constraint is

$$\theta_k = |x_{ik} - x_{ki}|^2 - b_{ij}^2 = 0, k = 1,2,\cdots,l \qquad \textit{(II-6)}$$

Hence, the constraint force Gi from the stretch of a covalent bond between two atoms acted on the ithatom can be written as

$$G_i = \sum_{k=1}^{l} \lambda_k \nabla_i \theta_k = -2\sum_{k=1}^{l} \lambda_k (x_{ik} - x_{jk}) \qquad \textit{(II-7)}$$

Whereλ_k is the Lagrangian multiplier associated withθ_k . Hence, the motion equation of atoms with theconstraint can be modified as

$$F_i + G_i = m_i a_i \qquad \textit{(II-8)}$$

For equation (II-8), the forces exerted on the atoms include not only all non-constraint interaction forces among molecules, but also the constraint force(s) within each molecule, thus embodying the essence of atomic motion.

In summary, basic molecular dynamics describes the movement principles of atoms, including the characteristics of the potential function, the motion mode of atoms with a non-constraint interaction force, and a geometric constraint force. Despite the simplicity of the analytical model, the physics-based study of molecular dynamics can be used to determine thermodynamic properties of the system, and indeed presents opportunities for many theoretical studies and practical applications [16-17].

II-4-2-Atom search optimization

In this section, a novel optimization algorithm named atom search optimization (ASO) that is inspired by molecular dynamics is introduced. In ASO, the position of each atom within the search space represents a solution measured by its mass, with a better solution indicating a heavier mass [15], and vice versa. All atoms in the population will attract or repel each other according to the distance among them, encouraging the

lighter atoms to move towards the heavier ones. Heavier atoms have smaller acceleration, which makes them seek intensively for better solutions in local spaces. Lighter atoms have greater acceleration, which makes them search extensively to find new promising regions in the entire search space.

The general unconstrained optimization problems can be defined as

$$Minimize\ f(x), x = (x^1, \cdots, x^D) \qquad \textit{(II-9)}$$

For

$$Lb \leq x \leq Ub, Lb = [lb^1, \cdots, lb^D], Ub = [ub^1, \cdots, ub^D] \qquad \textit{(II-10)}$$

Where: $x^{d} (d = 1, \ldots, D)$ is the dth component of the search space, lb^D and ub^D are the dth components ofthe lower and upper limits, respectively, and D is the dimension of the search space.

In order to solve this unconstrained optimization, suppose an atom population with N atoms. The position of the ith atom is expressed as

$$x_i = [x_i^1, \cdots, x_i^D], i = 1, \cdots, N \qquad \textit{(II-11)}$$

Where: $x_i^d (d = 1, \ldots, D)$ is the dth position component of the ith atom in a D-dimension space. In the initial iterations of ASO, each atom interacts with others by the attraction or the repulsion among them, and there pulsion can avoid the over-concentration of atoms and the premature convergence of the algorithm, thus enhancing the exploration ability in the entire search space. As iterations pass, the repulsion gradually weakens and the attraction gradually strengthens, which signifies that the exploration decreases and the exploitation increases. In the final iterations, each atom interacts with others just by the attraction, which ensures that the algorithm has a good exploitation capability.

II-4-2-1-Mathematical representation of interaction force

The interaction force resulting from the L-J potential is the priming power of atomic motion. The interaction force acted on the ith atom from the jth atom at the tth iteration in equation (3) can be rewritten as

$$F_{ij}(t) = \frac{24\varepsilon(t)}{\sigma(t)}\left[2\left(\frac{\sigma(t)}{r_{ij}(t)}\right)^{13} - \left(\frac{\sigma(t)}{r_{ij}(t)}\right)^{7}\right]\frac{r_{ij}(t)}{r_{ij}^{d}(t)} \qquad (II\text{-}12)$$

and

$$F'_{ij}(t) = \frac{24\varepsilon(t)}{\sigma(t)}\left[2\left(\frac{\sigma(t)}{r_{ij}(t)}\right)^{13} - \left(\frac{\sigma(t)}{r_{ij}(t)}\right)^{7}\right] \qquad (II\text{-}13)$$

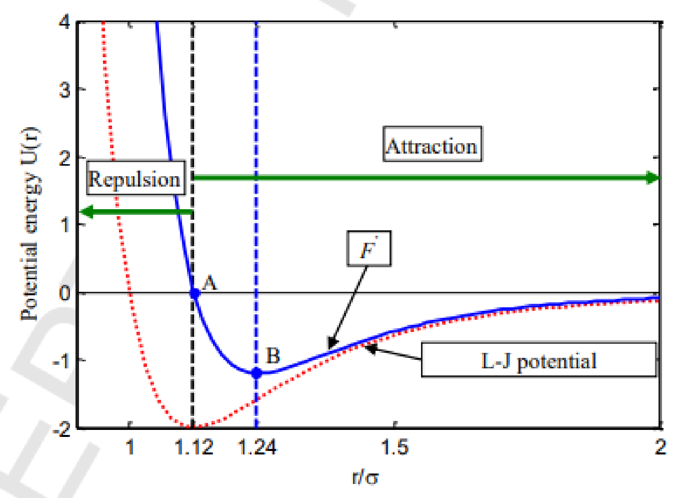

Figure-II-6. Force curve of atoms.

The force curve of atoms is shown in Fig. 6. As shown, the atoms keep a relative distance, varying in a certain range all the time from the repulsion or attraction, and the change amplitude of the repulsion relative to the equilibration distance ($r = 1.12\sigma$) is much greater than that of the attraction. However, this model cannot be used directly to handle optimization problems, mainly because ASO needs to obtain more positive attraction and less negative repulsion as iterations increase, as shown in fig.6, equation (13) cannot satisfy this point. Accordingly, a revised version of this equation is developed, as follows, to solve optimization problems

$$F'_{ij}(t) = -\eta(t)\left[2\left(h_{ij}(t)\right)^{13} - \left(h_{ij}(t)\right)^{7}\right] \qquad (II\text{-}14)$$

where$\eta(t)$is the depth function to adjust the repulsion region or attraction region, which can be defined as:

$$\eta(t) = \alpha\left(1 - \frac{t-1}{T}\right)^{3} e^{-\frac{20t}{T}} \qquad (II\text{-}15)$$

where α is the depth weight and T is the maximum number of iterations. The function behaviors of F' ,

with different η corresponding to h ranging from 0.9 to 2, are illustrated in Fig. 4. From the figure, the repulsion occurs when h ranges from 0.9 to 1.12, the attraction occurs when h is between 1.12 and 2, and the equilibration occurs when h=1.12 . The attraction gradually increases with the increase of h from the equilibration (h =1.12) , reaches a maximum (h =1.24) and then begins to decrease. The attraction is approximately equal to zero when h is greater than or equal to 2. Therefore, in ASO, to improve the exploration, a lower limit of the repulsion with a smaller function value is set to h =1.1 and an upper limit of attraction with a larger function value is set to h=1.24 . Therefore, h is defined as

$$h_{ij}(t) = \begin{cases} h_{min} & \frac{r_{ij}(t)}{\sigma(t)} < h_{min} \\ \frac{r_{ij}(t)}{\sigma(t)} & h_{min} \leq \frac{r_{ij}(t)}{\sigma(t)} \leq h_{max} \\ h_{max} & \frac{r_{ij}(t)}{\sigma(t)} > h_{max} \end{cases} \tag{II-16}$$

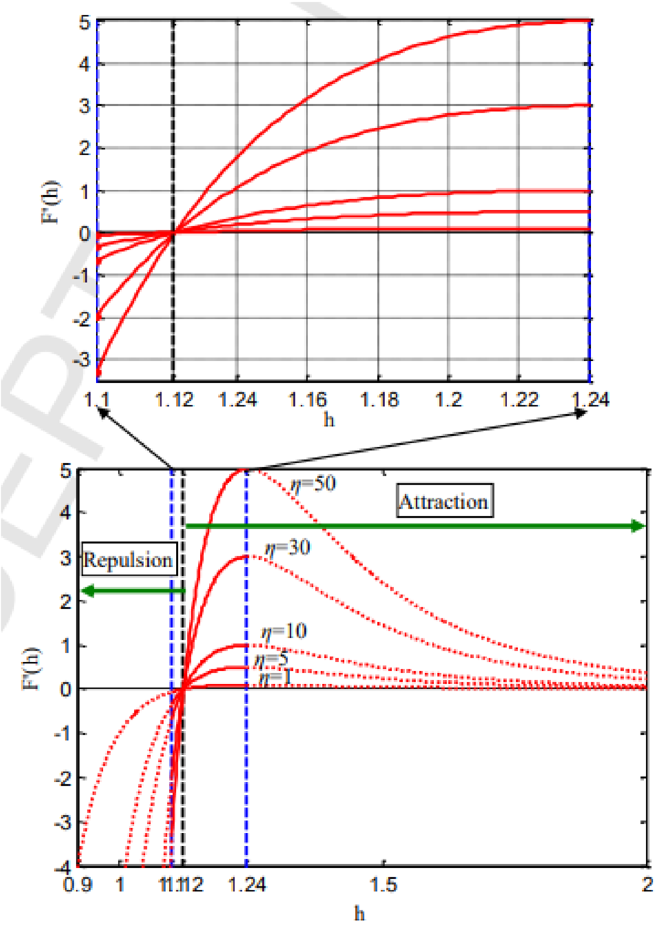

Figure-II-7. Function behaviors of F' with different values of η .

where h_{min} and h_{max} are the lower and the upper limits of h , respectively, and the length scale $\sigma(t)$ is defined as

$$\sigma(t) = \left\| x_{ij}(t), \frac{\sum_{j\in K\,best} x_{ij}(t)}{K(t)} \right\|_2 \quad \text{(II-17)}$$

and

$$\begin{cases} h_{min} = g_0 + g(t) \\ h_{max} = u \end{cases} \quad \text{(II-18)}$$

Where:

$Kbest$, which is a subset of an atom population, is made up of the first K atoms with the best function fitness values. As a drift factor, g can make the algorithm drift from the exploration to the exploitation and is given as

$$g(t) = 0.1 \times \sin\left(\frac{\pi}{2} \times \frac{t}{T}\right) \quad \text{(II-19)}$$

Then the sum of components with random weights acted on the ith atom from the other atoms can be considered a total force, which is expressed as

$$F_i^d(t) = \sum_{j\in Kbest} rand_j F_{ij}^d(t) \quad \textit{(II-20)}$$

Where $rand_j$ is a random number in [0,1].

II-4-2-2-Mathematical representation of geometric constraint

The geometric constraint in molecular dynamics plays an important role in atomic motion. For simplicity, suppose each atom in ASO has a covalence bond with the best atom. Thus each atom is acted on by a constraint force from the best atom, so the constraint of the ith atom can be rewritten as

$$\theta(t) = \left[|x_i(t) - x_{best}(t)|^2 - b_{i,best}^2\right] \quad \text{(II-21)}$$

Where $x_{best}(t)$ is the position of the best atom at the tth iteration, and $b_{i,best}$ is a fixed bond length between the ith atom and the best atom. Hence the constraint force can be obtained as

$$G_i^d(t) = -\lambda(t)\nabla\theta_i^d(t) = -2\lambda(t)\left(x_i^d(t) - x_{best}^d(t)\right) \quad \text{(II-22)}$$

where $\lambda(t)$ is the Lagrangian multiplier. Then, making the substitution of $2\lambda \rightarrow \lambda$, the constraint force can be redefined as

$$G_i^d(t)\lambda(t)\left(x_i^d(t) - x_{best}^d(t)\right) \quad \text{(II-23)}$$

The Lagrangian multiplier is defined as

$$\lambda(t) = \beta e^{-\frac{20t}{T}} \quad \text{(II-24)}$$

where: β is the multiplier weight.

II-4-2-3-Mathematical representation of atomic motion

With the interaction force and the geometric constraint, the acceleration of the ith atom at time t can be written as

$$a_i^d(t) = \frac{F_i^d(t)}{m_i^d(t)} + \frac{G_i^d(t)}{m_i^d(t)} = -\alpha\left(1 - \frac{t-1}{T}\right)^3 e^{-\frac{20t}{T}} \sum_{j\epsilon Kbest} \frac{rand_j\left[2\times\left(h_{ij}(t)\right)^{13} - \left(h_{ij}\right)^7\right]}{m_i(t)} \frac{\left(x_j^d(t) - x_i^d(t)\right)}{\left\|x_i(t), x_j(t)\right\|_2} + \beta e^{-\frac{20t}{T}} \frac{x_{best}^d(t) - x_i^d(t)}{m_i(t)}$$

(II-25)

where $m_i(t)$ is the mass of the ith atom at the tth iteration, which can be measured at the simplest level by its function fitness value. The mass of the ith atom can be calculated as

$$M_i(t) = e^{-\frac{Fit_i(t) - Fit_{best}(t)}{Fit_{worst}(t) - Fit_{best}(t)}} \quad \text{(II-26)}$$

$$m_i(t) = \frac{M_i(t)}{\sum_{j=1}^{N} M_i(t)} \quad \text{(II-27)}$$

where $Fit_{\text{best}}(t)$ and $Fit_{\text{worst}}(t)$ are the atoms with the minimum fitness value and the maximum fitness value at the tth iteration, respectively. $Fit_i(t)$ i is the function fitness value of the ith atom at the tth iteration. $Fit_{best}(t)$ and $Fit_{worst}(t)$ are expressed as

$$F_{it_{best}}(t) = \min_{i\in\{1,2,\cdots,N\}} Fit_i(t) \quad \text{(II-28)}$$

$$Fit_{wors}(t) = \max_{i\in\{1,2,\cdots,N\}} Fit_i(t) \quad \text{(II-29)}$$

To simplify the algorithm, the position and velocity of the ith atom at the $(t+1)$th iteration can be denoted as follows

$$v_i^d(t+1) = rand_i^d \; v_i^d(t) + a_i^d(t) \quad \text{(II-30)}$$

$$x_i^d(t+1) = x_i^d(t) + v_i^d(t+1) \quad \text{(II-31)}$$

In ASO algorithm, to enhance the exploration in the first stage of iterations, each atom needs to interact with as many atoms with better fitness values as its K neighbors. To enhance the exploitation in the final stage of iterations, the atoms need to interact with as few atoms with better fitness values as its K neighbors. Therefore, as a function of time, K gradually decreases with the lapse of iterations. Kcan be calculated as

$$K(t) = N - (N-2) \times \sqrt{\frac{t}{T}} \qquad \text{(II-32)}$$

The forces of an atom population are shown in Fig. 5, in which the first 5 atoms with the best fitness values are regarded as the $KBest$. As shown in the figure, A_1, A_2, A_3 and A_4 compose the $KBest$. A_5, A_6 and A_7 attract or repel each atom in the $KBest$, and A_1, A_2, A_3 and A_4 attract or repel each other. Each atom in the population except for A1 (xbest) has a constraint force from the best atom A_1.

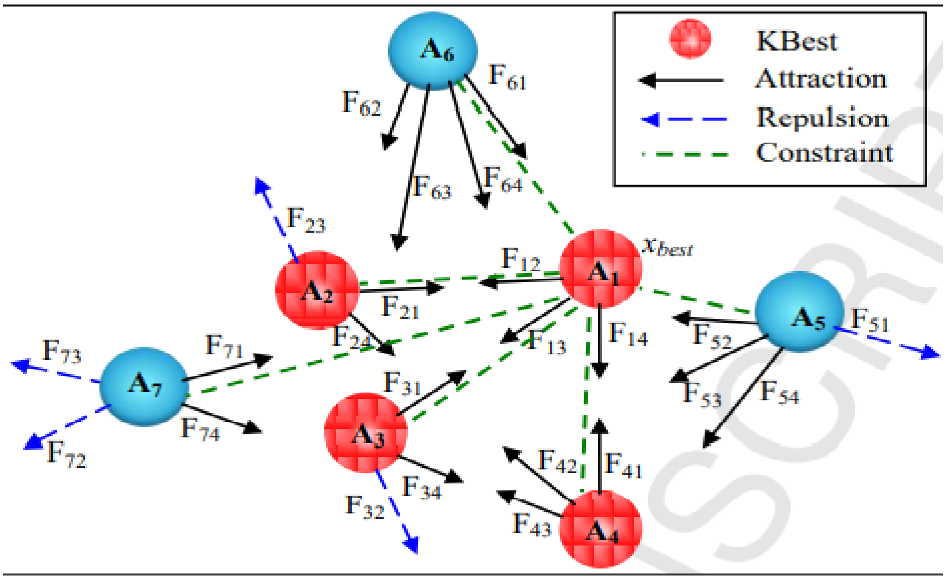

Figure-II-8. Forces of an atom system with KBest for K=5.

A simulation is conducted to examine how atoms move with this mathematical model. The swarm motion of 5 atoms around a target in a 3-D space is illustrated in Fig. 9, in which 5 different colored balls represent 5 different atoms, and the red point represents the desired target that every atom wants to reach. Initially, the positions of the 5 atoms are randomly generated in the search space. With the lapse of time t, all the atoms gradually approach the target using the mathematical mode and form a swarm. Finally, all the atoms converge to the target. Additionally, it can be found that, although the green atom is far away from the swarm when t=20, the other atoms also pull it back by the attraction in the subsequent iterations, and all the atoms do not become too concentrated because of the repulsion. The motion histories of the 5 atoms during 50 iterations are illustrated in Fig. 10. It is apparent that the atoms grow denser when they are closer to the target, and the distribution of atoms in the search space is sufficient to demonstrate that the model proposed can achieve the transition from the exploration for the entire search space to the exploration for a focused region. It is obvious that this search characteristic can be extended to a n-D space

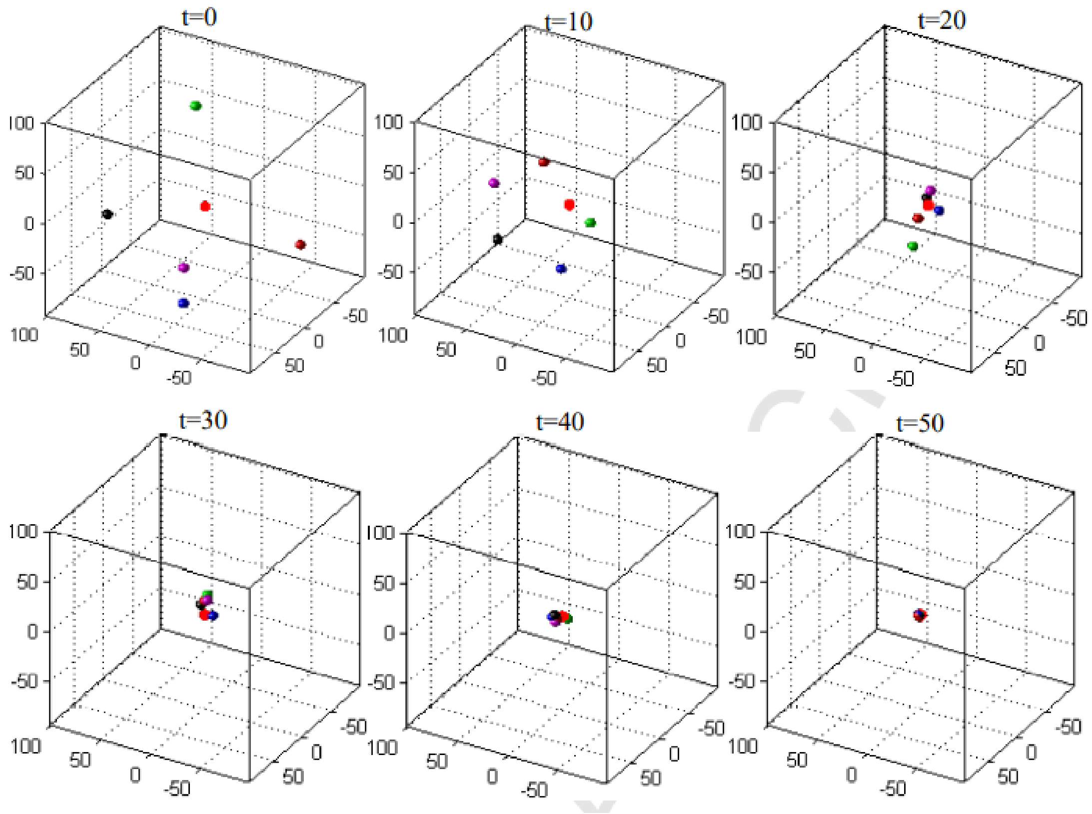

Figure-II-9. Swarm motion of 5 atoms around a target in a 3-D space.

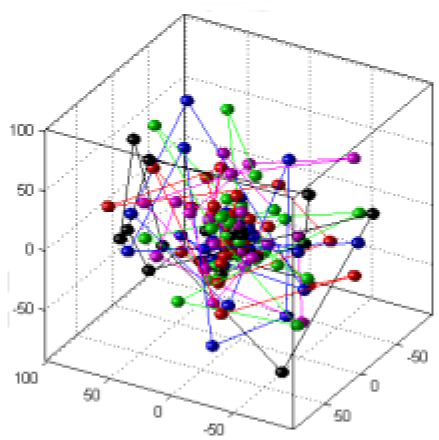

Figure-II-10Swarm motion of 5 atoms around a target in a 3-D space.

II-4-2-4-Framework of ASO algorithm

ASO starts the optimization by generating a set of random solutions. The atoms update their positions and velocities in each iteration, and the position of the best atom found so far is also updated in each iteration. In addition, the acceleration of atoms comes from two parts. One is the interaction force caused by the L-J potential, which actually is the vector sum of the attraction and the repulsion exerted from other atoms. Another is the constraint force caused by the bond-length potential, which is the weighted position difference between each atom and the best atom. All the updating and the calculation are performed interactively until the stop criterion is satisfied. Finally, the position and the fitness value of the best atom are returned as an approximation to the global optimum. The pseudo code of ASO algorithm is provided in

```
Randomly initialize a set of atoms X (solutions) and their velocity v, and Fit_Best=Inf.
 While the stop criterion is not satisfied do
   For each atom X_i do
      Calculate the fitness value Fit_i;
      If Fit_i < Fit_Best then
        Fit_Best = Fit_i;
         X_Best = X_i;
       End If.
       Calculate the mass using equations (II-26) and (II-27);
       Determine its K neighbors using equation (II-32);
       Calculate the intraction force Fi and the constraint force G_i using equations (II-20)
       and (II-23), respectively;
      Calculate the acceleration using equation (II-25);
      Update the velocity using equation (II-30);
      Update the position using equation (II-31);
   End For.
 End While.
Find the best solution so far X_Best
```

Figure-II-11. Pseudo code of ASO algorithm.

ASO algorithm is very simple to implement and does not require many parameters except for the maximum number of iterations, the number of the atom population, and the dimension of problems to be solved [14], which are common parameters to all optimization algorithms. Moreover, the upper limit and the starting point of the lower limit can be selected as fixed values by the analysis of Fig. 7. In equation (II-18), when the starting point of function ' F is fixed at $g_0 = 1.1$, ASO algorithm performs well. The upper limit should be set as:

$u = 1.24$ which is the maximum value of function F' . Therefore, the only parameters to be determined are the depth and multiplier weights. Empirically, it is recommended to set them in the range from 0 to 100 and from 0 to 1, respectively. The values of these parameters can be properly selected by four different benchmark functions, namely the Sphere, Rosen rock, Ackley, and Griewank functions. For each test function, all combinations of the following sets of parameter values are adopted

$\alpha = [10;\ 20;\ 30;\ 40;\ 50;\ 60;\ 70;\ 80;\ 90;\ 100]$

$\beta = [0.1;\ 0.2;\ 0.3;\ 0.4;\ 0.5;\ 0.6;\ 0.7;\ 0.8;\ 0.9;\ 1]$.

Through testing these functions, it can be found that their valley bottom with the optimum can be obtained for parameter ranges of $40 \leq \alpha \leq 60$ and $0.1 \leq \beta \leq 0.3$. Nevertheless, different problems may require a single value for each parameter, so the parameters of ASO are set as $\alpha = 50$ and $\beta = 0.2$ in the following experiments.

With the above formulation of ASO, the following remarks are made:

1) ASO inherits the innate stochastic motion of atoms in the real world, hence it intrinsically has the high exploration ability in the search space and thus can well avoid being trapped into the local optima compared to its competitors.
2) ASO is also a population-based optimization algorithm where the interaction forces include attraction and repulsion. The constraint force is an important media for delivering information within the population.
3) The attraction and repulsion can guarantee the exploration and exploitation, respectively, with the lapse of iterations. The drift factor can enable the interaction forces exerted on the atoms to gradually switch from the combination of attraction and repulsion to the repulsion alone, thus indicating the switch from the exploration to the exploitation
4) In the former phase of ASO, whether the interaction forces exerted on the atoms show the attraction or the repulsion depends on the function value of the ratio of $r_{ij}(t)$ to $\sigma_i(t)$, and $\sigma_i(t)$ can adaptively adjust the category (attraction or repulsion) of the interaction forces acted on the atoms.
5) The atoms with better fitness values have a larger mass, which leads to a smaller acceleration, thus signifying the local search. Atoms with worse fitness values have the lighter mass, thus signifying the global search.
6) Each atom in the population interacts only with its neighbours $KBest$ by the interaction force. The number of $KBest$ gradually decreases with the lapse of iterations. Meanwhile, each atom and the best one always generate the constraint force at each iteration.

II-5-EQUILIBRIUM OPTIMIZER

This section presents the inspiration, mathematical model, and algorithm of the Equilibrium Optimizer (EO) [18]:

II-5-1-Inspiration

The inspiration for the EO approach is a simple well-mixed dynamic mass balance on a control volume, in which a mass balance equation is used to describe the concentration of a nonre- active constituent in a control volume as a function of its various source and sink mechanisms. The mass balance equation provides the underlying physics for the conservation of mass entering, leaving, and generated in a control volume. A first-order ordinary differential equation expressing the generic mass-balance equation, in which the change in mass in time is equal to the amount of mass that enters the system plus the amount being generated inside minus the amount that leaves the system, is described as:

$$V\frac{dC}{dt} = QC_{eq} - QC + G \qquad \text{(II-33)}$$

C is the concentration inside the control volume (V), $V\frac{dC}{dt}$ is the rate of change of mass in the control volume, Q is the volumetric flow rate into and out of the control volume, C_{eq} represents the concentration at an equilibrium state in which there is no genera-tion inside the control volume, and G is the mass generation rate inside the control volume. When $V\frac{dC}{dt}$ reaches to zero, a steady equilibrium state is reached. A rearrangement of Eq. (II-33) allows to solve for $\frac{dC}{dt}$ as a function of $\frac{Q}{V}$; where $\frac{Q}{V}$ represents the inverse of the residence time, referred to here as λ, or the turnover rate($i.e., \lambda = \frac{Q}{V}$). Subsequently, Eq. (II-33) can also be rearranged to solve for the

concentration in the control volume (C) as a function of time (t):

$$\frac{dC}{\lambda C_{eq} - \lambda C + \frac{G}{V}} = dt \qquad \text{(II-34)}$$

Eq. (II-34) shows the integration of Eq. (II-35) over time:

$$\int_{c0}^{c} \frac{dC}{\lambda C_{eq} - \lambda C + \frac{G}{V}} = \int_{t0}^{t} dt \qquad \text{(II-35)}$$

This Results in:

$$C = C_{eq} + (C_0 - C_{eq})F + \frac{G}{\lambda V}(1 - F) \qquad \text{(II-36)}$$

In the Eq. (II-36), F is calculated as follows:

$F = exp\,[-\lambda\,(t - t0)]$ *(II-37)*

Wheret_0 and C_0 are the initial start time and concentration, dependent on the integration interval. Eq. (II-36) can be used to either estimate the concentration in the control volume with a known turnover rate or to calculate the average turnover rate using a simple linear regression with a known generation rate and other conditions.

EO is designed in this sub-section using the above equations as the overall framework. In EO, a particle is analogous to a solution and a concentration is analogous to a particle's position in the PSO algorithm. As Eq. (II-36) shows, there are three terms presenting the updating rules for a particle, and each particle updates its concentration via three separate terms. The first term is the equilibrium concentration, defined as one of the best-so-far solutions randomly selected from a pool, called the equilibrium pool. The second term is associated with a concentration difference between a particle and the equilibrium state, which acts as a direct search mechanism. This term encourages particles to globally search the domain, acting as explorers. The third term is associated with the generation rate, which mostly plays the role of an exploiter, or solution refiner, particularly with small steps, although it sometimes contributes as an explorer as well. Each term and the way they affect the search pattern is defined in the following.

II-5-1-1-Initialization and function evaluation

Similar to most meta-heuristic algorithms, EO uses the initial population to start the optimization process. The initial concentrations are constructed based on the number of particles and dimensions with uniform random initialization in the search space as follows:

$C_i^{initial} = C_{min} + rand_i(C_{max} - C_{min}) \qquad i = 1,2, \dots . n$ *(II-38)*

is the initial concentration vector of the ith particle, C_{min} and C_{max} denote the minimum and maximum values for the dimensions [18], $Rand_i$is a random vector in the interval of $[0, 1]$, and $n$is the number of particles as the population. Particles are evaluated for their fitness function and then are sorted to determine the equilibrium candidates.

II-5-1-2-Equilibrium pool and candidates (C_{eq})

The equilibrium state is the final convergence state of the algorithm, which is desired to be the global optimum. At the beginning of the optimization process, there is no knowledge about the equilibrium state and only equilibrium candidates are determined to provide a search pattern for the particles. Based on different experiments under different type of case problems, these candidates are the four best-so-far particles identified during the whole optimization process plus another particle, whose concentration is the arithmetic mean of the mentioned four particles. These four candidates help EO to have a better exploration capability, while the average helps in exploitation. The number of candidates is arbitrary and based on type of the optimization problem. One might use other numbers of candidates, which is consistent with the literature. For example, GWO uses three best-so-far candidates (alpha, beta, and gamma wolves) to update the positions of the other wolves. However, using less than four candidates degrades the performance of the method in multimodal and composition functions but will improve the results in unimodal functions. More than four candidates will have the opposite effect. These five particles are nominated as equilibrium candidates and are used to construct a vector called the equilibrium pool:

$$\vec{C}_{eq,pool} = \{\vec{C}_{eq(1)}, \vec{C}_{eq(2)}, \vec{C}_{eq(3)}, \vec{C}_{eq(4)}, \vec{C}_{eq(ave)}\} \quad \text{(II-39)}$$

Each particle in each iteration updates its concentration with random selection among candidates chosen with the same probability. For instance, in the first iteration, the first particle updates all of its concentrations based on $\vec{C}_{eq\,(1)}$; then, in the second iteration, it may update its concentrations based on $\vec{C}_{eq(ave)}$. Until the end of the optimization process, each particle will experience the updating process with all of the candidate solutions receive approximately the same number of updates for each particle.

II-5-1-3-Exponential term(F)

The next term contributing to the main concentration updating rule is the exponential term(F). An accurate definition of this term will assist EO in having a reasonable balance between exploration and exploitation. Since the turnover rate can vary with time in a real control volume, $\lambda$is assumed to be a random vector in the interval of $[0, 1]$.

$$\vec{F} = e^{-\vec{\lambda}(t-t0)} \quad \textit{(II-40)}$$

Where time$t$, is defined as a function of iteration $(Iter)$ and thus decreases with the number of iterations:

$$t = \left(1 - \frac{Iter}{Max\_iter}\right)^{\left(a_2 \frac{Iter}{Max\_iter}\right)} \quad \textit{(II-41)}$$

where $Iter$and Maxpresent the current and the maximum number of iterations, respectively, and $a_2$is a constant value used to manage exploitation ability. In order to guarantee convergence by slowing down the search speed along with improving the exploration and exploitation ability of the algorithm, this study also considers:

$$\vec{t}_0 = \frac{1}{\vec{\lambda}} ln \left(-a_1 sign\,(\vec{r} - 0.5)\left[1 - e^{-\vec{\lambda}t}\right]\right) + t \quad \textit{(II-42)}$$

Where$\boldsymbol{a_1}$is a constant value that controls exploration ability. The higher the $\boldsymbol{a_1}$, the better the exploration ability and consequently the lower exploitation performance. Similarly, the higher the $\boldsymbol{a_2}$, the better the exploitation ability and the lower the exploration ability. The third component, *sign* $(\boldsymbol{r} - \boldsymbol{0.5})$, effects on the direction of exploration and exploitation. r is a random vector between 0 and 1. For all of the problems subsequently solved in this paper, $\boldsymbol{a_1}$and $\boldsymbol{a_2}$are equal to 2 and 1, respectively. These constants are selected through empirical testing of a subset of test functions. However, these parameters can be tuned for other problems as needed.

Eq. (II-43) shows the revised version of Eq. (II-40) with the substitution of Eq. (II-42) into (II-40):

$$\vec{F} = a_1 sign\ (\vec{r} - 0.5)\left[e^{-\vec{\lambda}t} - 1\right] \qquad (II\text{-}43)$$

II-5-1-4-Generation rate (G)

The generation rate is one of the most important terms in the proposed algorithm to provide the exact solution by improving the exploitation phase. In many engineering applications, there are many models that can be used to express the generation rate as a function of time. For example, one multipurpose model that describes generation rates as a first order exponential decay process is defined as:

$$\vec{G} = \vec{G}_0 e^{-\vec{k}(t-t0)} \qquad (II\text{-}44)$$

Where$G_0$is the initial value and $k$indicates a decay constant. In order to have a more controlled and systematic search pattern and to limit the number of random variables, this study assumes $k = \lambda$and uses the previously derived exponential term. Thus, the final set of generation rate equations are as follows:

$$\vec{G} = \vec{G}_0 e^{-\vec{\lambda}(t-t0)} = \vec{G}_0 \vec{F} \qquad (II\text{-}45)$$

Where:

$$\overrightarrow{G_0} = \overrightarrow{GCP}\left(\overrightarrow{C_{eq}} - \vec{\lambda}\vec{C}\right) \qquad (II\text{-}46)$$

$$\overrightarrow{GCP} = \begin{cases} 0.5r_1 & r_2 \geq GP \\ 0 & r_2 < GP \end{cases} \qquad (II\text{-}47)$$

Where$r_1$and $r_2$are random numbers in $[0, 1]$ and GCP vector is constructed by the repetition of the same value resulted from Eq. (II-47) In this equation, *GCP* is defined as the Generation rate Control Parameter [18], which includes the possibility of generation term's contribution to the updating process. The probability of this contribution which specifies how many particles use generation term to update their states is determined by another term called Generation Probability (GP). The mechanism of this contribution is determined by Eq. (II-46) and (II-47). Eq. (II-47) occurs at the level of each particle. For example, if GCP is zero, $G$is equal to zero and all the dimensions of that specific particle are updated without a generation rate term. A good balance between exploration and exploitation is achieved with $GP = 0.5$. Finally, the updating rule of EO will be as follows:

$$\vec{C} = \vec{C}_{eq} + \left(\vec{C} - \vec{C}_{eq}\right) \cdot \vec{F} + \frac{\vec{G}}{\vec{\lambda} V}(1 - \vec{F}) \qquad \text{(II-48)}$$

Where F is defined in Eq (II-43), and V is considered as unit.

The first term in Eq (II-48) is an equilibrium concentration, where the second and third terms represent the variations in concentration. The second term is responsible for globally searching the space to find an optimum point. This term contributes more to exploration, thereby taking advantage of large variations in concentration (i.e., a direct difference between an equilibrium and a sample particle). As it finds a point, the third term contributes to making the solution more accurate. This term thus contributes more to exploitation and benefits from small variations in concentration, which are governed by the generation rate term Eq. (II-45). Depending on parameters such as the concentrations of particles and equilibrium candidates, as well as the turnover rate (λ), the second and third terms might have the same or opposite signs. The same sign makes the variation large, which helps to better search the full domain, and the opposite sign makes the variation small, aiding in local searches.

Although the second term attempts to find solutions relatively far from equilibrium candidates and the third term attempts to refine the solutions closer to the candidates, this is not always happening. Small turnover rates ($e.g., \leq 0.05$) in the denominator of the third term increase its variation and helps the exploration in some dimensions as well. Fig.12 demonstrates a 1-D version of how these terms contribute to exploration and exploitation. $C_1 - C_{eq}$ is representative of the second term in Eq.(II-48) while $C_{eq} - \lambda C_1$represents the third term (G is the function of $G0$). The generation rate terms (Eqs. (II-45) - (II-47)) control these variations. Because λchanges with each dimension's change, this large variation only happens to those dimensions with small values of λ. It is worth mentioning that this feature works similar to a mutation operator in evolutionary algorithms and greatly helps EO to exploit the solutions.

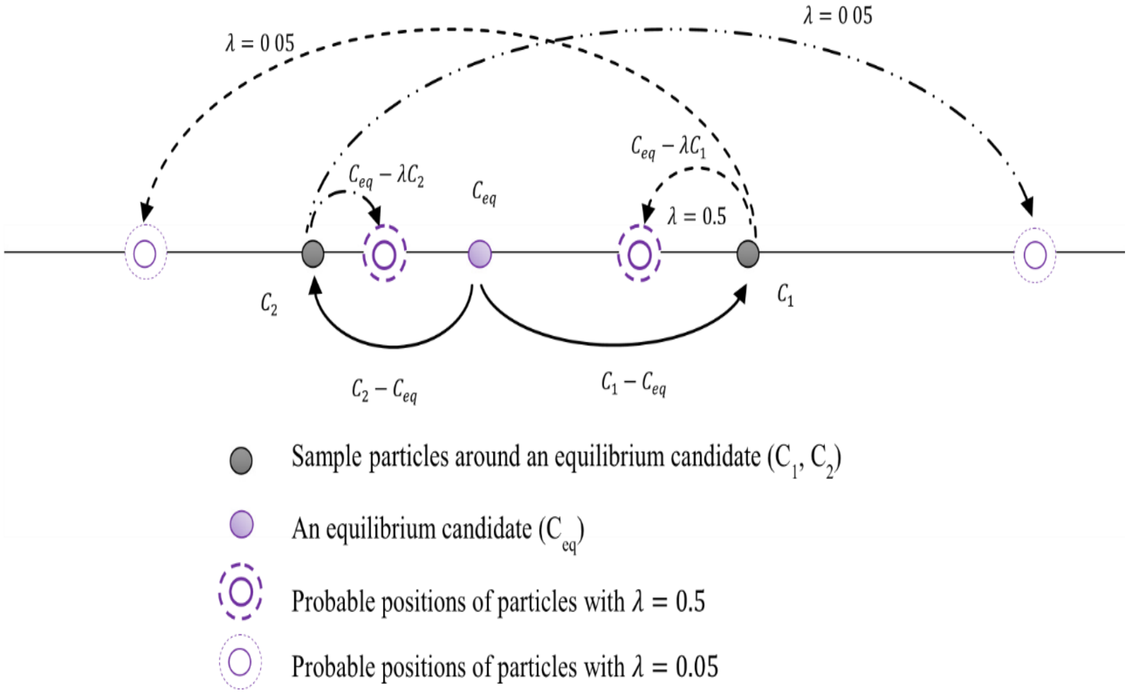

Figure-II-12. D presentation of concentrations updating aid in exploration and exploitation.

Fig. 13 shows a conceptual sketch of the collaboration of all equilibrium candidates on a sample particle and how they affect concentration updating, one after another, in the proposed algorithm. Since the topological positions of equilibrium candidates are diverse in initial iterations, and the exponential term generates large random numbers, this step by step updating process helps the particles to cover the entire domain in their search. An opposite scenario happens in the last iterations, when the candidates surround the optimum point by similar configurations. At these times, the exponential term generates small random numbers, which helps in refining the solutions by providing smaller step sizes. This concept can also be extended to higher dimensions as a hyperspace whereby the concentration will be updated with the particle’s movement in n-dimensional space.

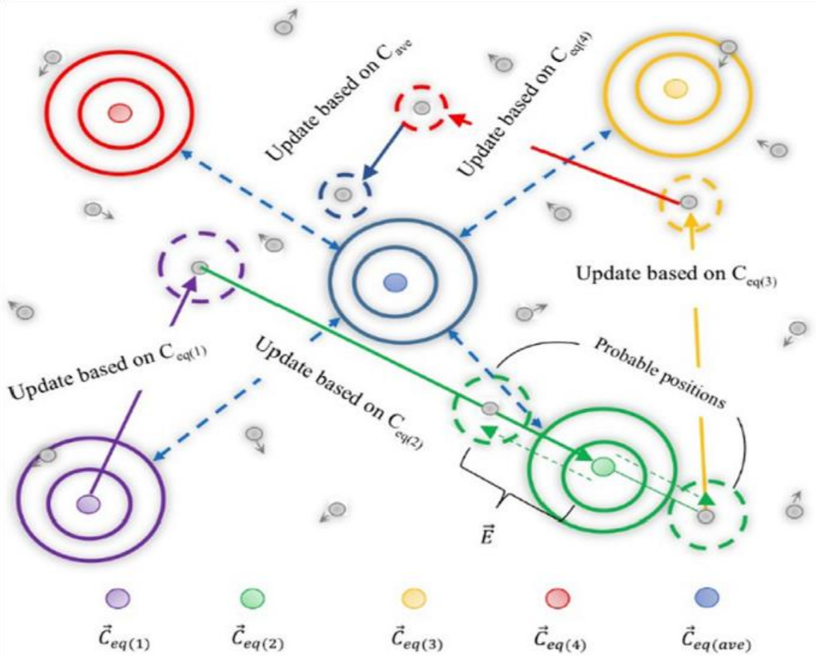

Figure-II-13. Equilibrium candidates' collaboration in updating a particles' concentration in 2D dimensions.

II-5-1-5-Particle's memory saving

Adding memory saving procedures assists each particle in keeping track of its coordinates in the space, which also informs its fitness value. This mechanism resembles the *pbest* concept in PSO. The fitness value of each particle in the current iteration is compared to that of the previous iteration and will be overwritten if it achieves a better fit. This mechanism aids in exploitation capability but can increase the chance of getting trapped in local minima if the method does not benefit from global exploration ability. The pseudo code of the proposed EO algorithm along with a memory saving function is presented in Fig. 14.

II-5-1-6-Exploration ability of EO

To summarize these terms, there are several parameters and mechanisms in EO that lead to exploration, as follows [19]:

a_1: controls the exploration quantity (magnitude) of the algorithm. It determines how far the new position would be to the equilibrium candidate. The higher the a_1 value, the higher the exploration ability. Note that numbers greater than three would considerably degrade the exploration performance. Since a_1 can magnify the concentration variation, it should be large enough to expand the exploration ability. However, based on empirical testing, it was found that values greater than three push the agents to search on boundaries. This recommendation is similar to the recommendation for free parameters in other algorithms. For example, in PSO, it is recommended that the sum of social and cognitive parameter should be less than or equal to four.

$sign\ (r - 0.5)$: controls the exploration direction. Since r is in $[0, 1]$ with uniform distribution, there is equal probability of negative and positive signs.

Generation probability (GP):controls the participation probability of concentration updating by the generation rate. $GP = 1$ means that there will be no generation rate term participating in the optimization process. This state emphasizes high exploration capability, and often leads to non-accurate solutions. $GP = 0$ means that the generation rate term will always be participating in the process, which increases the stagnation probability in local optima. Based on empirical testing, $GP = 0.5$ provides a good balance between exploration and exploitation phases.

Equilibrium pool: This vector consists of five particles. The selection of five particles is somewhat arbitrary but was chosen based on empirical testing. In the initial iterations, the candidates are all far away from each other in distance. Updating the concentrations based on these candidates improves the algorithm’s ability to globally search the space. The average particle also helps to discover unknown search spaces at initial iterations when particles are far away from each other.

Initialize the particle's populations i=1,…, n
Assign equilibrium candidates 'fitness a large number
Assign free parameters $\alpha_1 = 2; \alpha_2 = 1$; $GP = 0.5$;
While Iter<Max_iter
For $i = 1$:number of particles (n)
Calculate fitness of i_{th} particale
If f $it(\vec{C}_i)$ < f $it(\vec{C}_{eq1})$
Replace $\vec{C}_{eq1}$ with $\vec{C}_i$ and f$it(\vec{C}_{eq1})$ with f$it(\vec{C}_i)$
Elseif f$it(\vec{C}_i)$ > f$it(\vec{C}_{eq1})$ & f$it(\vec{C}_i)$ < fit $(\vec{C}_{eq1})$
Replace $\vec{C}_{eq2}$ with $\vec{C}_i$ and fit $(\vec{C}_{eq2})$ with f$it(\vec{C}_i)$
Elseif f$it(\vec{C}_i)$ > fit $(\vec{C}_{eq1})$ & fit $(\vec{C}_i$< fit $(\vec{C}_{eq2})$& fit $(\vec{C}_i)$ < fit $(\vec{C}_{eq3})$
Replace $\vec{C}_{eq3}$ with $\vec{C}_i$ and fit $(\vec{C}_{eq3})$ with fit $(\vec{C}_i)$
Elseif fit $(\vec{C}_i)$ > fit $(\vec{C}_{eq1})$ & fit $(\vec{C}_i)$ < fit $(\vec{C}_{eq2})$ & fit $(\vec{C}_i)$ <fit $(\vec{C}_{eq3})$ & fit $(\vec{C}_i)$ < fit $(\vec{C}_{eq4})$
Replace $\vec{C}_{eq4}$ with $\vec{C}_i$ and f$itt(\vec{C}_{eq4})$ with fit $(\vec{C}_i)$
End (If)
End (For)
$\vec{C}_{ave} = (\vec{C}_{eq1}+\vec{C}_{eq2} + \vec{C}_{eq3}\vec{C}_{eq4})/4$
Construct the equilibrium pool $\vec{C}_{eq.pool}= \{\vec{C}_{eq(1)}, \vec{C}_{eq(2)}, \vec{C}_{eq(3)}, \vec{C}_{eq(4)}, \vec{C}_{(ave)}\}$
Accomplish memory saving (if Iter >1)
Assign $t = \left(1 - \frac{iter}{Max_{iter}}\right)^{\left(a_2 \frac{iter}{Max_{iter}}\right)}$ Eq (II-41)
For i = 1: number of particles (n)
Randomly choose one candidate from the equilibrium pool (vector)
Generate random vectors of $\vec{\lambda}, \vec{r}$ from Eq (II-43)
Construct $\vec{F}=a_1 sing(\vec{r} - 0.5)[e^{-\vec{\lambda}t} - 1]$ Eq (II-43)
Construct $\overrightarrow{GCP}= \begin{cases} 0.5r_1 & r_2 \geq GP \\ 0 & r_2 < GP \end{cases}$ Eq (II-47)
Construct $\overrightarrow{G_0} = \overrightarrow{GCP}\ (\vec{C}_{eq} - \vec{\lambda}\vec{C})$ Eq (II-46)
Construct $\vec{G} = \overrightarrow{G_0}.\vec{F}$ Eq (II-45)
Update concentrations $\vec{G}=\vec{C}_{eq} + (\vec{G} - \vec{C}_{eq}).\vec{F} + \frac{\vec{G}}{\vec{\lambda}v}(1 - \vec{F})$ Eq (II-48)
End(For)
Iter=Iter+1
End while

Figure-II-14. Detailed pseudo code of EO

II-5-1-7-Exploitation ability of EO

The main parameters and mechanisms to perform exploitation and local search in EO are as follows [19]:

a_2: this parameter is similar to a_1, but controls the exploitation feature. It determines the quantity (magnitude) of exploitation by digging around the best solution.

sign$(r - 0.5)$: controls the exploitation quality (direction) as well. It specifies the direction of a local search.

Memory saving: memory saving, saves a number of best-sofar particles and substitutes them for worse particles. This feature directly improves the EO's ability for exploitation.

Equilibrium pool: by lapse of iteration, exploration fades out and exploitation fades in. Thus, in the last iterations, where the equilibrium candidates are close to each other, the concentration updating process will aid in local search around the candidates, leading to exploitation.

II-5-1-8-Computational complexity analysis

Computational complexity of an optimization algorithm is presented by a function relating the running time of the algorithm to the input size of problem. For this purpose, $Big - O$ notation is used here as a common terminology. Complexity is dependent upon the number of particles (n), the number of dimensions (d), and the number of iterations (t), and (c) is the cost of function evaluation.

$$\begin{aligned} \mathrm{O}\ (\mathrm{EO})\ &=\ \mathrm{O}\ (\text{problem definition})\ +\ \mathrm{O}\ (\text{initialization}) + \\ &\mathrm{O}(\mathrm{t}\ (\text{function evaluations})) +\ \mathrm{O}(\mathrm{t}\ (\text{Memory saving}))\ + \\ &\mathrm{O}(\mathrm{t}\ (\text{Concentration Update})) \end{aligned} \quad \text{(II-49)}$$

Therefore, the overall computational complexity is defined as:

$$\boldsymbol{O(EO)\ =\ O(1\ +\ nd +\ tcn +\ tn +\ tnd)\ =\sim O(tnd +\ tcn)} \quad \textit{(II-50)}$$

As it is shown, the complexity is of the polynomial order. Thus, EO can be considered as an efficient algorithm. The complexity of EO with that of PSO and GA (as two of the most well-known meta-heuristics) is compared in Appendix A.

II-5-2-Results on benchmark functions

This section demonstrates the effectiveness of the proposed algorithm on a set of 58 benchmark test functions, including 29 commonly used unimodal, multimodal, and composition functions, as well as another 29 functions from the CEC-BC-2017 test suite. This study utilizes both quantitative and qualitative validation metrics. Quantitative metrics include the average and standard deviation values for different test functions and qualitative metrics include trajectory, search, optimization, and average fitness history [18].

II-6-MEXICAN AXOLOTL VARIABLE OPTIMIZATION

This section briefly explains the life of the axolotl, a very interesting creature native to Mexico, as well as the proposed bioinspired optimization procedure [20].

II-6-1-The Artificial Axolotl

The proposed Mexican Axolotl Optimization (MAO) algorithm inspired by the life of the axolotl is explained in this section. We were inspired by the birth, breeding, and restoration of the tissues of the axolotls, as well as the way they live in the aquatic environment. As axolotls are sexed creatures, our population is divided into males and females. We also consider the ability of axolotls to alter their color, and we consider they alter their body parts' color to camouflage themselves and avoid predators.

Let us assume that we have a numeric optimization problem, defined by a function O whose arguments are vectors of dimension D , such that each dimension di is bounded by $[mini, maxi]$. We also have a set of solutions (axolotls) of size np, conforming the population $P = \{S1, \dots, Snp\}$, and each solution (axolotl) $Sj \in P,\ 1 \leq j \leq np$, is represented as a vector of form $Sj = [sj1, \dots, sjD]$, with $mini \leq sji \leq maxi$, such that $O(Sj) \in R$. In the following, we assume that we want to find the minimum value of the function O.

The proposed MAO algorithm operates in four iterative stages, defined by the TIRA acronym: Transition from larvae to adult state, Injury and restoration, Reproduction and Assortment.

First, the initial population of axolotls is initialized randomly. Then, each individual is assigned as male or female, due to axolotls developing according to their sex, and two subpopulations are obtained. Then, the Transition from larvae to adult begins. Male individuals will transition in water, from larvae to adult, by adjusting their body parts' color towards the male who is best adapted to the environment (Figure 15).

Transitons procédure
Input paramètres : Différentiation constant: $\lambda \in [0,1]$; Male population: M; Optimization values for male population: OM; Female population: F; Optimization values for female population : OF; current number of evaluations E
Outputs: Updated male and female population M and F, Updated number of evaluations E
Phase 1. Tranition from larvae to adult state; $r, r \in [0,1]$ are random numbers 1. Select the best male m_{best} and female f_{best} axolotle, according to the function O 2. For each male axolotl m_j, with optimization value om_j and $1 \leq j \leq \lvert M \rvert$ 2.1. Compute the inverse probability of transition, as 2.2. If $pm_j < r$, then update each component i of the current axolotl as $m_{ji} \leftarrow m_{ji} + (m_{best,i} - m_{ji}) * \lambda$; else $m_{ji} \leftarrow min_i + (max_{i\_}min_i) * r_i$ 2.3. Update the optimization value as $om_j \leftarrow \boldsymbol{O}(\boldsymbol{m_j}), E \leftarrow E + 1$ 2.4. Update m_{best} 3. For each female axolotl f_j 3.1. Compute the inverse probability of transition, as $pf_j = \frac{of_j}{\sum of_j}$ 3.2. If $pf_j < r$, then update each component i of the current axolotl as $f_{ji} \leftarrow f_{ji} + (f_{best} - f_{ji}) * \lambda$; else $f_{ji} \leftarrow min_i + (max_{i\_}min_i) * r_i$ 3.3. Update the optimization value as $of_j \leftarrow \boldsymbol{O}(\boldsymbol{f_j}), E \leftarrow E + 1$ 3.4. Update f_{best}

Figure-II-15. Pseudo code of the Transition procedure, corresponding to the Transition from larvae to adult state phase in the Mexican Axolotl Optimization (MAO) algorithm.

We assume that best adapted individuals have better camouflage, and the other individuals will change their color accordingly. However, the ability of the axolotls to change color is limited, and we do not want every individual to be able to fully adapt towards the best, which is why we introduce an inverse probability of transition. According to such probability, an axolotl will be selected to camouflage towards the best.

Let m_{best} be the best adapted male (the one with best value of the objective function O), and λ be a transition parameter in $[0, 1]$ for the male axolotl mj, which will change its body parts' color as in Equation (II-51).

$$m_{ji} \leftarrow m_{ji} + (m_{best,i} - m_{ji}) * \lambda \qquad \textit{(II-51)}$$

Similarly, female axolotls change their bodies from larvae to adults towards the female with best adaptation, using Equation (II-52), where f_{best} is the best female and f_i is the current female axolotl.

$$f_{ji} \leftarrow f_{ji} + (f_{best,i} - f_{ji}) * \lambda \qquad \textit{(II-52)}$$

However, and according to the inverse probability of transition, dummy individuals unable to camouflage themselves towards the best, and having their own colors are selected. To do so, if a random number $r \in [0,1]$ is lower than the inverse probability of transition, the corresponding individual is selected. For a minimization problem, for a male m_j , with optimization value m_j the inverse probability of transition is computed as in Equation (II-53); for female axolotl *fj*, with optimization value f_j we use Equation (II-54).

The worst individuals will have greater chances of random transition.

$$pm_j = \frac{om_j}{\sum om_j} \qquad \textit{(II-53)}$$

$$pf_j = \frac{of_j}{\sum of_j} \qquad \textit{(II-54)}$$

Those individuals will transition their i-th body parts randomly (considering each body part as a function dimension), as in Equations (II-55) and (II-56), where $ri \in [0,1]$ is a random number chosen for each i-th body part. The individuals with random transition will be selected according to the value of the optimization function.

$$\mathrm{m_{ji}} \leftarrow \mathrm{min_i} + (\mathrm{max_i} - \mathrm{min_i}) * \mathrm{r_i} \qquad \text{(II-55)}$$

$$f_{ji} \leftarrow min_i + (max_i - min_i) * r_i \qquad \text{(II-56)}$$

In moving across the water, axolotls can suffer accidents and be hurt. This process is considered in the Injury and restoration phase. For each axolotl Si in the population (either male or female), if a probability of damage (dp) is fulfilled, the axolotls will lose some part or parts of its body. In the process, using the regeneration probability (rp) per bit, the axolotl will lose the j-th body part (bit), and will replace it as:

$$p'_{ji} \leftarrow min_i + (max_i - min_i) * r_i \qquad \textit{(II-57)}$$

where $0 \leq ri \leq 1$ is randomly chosen for each body part.

The pseudocode of the Injury and Restoration phase of the Mexican Axolotl optimization algorithm is provided in Figure 16. Then, the Reproduction of the population begins. The pseudocode of the Reproduction and Assorting phase is given in Figure 17. For each female axolotl in the population, a male is selected from which offspring will be obtained. To do so, we use tournament selection.

Accidents procedure
Input parameters: Male population: M; Optimization values for male population: OM; Female population: F; Optimization values for female population: OF; current number of evaluations E, Damage probability: $\lambda \in [0,1]$; Regeneration probability: $rp \in [0,1]$;
Outputs: Updated populations M and F, updated number of evaluations E
Phase 2. Injury and restoration; $r, r_i \in [0,1]$ are random numbers 1. For each male axolotl m_j 1.1. If $r \leq dp$ 1.1.1. For i=1…D 1.1.1.1. If $r \leq dp$ then $m_{ji} \leftarrow min_i + (max_{i\_}min_i) * r_i$ 1.1.2. $om_j \leftarrow \boldsymbol{O}(\boldsymbol{m_j}), E \leftarrow E + 1$ 1.2. Update m_{best} 2. For each female axolotl f_j 2.1. If $r \leq dp$ 2.1.1. For i=1…D 2.1.1.1. If $r \leq dp$ then $f_{ji} \leftarrow min_i + (max_{i\_}min_i) * r_i$ 2.1.2. $of_j \boldsymbol{O}(\boldsymbol{f_j}), e \leftarrow e + 1$ 2.2. Update f_{best}

Figure-II-16. Pseudocode of the Accidents procedure, corresponding to the Injury and restoration state phase in the MAO algorithm.

After that, the male places spermatophores and the female collects them with the cloaca to deposit them in her spermatheca. The eggs are formed using the genetic information of both parents uniformly (Figure 18). For simplicity, we assume that each pair of male and female axolotls has two eggs. The female deposits the eggs and waits until hatching. Once hatching, the Assortment process starts. The newly created individuals (larval state) will compete with their parents to be in the population. If the young are better according to the objective function, the young will replace them.

New Life procedure
Input parameters: Tournament size: $k \in [1, np]$; Male population: M; Optimization values for male population: OM; Female population: F; Optimization values for female population: OF; current number of evaluations E
Outputs: Updated male and female populations M end F, Updated number of evaluations E
Phase 3. Reproduction and Assortment;$r_i \in [0,1]$ is a random number 1. For each female axolotl f_j 1.1. Select a suitable male $\boldsymbol{m_j} \in \boldsymbol{M}$, using tournament selection of size k 1.2. Obtion two eggs, egg_1 and $egg_2$by uniformly combining the body parts of the parents, as follows: 1.2.1. For$i$=1…D 1.2.1.1. If $r_i \leq 0.5$, then $egg_{1i} \leftarrow m_{ji}$ and $egg_{2i} \leftarrow f_{ji}$; else $egg_{2i} \leftarrow m_{ji}$ and $egg_{1i} \leftarrow f_{ji}$ 1.3. Compute the fitness of the eggs, as $oegg_1 \leftarrow \boldsymbol{O}(\boldsymbol{egg_1})$ and $oegg_2 \leftarrow \boldsymbol{O}(\boldsymbol{egg_2}), E \leftarrow E + 2$ 1.4. Sort f_j, m_j, egg_1, egg_2 according to their optimisation values. 1.5. Assign the first individual in the ranking to f_j, and the second-best to m_j

Figure-II-17. Pseudocode of the New Life procedure, corresponding to the Reproduction and Assortment phase in the MAO algorithm of the proposed Mexican Axolotl Optimization.

After the Assortment procedure, the TIRA process (Phase 1. Transition from larvae to adult state; Phase 2. Injury and restoration and Phase 3. Reproduction and Assortment) repeats, until the stopping condition of the algorithm is fulfilled. Figure 19 shows the pseudocode of the proposed MAO algorithm, considering a minimization problem.

$m_{\text{\_parent}} = [0.32, 4.56, 6.08, 0.54, 1.67]$
(a)

$f_{\text{\_parent}} = [1.23, 5.43, 7.83, 0.76, 4.34]$
(b)

$rdm = [0.1, 0.3, 0.7, 0.3, 0.9]$
(c)

Offspring:
off_ 1 = [1.23,5.43,6.08,0.76,1.67]
off_2 = [0.32,4.56,7.83,0.54,4.34]
(d)

Figure-II-18. Reproduction in the MAO. (a) Male parent, (b) female parent, (c) random numbers generated to uniformly distribute the parents' information, and (d) the resulting offspring.

Th proposed Mexican Axolotl Optimization algorithm incorporates in the optimization process several aspects of the life of the axolotl, such as its aquatic development, its ability to transform its body from larvae to adult state, its sexed reproduction, and its capability of regenerating organs and body parts.

Our proposal differentiates from other evolutionary and swarm intelligence algorithms in the following:

We divide the individuals into males and females.

We consider the females more important, due to the fact that for each female we find the best male according to tournament selection, to obtain the offspring.

We have an elitist replacement procedure to include new individuals in the population. In such a procedure, the best individual is considered to be a female, and the second-best to be a male. That is, our procedure has the possibility of converting a male into a female, if the male is best.

In the following, we address the experiments made to evaluate MOA for numerical optimization [19].

MexicanAxolotl Optimization

Input parameter:
Population : P; P size: np, Female population: F; Male population :M; Damage probability Regeneration probability: $dp \in [0,1]$; Regeneration probability: $rp \in [0,1]$; Differentiation constant : $\lambda \in [0,1]$; Tournament size: $k \in [0, np]$; Termination criteria: number of evaluations (eval) Of objective function O; Number of dimensions of the function: D; Limits of the variables:$[min_i, max_i]$, with $i \in \{1, \ldots, D\}$

Output : Best axolotl ($b\_axolotl$)

Initialization
1. Obtain a random population of size np and evaluate it according to O
 1.1. $\mathrm{P} = \emptyset, \mathrm{OM} = \emptyset, \mathrm{OF} = \emptyset, E = 0$
 1.2. For $j = 1..\mathrm{np}$
  1.2.1.Create an axolotl $\boldsymbol{p}_j$as a vector of size D, with random components in the limits of the variables
  1.2.2. $P \leftarrow \boldsymbol{O}(\boldsymbol{p}_j), E \leftarrow E + 1$
  1.2.3.. $P \leftarrow P \cup \{p_j\}, \mathrm{OP} \leftarrow \mathrm{OP} \cup \{\mathrm{op}_j\}$
2. Divide the population in males and females
 2.1. $\mathrm{M} = \emptyset, \mathrm{F} = \emptyset$
 2.2. For$j = 1..\mathrm{np}$
  2.2.1. If i is an odd number
   2.2.1.1. $\mathrm{M} \leftarrow \mathrm{M} \cup \boldsymbol{p}_j$,
   2.2.1.2. $om_j \leftarrow \boldsymbol{O}(\boldsymbol{p}_j), E \leftarrow E + 1$
   2.2.1.3. $\mathrm{OM} \leftarrow \mathrm{OM} \cup \mathrm{om}_j$,
  2.2.2. else
   2.2.2.1. $\mathrm{F} \leftarrow \mathrm{F} \cup \{\boldsymbol{p_j}\}$
   2.2.2.2. $of_j \leftarrow \boldsymbol{o}(\boldsymbol{p}_j), E \leftarrow E + 1$
   2.2.2.3. $\mathrm{OF} \leftarrow \mathrm{OF} \cup of_j$,

Iterative phases
3. While $E \leq \mathrm{eval}$
 3.1. $\{\lambda, \mathrm{M}, \mathrm{OM}, \mathrm{F}, \mathrm{OF}, E\} \rightarrow$ Transition $\rightarrow \{\mathrm{M}', \mathrm{OM}', \mathrm{F}', \mathrm{OF}', E'\}$// Phase 1
 3.2 $\{dp, rp, \mathrm{M}', \mathrm{OM}', \mathrm{F}', \mathrm{OF}', E'\} \rightarrow$ Accidents $\rightarrow \{\mathrm{M}'', \mathrm{OM}'', \mathrm{F}'', \mathrm{OF}'', E''\}$// Phase
 3.3. $\{\mathrm{k}, \mathrm{M}, \mathrm{OM}, \mathrm{F}, \mathrm{OF}, E\} \rightarrow$ NewLife $\rightarrow \{\mathrm{M}''', \mathrm{OM}''', \mathrm{F}''', \mathrm{OF}''', E'''\}$// Phase 3
4. If $\boldsymbol{o}(\boldsymbol{m}_{\mathrm{best}}) < \boldsymbol{O}(\boldsymbol{f}_{\mathrm{best}})$then $\boldsymbol{b}\_\mathrm{axolotl} \leftarrow \boldsymbol{m}_{\mathrm{best}}$
  Else $b\_\mathrm{axolotl} \leftarrow f_{\mathrm{best}}$

Figure-II-19. Pseudocode of the proposed Mexican Axolotl Optimization.

II-7-CONCLUSION

This chapter provides a general introduction and provides an overview of global (metaheuristic) improvement methods. Among the best known and most widely used metaheuristic methods in engineering fields, we have studied four Lichtenberg Optimization (LA) algorithm, Axolotl Variable Optimization (MAO), Equilibrium Optimizer (EO), and Atomic Search Optimization (ASO) which is a new method reviewing the development and application of some methods Hybrids and explains it in a streaming chat about how to use it to solve the problem. In the next chapter, we will apply this technique, with a discussion of the results.

CHAPTRE III

III-1-INTRODUCTION

In this section, the performance of Atom search optimization (ASO) for resolving the Combined Heat Dynamic Economic Environmental Dispatching (CHPDEED) problems with Renewable Energy Source in the field of quality of solution and convergence speed is studied. Two typical test cases are chosen from literature (6) for comparison, which are used to evaluate the algorithm in most literature of studying the CHPDEED problems. The first case is the classical simple representation of the CHPDEED problem, and the second case is the classical sophisticated representation. If different values are not clearly described in the test cases, the parameters of the ASO for all test cases are set as follows: Depth weight:50; Multiplier weight:0.2; Niter=500. Cost is in $, heat output is in $MWth$, and power output is in MW in all the test cases.

III-2-CASE STUDIES AND RESULTS

III-2-1-Numerical Simulations

In order to investigate the efficacy of our proposed mathematical formulations of CHPDEED with PV and wind energy, four different cases are used. The cases differ based on their load profile and are detailed as:

- **Case 1:** CHPDEED with and without renewable of energy source and residential load.
- **Case 2:** CHPDEED with and without renewable of energy source and commercial load.

For all case studies, the eleven unit system consisting of (eight conventional units, two CHP units, and one heat-only unit) is utilized. The data for the conventional, CHP, and heat units are given in Tables 1–3, respectively, and are obtained from (6). Feasible operating regions for the CHP units are given in Figures 1 and 2, respectively. The power and heat demand, PV and wind energy output are given in Table 4. The transmission loss formula coefficients for the thermal only units and the CHP units are given by Equations (III.1).

Thermal Units	a_i	b_i	c_i	e_i	f_i	α_i	β_i	γ_i	η_i	δi	$P_{i,\min}^{TU}$	$P_{i,\max}^{TU}$
i=1	786.7988	38.5397	0.1524	450	0.041	103.3908	2.4444	0.0312	0.5035	0.0207	150	470
i=2	451.3251	46.1591	0.1058	600	0.036	103.3908	2.4444	0.0312	0.5035	0.0207	135	470
i=3	1049.998	40.3965	0.028	320	0.028	300.391	4.0695	0.0509	0.4968	0.0202	73	340
i=4	1243.531	38.3055	0.0354	260	0.052	300.391	4.0695	0.0509	0.4968	0.0202	60	300
i=5	1356.659	38.2704	0.0179	310	0.048	320.0006	3.9023	0.0344	0.4972	0.02	57	160
i=6	1450.705	36.5104	0.0121	300	0.086	330.0056	3.9524	0.0465	0.5163	0.0214	20	130
i=7	1455.606	39.5804	0.109	270	0.098	350.0056	3.9524	0.0465	0.5475	0.0234	20	80
i=8	1469.403	40.5407	0.1295	380	0.094	360.0012	3.9864	0.047	0.5475	0.0234	10	55

Table III-1- Data of thermal units.

CHP Units	a_k	b_k	c_k	d_k	e_k	f_k	α_k	β_k
K=1	2650	14.5	0.0345	4.2	0.03	0.031	0.00015	0.00015
K=2	1250	36	0.0435	0.6	0.027	0.011	0.00015	0.00015

Table III-2- Data of CHP units.

HeatUnit	a_k	b_k	c_k	α_i	β_i	$H_{l,\min}^{H}$ (MW/h)	$H_{l,\max}^{H}$ (MW/h)
l=1	950	2.0109	0.038	0.0008	0.001	0	2695.2

TableIII-3- Data of heat only u

Time (hours)	Heat Demand (MWth)	Commercial load (MW)	Residential load (MW)	PV(MW)	WT(MW)
1	390	1036	963	0	1,7
2	400	1110	1110	0	8,5
3	410	1258	1258	0	9,27
4	420	1406	1406	0	16,66
5	440	1480	1480	0	7,22
6	450	1628	1628	0	4,91
7	450	1702	1702	0,3	14,66
8	455	1776	1776	6,27	25,56
9	460	1924	1924	16,18	20,58
10	460	2022	2072	24,05	17,85
11	470	2106	2146	39,37	12,8
12	480	2150	2220	7,41	18,65
13	470	2072	2072	31,94	14,35
14	460	1924	2050	26,81	10,35
15	450	1776	2000	10,08	8,26
16	450	1554	1850	5,3	13,71
17	420	1480	1805	2,31	3,44
18	435	1628	1792	0	1,87
19	445	1776	1776	0	0,75
20	450	1972	1705	0	0,17
21	445	1924	1650	0	0,15
22	435	1628	1628	0	0,31
23	400	1332	1332	0	1,07
24	400	1184	1184	0	0,58

TableIII-4- Hourly output of PV and wind and hourly load demand and Heat demand and power demand.

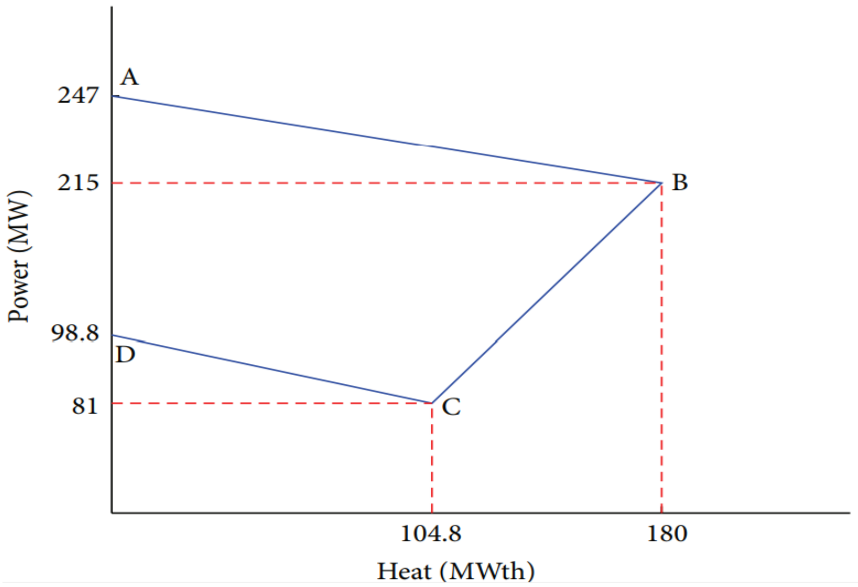

Figure-III-1. Power heat feasible operating region for CHP Unit 1.

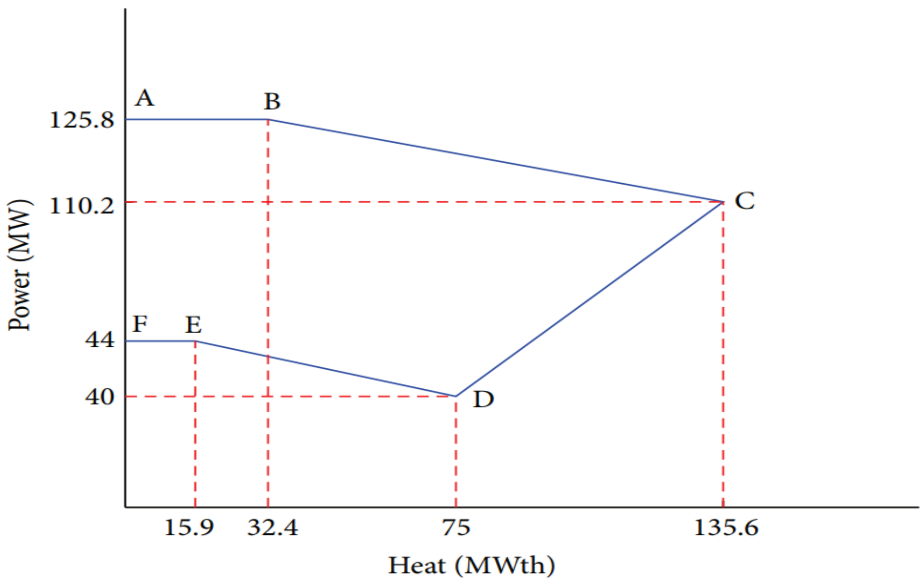

Figure-III-2. Power heat feasible operating region for CHP Unit 2.

$$B = 10^{-5} \times \begin{bmatrix} 4.90 & 1.40 & 1.50 & 1.50 & 1.70 & 1.70 & 1.90 & 2.00 \\ 1.40 & 4.50 & 1.60 & 1.60 & 1.50 & 1.50 & 1.80 & 1.80 \\ 1.50 & 1.60 & 3.90 & 1.00 & 1.20 & 1.40 & 1.60 & 1.60 \\ 1.50 & 1.60 & 1.00 & 4.00 & 1.00 & 1.10 & 1.40 & 1.50 \\ 1.70 & 1.50 & 1.20 & 1.00 & 3.60 & 1.30 & 1.40 & 1.50 \\ 1.70 & 1.50 & 1.40 & 1.10 & 1.20 & 3.80 & 1.60 & 1.80 \\ 1.90 & 1.80 & 1.60 & 1.40 & 1.40 & 1.60 & 4.20 & 1.90 \\ 2.00 & 1.80 & 1.60 & 1.50 & 1.50 & 1.80 & 1.90 & 4.40 \end{bmatrix} per MW$$

$$B = 10^{-5} \times \begin{bmatrix} 3.50 & 1.30 \\ 1.30 & 4.00 \end{bmatrix} per MW \qquad \text{(III.1)}$$

III-2-2-Results and Discussion

The multi-objective optimization problem has three objective functions and we assume that equal objectives were given to all three objectives. Thus, w1 = w2 = 0.50. Figures (III-1), (II-2) give the load (commercial and industrial load profiles) and heat profiles and PV and wind output power respectively.

The loads profiles are given in Figure (III-3). Figures (III-4) correspond to the PV and wind energy output operating hours.

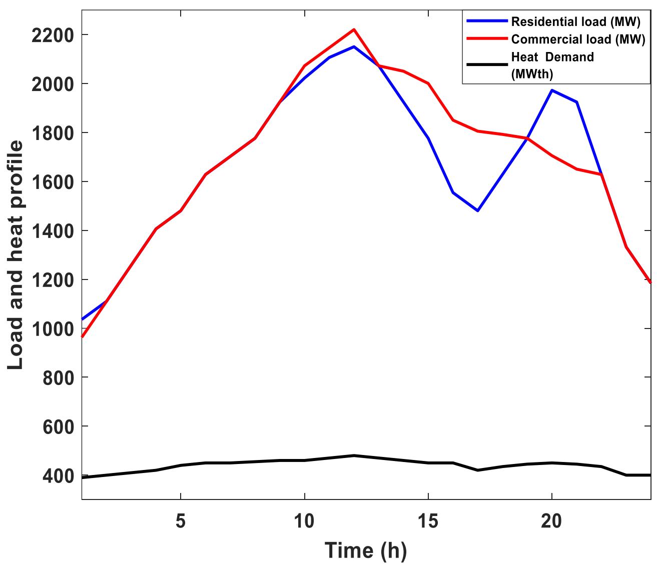

Figure-III-3. Daily load demands.

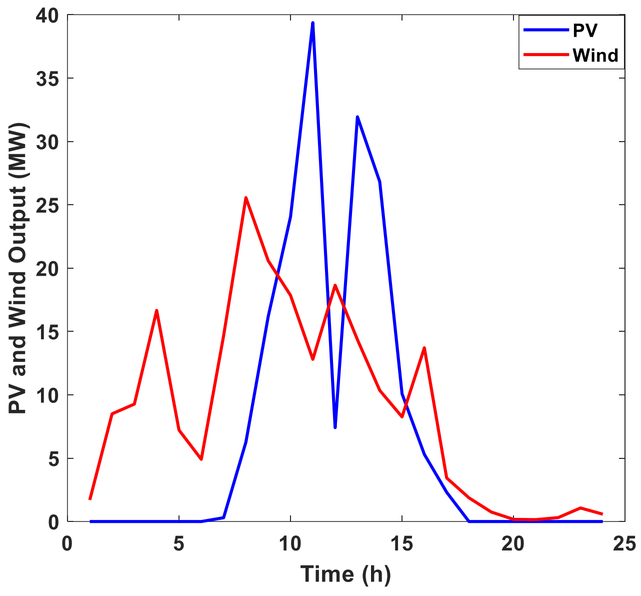

Figure-III-4. PV and Wind Output power

III-2-2-1-Case 1

The full results for case 1 are given in Table 6. It shows the fuel cost ($), emissions ($lb$), total energy generated (MWh), total heat ($MWth$), total losses (MW), total incentive ($), and total energy saved/curtailed (MWh) for all cases over 24 h. In order to benchmark the CHPDEED with and without RES results, results from conventional CHPDEED using the data of Case 1 are also provided in the second column of Table 5.

Parameters	**Total power generated (MW)**	**Total heat generated ($MWth$)**	**Objective function($)**
DELD Cost with RES ($)	39848,0001	10544,99999	2683619,398
DELD Cost without RES ($)	39451,66	10544,6633	2637831,07
DEnD Emiss with RES (Kg)	39848,0001	10545,2478	830056,7769
DEnD Emiss without RES (Kg)	39451,66001	10545,00001	732228,15
DEED Cost Emiss with RES ($)	39848,0001	10544,7105	1757325,159
DEED Cost Emiss without RES ($)	39451,66	10545	1666807,25
CHPDEED Cost Emiss with RES ($)	39848	10544,5317	1871348,727
CHPDEED Cost Emiss without RES ($)	39451,66001	10545	1810099,47

TableIII-5-CHPDEEDs results for residential load.

For Case 1of residential load, The Combined Heat Economic Load Dispatch CHPDELD with and without RES over 24 h esteemed at 2683619.398 $ and 2637831.07$.

The pollutants emitted (DEnD) using ASO are 830056.7769 Kg and 732228.15 Kg respectively. It is also to be noted that the maximum pollutants are emitted when no RES were used. This is obviously because the entire load demand was to be fulfilled by the conventional generators, thus consuming more fuel and releasing harmful pollutants.

The various dynamic economic emission with and without RES by ASO attained the values 1757325.159$ and 1666807.25$. These values are much higher when RES are not considered and the generators satisfy the load demands among themselves.

Again, the total daily cost of the Combined Heat Dynamic Economic Environmental Dispatching (CHPDEED) without Renewable Energy Source esteemed in1810099,47 $ and 1871348,727$ for the Combined Heat Dynamic Economic Environmental Dispatching (CHPDEED) with Renewable Energy Source. Other remark, the constraints equalities are verified, that the summation of the total powers without RES are 39451,6600 MW compared at 39848MW with RES and heats generated is the same of demand, so equal 10544.99999 MWth.

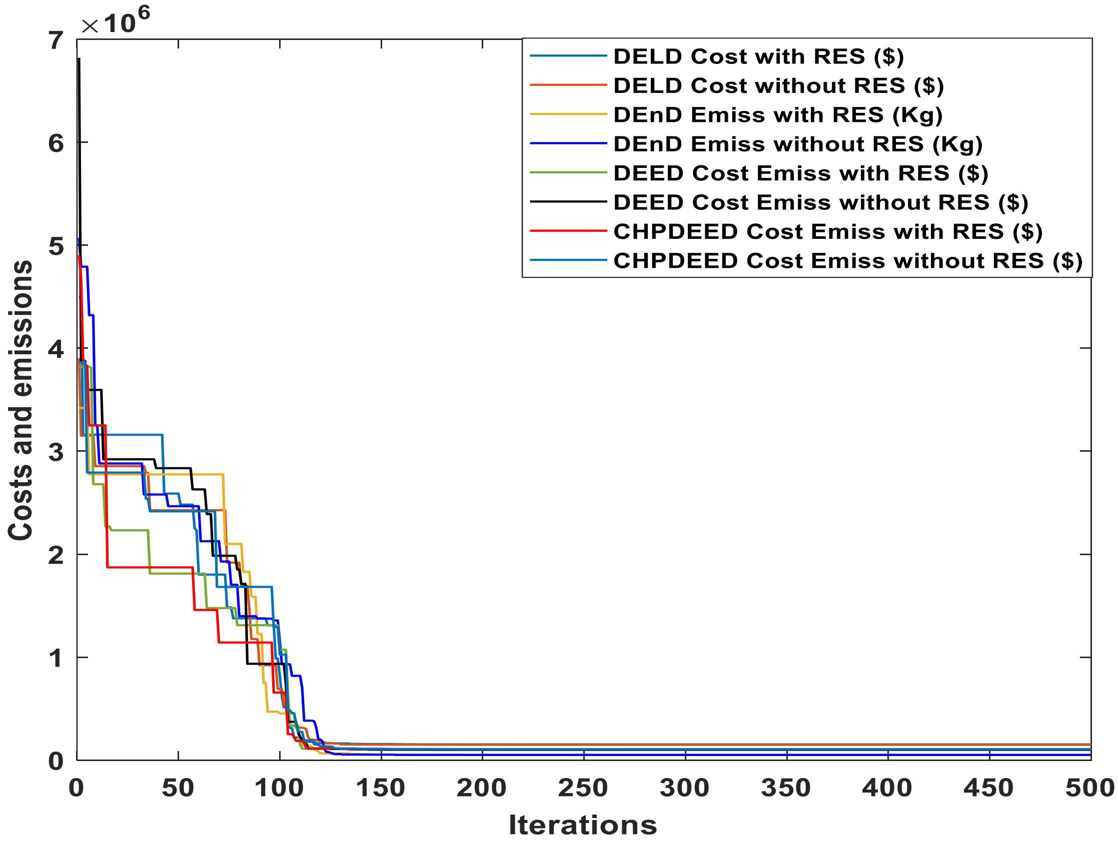

Figure-III-5. Convergence Costs with iterations for PD= 2150MW and 480 $MWth$ for residential load.

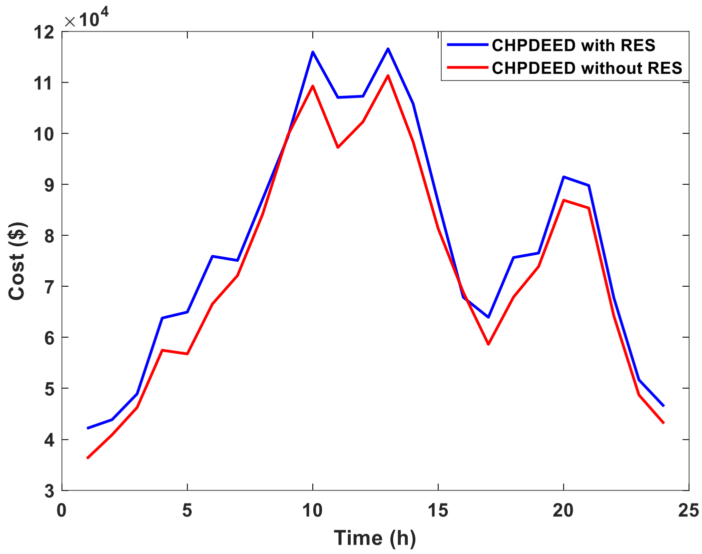

Figure-III-6. Profile CHPDEEDs Cost for residential load.

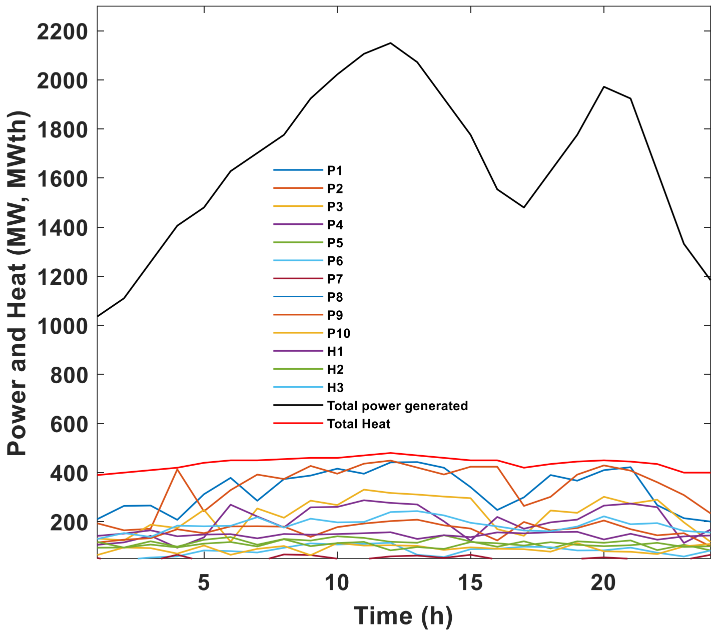

Figure-III-7. Profile powers and heats of CHPDEEDs Cost With RES and residential load.

By analyzing Figure (III-7), between 09:00–16:00 h the operational hours of the CHPDEED cost with Renewable Energy Source are more than the CHPDEED cost without Renewable Energy Source, and between 01:00–09:00 h and 1600–00:00 the CHPDEED cost with Renewable Energy Source are more less than the CHPDEED cost without Renewable Energy Source.

The convergence characteristics shown in Figure (III-7) prove that ASO has better qualities and we conclude that ASO is favorable for large-scale power systems.

III-2-2-2-Case 2

The full results for case 2 with commercial load are given in Table 7. It shows the fuel cost (\$), emissions (lb), total energy generated (MWh), total heat ($MWth$), total losses (MW), total incentive (\$), and total energy saved/curtailed (MWh) for all cases over 24 h. In order to benchmark the CHPDEED with and without RES results, results from conventional CHPDEED using the data of Case 2 are also provided in the second column of Table 6.

Parameters	**Total power generated (MW)**	**Total heat generated (MWth)**	**Objective function($)**
DELD Cost with RES ($)	40528,9996	10544,9999	2772263,729
DELD Cost without RES ($)	40132,6598	10544,9998	2674936,991
DEnD Emiss with RES (Kg)	40528,9996	10544,9998	867710,2329
DEnD Emiss without RES (Kg)	40132,6595	10544,9999	752207,5585
DEED Cost Emiss with RES ($)	40528,9996	10544,99985	1792864,308
DEED Cost Emiss without RES ($)	40132,6595	10544,9998	1690856,538
CHPDEED Cost Emiss with RES ($)	40528,9996	10544,9999	1950510,842
CHPDEED Cost Emiss without RES ($)	40198,8596	10544,9999	1851253,292

TableIII-6- CHPDEEDs results for commercial load.

For Case 1of residential load, The Combined Heat Economic Load Dispatch CHPDELD with and without RES over 24 h esteemed at 2772263,729 $ and 2674936,991 $.

The pollutants emitted (DEnD) using ASO are 867710.2329 Kg and 752207.5585Kg respectively. It is also to be noted that the maximum pollutants are emitted when no RES were used. This is obviously because the entire load demand was to be fulfilled by the conventional generators, thus consuming more fuel and releasing harmful pollutants.

The various dynamic economic emission with and without RES by ASO attained the values 1792864,308$ and1690856,538$. These values are much higher when RES are not considered and the generators satisfy the load demands among themselves.

Again, the total daily cost of the Combined Heat Dynamic Economic Environmental Dispatching (CHPDEED) without Renewable Energy Source esteemed in1950510.842$ and 1851253.292 $ for the Combined Heat Dynamic Economic Environmental Dispatching (CHPDEED) with Renewable Energy Source. Other remark, the constraints equalities are verified, that the summation of the total powers without RES are 40198,8596 MW compared at 40528,9996 MW with RES and heats generated is the same of demand, so equal 10544.99999 $MWth$.

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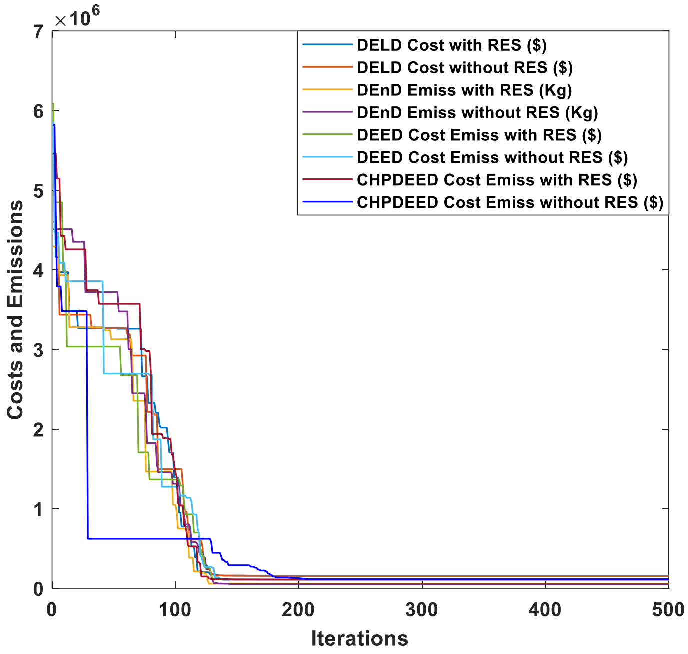

Figure-III-8. Convergence Costs with iterations for PD= 2150MW and 480 $MWth$ with commercial load.

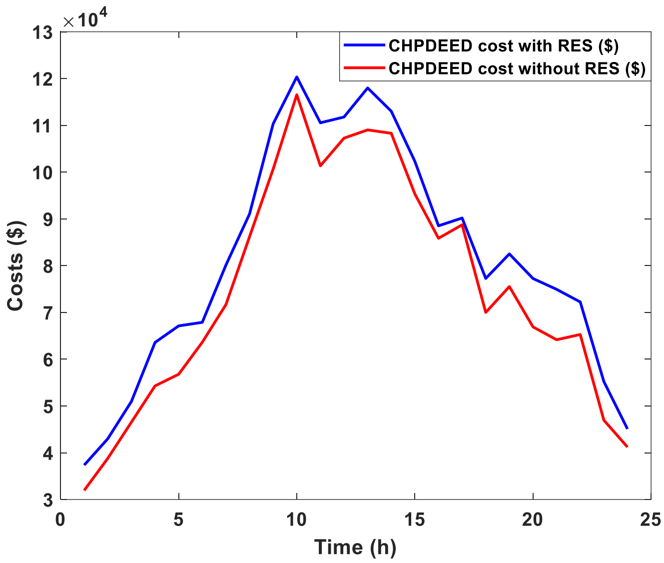

Figure-III-9. Profile CHPDEEDs Cost with commercial load.

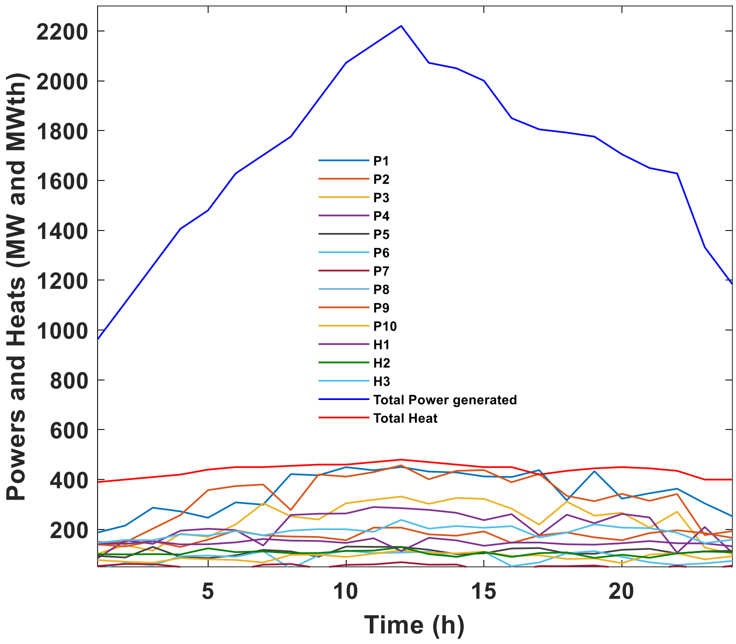

Figure-III-10. Profile powers and heats of CHPDEEDs Cost with RES and commercial load.

By analyzing Figure (III-6), in different with case 1, all the operational hours of the CHPDEED cost with Renewable Energy Source is more than the CHPDEED cost without Renewable Energy Source. As stated earlier, the heat demand is required to be always satisfied (heat balance constraint) and even though the power output and heat output for the CHP units are satisfied both the power and heat balance constraint.

The convergence characteristics shown in Figure (III-9) prove that ASO has better qualities and we conclude that ASO is favorable for large-scale power systems.

The complete power flow and demand response results for all four cases are given in Tables A1–A8 in the Appendix A.

III-3-CONCLUSIONS

This work presented the incorporation of Renewable Energy Source (Photovoltaic and wind energy) with the Combined Heat and Power Dynamic Economic Emissions Dispatch (CHPDEED) problem. The CHPDEED problem incorporates a valve point effect which leads to non-smooth and non-convex cost functions with residential and commercial load. Taken together, the CHPDEED with renewable energy source is a complicated and difficult formulation which ensures that there is optimality at both the supply side and demand side of the power system. Moreover, the optimization method using ASO, constraints and type of RE sources for the previous studies were reviewed. It presented and applied optimization method called Atom search optimization (ASO) to different test systems to minimize emission and cost for power dispatch with PV and wind. According to previous researches, it is clear that our method and non-conventional methods have high efficiency and more suitable methods for solving the CHPDEED problem. This review study hoped can help and achieve more optimal power dispatch considering PV and wind energy. Future work will consider the incorporation of heat energy storage devices to store the heat produced from the CHP and heat units.

	p1	p2	p3	p4	p5	p6	p7	p8	B1	B2	H11	H12	H13	COST($)
1	218,9227145	166.5448817	144,918674	96,3790347	91,46336841	76,07368056	47,73666325	24,10529402	103,1706007	64,98508817	144,6696907	110,0157669	135,3145424	36389,1629
2	196,4780518	145,6632501	146,5574343	120,8959649	124,3531879	83,09249031	46,47706721	29,23930452	117,6525231	91,09072588	127,7057057	97,2245888	175,0697055	38434,0622
3	173,4836812	196,4289191	123,4468304	281,4287301	113,2191463	71,83384293	42,17489151	19,12423902	126,6196084	100,970111	152,6737755	97,77958395	159,5466406	44656,128
4	258,2171477	299,7512933	155,3790968	173,7839361	123,32524	77,17062577	57,02394022	28,56152438	153,1642762	62,9629195	154,5491452	108,6556828	156,795172	54067,5111
5	327,3860485	300,634737	210,1857833	188,4817557	109,69119	53,63532703	56,19129316	24,41235156	126,5655272	75,5959867	156,0072783	108,9037097	175,089012	59446,8216
6	302,9049922	376,0488637	141,0766098	236,2825174	112,7687483	60,82284754	71,7348575	47,53539261	170,4688249	103,4463462	157,1549125	108,9868101	183,8582774	65051,7669
7	321,3106085	368,9527056	194,4193581	209,0022544	147,6360901	107,3898344	50,37613852	31,37517196	145,2258	111,3520384	138,5110966	102,5012861	208,9876174	69215,3391
8	392,0216955	322,1043081	261,6456976	275,119397	128,9740473	50,91440363	47,87081746	29,63500712	175,944851	59,93977528	119,7960131	107,3709007	227,8330862	79136,32
9	399,0288694	427,4143553	287,2493625	267,2885815	73,35953803	88,95225172	74,2769644	37,90094929	135,9822279	95,78690005	152,2069906	105,0998752	202,6931342	97560,7182
10	409,0405065	431,3512922	319,2496261	243,6274349	103,7705346	112,0481167	38,93267401	43,72811274	161,9137813	116,4379207	133,5553785	97,93680169	228,5078198	104466,287
11	439,6219294	444,6272711	314,0631806	258,5632718	117,2530769	109,1003322	53,75115737	33,90264795	178,4832526	104,4638801	150,8510983	103,6872711	215,4616306	118305,659
12	453,4757408	449,6210645	313,3806434	290,8620932	137,8289544	96,1788996	49,31216012	37,19674106	196,3666029	99,71710007	142,3778269	84,38386671	253,2383064	105952,23
13	420,4878063	446,5622538	286,6313751	256,0330383	127,3950951	118,9011763	60,99529885	41,58408589	172,668782	94,45108852	154,1822077	94,89248834	220,925304	111608,471
14	401,4418099	358,463605	327,1670685	225,2513403	120,0500808	102,6146126	41,45597331	35,21663686	157,7365556	117,4423172	164,9168244	96,61148756	198,4716881	95689,121
15	328,3739214	371,952916	281,2197114	211,9740108	122,0005948	71,97250591	69,9108963	22,37628485	165,6561886	112,22297	149,123836	100,7451172	200,1310468	77258,0576
16	319,7520248	397,3618623	180,4484426	145,7861374	74,9131896	65,2964709	53,77382568	48,75923889	164,5148769	84,38393095	146,3135188	107,1997601	196,4867211	68581,5831
17	207,6822904	328,4161276	178,4824678	230,648281	129,9865159	92,43990039	34,27880524	35,24657687	146,3244128	90,74462201	155,6719294	109,0999805	155,2280901	55542,1654
18	271,3985732	378,955845	195,9224535	245,1167427	118,068503	52,60260226	53,25157936	28,66124711	187,7834113	94,36904263	132,543634	95,5722869	206,8840791	63177,6446
19	422,8068069	314,0394794	252,9974	219,66052	115,4581502	41,42882117	45,81430374	47,49049486	201,1156891	114,4383345	132,1169379	90,85329203	222,0297701	74431,6925
20	440,5139977	408,3167868	301,961893	254,4267232	120,9105364	98,96543157	51,78725484	35,85258659	163,238315	95,85647489	132,7750753	99,02953405	218,1953907	89178,0493
21	436,8884952	428,4321879	305,603655	209,97644	122,1144262	122,7515906	37,56951526	44,28532045	157,9099769	58,31839246	138,2920712	89,0460784	217,6618504	87968,4417
22	229,7974254	409,465433	267,8751576	220,705521	112,4599527	95,65345481	64,11876712	35,01085188	118,8702228	73,73321363	136,9155044	107,0354691	191,0490265	65803,336
23	215,3616153	413,216051	150,1162946	94,05145174	101,9265219	69,60332564	45,74658488	32,14459568	136,3995549	72,36400434	135,47513	110,8493491	153,675521	54296,68
24	262,8496794	158,073	147,2427226	167,8837086	72,77100522	51,43404235	54,38873794	21,00277672	189,9632809	57,81104624	136,0341852	88,70497313	175,2608417	40216,5509

Table A1-CHPDEED Cost Emiss ($) with RES for commercial load

	p1	p2	p3	p4	p5	p6	p7	p8	B1	B2	H11	H12	H13	COST($)
1	204,619462	208,340989	89,7940546	131,249832	81,6162083	57,9755702	37,3658594	25,3635507	112,525847	78,6486258	148,432337	119,317003	122,25066	37352,6189
2	202,016887	192,628612	135,892491	124,258457	78,9893306	56,655793	44,16289	24,2906706	157,140934	85,4639342	139,040311	100,028337	160,931352	42999,4679
3	220,440899	277,912012	166,176303	100,594837	103,494736	106,647644	54,5104118	25,1460123	129,881621	63,9255234	139,303541	101,715279	168,98118	50967,6962
4	358,201992	290,879238	170,143665	94,9464152	79,1673741	53,5584549	52,9702254	32,6803407	158,377993	98,4143016	136,171161	87,1631538	196,665685	63581,0623
5	414,445764	210,757844	197,213941	146,681574	112,195804	49,9852259	55,4882863	25,3318956	171,456443	89,2232234	146,435163	100,606561	192,958276	67123,4613
6	275,356225	337,673683	264,953535	209,865417	117,592931	62,9858954	63,9392382	42,0124985	172,665	76,0155776	143,551736	103,78636	202,661904	67882,5612
7	354,496177	365,285262	270,744828	224,75034	75,7277272	57,9241371	56,5973202	47,4614628	157,05715	71,0255955	138,623291	116,315438	195,061272	80108,3615
8	414,001597	299,695516	255,763752	191,406221	139,923117	61,0224708	63,5291913	23,5491483	174,82486	110,544126	148,171988	99,2028292	207,625183	91033,1506
9	441,982957	435,532332	289,899901	251,04353	97,2036103	88,3229866	38,0154928	29,9900991	150,394948	56,9841439	136,906566	94,5344447	228,558989	110304,9
10	428,081172	423,454286	283,018968	268,781423	139,279203	100,621533	53,5942774	36,3818699	175,658545	105,908723	141,890103	116,144518	201,965379	120343,782
11	449,426608	446,03726	324,381166	272,491924	141,753107	116,474499	56,0553996	31,8147738	183,598487	103,756777	132,088532	95,9411294	241,970338	110542,457
12	435,878657	459,183261	325,32995	277,361389	146,035178	118,888442	67,0146598	43,1323413	208,14531	116,73081	131,361865	111,429002	237,209133	111774,845
13	455,329516	406,994405	299,729036	287,713003	92,9853579	104,263835	47,8097083	23,8545732	191,086516	115,94405	124,796466	106,58029	238,623244	117986,733
14	425,232179	445,739776	303,854238	254,095308	128,720166	110,348313	47,6180635	39,2318895	198,892832	59,1072353	149,32932	104,586035	206,084645	113016,026
15	416,150885	438,723533	307,845337	267,786396	130,52405	100,431184	48,5520252	36,6970892	151,4989	83,4505989	154,139303	100,49665	195,364046	102294,325
16	361,687648	423,18932	273,365827	221,446992	96,3942207	98,4245907	53,8749417	33,9268406	167,2827	101,39692	150,492165	95,5616387	203,946196	88518,8748
17	382,836193	432,411357	210,296489	261,197983	92,8459526	61,2623099	46,8883338	22,6226795	187,960369	93,6683333	138,05779	100,072101	181,870109	90177,3122
18	356,251	331,854618	298,933916	238,880331	122,29131	88,6513406	38,9147985	33,0321657	194,559721	84,4507998	143,785322	112,67029	178,544388	77263,5023
19	422,829472	353,833564	280,16674	178,459565	103,330398	72,9969773	58,139472	39,4184366	164,895548	101,179826	135,254487	95,4219907	214,323522	82509,2854
20	414,97194	281,20339	263,282489	250,677329	101,169515	64,874376	64,1184756	31,2941447	162,323634	70,9147053	152,551586	90,9902533	206,458161	77251,8393
21	365,653149	397,550987	205,68906	176,858325	105,193653	66,3071733	44,593091	36,7606422	172,389559	78,8543609	121,097245	101,312157	222,590598	74934,3168
22	412,018732	254,665016	232,692667	213,414876	118,871703	88,4177994	47,2694326	22,8736713	170,129823	67,3362788	145,068937	104,351133	185,57993	72237,1715
23	273,665177	300,316282	152,878969	134,466671	105,376463	43,5938145	51,2901135	39,7215388	155,483816	74,1371544	132,483364	90,4639532	177,052683	55223,7528
24	196,452024	214,627594	203,347332	129,946369	100,230157	50,6624601	43,9886116	24,9435098	153,061894	66,1600477	136,308646	111,618168	152,073186	45083,3392

Table A2-CHPDEED Cost Emiss ($) with RES for residential load.

	p1	**p2**	**p3**	**p4**	**p5**	**p6**	**p7**	**p8**	**B1**	**B2**	**H11**	**H12**	**H13**	**COST($)**
1	210,568553	193,490422	131,656966	106,006039	94,2623065	41,736595	52,2504272	24,6376277	115,285387	64,40567656	142,374365	117,835328	129,790306	36231,0872
2	264,387364	165,064573	124,034392	115,912489	94,8936616	44,9352106	33,2456816	37,1930102	126,776577	95,05704176	151,72003	94,5601344	153,719836	40890,8245
3	265,962448	171,464663	187,879884	142,479215	120,331162	54,2035216	39,2708961	41,8440647	132,906014	92,38813207	164,987784	106,93868	138,073537	46264,2486
4	207,759194	413,233662	174,432145	94,0631407	98,5441945	58,9865227	65,6834579	37,1121631	169,320424	70,20509559	140,650998	95,3784477	183,970554	57476,5279
5	312,006212	242,4896	248,510212	136,092998	126,437745	83,021091	37,2593586	30,5513663	153,289664	103,1217533	147,781772	110,802869	181,41536	56761,5841
6	378,715614	328,798785	118,792262	269,355334	137,470405	80,203836	38,3848465	24,9840052	180,953711	65,40120109	149,426528	117,245446	183,328026	66549,9214
7	285,469509	392,022849	253,999992	221,419218	106,393356	74,7142102	36,9963556	38,9869293	181,631074	89,43650593	132,308263	99,2066928	218,485044	72124,1388
8	373,748716	374,065343	216,24952	176,938497	129,632617	93,9265683	66,6510252	21,9339858	180,062972	101,0507563	149,980093	128,693277	176,326629	84131,5779
9	388,027949	427,243634	285,805906	258,623004	123,170611	111,840895	64,1654212	18,5492605	138,262845	63,68047337	147,236906	100,46149	212,301604	99554,9957
10	416,086675	395,714599	267,885493	260,300782	140,694159	107,151286	49,6495325	36,2902106	177,9387	113,0685636	149,692267	112,915162	197,392571	109300,175
11	395,54473	436,409794	330,651951	287,373546	134,045495	110,131906	47,6725744	48,456968	192,56411	102,9389262	153,17838	117,829047	198,992573	97247,6319
12	441,633311	449,01857	317,083194	276,689542	118,116586	114,191018	58,8792286	45,3850328	202,505885	104,1976334	157,203426	83,451061	239,345513	102271,586
13	442,893856	420,578	310,759835	270,248449	114,385199	65,4278114	62,0248025	29,6075225	208,247829	101,5366969	129,923369	96,7958673	243,280764	111334,342
14	419,86046	392,406126	302,489645	201,566911	145,05981	56,0733721	52,6223982	46,1661581	185,283386	85,31173392	144,982227	89,2021273	225,815645	98339,1052
15	340,879966	423,983865	295,967246	122,70259	119,568974	88,1207363	65,2177572	33,3247699	172,193859	95,70023628	137,037358	117,25549	195,707153	81313,7784
16	247,910131	424,047691	169,73291	219,451924	98,161199	89,4856713	46,1242229	26,3900968	123,741213	89,94494199	156,551801	112,288375	181,159824	68829,9555
17	299,23442	264,304657	142,814493	171,479412	120,268209	98,4991122	43,2868558	39,9339308	199,014791	88,15411992	152,617476	103,094287	164,288237	58643,2913
18	390,132237	301,401489	245,616344	197,417176	91,0379882	96,1770679	29,836517	29,3007114	164,773545	78,12692476	157,239184	116,59863	161,162186	67892,8837
19	367,11149	391,90798	236,219581	208,635673	120,212195	83,0218751	48,7683219	32,3059073	174,210323	112,8566543	158,853338	105,804065	180,342597	73885,9055
20	409,98304	429,387219	301,516188	265,641638	114,258251	83,6570391	54,7596992	28,1417742	204,929974	79,55517791	127,6984	100,349856	221,951744	86902,9231
21	422,110104	408,10627	273,41311	273,780036	123,84081	94,4824047	49,0790287	31,842858	169,625478	77,56990068	150,842359	104,368099	189,789542	85363,7747
22	267,457598	360,867043	289,630344	259,11251	84,3136965	73,9301231	49,551222	29,9682566	144,593264	68,26594261	126,795546	113,906766	194,297688	64203,0599
23	214,351936	308,605036	197,53466	113,637674	106,099594	58,3357274	44,7822874	34,9751664	153,189086	99,41883206	140,199508	97,4057759	162,394716	48706,1179
24	200,751409	233,908558	117,958795	167,968855	83,2481109	82,6291086	65,151524	22,5408097	99,6719263	109,5909036	144,008563	100,148336	155,843102	43105,7229

Table A3: Cost Emiss ($) with RES for commercial load.

	p1	p2	p3	p4	p5	p6	p7	p8	B1	B2	H11	H12	H13	COST($)
1	187,538104	149,721725	102,535073	84,2970399	93,7633963	41,6659358	53,1686334	32,3840213	139,398413	76,8276586	143,316833	100,512093	146,171073	31948,3534
2	215,363572	148,332039	136,698358	156,379507	87,3958366	65,5781374	61,4184643	28,2609359	131,758943	70,3142069	142,48931	99,7871491	157,723541	38810,5393
3	287,133986	203,060601	114,583072	142,140521	129,733925	56,3095736	60,8597947	35,9628394	152,590728	66,3549602	152,434503	100,874265	156,691232	46539,4738
4	272,272517	257,694044	182,597764	194,944653	89,8804582	92,502179	49,6538218	35,3385263	129,535673	84,9203628	140,011211	99,6060829	180,382706	54291,149
5	246,756647	357,757159	170,062529	202,56256	84,8480334	95,0147389	48,5452509	28,2933927	159,0169	79,922789	140,588154	124,154698	175,257148	56780,3504
6	308,370924	373,896965	219,656155	197,204894	96,0741	90,5816085	36,9335791	26,7724941	196,014195	77,5550855	147,978665	108,882498	193,138837	63621,0106
7	299,19593	380,108981	304,646323	135,498598	117,901378	112,5002	58,6665239	29,0304532	176,229244	67,29237	161,611544	112,071029	176,317427	71660,7148
8	421,798729	278,009561	252,503801	257,955802	111,805747	42,3298756	61,4882139	39,0760915	171,563232	97,7289484	154,986117	104,751131	195,262753	86173,895
9	417,097681	420,382173	239,698525	262,943544	90,4108691	95,9185708	44,503158	40,349019	169,693555	98,3729058	153,73316	105,219579	201,047261	100629,13
10	449,812458	411,782778	305,008349	263,891753	131,235871	115,062398	57,9066578	34,0832071	156,517683	89,4788447	145,84509	113,568239	200,586671	116539,402
11	437,459218	429,734595	319,245232	289,800531	129,929555	105,206418	59,6303798	45,2967671	206,908553	102,578752	164,46206	114,99645	190,54149	101346,367
12	450,409672	457,119164	331,839372	285,392509	129,733214	107,107917	68,5393083	44,7409994	207,056434	115,761409	113,105221	128,729511	238,165268	107260,034
13	431,989211	401,097009	302,675858	278,440081	118,254651	110,176879	58,4785322	37,9506719	180,22955	106,417557	166,185041	100,730478	203,084481	109021,7
14	428,576073	434,853412	326,201327	266,645321	101,037539	89,0978618	59,1642681	28,5546312	174,811948	103,897621	156,021251	90,3726146	213,606135	108295,331
15	412,670524	438,085689	322,503494	237,133539	104,107251	110,0188	33,57023	20,6432611	191,929483	110,997728	134,392595	108,986471	206,620934	95317,7419
16	410,181245	389,432714	283,294682	261,19259	123,385509	52,599832	35,1324339	37,1386677	145,549823	93,0825036	147,159035	89,7575041	213,083461	85852,4473
17	437,848487	422,616113	219,320858	176,253473	125,322764	67,330654	52,8126189	17,9256499	175,986684	96,572698	147,340898	104,96555	167,693552	88727,2542
18	316,775647	334,73884	311,406831	259,033169	103,596163	104,664042	52,6543243	35,9131059	187,748538	81,2893391	140,467278	107,57839	186,954332	69996,7546
19	433,396408	313,157133	255,060938	224,81134	102,369466	112,805981	55,1926522	26,6630499	168,305318	83,4877147	138,844885	85,7301015	220,425014	75522,6396
20	323,599751	342,607257	266,96145	262,276522	118,170544	90,1211878	44,6272454	35,2161367	156,68651	64,5633966	144,539087	98,2390282	207,221885	66905,9341
21	345,018969	314,739525	206,925605	247,930243	122,279138	67,8850608	39,4674969	21,1204125	185,391864	99,0916846	153,316526	86,5599397	205,123534	64161,53
22	363,26551	342,016046	271,102035	106,241823	103,444404	57,4627358	54,2834092	28,7685389	196,635235	104,470263	144,420482	103,867312	186,712206	65280,1563
23	304,413315	177,293424	127,379653	209,617029	111,936262	63,9454285	40,821237	30,6941927	185,00322	79,8262393	143,813684	111,243749	144,942566	46966,5444
24	252,821902	193,137107	101,46088	105,848432	114,23923	73,4097372	54,7009048	29,1834247	166,076105	92,542278	132,389119	108,539217	159,071665	41215,8542

Table A4- Cost Emiss ($) with RES for residential load.

Parametre	p1	p2	p3	p4	p5	p6	p7	p8	B1	B2	H11	H12	H13	Pl	Objective function($)
DELD Cost with RES ($)	8043,04875	8296,3408	5842,87377	4547,97367	2819,44212	1905,60921	1210,66116	800,170449	3985,74611	1999,79396	3459,82061	2524,25816	4560,92122	234,8156	2683619,3981
DELD Cost without RES ($)	8618.3183	8181.6369	5529.8496	5073.3437	2597.8138	1874.7619	1164.8119	774.3630	3862.7442	2170.3568	3377.1319	2557.5314	4610	241,0088	2637831.07
DEnD Emiss with RES (Kg)	8229,08566	7731,76138	5782,32472	5013,19502	2734,22316	1851,39023	1220,22707	864,973769	3983,96092	2040,51808	3471,75234	2495,89378	4577,35389	233,4223	830056,7769
DEnD Emiss without RES (Kg)	8735.9875	8293.1270	5280.6717	4925.3711	2803.8606	1906.9727	1279.7070	751.8370	3824.8128	2045.6527	3419.8077	2491.4401	4634	243,0209	732228.15
DEED Cost Emiss with RES ($)	7962,58692	8348,52042	5540,63507	4816,89665	2744,44634	1944,88271	1201,31344	790,422586	3950,97204	2150,98382	3513,28994	2542,53531	4489,17475	233,4160	1757325,159
DEED Cost Emiss without RES ($)	8262.8422	8389.2584	6026.7267	4635.6149	2540.7338	1989.1593	1253.2682	784.7154	3889.0148	2076.6664	3441.8910	2533.8195	4569	241,1750	1666807.25
CHPDEED Cost Emiss with RES ($)	7812,1754	8182,61372	5671,43394	5281,87549	2662,43387	1841,63319	1287,2128	831,674615	3848,17522	2032,43176	3423,63593	2487,02638	4634,33769	234505,398526	1871348,727
CHPDEED Cost Emiss without RES ($)	8686.9515	7992.7754	5738.9128	4729.5257	2848.4624	2142.8702	1267.2026	814.6385	3589.6419	2037.0190	3490.5110	2540.0207	4514	243931,473489	1810099.47

Table A5- Comparison case 1 of CHPDEED.

Parametre	p1	p2	p3	p4	p5	p6	p7	p8	B1	B2	H11	H12	H13	Pl	Objective function($)
DELD Cost with RES ($)	7891,3205	8868,2861	5807,5339	4975,9334	2728,3153	2038,0231	1288,4457	729,0351	3697,3966	2108,3701	3380,7949	2479,8119	4684,3931	245,7203	2772263,729
DELD Cost without RES ($)	8533,4954	8276,0243	6094,1977	4852,2107	2838,6688	1962,7129	1259,3632	801,0426	3754,8937	2156,3903	3519,6555	2572,6788	4452,6655	250,1911	2674936,991
DEnD Emiss with RES (Kg)	8373,7945	8355,1792	5700,9930	4988,3953	2670,9045	1951,2511	1281,5986	782,4283	3918,9336	2109,1814	3362,6604	2513,8467	4668,4927	243,9645	867710,2329
DEnD Emiss without RES (Kg)	8346,9351	8359,4638	5958,2213	5236,4331	2749,3697	1938,7419	1247,3401	838,3678	3741,7750	2112,3518	3362,5433	2521,3159	4661,1407	250,2423	752207,5585
DEED Cost Emiss with RES ($)	8453,7664	7971,3740	5673,3681	5108,4354	2640,8553	2019,2957	1242,2191	769,3604	4110,6378	2143,3473	3509,45175	2509,7230	4525,8251	240,9959	1792864,308
DEED Cost Emiss without RES ($)	8291,4541	8173,5385	6095,6446	5125,3798	2809,7650	2013,9381	1284,4564	754,7315	3889,3128	2090,7788	3490,2240	2513,6400	4541,1358	248,1796	1690856,538
CHPDEED Cost Emiss with RES ($)	8682,0263	8228,4901	5805,3946	4908,3745	2610,9112	1881,2968	1236,3003	771,5318	4021,2924	2053,2416	3365,3412	2460,3087	4719,3500	245,4747	1950510,842
CHPDEED Cost Emiss without RES ($)	8480,0989	8468,2632	6027,5029	5122,8523	2586,8333	2075,7628	1201,3448	795,1256	3670,4616	2100,7542	3393,1511	2499,6771	4652,1717	252,0143	1851253,292

Table A6- Comparison case 2 of CHPDEED.

	p1	p2	p3	p4	p5	p6	p7	p8	B1	B2	H11	H12	H13	COST($)
1	183.5139	143.7900	149.4428	88.0207	120.0998	68.2157	51.4858	31.1420	126.1528	74.1366	160.2070	121.9389	107.8540	38870.1532
2	210.7353	174.7092	190.8803	80.1922	82.4714	109.3785	46.5101	27.3153	107.9704	79.8374	123.6843	114.0530	162.2627	42473.0419
3	383.9979	147.2285	112.9252	115.2776	124.9761	51.0013	64.8610	40.2790	115.0542	102.3992	147.4086	104.5536	158.0378	55883.9268
4	298.0982	283.4348	219.4083	148.9863	100.8597	57.8879	47.7435	21.1994	154.8558	73.5260	150.1724	101.2966	168.5311	58716.0035
5	294.1166	270.8256	178.1325	246.5995	137.9901	69.5624	47.1471	31.7104	139.8484	64.0675	153.1421	106.7561	180.1018	61056.7966
6	394.4302	312.7460	264.4598	255.5657	92.2226	53.5718	39.3957	36.0998	123.4663	56.0420	134.6238	103.5608	211.8154	74162.0376
7	438.8189	273.4650	224.4911	200.6597	122.6431	106.6035	56.1959	45.4398	141.6031	92.0799	134.9061	105.9224	209.1715	78480.3314
8	413.8899	413.8067	262.9550	182.3381	100.6489	82.5461	43.9625	19.3251	172.8540	83.6737	149.2778	112.9363	192.7859	84975.6542
9	446.1456	405.3751	287.9432	238.0172	126.6201	83.6684	49.4534	23.8420	159.9418	102.9933	155.9258	97.0012	207.0730	93522.9835
10	438.3094	442.3243	294.9689	259.6681	112.5584	105.5361	47.1704	37.8174	178.4340	105.2131	132.3369	106.1517	221.5113	98887.1152
11	436.3355	454.4031	324.4966	273.4478	131.3282	99.3726	53.5928	39.9309	192.1292	100.9634	164.6949	107.4748	197.8303	103326.7563
12	452.9141	444.4230	326.2670	281.8874	133.0611	102.6827	62.1340	45.8169	187.0661	113.7477	129.6331	101.0030	249.3639	106190.5208
13	455.8819	435.3045	293.5023	277.5537	132.5114	111.2492	60.5696	29.6278	184.5504	91.2491	166.4262	109.0195	194.5544	101990.4434
14	423.4774	405.9683	316.2050	194.4351	130.9835	102.3291	47.3813	35.1126	163.3967	104.7110	151.7471	116.4826	191.7703	90710.0678
15	385.9633	418.4231	230.8232	220.9562	91.2799	99.8857	61.4986	29.7806	163.6988	73.6906	156.8630	116.9701	176.1669	82542.3113
16	332.5357	278.3631	241.5621	188.3905	123.9856	69.2250	41.9234	44.2326	160.6522	73.1296	142.0825	112.3739	195.5437	65205.7337
17	313.7525	265.1302	249.7675	154.1532	112.5094	97.9824	51.7137	31.5492	138.5203	64.9215	165.5115	111.1916	143.2970	61327.5977
18	277.1915	374.3378	228.1049	204.3529	123.2092	96.7433	63.7147	21.8786	152.8788	85.5882	151.0163	103.3715	180.6122	68711.0349
19	385.4364	418.4688	266.9519	182.3391	141.9169	99.2182	44.2259	34.1385	138.8313	64.4730	132.7950	115.6225	196.5825	82862.46
20	438.3344	419.3989	264.2179	275.0774	111.6701	104.6360	61.5123	32.4987	178.9231	85.7313	126.2049	110.1035	213.6916	94786.5656
21	425.0507	437.7036	278.1799	181.9108	146.9674	108.2387	59.3996	43.6933	160.9695	81.8865	142.4420	99.9596	202.5984	93068.8618
22	251.3208	328.9296	258.0126	256.8967	119.0851	102.9356	59.2628	37.2320	117.9295	96.3953	146.9326	93.8499	194.2176	67193.6003
23	358.7558	204.2804	166.7980	78.7138	127.5926	94.2833	57.4470	39.2641	111.2318	93.6332	125.1798	89.6263	185.1939	56911.9035
24	247.9455	239.9358	108.4170	144.0860	101.2720	66.1167	48.9015	35.7124	118.6833	72.9298	147.2972	78.8016	173.9012	48243.5695

Table A7- CHPDEED Cost Emiss ($) without RES for commercial load.

	p1	p2	p3	p4	p5	p6	p7	p8	B1	B2	H11	H12	H13	COST($)
1	176.3179	154.0849	107.9801	106.3583	83.3826	63.1046	54.1634	31.1157	112.6227	73.8698	138.5775	102	149	36673.9872
2	221.0952	146.4458	144.9120	103.2368	90.7362	89.5649	30.9026	38.0793	142.9917	102.0354	135.5159	116	148	42213.8981
3	199.8357	355.3289	166.0202	96.9848	89.7586	62.0115	48.9885	34.5200	134.8583	69.6935	145.9103	105	159	52117.9388
4	312.6264	345.8675	211.4587	81.3924	70.2779	83.1991	43.5935	21.8274	163.3817	72.3754	174.1320	112	134	60924.4859
5	255.5706	252.1108	241.1828	177.3915	88.8745	101.1773	55.4695	28.4498	191.9901	87.7831	117.1800	111	212	58130.1097
6	300.3673	326.4130	263.6630	248.1113	101.0612	66.6758	45.4966	26.3798	179.6857	70.1464	123.7211	104	223	67843.2037
7	349.8461	366.7430	245.4797	234.8982	77.1924	89.7553	55.0568	31.8332	145.7494	105.4458	153.7578	106	190	74999.3682
8	364.5760	363.2271	288.2926	250.1600	100.6088	106.2377	57.9186	44.5317	112.6218	87.8258	137.1112	109	209	79007.906
9	421.1873	423.6601	271.6504	290.4031	95.7792	95.8187	30.5217	32.5853	157.3270	105.0670	147.8583	105	207	92887.5768
10	445.7828	426.3943	303.0591	273.4518	131.6579	106.5098	60.6639	30.7478	186.0375	107.6949	145.1712	112	203	100117.8374
11	445.2878	447.8654	321.0428	270.4971	145.3953	120.3682	56.1511	41.0048	204.4486	93.9388	157.3769	89	224	104450.2991
12	469.3473	469.7274	323.1194	294.0542	159.5267	126.7155	79.2633	43.6013	130.7593	123.8856	113.1974	82	285	114864.287
13	437.6163	452.0388	317.6891	272.7204	114.2023	89.0485	61.3102	32.4604	209.0417	85.8723	148.0197	113	209	101649.4991
14	447.9934	449.8810	311.2103	272.9099	111.8095	98.6331	42.5940	35.0262	174.6745	105.2681	155.7396	91	214	102200.2809
15	417.0689	439.5768	294.6568	256.9194	136.5995	81.3022	62.3016	26.5356	177.9390	107.1001	140.2103	96	214	96262.6517
16	379.3308	385.1100	278.4752	253.8097	116.5317	105.8081	62.9924	34.2505	150.1627	83.5291	115.4770	102	233	83030.1153
17	449.7360	432.4542	268.9643	194.2262	92.1489	102.8099	41.2512	22.4669	118.6507	82.2916	125.7296	95	199	91632.4695
18	407.3852	398.2836	287.5683	264.4793	96.4907	57.5076	38.3419	35.9540	143.2310	62.7583	119.3750	104	212	84881.7485
19	432.8023	297.2745	273.9781	236.9621	94.5101	101.3080	48.6570	23.5045	178.8273	88.1760	130.9644	102	212	80850.0134
20	315.5881	391.3090	229.7071	199.1183	123.0923	101.2839	40.0128	34.9438	194.3611	75.5836	152.3550	105	192	72788.624
21	339.3880	450.3848	304.1333	160.1384	127.5437	36.6171	44.8383	35.2256	96.2616	55.4692	171.1902	111	163	80194.5458
22	415.1980	304.3672	203.7262	196.7003	123.6598	81.7303	62.9925	42.8352	112.9093	83.8811	152.3633	113	169	75062.2992
23	296.9333	201.8323	195.9525	212.7585	90.1080	53.4700	44.8488	30.2879	128.8884	76.9203	148.1939	96	156	53808.3162
24	179.2182	187.8830	173.5808	175.1703	125.8855	55.1053	33.0146	36.9589	123.0404	94.1429	144.0236	118	138	44661.8306

Table A8-CHPDEED Cost Emiss ($) without RES for residential load.

	p1	p2	p3	p4	p5	p6	p7	p8	B1	B2	H11	H12	H13	COST($)
1	184.6907	173.0007	136.7492	99.7730	98.9212	80.2238	40.9873	35.3145	102.1606	84.1791	150.3205	115.7363	123.9432	35388.2990
2	176.0996	203.7524	170.5731	129.4877	104.8557	51.3775	42.4284	34.8377	134.2861	62.3017	159.3184	83.6426	157.0390	37116.2313
3	278.0816	214.7855	219.6427	112.6477	94.3284	70.0302	48.9137	29.0391	115.5321	74.9990	118.1540	104.1187	187.7272	47082.0379
4	254.2639	290.6650	261.1115	153.0250	74.4343	59.5617	37.4182	36.6768	151.5105	87.3330	150.2556	93.3652	176.3792	52994.5162
5	281.9188	353.2200	214.5987	136.9710	81.1415	90.7668	49.7809	34.4498	142.5593	94.5931	137.0257	117.9472	185.0271	58232.4767
6	270.8138	326.5996	236.7114	264.9599	91.1790	91.9625	42.5203	34.9858	188.7247	79.5430	145.8756	124.7108	179.4137	60871.7466
7	354.5754	407.1653	217.6910	174.7907	99.3439	85.4835	45.3657	42.7481	189.7065	85.1299	144.0777	107.8854	198.0369	70681.6628
8	273.2122	430.1362	298.5066	222.6893	131.1248	75.5666	50.4838	31.7978	162.1954	100.2872	158.2994	90.4874	206.2132	73452.6813
9	405.3524	343.0210	297.1756	268.7464	90.0552	115.3128	68.4122	42.5776	183.3597	109.9872	143.4986	104.0823	212.4192	79877.6141
10	438.3754	434.0968	329.1613	247.9200	136.4049	102.1044	60.4400	23.2909	172.1176	78.0887	136.9022	101.0623	222.0355	92695.0020
11	434.1710	444.9398	324.1981	239.9811	135.4283	115.9480	74.1440	49.4751	185.8131	101.9015	133.8066	102.1386	234.0548	95771.2529
12	455.7981	459.0425	306.4656	266.7379	144.6815	115.3619	57.0041	28.6630	203.8846	112.3610	128.2554	86.1262	265.6184	100610.6532
13	438.2386	439.3036	307.5554	275.2785	122.1602	99.5765	56.0690	40.9769	190.0044	102.8368	161.8824	102.3800	205.7376	94673.6464
14	449.6622	422.7397	281.1639	221.0163	127.0208	101.8129	54.6967	28.2147	166.5562	71.1166	146.0747	103.9927	209.9327	88729.0450
15	406.6862	303.1766	258.8041	245.7269	107.2828	88.9160	70.2031	24.5731	183.8278	86.8034	144.4968	120.2256	185.2776	73190.5564
16	410.2169	322.4479	279.2801	108.0677	88.6065	47.8181	54.8320	17.3614	157.4867	67.8827	116.1406	92.4360	241.4233	67049.8260
17	315.1113	310.6225	238.9724	180.3567	93.8814	97.5366	43.6942	27.1910	106.7252	65.9087	141.4881	115.6538	162.8580	58715.7664
18	410.0558	272.7064	276.1583	188.4998	98.5660	42.0934	52.6966	23.8609	150.9069	112.4559	160.2781	120.5748	154.1471	69059.3176
19	397.2576	417.0377	248.6795	177.1620	115.3733	72.1955	53.0552	32.7651	204.5951	57.8790	139.0825	121.3575	184.5600	76965.3114
20	393.1366	417.4360	284.6877	259.6202	142.1905	93.7943	62.0115	41.6810	173.1072	104.3351	134.9684	95.3325	219.6991	85388.4681
21	397.2190	448.5077	310.9900	212.4873	106.5128	74.7411	60.3792	30.0377	192.3808	90.7444	156.4148	110.3791	178.2061	86170.6394
22	388.3742	357.8935	162.3736	236.2855	93.4245	76.5634	53.4603	32.3804	172.2438	55.0008	158.8668	105.8289	170.3043	67705.3250
23	228.5273	348.7822	217.8193	108.7628	69.3094	61.7530	36.8301	34.3662	139.5903	86.2594	130.8118	110.6407	158.5475	51307.9718
24	221.0037	248.1797	147.6575	104.6216	94.5069	78.6589	37.4415	27.4508	119.7401	104.7394	145.5961	103.7151	150.6888	43077.2056

Table A9: Cost Emiss ($) without RES for commercial load.

	p1	p2	p3	p4	p5	p6	p7	p8	B1	B2	H11	H12	H13	COST ($)
1	163.5196	166.8481	135.3152	91.3686	110.4127	47.4274	39.0849	28.9562	104.1672	75.9001	162.1264	110.6393	117.2343	32427.5335
2	219.8240	193.1079	122.2289	126.2295	113.0698	47.6063	43.2608	23.4488	129.6571	91.5669	157.1525	109.7241	133.1233	38537.5877
3	281.7101	231.9343	162.6331	156.7679	83.1631	78.0258	47.1064	27.2287	103.7441	85.6864	150.1798	114.6054	145.2148	48060.3417
4	313.0792	174.0664	299.0851	161.2156	84.5691	67.7412	49.0183	23.4046	150.4260	83.3946	138.0912	99.9685	181.9403	52196.9841
5	239.7996	253.6363	198.8739	270.3197	133.0072	116.1368	33.4946	27.9661	122.9239	83.8419	142.9558	105.9338	191.1104	54259.7852
6	400.2035	303.4761	270.8190	204.5770	79.8808	50.5632	39.6633	20.9245	173.4351	84.4574	143.3518	119.2487	187.3995	67895.7690
7	333.6111	347.2670	210.1646	239.5968	123.3086	114.6791	44.1204	29.1196	168.3166	91.8161	140.7801	118.7001	190.5198	66275.4983
8	361.0919	373.4752	270.5833	251.4692	142.2803	62.4608	58.3771	36.2155	141.2567	78.7899	133.8737	90.7179	230.4084	73836.2809
9	442.9543	381.0974	325.1571	286.0544	122.3427	82.4439	45.2099	36.6058	114.4847	87.6498	130.5998	102.6169	226.7833	88352.2030
10	448.2520	442.5197	289.7914	280.8474	133.3346	104.9914	48.0861	43.4261	182.3408	98.4105	142.5137	104.7592	212.7271	96087.2178
11	439.4148	449.3679	329.1739	277.8653	146.1925	95.7461	65.0420	38.7665	194.8947	109.5364	123.8937	117.4300	228.6763	98788.8132
12	456.9975	461.0591	332.6582	290.2369	147.6787	117.4142	74.1949	34.1644	202.3791	103.2171	160.0787	92.6231	227.2983	103983.4353
13	445.1256	427.7991	297.0684	268.8455	139.5884	106.9114	67.5379	39.2648	187.4728	92.3860	129.8717	118.9458	221.1825	94178.1265
14	447.6819	445.9102	324.2654	275.5852	134.7500	88.4361	37.1806	35.4889	176.1773	84.5244	135.5243	101.2644	223.2113	96189.3627
15	388.1983	440.5938	298.6712	280.2036	124.1882	112.4405	61.7206	44.3284	183.0760	66.5793	151.0796	82.5983	216.3220	87350.5432
16	330.5500	420.9872	306.2503	271.0874	81.7490	73.1680	65.3205	34.1014	192.6197	74.1665	165.3962	110.1505	174.4533	77191.1984
17	410.6954	353.5111	259.2641	239.9659	76.2743	94.4337	54.4177	37.3955	198.3766	80.6656	140.7271	119.2500	160.0229	75592.9402
18	314.9436	454.0394	293.3427	210.3807	124.2051	94.0985	62.0717	17.4847	123.5459	97.8878	148.9985	92.2389	193.7626	78915.5827
19	368.4230	359.3227	214.9732	270.9517	150.0291	39.3023	61.4901	39.4704	200.8212	71.2165	142.7994	94.9896	207.2109	71391.4355
20	397.0615	343.4658	240.8837	166.6502	132.1065	81.5465	61.2449	29.1665	150.0329	102.8415	138.2752	115.1222	196.6026	72044.5562
21	396.2261	291.6910	321.8239	98.3412	102.8529	87.6855	62.5155	23.4738	192.7699	72.6203	153.8607	95.0252	196.1141	67251.1370
22	292.6521	304.1229	279.8968	203.2957	120.7955	86.5189	59.7563	26.6397	166.8539	87.4683	148.5798	93.1676	193.2526	61369.1147
23	206.9862	283.9437	200.6383	118.9875	120.8190	78.2842	48.4800	23.6107	157.1103	93.1402	143.6771	97.7127	158.6103	47558.7596
24	192.4528	270.2960	112.0829	84.5370	83.1670	85.8763	56.0618	34.0804	172.4305	93.0153	165.8374	106.2076	127.9550	41122.3311

Table A10: Cost Emiss ($) without RES for residential load.

GENERAL CONCLUSIO

GENERAL CONCLUSIONS

The Combined Heat and Power Economic dispatch (CHPED) and Combined Heat and Power Economic Emission Dispatch (CHPEED) Combined Economic-Emission Dispatch (CEED) with integration of renewable energy source RES are a non-convex, nonlinear, and hard constrained combinatorial problem. This conundrum becomes complex as it deals with two conflicting objectives of fuel cost and the mass of emissions. In this study, a novel physics-inspired metaheuristic algorithm, namely atom search optimization (ASO) algorithm, has been developed for global optimization problems. ASO is inspired by the basic molecular dynamics to mathematically establish the atomic motion model, which is based on the interaction and constraint forces. In ASO, each atom is affected by the attractive force or repulsive force from its neighbors and the constraint force from the atom with the best fitness value. The atomic motion follows Newton's second law. The attractive force encourages atoms to explore the entire search space extensively, and the repulsive force enables them to exploit the promising regions intensively. The proposed ASO is tested on different CHPEED case studies.

It can be found that proposed ASO outperform better than the mentioned methods to provide good quality of compromise solution and found to be better optimization method for solving hard constraints problem. This study is limited to solve multi-objective Combined Heat and Power Economic Emission Dispatch (CHPEED) problem with integration of RES and ASO approach consisting of thermal generators, CHP units and heat units with limited constraints. The constrains considered in this work is limited to power & head balance constraints, minimum & maximum limits of electrical generators, CHP units and heat generator units. However, this proposed ASO can be extended to solve CHPEED problem in the presence of renewable energy sources, for cost benefit analysis with related constraints.

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