Abstract—Computational Intelligence algorithms have gained a lot of attention of researchers in the recent years due to their ability to deliver near optimal solutions. In this paper we propose a new hierarchy which classifies algorithms based on their sources of inspiration. The algorithms have been divided into two broad domains namely modelling of human mind and nature inspired intelligence. Algorithms of Modelling of human mind take their motivation from the manner in which humans perceive and deal with information. Similarly algorithms of nature inspired intelligence domain are based on ordinary phenomenon occurring in nature. The latter has further been broken into swarm intelligence, geosciences and artificial immune system. Geoscience based is the new domain whose algorithms are based on geographic phenomenon on the earth’s surface. A comprehensive tabular comparison is done amongst algorithms in each domain in various attributes such as problem solving method, application, characteristics and more. For further insights, we examine a variant of every algorithm and its implementation for a specific application. To understand the performance and efficiency better, we compare the performance of select algorithms on travelling salesman problem.

Index Terms—Computational Intelligence, Nature Inspired Algorithms, Swarm Intelligence, Real life applications, travelling salesman problem.

I. INTRODUCTION

Optimization refers to maximizing or minimizing a particular function by exploring the solutions in a guided manner and it is a sought after research area because it includes development of a solution under the given constraints, much like real world scenarios. Computational intelligence algorithms are a class of optimization algorithms. Commonly known as soft computing their key application is in the area of NP-hard problems to find optimal solutions or near optimal solutions in polynomial time. Due to the sheer number of computational intelligence algorithms and their variations, there is a lack of hierarchy and their basis for classification. Hence in this paper, we propose our own hierarchy where the algorithms are classified based on their sources of inspiration. Two broad categories are nature inspired and modelling of human. Modelling of human mind aspect deals with the techniques based on human cognition while nature inspired domain has been further broken down into artificial immune systems, swarm intelligence and geosciences based algorithms. The latter are a new domain of algorithms that we have introduced and compared with respect to their affecting factors and equilibrium condition. Under each of the domain a wide variety of algorithms have been taken under consideration from the fundamental ones to the latest developments in the domain. A tabular format has been used for every domain to facilitate an exhaustive and concise comparison. Numerous attributes ranging from nature of solution to characteristics to problem solving method have been included. To further explore into the far reaching applications and effectiveness of algorithms, we take a variant of each algorithm and understand its working towards a specific goal. A select number of algorithms have been chosen and applied to travelling salesman problem to draw a comparative conclusion amongst one another. In section II, we take a look at each of the classification domain, their algorithms and their respective properties. Section III gives a brief about a variant of the algorithm and their application in a
specific domain. The results of applying various algorithms has been dealt with in section IV followed by concluding remarks.

II. OVERVIEW OF COMPUTATIONAL INTELLIGENCE DOMAINS

Computational Intelligence algorithms simulate the way human’s reason by incorporating their rate of efficiency and randomness during decision making. They have broadly divided into techniques based on modelling of human mind and nature inspired algorithms. A complete list of algorithms taken under consideration are mentioned in Table 1.

A. MODELLING OF HUMAN MIND

This domain of techniques are based on human cognition, designed to understand the manner in which the human brain processes information. All the approaches based on the modelization of human mind tend to be generalized to the form of integrated computational models of synthetic/abstract intelligence, applied to the explanation and improvement of individual and social/organizational decision making and reasoning. As part of this domain we have considered the algorithms as listed in table 1.

Rough Set theory [1] aims to learn total or partial dependency in data while eliminating redundant data. The inference mechanism of rough sets takes polynomial time with respect to the largest domain of the variables in the decision tables. Rough mereology and ontology based are some of the extensions. Extension of the classical notion of set lead to Fuzzy Set Theory [2] which the membership of a set in terms of a possibility distribution. Rules for defining the fuzziness of a set are fuzzy too. The membership can be broken down into core, support and boundary regions. Value of the membership range includes the entire range of zero and one. Majorly used variants are L-fuzzy sets and disjoint fuzzy sets. Granular computing [3] as the name suggests deals with processing information in the form of granules of different sizes which leads to formation of a pyramid hierarchy architecture. Lowest level of such pyramids deals with processing of low level data such as numerical data while the top of the pyramid represents symbol computing. As we traverse from top to bottom we encode information while the reverse is called decoding. The layers communicate amongst themselves and is commonly used in knowledge discovery databases. Perception Computing [4] is based on the idea of human perception i.e. the way in which the human mind perceives the environment. The idea is to make use of natural language to perform computing tasks. A vocabulary has to be specifically defined for every different problem as well as its construction. It is made of an encoder, words computing engine and a decoder. Words are passed on to the words-computing engine which passes it on to the decoder. This output in the form of a recommendation can be a word, rank or class. Common applications are data mining, distributed decision making. Performing tasks based on the events which are yet to occur in the near future is the basis of Anticipatory computing [5]. A vital component of natural cognitive systems it adapts to the environment and follows the routine expectation-forecast-prediction. The environment, past events and the predictions affect this system which can be applied to voice assistants, home automation. Wisdom technology [6] derives its inspiration from ubiquitous computing. Based on knowledge sources network, adaptive judgment and interactive processes it is expensive and computationally intensive. The primary reason for the lack of development is the failure to model adaptive judgment.

B. ARTIFICIAL IMMUNE SYSTEMS

A domain of computational intelligence algorithms based on immunology is Artificial Immune System. The biological immune is made up of two components. Firstly, the innate immune system possess a fixed set of rules to identify and eliminate foreign cells. Secondly, the adaptive immune system responds to unknown foreign cells (previously un-
encountered). It a robust, complex and adaptive system. Under this domain we take a look at the algorithms as listed in table 1.

Clonal Selection Algorithm [7] is based on the response of the immune system to antigen cells. In this new cells are cloned of their parents by means of somatic hyper-mutation (high rate mutation). When an antibody and an antigen match, it leads to cloning of antibodies thereby increasing the production of antibodies. Cells which are identified by the antigens grow their population while the others do not. Its application is in pattern recognition and combinatorial optimization. Negative Selection Algorithm [8] takes inspiration from the self vs. foreign discrimination behavior of the immune system. The aim of this system is to develop tolerance towards self-cells i.e. identify and remove cells which are self-reactive during cell creation as well as cell proliferation. Production of T-lymphocytes follows this routine. Lack of detectors dependence supports distributed and parallel architecture. It is majorly applied to classification domain and in intrusion detection role of dendritic cells, Dendritic Cell Algorithm [9] was developed. This canonical algorithm creates a set of dendritic cells which assist in classification of input patterns by providing context specific information. These are the type of signals involved - pathogens associated molecular patterns, safe signals resulted from programmed cell death and danger signals derived from uncontrolled cell death. The danger and safe signals are problem dependent. Deterministic Dendritic Cell Algorithm is a common variant. One of the first nature inspired algorithms to be developed, Genetic Algorithm [10] is a metaheuristic algorithm based on natural selection by selection of fittest individuals of a generation to reproduce. The phases of the algorithm are initialization, fitness, selection, crossover and mutation. Adaptive Genetic Algorithm and Coarse Grained Parallel Genetic Algorithm are some of the variants. The phases of the algorithm are initialization, fitness, selection, crossover and mutation. Adaptive Genetic Algorithm and Coarse Grained Parallel Genetic Algorithm are some of the variants. Feature selection, engineering design and travelling salesman problem are some of its applications. The algorithm with the widest range of applications is Artificial Neural Network [11]. It is inspired by the neuron networks that exist in the brain. The structure of a neural network can be broken into input layer, middle layer and output layer. The input layer is a single layer of neurons followed by n number of middle layers and then a single output layer. Each neuron in a layer is connected to every other neuron in the adjacent layer(s). This system learns the patterns present in the input data by assigning weights to each edge. Convolution neural network, Long Short Term Memory, Deep belief networks are some of the commonly known variants. Application areas include diagnosing cancer, predicting natural calamities, sequence recognition, spam filtering, finance modelling and many more. Cellular automata [12] is a discrete system comprising of a group of cells which update their state depending on the neighbors. A common update rule is applicable for all the cells. For any cellular automata system all the cells are contained on a grid, every cell possess a neighborhood and each cell has a finite state. Some of the variants are Probabilistic Cellular Automata, Continuous Cellular Automata. A few of the application areas are computer processors, error correction coding. Membrane computing [13] or P-systems takes its inspiration from the structure of cell membrane of a biological cell. It deals with multiple datasets of symbol objects in a localized manner. Multiple layers of cell membranes allow encapsulation of elements. Major components of a P-system are membrane structure, multiple sets of objects and reaction rules. The main types are Cell like P-system, Tissue like P-system and Neural like P-system. DNA computing is based on its ability to perform the same operation simultaneously and has the potential to tackle computationally difficult problems that have real world implications. DNA computing is characterized by its ability of fast and parallel information processing, remarkable energy efficiency and high storing capacity. Since the duration of the operation does not depend on the size of the problem, operations can be performed in parallel with no added cost.

C. GEOSCIENCES

Geoscience is a study of earth and its physical components which include rocks, minerals, mountains, etc. It also includes study of the processes ongoing in the earth’s atmosphere, earth’s surface or beneath the surface of earth. The algorithms under this domain take inspiration from such phenomenon. They involve complex nonlinear dynamics which
can lead to exponential time periods. Under this domain we will be taking a look at plate tectonics, ocean currents, and volcano eruptions and earthquake. The outer layer called the lithosphere is a hard rocky layer which includes the crust and the upper part of the mantle. The asthenosphere is present below the lithosphere which comprises of liquid or semi-solid mantle. The driving force behind plate tectonics is convection in the mantle. Hot material near the Earth's core rises, and colder mantle rock sinks. Many factors such as gravity, wind, heat contribute to the directed movement of sea water commonly known as ocean currents. Ocean conveyor belt is the continuous movement of water in the ocean which occurs at the bottom and surface of the ocean. Generally the currents flow in a clockwise fashion in the northern hemisphere and in the opposite manner in the southern hemisphere. There is always a balance maintained between the gravity and the Coriolis force. This equilibrium leads to the balanced flow of water called the Geostrophic current due to which the season changes are maintained on earth.

| Algorithm                                      | Author             | Year | Reference |
|------------------------------------------------|--------------------|------|-----------|
| Rough Set                                      | Pawlak et al       | 1982 | [1]       |
| Fuzzy Set                                      | Zimmerman et al   | 2010 | [2]       |
| Granular Computing                             | Pedrycz            | 2001 | [3]       |
| Perception based Computing                     | Skowron et al      | 2010 | [4]       |
| Anticipatory Computing                         | Nadin et al        | 2000 | [5]       |
| Wisdom Technology                              | Jankowski          | 2009 | [6]       |
| **MODELLING OF HUMAN MIND**                   |                    |      |           |
| Clonal Selection                               | De Castro et al    | 2000 | [7]       |
| Negative Selection                             | Ji et al           | 2007 | [8]       |
| Dendritic Cell                                 | Greensmith         | 2005 | [9]       |
| Genetic Algorithm                              | Mitchell et al     | 1998 | [10]      |
| Artificial Neural Network                      | Russell et al      | 2016 | [11]      |
| Cellular Automata                              | Niescie et al      | 2006 | [12]      |
| Membrane Computing                             | Paun et al         | 2010 | [13]      |
| **ARTIFICIAL IMMUNE SYSTEM**                   |                    |      |           |
| Ant Colony Optimization                        | Dorigo et al       | 1996 | [14]      |
| Artificial bee colony                          | Karaboga et al     | 2007 | [15]      |
| Artificial Fish Swarm                          | Li et al           | 2002 | [16]      |
| Bacteria Foraging Optimization                 | Das et al          | 2009 | [17]      |
| Bat algorithm                                  | Yang et al         | 2010 | [18]      |
| Bees algorithm                                 | Pham et al         | 2009 | [19]      |
| Biogeography Based Optimization                | Simon et al        | 2008 | [20]      |
| Charged System Search                          | Kaveh et al        | 2010 | [21]      |
| Cuckoo Search                                  | Yang et al         | 2009 | [22]      |
| Cuttlefish Optimization                        | Eesa et al         | 2013 | [23]      |
| Duelist Algorithm                              | Biyanto et al      | 2016 | [24]      |
| Flower Polination                              | Yang et al         | 2017 | [25]      |
| Glowworm Swarm Optimization                    | Kaipa et al        | 2017 | [26]      |
| Gravitational Search                           | Rashedi et al      | 2009 | [27]      |
| Grey Wolf Optimizer                            | Mirjalili et al    | 2014 | [28]      |
| Harmony Search                                 | Yang et al         | 2009 | [29]      |
| Hydrological Cycle                             | Wedyan et al       | 2017 | [30]      |
| Imperialist Competitive                        | Gargari et al      | 2007 | [31]      |
| Intelligent Water Drop                         | Shah et al         | 2009 | [32]      |
| Particle Swarm Optimization                    | Kennedy et al      | 1995 | [33]      |
| River Formation Dynamics                       | Rabanal et al      | 2007 | [34]      |
| Shuffled Frog Leaping                          | Eusuff et al       | 2006 | [35]      |
| Simulated Annealing                            | Laarhoven et al    | 1987 | [36]      |
| Spiral Optimization                            | Tamura et al       | 2011 | [37]      |
| Stochastic Diffusion Search                    | Meyer et al        | 2006 | [38]      |
| Whale Optimization                             | Mirjalili et al    | 2016 | [39]      |
Table 2: Comparison of Modelling of Human Mind Algorithms.

| Algorithms              | Advantages                                           | Disadvantages                                                                 | Inspiration     | Application                          | Characteristics                                                                                       | Factors which affect this                                      |
|-------------------------|------------------------------------------------------|-------------------------------------------------------------------------------|-----------------|--------------------------------------|-------------------------------------------------------------------------------------------------------|---------------------------------------------------------------|
| Rough Set Theory        | • Easy operation                                      | • Cannot deal with continuous data                                           | Two precise     | • Intelligent information processing | • Precise & simplified rules can be produced by rough sets                                           | • Set of objects,                                            |
|                         | • Various types of data can be processed             | • Heavily dependent on a decision table,                                      | boundaries used | • Traffic control                    | • A combination of probability theory, fuzzy math and other uncertainty theories                    | • Condition attribute set                                    |
|                         | • Mathematical structure is mature and does need     | • To describe imprecise concepts.                                              | to describe     | • Satellite altitude control         | • Basic operations - union, intersection, difference and complementary.                             | • Decision attribute set                                     |
|                         | prior knowledge                                       |                                                                                | imprecise       | • Vacuum cleaner                     |                                                                                                       |                                                               |
|                         | • Inspiration                                        |                                                                                | concepts.       |                                      |                                                                                                       |                                                               |
| Fuzzy set theory        | • Efficient computing                                 | • Not robust                                                                  | Reasoning based | • Traffic control                    |                                                                                                       |                                                               |
|                         | • System description as a combination of numerals &   | • Proof of characteristics is difficult.                                      | on subjectivity  | • Satellite altitude control         |                                                                                                       |                                                               |
|                         | symbols                                              | • Function approximation in certain applications.                             | and imprecision  | • Vacuum cleaner                     |                                                                                                       |                                                               |
| Granular computing      | • Less computational complexity                       | • Decomposition is based on construction of fuzzy controllers                  | Information     | • Information processing             | • Various information extraction levels                                                               |                                                               |
|                         | • Storing information in the form of a hierarchy     |                                                                                | abstraction in   |                                      | • Philosophical thinking,                                                                          | • Membership function                                        |
|                         |                                                       |                                                                                | granules         |                                      | • Methodological problem solving,                                                                   | • Reference set                                              |
| Perception based        | • Efficient computing                                 | • Its construction and vocabulary depends on application.                     | Process of       | • Data mining                        | • Structured information processing.                                                                |                                                               |
| computing               |                                                       |                                                                                | understanding    | • Investment decision making        |                                                                                                       |                                                               |
|                         |                                                       |                                                                                | sensory          |                                      |                                                                                                       |                                                               |
|                         |                                                       |                                                                                | information      |                                      |                                                                                                       |                                                               |
| Anticipatory Computing  | • Determine the future to some extent,               | • Computationally intensive, No algorithms evolved yet.                       | Predict future   | • Voice assistants                  | • Comprise of a encoder                                                                              | • Past events                                                |
|                         | • Adaptive to environment.                           |                                                                                | state of the     | • Information systems               | • Computing with words engine,                                                                       | • Environment                                               |
|                         |                                                       |                                                                                | environment      |                                      | • Decoder words transformed into a fuzzy set to form a codebook                                      | • Previous predicted results.                                |
| Wisdom Technology       | • Self-growth                                        | • Computationally intensive, Expensive, Difficult to implement in reality.    | Ubiquitous       | • Fraud detection                   | • Combination of knowledge sources network,                                                         | • Knowledge sources network                                  |
|                         | • Adaptation to changing environment                 |                                                                                | computing        | • Intelligent marketing             | • Adaptive judgment & interactive processes                                                         | • Adaptive judgment                                         |
|                         | • Key concept extraction.                            |                                                                                |                  | • Robotics                           | • Understand organized information with inference rules                                            | • Interactive processes                                     |

Granules - objects, classes, clusters.

Vocabulary
 Movement of the lithospheric plates near convergent boundaries leads to Earthquakes. It leads to strong vibrations that take place due to the sudden release of energy from the Earth’s lithosphere which leads to seismic waves. Earthquakes are classified based on the fault type. Their occurrence is mostly at geologic faults and it depends on frictional forces, potential and kinetic energy. When the emission of energy comes to a halt the earthquake stabilizes. Its application is in solving knapsack problem and in clustering of land cover features. Volcanic eruptions depend upon temperature, density, pressure and buoyancy. It needs magma i.e. the melted rock and when the pressure crosses the threshold value it creates a fracture to erupt from the surface. The eruption and cooling can represent the maximum flow and minimum cut problems. Maximum number of volcanic eruptions take place at the plate boundaries, when two plates are in motion either away from each other (diverging) or towards each other (converging). To summarize volcanic eruption is directly proportional to buoyancy, pressure and inversely proportional to density, temperature. To summarize volcanic eruption is directly proportional to buoyancy and pressure and inversely proportional to density and temperature. The stability point of the volcanoes is reached when all the trapped volatile gases are released and the pressure is not enough to make the magma come out of the crust of earth.

D. SWARM INTELLIGENCE

Swarm intelligence was coined in the year 1989 and it is a natural or artificial self-adaptive, decentralized systems comprising of interaction of individuals with one another and their environment. The most common source of inspiration is from nature, especially biological systems. As part of this domain we explore further into numerous algorithms as mentioned in table 1. Ant Colony Optimization [14] is inspired by the foraging behavior of ant species. The ants leave pheromone, a path marker to indicate a favorable path which can be traversed by others. A constructive greedy heuristic algorithm which reduces problems to find good paths through graphs. A Meta heuristic algorithm, Artificial Bee Colony Algorithm [15] comprises of employed foraging bees, unemployed foraging bees and food source. Feedback given by the foragers about a food source provides adaptability and information sharing amongst honey bees. There is active research in the application of this algorithm to neural network training, image processing. Multiple Swarm fishes act as agents in Artificial Fish Swarm algorithm [16], a stochastic and global optimum algorithm inspired by the movement and social behavior of fish. A useful and parallel algorithm widely applied to job scheduling problems and image processing domains. Bacteria Foraging Optimization [17] inspired by the chemotaxis behavior of bacteria and their movement in response towards or away from specific signals. Initial parameter tuning offers a wide range of search behaviors. A living multi agent algorithm designed for continuous optimization problems. Bat algorithm [18] based on the echolocation behavior of bats is a multi-agent metaheuristic algorithm. Using echolocation they understand the topography of the environment around them and make a difference between food and prey. Loudness and pulse emission are varied according to the iterations. Based on the foraging behavior of honey bees, Bees Algorithm [19] a population based search method uses local search combined with global search to solve combinatorial and continuous optimization problems. The agent is a honey bee while the flower or the food source is analogous to a food source. The quality of the source is shared via means of a dance. Biogeography Based Optimization [20] is a living multi-agent time-space invariant population based evolutionary algorithm based on the migration,
speciation, and extinction of species. It optimizes a function by stochastically and iteratively improving candidate solutions with regard to a given measure of quality, or fitness function. Charged System Search Optimization [21] is a nonliving multi agent algorithm based on Coulomb's electrostatic law suited for non-smooth or non-convex domains. Each agent is a charged particle and affects one another depending on fitness value and separation distance. Cuckoo Search Algorithm [22] is based on the obligate brood parasitic behavior of cuckoo species. The nest of the foreign host represents the solution space, the eggs of the foreign host represent solutions and cuckoo egg represents a new solution. This assists in removal of the worst solution in each iteration. Drawn by the color changing behavior of cuttlefish, Cuttlefish Optimization [23] a living multi agent algorithm uses two solution groups, one to represent global search with random factor and the other represents local search followed by solution comparison. The idea is to conceal the fish in the environment by reflection and visibility. It is frequently applied to tackle unimodal and multimodal optimization problems. Duelist Algorithm [24] based on human warfare is a living multi agent method commonly applied to safety instrumented systems. The properties of each duelist are encoded in a binary array. It simulates a war between humans, wherein after each battle there is a champion, winner, loser and worst duelist. The champion represents the best solution while the worst duelist is the worst solution which is eliminated. Inspired by the pollination process in flowers, Flower Pollination algorithm [25] is a living multi agent where cross pollinators perform global pollination with levy flights and local pollination is similar to local search. Use of levy flights leads to exploring domain outside search space and tuning initial parameters is hard. Glowworm Swarm optimization [26] is a decentralized algorithm based on luciferin update using the information available in the local neighborhood to update the position. The movement of each glowworm is governed by positive taxis, fitness broadcast and adaptive neighborhood. Quantity of luciferin is solely responsible for the fitness of the location. Rules of gravity have inspired the Gravitational Search algorithm [27], a deterministic iterative algorithm which uses simulation of gravitational forces between masses. The quality of a solution is dependent on the mass of the object. Position of mass is analogous to a solution and the inertial mass and gravitational mass are evaluated using a fitness function. Grey Wolf Optimization [28] is a living multi agent based on the leadership ranking and hunting behavior of grey wolves for single objective optimization problems. A strict hierarchy of wolves i.e. alpha, beta, delta and omega is followed along with a balance between exploration and exploitation. Harmony Search Algorithm [29], a nonliving multi agent metaheuristic algorithm is based on the harmonic orchestra is a randomized algorithm which keeps evaluating each harmony as a potential solution. It is often applied to single objective functions with linear and nonlinear constraints. The governing factors are considering rate, pitch adjustment rate and randomization. Water cycle and the rotation of water in nature is the basis of Hydrological Cycle Algorithm [30]. Sea represents the best solution while the other good solutions are represented by rivers which guide individuals towards the best solution. Imperialist competitive algorithm [31] is a nonliving multiple agent method based on imperialistic competition in today’s world. Division of the world into empires and colonies. The competition gradually results in an increase in the power of the dominant empires while the weaker ones further lose their strength. It halts when there is only one empire left which represents the best solution. Intelligent Water Drop Algorithm [32] is based on the natural rivers and how they find their optimal paths to their destination. Each problem is represented as a graph where each intelligent water drop traverses it generating a best solution which is used to update the global best solution in cycles. Particle Swarm Optimization [33] is a non-living multi-agent space variant population based stochastic optimization algorithm which finds global optima by the best position of particles and swarm by considering the best solution as a point or surface in an n-dimensional space. Commonly applied for solving highly mixed integer and nonlinear complex optimization problems. Traversal of water drops from riverbed depositing and eroding soil is the inspiration of River Formation Dynamics [34], a heuristic algorithm used for unimodal optimization problems. The agent is a water drop and a specific amount of soil is assigned to each node. Flow of river solely depends on the altitude between two points.
| ALGORITHMS                          | Living / Non Living Agent | advantages                                                                 | characteristics                                                                 | Factors which affect this | Variations | Problem solving method                                                                 | Applications                                                                 | Disadvantages                                                                                                                                                                                                 | Usage                                                                                                                                                                           |
|------------------------------------|---------------------------|----------------------------------------------------------------------------|--------------------------------------------------------------------------------|----------------------------|-----------|------------------------------------------------------------------------------------------|----------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Clonal Selection Algorithm (CSA)   | Living                    | ● Parallel operation,                                                     | New lymphocytes possessing self-reactive receptors are eliminated as soon as their creation. New cells are frequently cloned. | cloning rate, affinity values | nil       | Selection of antibodies based on affinity for minimizing a cost function. | ● Pattern recognition, multimodal & combinatorial optimization | ● Selection of the affinity value in the mutation stage, not effective on less number of iterations. | Optimize a smooth unimodal & multimodal function.                                                                 |                                                                                                                                                                                                                                    |
| Artificial Neural Network (ANN)    | Living                    | ● Diverse population                                                     | System which recognizes only particular patterns as self while the others as non self. Non self-samples are removed so that they do not become a detector. | detector and antigen training | Greedy NSA, Random real valued NSA | Modeling of the unencountered pathogen by modeling the complement of the known ones. | ● Classification, Pattern recognition, Anomaly detection | ● Determining the required detectors is difficult. | two class classification problems                                                                                                                                                                            |
| Cellular Automata (CA)             | Living                    | ● Less training time,                                                   | Each cell has separate migration threshold, Safe & danger signals need not necessarily be reciprocal of one another and may be conflicting Based on the signals they encounter immature dendritic cells become semi-mature or mature. | random selection of cells, variable threshold & more | Deterministic DCA | Using migration, maturation and labelling of dendritic cells to provide context specific information about classification of input patterns. | ● File allocation for a distributed system, Chemical kinetics, Finding hardware bugs, Signal processing | ● Large number of initial parameters, Number of interacting entities is high, Initial parameter values are arbitrary | Data filtering algorithm which can be run on single discrete, ordinal as well as categorical input.                                                                 |
| Membrane Computing (P-systems)     | Living                    | ● Faster convergence,                                                   | Randomly select individuals from the current generation to produce children of the next generation Use of crossover rules while forming the children. | fitness function, number of iterations | Adaptive GA, Coarse grained parallel GA | For each generation selection and crossover happens followed by evaluating the fitness function until stopping criteria has met. | ● Computationally demanding, Transform every form input into numerical values, Training time dependent on the data size. | ● Tendency to converge towards local optima than global optima, Not scalable, Not effective on decision problems | Find the global optimum given the input constraints and loss functions. Find the global optimum given the input constraints and loss functions.                                                                 |
| Table 4: Modelling of Human Mind Algorithms                                                                 |                           | ● Easy implementation,                                                  |                                                  |                             |                                 |                                                                 |                                                                 |                                                                                                                                                                                                                                                                          |                                                                                                                                                                                                                                    |
|                                    |                           | ● Wide variety of functions which can be optimized.                       |                                                  |                             |                                 |                                                                 |                                                                 |                                                                                                                                                                                                                                                                          |                                                                                                                                                                                                                                    |
|                                    |                           | Model nonlinear and complex relationships Predicts on unseen data No default limitation on the input parameter values Wide variety of input taking | Processing time increases with the increase in the number of neurons and layers Computing time depends on the objective function chosen Backpropagation used for calculating gradient. | number of neurons, loss function | Convolutive ANN, Deep stacking networks, LSTM | Single iteration where the network is a forward or back propagation leads to one optimal solution | ● Medical diagnosis, Speech recognition, Social network filtering | ● Computationally demanding, Transform every form input into numerical values, Training time dependent on the data size. | Find the global optimum given the input constraints and loss functions.                                                                 |                                                                                                                                                                                                                                    |
|                                    |                           | Behavior of simple and complex group can be distinguished                | All the cells simultaneously switch from current state to the next Effective measure complexity increases linearly in time for an additive rule with a random initial state | Cell state, neighborhood of a cell. | Stochastic CA, Asynchron ous CA | Array of similarly programmed cells with definite states interacting in a neighborhood. | ● Error correction coding, Generate public keys in cryptography, Computer processors. | ● Output is hard to analyze, Difficult to understand the rules that govern the system. | single and multi-dimensional classification.                                                                 |                                                                                                                                                                                                                                    |
|                                    |                           | Efficient, Parallel computation, interactive simulation results.         | Multiple groups of objects evolve according to reaction rules | Membrane structure reaction rule. | Cell like P, Tissue like P, Neural like P. | System for creating cell like computational model which processes multisets in compartments within membranes. | ● NP-complete problems such as TSP, Computer graphics, Ranking and sorting algo. | ● Lack of benchmark functions, Computationally demanding. | processing multisets of symbol objects in a localized manner.                                                                 |                                                                                                                                                                                                                                    |
|                                    |                           | ● Models are distributed.                                               | Membrane systems solve PSPACE problems in polynomial time. | Membrane structure reaction rule. |                                         |                                                                 |                                                                 |                                                                                                                                                                                                                                                                          |                                                                                                                                                                                                                                    |
Inspired by the evolution of memes, Shuffled Frog Leaping Algorithm [35] is a living multi agent technique which follows an informed heuristic search to find solution of a combinatorial optimization problem using a mathematical function. The agents share information amongst themselves and each agent carries a single meme. Simulated Annealing algorithm [36] inspired by the action of heat to metal followed by the cooling process picks a solution randomly in each iteration, measures it quality based on the two probabilities and decides to keep it or forget it. The iteration governs the temperature which gradually decreases over the iterations. Spiral phenomena in nature is the basis of Spiral Optimization algorithm [37], a deterministic dynamical system which searches the solution space with logarithmic spirals. It can be extended to an n dimensional spiral model which comprises of a composite rotation matrix and step rate. Based on the hill mining game, Stochastic Diffusion Search [38] is a single nonliving agent method which has two phases: Test phase and Diffusion phase. In test phase agents are categorized as active and passive and a domain independent value is returned based on partial hypothesis evaluation. In diffusion phase agents share information and every agent does partial function evaluation. Whale optimization algorithm [39] is based on the humpback whales which comprises of cycles of exploring the search space for optimal solution based on the position of search agents. Every hunt is an attempt to reach the optimal solution of its neighborhood and applied to unimodal and multimodal optimization problems. Bubble net feeding behavior is exclusive to this whale which helps in optimization. Experimental results show that it outperforms the Pawlak Rough model.

Artificial Immune Systems – Variations of negative selection algorithm (NSA) are Greedy NSA, Real valued NSA. Real valued NSA is used for anomaly detection [62]. This algorithm is more robust to noise and outliers because the detector is considered to match self if the median distance between the k neighbors is less than threshold. Deterministic Dendritic Cell is a variant of dendritic cell algorithm which is used for smart grid cyber-attack detection [60]. The algorithm is run on the server side with the checking of the incoming signal. If the signal is anomalous it is added to the anomalous antigen database otherwise traffic passes through. Variants of genetic algorithm (GA) are adaptive GA and coarse grained parallel GA. Adaptive genetic algorithm is applied to image segmentation wherein the algorithm locates the ideal threshold in grey image [61]. Lower grey levels correspond to objects while higher correspond to the background. Some of the variants of artificial neural networks are recurrent neural networks, convolutional neural networks. Recurrent neural networks are applied in the next word prediction domain where the occurrence of the previous and the current word is a part of the memory of the network and the output of the model represents the next word in sequence. Variants of membrane computing are cell like P systems, tissue like P systems. Cell like P system [63] was used to design a variant of particle swarm optimization where the transformation rules used were the evolutionary rules of PSO with the communication of global best of each membrane to skin and best of entire population back to each membrane. It is observed that this performs better on the CEC 2014 benchmarks than particle swarm optimization.

III. APPLICATIONS

Computational Intelligence algorithms are applicable to complex real world dynamic problems. Modelling of Human Mind – Some prominent Rough sets variants are Game theoretic rough set, Multi granulation rough set, and Variable precision rough set. Game theoretic rough sets have been commonly used in recommender systems as in [59]. Every recommender system is dependent on the threshold of appropriateness and coverage. These thresholds are implemented by a balance between a trade-off and a solution is determined using a game.
Parallel AFS [40] is applied to packing and layout problems. This algorithm divides the population into two equals for exploration and exploitation phase. Both the sub populations adapt their visual and step in different ranges independently. It results in a harmony between convergence speed, accuracy and balance between global and local search. Types of Bacteria foraging optimization (BFO) are Velocity modulated (BFO) and Adaptive BFO. Adaptive BFO [41] is applied to optimization of antenna array for faster convergence. In this algorithm, to control the step we use adaptive delta modulation. Error between the actual and modulated signal is combined and their integration is fed into a voltage controller that governs the step size. This variant performs better than the standard BFO and can synthesize patterns with multiple nulls at any desired direction. Variations of Bat algorithm (BA) are Multi objective BA, Fuzzy logic based BA and Differential operator and levy flights based BA. Fuzzy logic based BA [42] is applied for dynamic parameter optimization in metaheuristic optimization problems. The fuzzy system is used to adapt the loudness, low and high frequency over trial and error. The results second this as this algorithm performs better than the standard in all aspects. Variations of Bees algorithm (BA) are Grouped BA, Hybrid BA and Multi objective BA. Multi objective BA along with clustering techniques is used for environmental/economic dispatch as in [64].Vector size is equal to the number of optimized parameters. It creates a pareto set by searching for non-dominated solutions from initial solutions and takes the best solutions for neighborhood search using clustering. Results indicate that this algorithms solution has lower fuel and emission cost. Some variants of Biogeography based optimization (BBO) are Extended species BBO, Support Vector Machine based BBO, and Particle swarm optimization based BBO.

Support Vector Machine based BBO [44] are applied to automated classification of brain images. Usage of BBO is crucial here because it can determine the optimal parameters of the kernel SVM which are hard to determine. This combination provides the best accuracy over the known approaches. Variants of Charged System Search (CSS) are Multi-objective CSS, Bayesian CSS and Adaptive CSS. The later variant has been used in path planning for multiple mobile robots based on [57]. In this algorithm, the elements of the path point sets are used to compute the objective function and as a solution. Path for each agent is created by a different population with a fixed number of agents. As compared to PSO, GSA and basic CSS, it shows promising improvements in convergence speed but not in terms of computational complexity. Variants of Cuckoo Search (CS) are Binary CS, Quantum CS and Parallel CS. Binary CS [45] is used for feature extraction in theft recognition in power distribution systems. The algorithm associates binary numbers with a feature which will determine whether the feature will be included in the final set and the classifier’s accuracy is the function to be maximized. It increases the theft recognition by 40% based on the features selected. Variations of Flower Pollination algorithm (FPA) are Chaotic FPA, Binary FPA and Hybrid FPA. Chaotic FPA [46] has been applied to compute the definite integral. One dimensional and noninvertible maps are used to create chaotic sets which determine the switch probability. This algorithm performs better and is more efficient than Monte Carlo Method and Simpson’s Rule in terms of convergence and time taken. Varieties of Glowworm Swarm Optimization (GSO) are Adaptive Step GSO, Multi-population GSO and Self-exploratory GSO. Adaptive Step GSO [47] has been applied in distance vector hop localization during the selection of beacon nodes. In this algorithm, size of the step is variable and it is affected by the density of the neighbor nodes and the distance between the current individual and the next moving individual. This property is used while calculating the distance between the specified nodes in the network area. Error comparison indicates that this algorithm performs better than the basic version of distance vector hop algorithm.

Variations in Gravitational Search Algorithm are of the following kind – Binary GSA, Immunity GSA and Multi-objective GSA. Quantum inspired Binary GSA [55] has been applied to thermal unit commitment with wind power integration for unit on/off state preprocessing. This algorithm uses a method based on the weight between average full load cost and maximal power output to determine the priority list for unit scheduling. Results indicate that this algorithm offers a better solution in terms of convergence speed and better searching ability than standard GSA and Binary PSO. Versions of Grey Wolf Optimizer (GWO) are Hybrid GWO, Parallel GWO and Binary GWO. Hybrid GWO [48] has been
applied to the clustering domain. It combines the approaches of GWO and K-means where the GWO chooses the starting centroids for the k-mean to overcome the dependency of the initial starting points. It has been observed that this hybrid performs better than the combination between k-means and particle swarm optimization, artificial bee colony.

Variants of Harmony Search Algorithm (HSA) are Improved HSA and Global optimum HSA. Improved HSA [56] has been applied in solving shortest path problems. This algorithm uses a priority coding scheme to set each variable values in the harmony vector which represents the priority value of the node. Shortest path is created by choosing maximum priority value of adjacent nodes. Results indicate that it performs better than standard HSA and PSO. Variants of Imperialist Competitive algorithm (ICA) are Fuzzy ICA, Modified ICA and Interaction based ICA. Modified ICA in combination K-means algorithm has been applied to solve data clustering problems as in [58]. Data values are represented by the countries and control variables correspond to cluster centers. Assigning of each data value is done based on the cost function following by Roulette wheel cost selection for imperialistic competition. Its performance is comparable to the standard ICA and can be applied to problems where the number of clusters are unknown beforehand. Following are the modifications to Particle Swarm Optimization (PSO) – Accelerated PSO, Hybrid PSO and Bare Bones PSO. Hybrid PSO [52] has been used to train neural network based controller to stabilize a mass spring damper system. It minimizes the value of performance index by scouting for the optimal values of the connection weights of the network and the scalar under the initial system. It indicates a confidence level of 98% which is better than other versions of PSO.

Variations of Shuffled Frog Leaping algorithm (SFL) are Modified SFL and Binary SFL. Modified SFL algorithm [51] has been widely applied to time cost trade-off problem. This algorithm minimized the total project cost by associating the decision variables with the construction methods for different activities. This variant surpassed standard SFL in parameters such as duration, cost and success rate. Types of Simulated Annealing (SA) algorithms are Adaptive SA and Hybrid SA. Adaptive SA [53] finds in application in infinite impulse response (IIR) filter design. This algorithm offers an alternative to IIR design by converting the direct form coefficients to lattice form reflection coefficients. It has been observed that Adaptive SA provides better results than other genetic algorithms for IIR filter.

Variants of Ant Colony Optimization (ACO) are Max-Min Ant System, Quantum ACO, Hybrid ACO, Elitist Ant based System and Rank based Ant System. Hybrid ACO [49] has been applied to solve vehicle routing problem. In this algorithm each ants tries to build a long, single route comprising of a number of vehicle paths. It performs better than the standard variant of ACO. Whale Optimization algorithm (WOA) has the following variants – Chaotic WOA, Binary WOA and Multi-objective WOA. Chaotic WOA [50] has been applied to transient stability constrained optimal power flow. It uses logistic chaotic maps to determine the value of coefficient vectors (C and D) followed by usage of WOA for minimizing total fuel cost of active power generation. Usage of chaotic WOA greatly improves the convergence and the performance of the power system over the standard WOA.

IV. RESULTS

Travelling salesman problem is a standard example of NP-hard problems which has been intensively worked upon and studied by scientists and researchers. As the number of cities increases the number of routes increases rapidly. Hence we take a look at some of the algorithms in each domain to obtain the optimal or near solution for the travelling salesman problem.

In the domain of swarm intelligent algorithms numerous algorithms have been applied towards the travelling salesman problem and we have considered the following algorithms in comparison – ant colony optimization, particle swarm optimization, intelligent water droplet and river formation dynamics. Besides standard versions two other algorithm variants have also been compared for ant colony optimization and particle swarm optimization. Eil51 and KroA100 are two examples of travelling salesman problem and the time taken by the various algorithms can be seen in table 6. From the table it can be clearly observed that IWD and C3DPSO perform much better than the standard PSO.
## Table 5 (a): Swarm Intelligence Algorithms

| ALGORITHM | Characteristics | Problem Solving Method | Nature of solution | Disadvantages | Type of Problem | single / multi agent | Variations | Applications | Information Sharing | Living / Non-Living Agent |
|-----------|-----------------|------------------------|--------------------|---------------|-----------------|----------------------|-------------|--------------|---------------------|--------------------------|
| Artificial bee colony (ABC) algorithm | • Fast convergence<br>• Few control parameters<br>• Ability to manage the objective cost<br>• Use of both exploration and exploitation | Foraging | Unimodal and multimodal minimization problems<br>Minimum number of iterations | Computationally demanding<br>Secondary information is not used<br>Time taken increases when a sequential method is followed | Multiple | Multi-Objective ABC, Modified ABC | • Image processing<br>• Clustering and data mining<br>• Economic dispatch problems<br>• Job scheduling | Yes | Honey Bees foraging behavior<br>Living |
| Artificial fish Swarm (AFS) | • Fast convergence<br>• Flexibility<br>• Fault tolerance with high accuracy | Swarming | Complex non-linear high dimensional problems<br>Multiple fish | A randomized parallel algorithm which simulates the behavior of fish to reach the global optimum or the best solution<br>Very sensitive to parameter tuning<br>Fast convergence | Multiple | Parallel fish swarm algorithm, quantum artificial fish swarm algorithm | • Job scheduling<br>• Clustering<br>• Image processing | Yes | School of fish<br>Living |
| Bacteria Foraging Optimization (BFO) | • Non gradient optimization<br>• Solutions improve over generations<br>• Robust | Metabolic search<br>Bacteria friendly<br>Honey Bees friendly | Robust<br>High search space<br>Multi-modal functions<br>Multi-strategy<br>Multi-objective | Computationally demanding<br>Offline<br>Hard to find global optima<br>Not set values for initial parameters<br>No method of stopping | Multiple | Multi objective BBO, Adapative BBO, Bacteria Foraging oriented by Particle Swarm optimization | • Image enhancement<br>• Radio frequency identification<br>• Tuning PID controller | Yes | Chemotaxis behavior of bacteria<br>Living |
| Bat algorithm (BA) | • Can switch autonomously from exploration to exploitation thereby providing parameter control<br>• Provision of frequency tuning by mimicking use of echolocation and variation in frequency | Echolocation | Robust<br>High accuracy<br>High number of objective function evaluations<br>Non gradient | High number of objective function evaluations<br>Not set values for initial parameters<br>No method of stopping | Multiple | Multi objective BA, Fuzzy Logic BA, Differential Operator and Levy Flights BA | • Classication<br>• Clustering<br>• Data mining<br>• Image processing | Yes | Echolocation behavior of bats<br>Living |
| BeesAlgorith (BA) | • Fast convergence<br>• Non gradient optimization<br>• Can readily escape from local minima | Foraging | Global optimisation<br>Continuous constrained optimisation problem<br>Multiple | Computationally demanding<br>Number of parameters to be tuned during initial parameters<br>No set values for initial parameters<br>High number of objective function evaluations | Multiple | Velocity modulated BBO, Adapative BBO, Bacteria Foraging oriented by Particle Swarm optimization | • Image enhancement<br>• Radio frequency identification<br>• Tuning PID controller | Yes | Chemotaxis behavior of bacteria<br>Living |
| Biogeography Based Optimization (BBO) | • Fast convergence, foraging<br>• Can readily escape from local optima | Foraging | Robust<br>High accuracy<br>High number of objective function evaluations<br>Non gradient | Computationally demanding<br>High number of objective function evaluations<br>No set values for initial parameters<br>No method of stopping | Multiple | Multi objective BA, Fuzzy Logic BA, Hybrid modified BA | • Load balancing in cloud computing<br>• Electronic component design<br>• Training neural networks | Yes | Honey Bees foraging behavior<br>Living |
| Charged System Search (CSS) | • Not easily trapped in the local minima during exploitation<br>• Easy implementation | Foraging | Unimodal and multimodal minimization problems<br>Multiple | Computationally demanding<br>Secondary information is not used<br>Time taken increases when a sequential method is followed | Multiple | Multi-Objective ABC, Modified ABC | • Image processing<br>• Clustering and data mining<br>• Economic dispatch problems<br>• Job scheduling | Yes | Honey Bees foraging behavior<br>Living |
| ALGORITHM                        | Advantages                                                                 | Characteristics                                                                 | Problem Method Solving Nature of solution | Disadvantages                                                                 | Type of Problem | single / multi agent | Variations | Applications                  | Information Sharing | Living / Non Living Agent |
|---------------------------------|-----------------------------------------------------------------------------|---------------------------------------------------------------------------------|------------------------------------------|--------------------------------------------------------------------------------|----------------|----------------------|-------------|-------------------------------|---------------------|--------------------------|
| Cuckoo Search (CS)              | Fast convergence, Easy to implement, Given sufficient time global optima is ensured, Use of Levy flights for global search | At a time one egg is laid in a random nest, The eggs which survive are solutions which are carried forward, Each cuckoo egg represents a new solution, as time passes the non-adequate solutions will be replaced by the better ones, Levy flights | Single algorithm iterates over the solutions (eggs) in the nest (search space) where in the quality of solutions keeps improving | It aims to generate new and better solutions, whose quality is evaluated using an objective function which is mostly maximized | Can get trapped into the local optima along the boundary, Low efficiency, Slow convergence | Binary Cuckoo Search (CS), Quantum Inspired CS, Parallelized CS | Training a neural network, Designing a wind turbine blade, Data fusion in wireless sensor networks | No | Egg laying behavior of cuckoo | Living                  |
| Cuttlefish Optimization (CFO)   | Can readily escape from local optima, Guaranteed location of global optimum, robust     | Using the different layers of celli chromatophores, iridophores, leucophores) the fish achieves reflection and visibility, Visibility simulates the pattern matching and reflection is simulates the matching light | | The algorithm attempts to conceal the fish in the environment using reflection, visibility and the final pattern is the global optimum solution. | | Unia and multi modal optimization | Single | Nil | Safety instrumented system, Clustering | Yes | Human warfare, Living      |
| Duelist (DA)                    | Fast convergence, Iteration time is very small, Robust                        | Contests battle one another to become champion, Contestant types - champion, winner, loser, worst duelist, Learning techniques - learning & innovation, Losers learn from the champion while the champion innovates, Elimination of worst duelist, Number of duelists is constant | Repetition of a duel between the contestants where in the champion of the last iteration is the best solution. | Each contestant is a solution. Throughout the generations the contestant fight one another and the global optimum survives. | Initial parameter tuning is difficult, Loss of diversity over generations, Results can be obtained in varied iterations | Multi | Nil | Safety instrumented system, Clustering | Yes | Human warfare, Living      |
| Flower Pollination (FFA)        | Can readily escape from local minima, Survival of fittest, Robust to continuous optimization problems. | Cross pollinators perform global pollination with levy flights, Local pollination is equivalent to local search, Reproduction is proportional to flower similarity. | Iterative process which achieves optimal solutions by use of abiotic (local) and biotic (global) pollination (modification). | Survival of the fittest and optimal reproduction with respect to the numbers and fitness | Maximization problems with less number of initial parameters | Binary FPA, Chaotic FPA, Hybrid FPA | Design pressure vessels, Image compression, Graph coloring | Yes | Pollination process of flowers | Living                  |
| Glowworm Swarm Optimization (GSO) | Adaptive local decision for location of multiple peaks, Effective for continuous domain problems, Memoryless | A population of glowworms is spread out into the search space with equal amount of luciferin, Value of luciferin depends on the location of the glowworms, Higher glow implies more luciferin. | Each iteration contains Glowworm position update followed by luciferin update and then movement phase. | A decentralized algo based on luciferin update using the information available followed by the local neighborhood to update position. | Poor performance for high dimensional problems, Slow convergence, Poor local search ability. | Variable step size GSO, Self-exploration local GSO, Multi population GSO | Locating multiple mobile signal sources, Public transport dispatch system, Wireless sensor networks | Yes | Glowworms | Living                  |
| Gravitational Search (GSA)      | Learning rate is adaptive, Memory-less algorithm, Consistent results & higher precision. | Each object is annotated by its active gravitational mass, inertial mass, position, passive gravitational mass, Gravitational & inertial mass regulate the velocity of an object, Location is equivalent to a solution. | Deterministic iterative algorithm which uses simulation of gravitational forces between masses and the final position is the optimal solution. | Algorithm navigates by adjusting the gravitational and inertial masses leading to the masses being attracted by the heaviest mass which is the optimum solution. | Computationally demanding, Performance depends on initial population & its size, Searching is slow in the last iterations. | Multi Objective GSA, Immunity based GSA, Binary GSA | Renewable micro grid, Economic load dispatch, Controller design, Wireless sensor networks | Yes | Rules of gravity, Non-Living | Non-Living                |
| Grey Wolf Optimizer (GWO)       | Easy to implement, Flexible, Scalable, Equilibrium between exploration and exploitation. | Hierarchy of wolves - alpha, beta, delta, omega, Three best solutions always guide one another towards the optimum search space, Maintaining a balance between exploration & exploitation is critical | Iterative cycle of encircling the prey followed by hunting of the target in the search space to locate the global optimum | Optimization process using a set of random solutions where each solution is a vector that represents the values for the parameters. | Limited to single objective problems, At high number of variables there is local optima stagnation as well as the performance gets affected. | Parallel GWO, Hybrid GWO | Design and tuning controllers, Clustering, robotics, Path planning. | Yes | Grey wolves | Living                  |
| ALGORITHM                       | advantages                                      | Characteristics                                                                 | Problem Method | Solving | Nature of solution | Disadvantages                                                                 | Type of Problem | single / multi agent | Variations                  | Applications                                                                 | Information Sharing | inspiration                                                                 |
|--------------------------------|-------------------------------------------------|---------------------------------------------------------------------------------|----------------|---------|-------------------|--------------------------------------------------------------------------------|-----------------|----------------------|-----------------------------|-------------------------------------------------------------------------------|---------------------|-----------------------------------------------------------------------------|
| Harmony Search (HSA)           | Fast convergence,                               | • Remembers the current harmony in the harmony memory,                         | Recursive       | algorithm which  | Randomized algorithm which keeps evaluating each harmony as a potential solution until stopping criteria is met. | Single objective function with linear and nonlinear constraints | Improved Harmony Search, Global Optimum Harmony Search | Multiple            | Improved Harmony Search, Global Optimum Harmony Search | • Scheduling problem            | • Training a neural network                                          | Harmonic music orchestra | Non-Living                                                                       |
| Hydrological Cycle (HCA)       | Fast convergence,                               | • Self-organizing nature due to the cycles and iterations,                      | Multiple cycles | wherein each cycle comprises of multiple iterations within each cycle. | Each iteration comprises of a solution being generated by every water droplet and each cycle comprises of reaching a constant temperature value where the water cycle keeps repeating. | Continuous optimization problem | Multiple            | Nil                    | Interaction enhanced ICA, Modified ICA, Fuzzy ICA | • Data mining                  | • Signal processing                                         | Continuous movement of water in nature | Non-Living                                                                       |
| Imperialist Competitive (ICA)  | Fast convergence,                               | • Power of an empire is inversely related to its cost,                          | Each IWD is associated with velocity and soil, | Random initialization of countries (solutions) followed by cost function evaluation (power), based on which some colonies start taking control. | • Computationally demanding, • Heavy dependence on initial parameter tuning, • Varied stopping criteria based on fitness. | Multimodal minimization problem | Multiple            | Nil                    | ICA, PSO, Hybrid PSO  | • Feature selection, • Minimax & maximin optimal design, • Training neural networks | Yes                  | Imperiastic competition | Non-Living                                                                      |
| Intelligent Water Drop (IWD)   | Easy to implement,                              | • Each IWD is associated with velocity and soil,                              | Bare Bones PSO | Searching for global optimum with respect to minimum direction and maximum velocity. | • Optimal solution is found for sufficiently large iterations, • Negative soil values halts it, • Next node selection is based on probability. | Continuous power optimization | Multiple            | Nil                    | Bare Bones PSO, PSO, Hybrid PSO | • Reactive power management, • Optimal power flow, • Neural network training, • Price and load forecasting | Yes                  | Behavior of water drops | Non-Living                                                                       |
| Particle Swarm Optimization (PSO) | No prerequisites for the optimization problem,  | • Looks for the optimal solution in a search space of candidate solutions,      | Bare Bones PSO | Different procedure | Algorithm searches for the best known solution in the candidate solution space and is dependent on best known position of the particle as well as the whole swarm's best position. | Continuous and non-continuous optimization | Multiple            | Nil                    | Bare Bones PSO, PSO, Hybrid PSO | • Routing protocol in computer network, • Location area management in GSM, • Data warehousing | Yes                  | Bird flock, school of fish | Both                                                                               |
| River Formation Dynamics (RFD) | Quick reinforcements of newly discovered shortcuts, | • The entity is a river water drop. Amount of soil is assigned to each node,     | Bare Bones PSO | Iterative traversal of multiple water drops along with initial parameters that are updated at every stage. | • Low convergence rate, • Dependent on the initial parameters such as location, velocity and acceleration, • Can fall into the trap of a local optima in a high dimensional space. | Continuous power optimization | Multiple            | Nil                    | Bare Bones PSO, PSO, Hybrid PSO | • Routing protocol in computer network, • Location area management in GSM, • Data warehousing | Yes                  | Bird flock, school of fish | Both                                                                               |

Table 5 (b): Swarm Intelligence Algorithms extended
| ALGORITHM                  | advantages                          | Characteristics                                                                 | Problem Solving Method                      | Nature of solution                  | Disadvantages                                                                 | Type of Problem | single / multi agent | Variations | Applications             | Information Sharing | Inspiration                     |
|---------------------------|-------------------------------------|---------------------------------------------------------------------------------|--------------------------------------------|--------------------------------------|--------------------------------------------------------------------------------|-----------------|----------------------|------------|------------------------|----------------------|-------------------------|
| Shuffled Frog Leaping (SFLA) | Flexible, Diverse population, Robust | Mixture of deterministic and random approaches, Frogs with better ideas contribute more to development of new ideas, Migration of frogs accelerates information sharing, Number of memeplexes & frogs is critical | Use of mimetic evolution to influence ideas to other individuals in a local search followed by a shuffling strategy resulting in a global optimum. | Follows an informed heuristic search to find solution of a combinatorial optimization problem using a mathematical function. | Computational demanding, parameter selection is critical, Ineffective on simpleton problems, slow convergence, Lack of adaptive acceleration in position update. | Uni and multi modal function optimizatio n | Mutli            | Modified SFLA, Binary SFLA |                       | Groundwater model calibration, Economic dispatch with multiple fuel options, Clustering. | Yes                  | Evolution of memes Living |
| Simulated Annealing (SA)  | Incorporates a wide range of cost functions and fitness functions, Given sufficient time global optima is ensured | Heuristic process wherein a random solution is picked, System decided whether to stay at this state or to jump to another state, Selection of parameters an important step in determining the outcome of the algorithm, Solution state has the least energy signature | Iterative procedure wherein a solution is taken at random and its transition and acceptance probabilities are measured | In each iteration the algorithm picks a solution randomly, measures its quality based on the two probabilities and decides to keep it or forget it | No set values for initial parameters, Problem dependent, variable parameters to solve achieve different objectives, Expensive cost functions increase computational time | Combinatorial and continuous optimizatio n | Single | Adaptive SA, Hybrid SA |                       | Design of special digital filters, Fingerprint matching, Flower shop scheduling problem | Yes                  | Action of heat to metal followed by the cooling process Non Living |
| Spiral Optimization (SOA) | Computationally efficient, Flexible with respect to the objective function, Generation of descent search direction. | Multi point search using many spiral models, Setting of spiral matrix with each initial point placement affects search performance, Spiral periodically generates at least one descent direction | Direct search algorithm in nonlinear programming using for diversification & intensification. | Searching the solution with logarithmic spirals which is a deterministic dynamical system. | Introduce randomness for better search performance, Performance is heavily dependent on initial parameter selection. | N-dimensional unconstrain ed optimizatio n | Multi            | Adaptive SPO. |                       | Job scheduling, Data mining, Path planning | Yes                  | Spiral phenomena in nature Non Living |
| Stochastic Diffusion Search (SDS) | Minimal convergence criteria, Linear time complexity, Convergence to global optimum is ensured, Robust | Has two phases: Test phase and Diffusion phase. In test phase agents are categorized as active and passive. In diffusion phase agents share information | Has a mathematical framework, Absorbs certain type of noise in objective function, Self-dynamic & adaptive resource allocation. | Has two phases: Test phase and Diffusion phase. In test phase agents are categorized as active and passive. In diffusion phase agents share information | When the objective function can be broken into n number of partial functions independent of each other | Data driven SDS, Coupled SDS, Parallel SDS. | Single            | Data driven SDS, Coupled SDS, Parallel Spos |                       | Object recognition, Text search, Sequence detection in bioinformatics. | Yes                  | Hill mining Non-Living |
| Ant colony Optimization (ACO) | Fast convergence, Parallel exploration of search space, Dynamic adaptation to environment. | Use of pheromones as path trackers, Simplistic organization, Ants interact amongst themselves, Creation of multiple paths to the source from which the most optimum is selected | Has two phases: Test phase and Diffusion phase. In test phase agents are categorized as active and passive. In diffusion phase agents share information | Has two phases: Test phase and Diffusion phase. In test phase agents are categorized as active and passive. In diffusion phase agents share information | When the objective function can be broken into n number of partial functions independent of each other | Elitist Ant System, Max-Min Ant System, Rank based Ant System | Single            | Elitist Ant System, Max-Min Ant System, Rank based Ant System |                       | Job shop scheduling problem, Period vehicle routing problem, Antenna optimization, Image processing | Yes                  | Ant Hill Living |
| Whale Optimization Algorithm (WOA) | Global optimizer, Emphasis to exploration via global search, Less number of adjustment parameters, Easy to implement. | Every hunt is an attempt to reach the optimal solution of its neighborhood, Update of the position vector simulates encircling the prey, Convergence behavior based on the objective function. | Cycles of exploring the search space for optimal solution based on the position of search agents. | Begins with a random solution followed by search space for optimal solution based on randomly chosen search agent or the best solution so far. | Low convergence rate, Less accuracy, Conversion phase depends on randomness | Unimodal and multi modal optimization functions | Multiple | Unimodal and multi modal optimizatio n functions |                       | Workflow planning of construction sites, Image segmentation, Optimal power flow problem | Yes                  | Humpback whales Living |
Table 6: Time comparison in TSP in SI algorithms.

| Algorithm   | Eil51     | KroA100   |
|-------------|-----------|-----------|
| ACO [67]    | 457.97    | N/A       |
| ACS [66]    | 428.06    | 21282     |
| ACS [65]    | N/A       | 21282     |
| PSO [68]    | 473.34    | 27725.4   |
| C3DPSO [68] | 433.64    | 21689.30  |
| IWD         | 432.62    | 21904.03  |
| RFD [67]    | 458.08    | N/A       |

As part of artificial intelligent systems domain, a modified version of clonal selection [69] has been applied towards this problem. Table 7 compares the performance of this algorithm against 2-opt based algorithm in Eil51 and Eil101, example of TSP variants.

Table 7: Time comparison in TSP for clonal selection.

| Algorithm               | Eil51      | Eil101    |
|-------------------------|------------|-----------|
| Clonal Selection        | 94.62      | 2500      |
| 2-opt based algorithm   | 310.66     | 11100     |

From the above table it can be clearly that the clonal selection variant clearly performs better than the other algorithm and is more efficient.

![Figure 2: Algorithm domain and number of citations.](image)

Figure 2 indicates the total number of citations of algorithms considered under each domain compared with one another. Swarm intelligence domain has a citation count of 88844. It can be clearly observed that swarm intelligence and artificial immune systems easily outperform modelling of human mind and swarm intelligence being significantly greater than artificial immune systems as well. It can also be inferred from the figure the growing interest and research in the swarm intelligence domain due to its wide application.

V. CONCLUSION

In this paper, we can clearly observe that there are numerous sources of inspiration on which algorithms have been designed and implemented. There is an absence of any hierarchical structure to rank the algorithms and hence we propose a new hierarchy where we classify algorithms on the basis of inspiration. We have proposed a new domain of algorithms based on geoscience and further study their dependencies as well as sources of inspiration. Computational intelligence algorithms have a very broad palette of applications ranging from power grid to health care. Some of the algorithms have very advanced applications while some algorithms such as those in Geosciences domain are barely being worked upon. Hence development of these algorithms should be encouraged equally. Finally using the travelling salesman problem as a standard, we apply a select number of algorithms to get an estimate of their performance of the algorithms. Swarm intelligence domain is the better domain in terms of time taken amongst the others. This paper can hence serve as a comprehensive source of information for researchers due to the inclusion of tabular comparison across a wide variety of attributes. This work can be extended by making use of further constraints such as unimodal and multimodal optimization as well as inclusion of more algorithms to compare.

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