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# Tabu Search Algorithm (TSA): A Comprehensive Survey

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**Abstract-** This paper presents a Comprehensive Survey on Tabu Search Algorithms (TSA). TSA is a meta heuristic kind of algorithm which works on global optimal solution for a given problem such as vehicle routing problem (VRP), open vehicle routing problem (OVRP), multi-trip vehicle routing and scheduling problem (MTVRSP), container loading problem (CLP) and job shop problem, etc. in this paper focuses on main characteristics of TSA and its behaviour.

**Index Terms—** Combinatorial Optimization, Tabu Search, Meta Heuristics, Vehicle Routing, Hamiltonian Path, Open Vehicle Routing and Scheduling.

## I. INTRODUCTION

An optimization technique has worked with different fields such as distributed network, data mining, Artificial Intelligent, neural network, wireless sensor network, & etc. It can be classified such as meta heuristics and heuristics and further meta heuristics can be classified with local based and evolutionary based algorithms as shown figure 1.1. TSA are Meta heuristic algorithms which are loosely connected to evolutionary computing. It might be tackle NP-hard problems, i.e. combinatorial optimization problems. TSA reduce the critical regions in the search space by applying this approach. There are several methods for diversification and intensification which applied. It depends on the specific problem and type of problem and it can be used what type of solutions like within or outside but it will give better result for within the set which are sought. TS are using memory in short term or long term as well as intermediate to achieve diversification and intensification. In addition, aspiration criteria can be used to optimization process. Similar to the TS algorithm are works described by Glover Fred in 1989. TS meta heuristic have several variants to solve the combinatorial optimization problems which are TSP, VRP, OVRP, Job Shop Problem, MTVRSP and various graph related problem.

Very first by Fred W. Glover was proposed a Tabu search (TS) in 1986, he has include several basic concept by applying many ideas which was suggested in sixteen century and it was formalized in 1989. The article by Glover 1989 and by Glover, 1990 proposed the whole principle of tabu search which are known as basic TSA. TS algorithm was

started to overcome the local minima or local maxima that is known as local optima. There are several methods which need to overcome local optima problem. At that time this search provide a drastically change to reduce the local optima problem. At the starting tabu search was not well understood by the researcher and by D. de Werra at the Swiss Federal Institute of Technology, Lausanne. He discovered the word tabu or taboo comes from Tongan which is a Polynesian language and according to Webster the tabu or taboo is a word to define the set apart as charged with dangerous supernatural power and forbidden to profane use or contact which is associated with difficult regions.

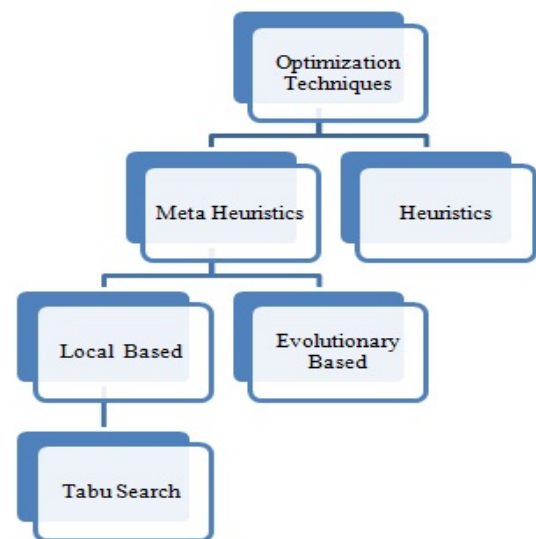


Fig. 1.1. Classifications of Optimization techniques

Last two decades TS algorithms are applied in several practical combinatorial optimization problems. Optimality's problem can be solve several way like minimum cost, minimum distance, maximum throughput, etc. There are several applications which are related to scheduling, in telecommunications and reorganization of character in natural processing language. In such kind of situation tabu search give an optimal or near optimal solution. By Fred Glover, the tabu

searches are applied to a broad class of problems. TS can be directly applied in several different kinds of decision problems without transforming to the mathematical formulations [5].

## II. TABU SEARCH FRAMEWORK

Currently we can discuss the concepts of TS. TS will provide necessary information about several strategies for diversification and intensification of the search which are used in TS.

### A. Overview

Basic feature of the TS was designed by Fred Glover for reducing the local optima problem, at that time other local based searching techniques are facing this problem. The author has used basic and sufficient feature at that time but some feature are not used at that time. Now here we will use basic principle of TS as described by Fred Glover et [2], [3] & [4]. The basic TS are exploring the several different areas for search space and artificial intelligence is one of the area which used by TS algorithm. So by using intelligence the TS becomes more effective and problem solving in adaptive memory as well as responsiveness of the given memory related problem like scheduling and job shop problem. It used direct and iterative manner to solve the given problem

Many researchers have worked over the past decade to improve the tabu search to find the optimal or near optimal solution for specified given desirable problem. Basic concepts and feature of TSA have not changed even added some other features like memory responsive that why TS is widely popular [4].

### B. Adaptive Memory

TS works with intelligent search for a specific problem, on the basis of previous process based on history data which is store in memory, based past actions to perform at search process. First store data performed action on search time and uses structure to store data and apply TS. TS faces challenges are used when ever past store data in memory storage space. In stored data, the explicit memory and attributive memory are record the complete solution. Memory are stored records with consistent and highly attractive solution and do not explore neighbours hence such kind of memory is known as explicit memory. This type of memory are used for define the neighbour and extend its neighbourhood in TS algorithm. In memory which stores the data or information on the basis of attribute for making the best solution that kind of memory is known as attributed memory. The basic things about attribute are values of functions or variable which is use for making a optimal solution. Some of the attributes are use hash function for storing the data that can be search become more efficient. A TS are used both kind of memory for making best search strategy.

The memory can be structured short term or long term. TS use both kind of memory structure and each has its own strategy and feature [6]. As per requirement we can use short

term or long term memory and modified the neighbourhood by using current solution to the next new solution. To find the new solution, modified neighbourhood is contain to history data or record and depending on type of the memory (short term or long term) structure used at different states of iteration in the TS Algorithm. So kinds of memory structure basically contain four principal which are based on quality, frequency, influence and regency [8]. Quality based memory are using for ability, influence are use for impact, regency are use for keeping the track and frequency are use for keep track the solution which is very commonly used in past and they all are work together so TS gives better performance.

### C. Move mechanism

Tabu search algorithm on the current solution that can be applying this mechanism by replacing selected edges. In this mechanism the swapping of edges are take place when current selected edge and new selected edges are exchange. First all the current selected edges are store in list that is known as candidate list. After that each move create a new possible solution and select best of them and apply the move mechanism. When choose move mechanisms there are some restrictions which are by selecting edges are no any cycle there. Selections of edges are satisfying the requirement of the given problem. There are two kind of swap process one is static and another are dynamic. These static and dynamic edges swap are belongs by Yajie Tian at all in 2000. Move mechanism example as following figure 2.2 are shown in this example there are dotted line show the deletion of the edge and dark line show the adding edge. Here two edges are exchange by using move mechanism we may select the two edges and connected these selected edges which is belong to the current solution that can be exchanged and these process done without any cycle in the graph.

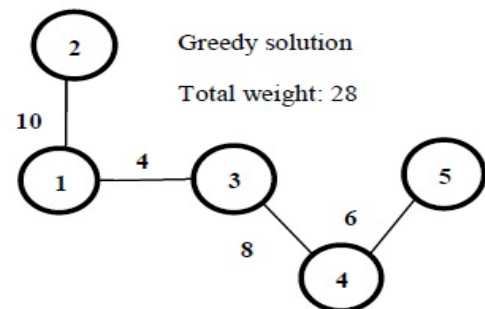
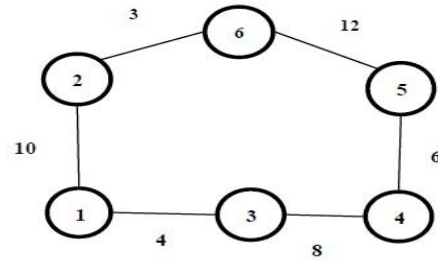
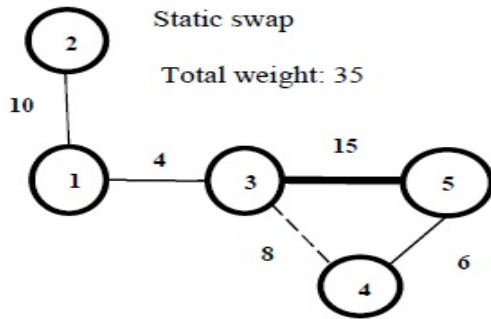


Fig. 2.1. Greedy approach



Greedy Solution

Total weight 43

First find the all move edges, select them and store in the candidate list. After that by move mechanism select best move and swap current selected edges to the new selected edges for best solution by applying TS. Here for each and every step for the searching process we need to find out all moves which applied in the current solution. This process is done in iterative manner.

In the above figure exchange the edge or swap process is done to performs 3 edges. Here exchange the edges need to reconnect these edges any cycles in the existing graph.

#### D. Tabus

Node and edge are restricted to the element when the next iteration of search which is defined by tabu search. In TS ignore the cycling and optimize the path cost to find the optimal solution. Neighbourhood need to apply when move mechanisms are applied in the tabu search. Here most important thing is that when becoming a various situations like local optima, they need to resolve the (Local optima) search from tracing back previous steps to where it came from. Those kinds of achievement are possible by tabu search. It recorded in short-term memory scheme for performing move from current state to next possible solution state. In Tabu search, candidate list have limited storage information for limited time period. We can store complete solutions but it needs a lot of storage memory. When memory is expand, the move become expensive to checking whether move is required or not in tabu search. That why need to define the candidate list size in tabu search. So the storage is remove first come first out techniques. At the initial solution we may apply to move and find the candidate list in tabu search [15].

#### E. Aspiration criteria Tabus

There may be some attractive but prohibited move even it may not a danger or critical condition like cycling but still these move are give attractive result and may handle stagnation of TS searching process. These kinds of situation are necessary for some conditions that are known as aspiration condition or criteria. This is also known as sensitive key factor in TSA. It is used for most and simple aspiration criteria. Aspiration criteria allow moving that way there are best move by using this criteria. With better solution on the basis of best known solution that allows Tabu. Such conditions are called aspiration criteria.

#### F. Intensification

If we need more effective and best admissible solution then there are some features and component, one of them intensification in tabu search. It is like exploitation. This strategy is based on improving the choice rules. It is based on

Dynamic swap

Total weight: 39

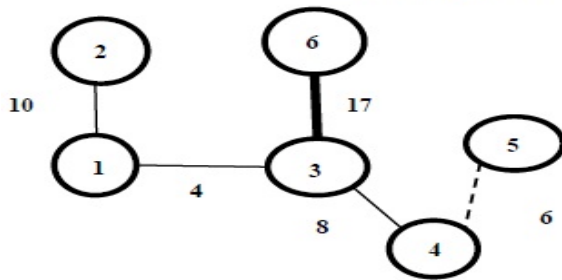
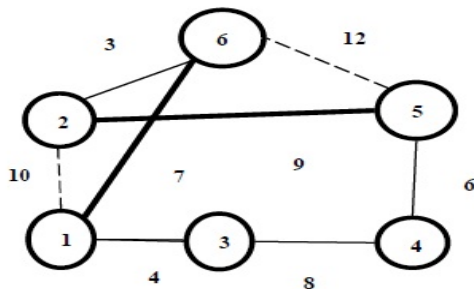


Fig. 2.2. Move mechanism

2 edge exchange

Total weight 37



between short term and lost term memory that is known as intermediate memory. Intermediate memory is a recently memory which applied to initial or best solutions or combination. It is uses traditional algorithm without any interruption. Intensification can be generating neighbours using grafting or evaluation strategies for good solution. It is used in many TS implementations, but it is not necessary examine when the normal search process give enough thorough or best possible solution. In this case no need to examine more carefully these nodes that we have already visited. In tabu search may use local optima problem solving when ever required and achieve good solution. Whenever we fail to explore the other interesting parts of given search space hence, diversification strategy is used to address such problem.

#### G. Diversification

Whenever we fail to explore the other interesting parts (do not explore by using intensification) of given search space it can be explore by using diversification strategy. It is used in long term memory that is frequency memory. Diversification means extending the search to a new direction. Diversification strategy is able to records the all iterations from initial state of the search which provides current solution. It is also perform moves whenever require for best solution. It is applicable in tabu search when design a critical issue. It is also case about initial step and it should perform more iteration if they obtained results are not up to expectations. This strategy proved the direction of new region of search space. In TSA, intensification and diversification works tother. If some space are restricted to a search space and also difficult to guide the search to different search regions, these cases mostly restart TSA with another initial solutions rather than random choosing initial solution. Diversification is use more efficient when it is symmetric. Some mechanisms are use to implement intensification and diversification strategies are: strategic oscillation, solutions evaluated but not visited, path relinking, reinforcement by restriction, creating new attributes etc.

#### H. Preventive Maintenance (PM)

PM is required to increase the availability of the equipment and also improve the overall efficiency. So maintenance management takes active role of manufacturing the equipment. PM decide which tasks to do and when, so it can be classified a scheduling as well as a resource allocation. By McCall (1965), Pierskalla & Voelker (1976) they mention two aspects first dichotomy and second aspects are proactive. In dichotomy lets the equipment fails stochastically & finds the actual state based on actual state is known or not. Proactive, it deals with equipment life so both can be work with the probability of failure and breakdown occurrence. PM\_TABU, scheduling the memory structure such as stored information search beyond the local optima. PM\_TABU, algorithm is gives a very good solution to PM scheduling problem by several states like initial solution, objective function, probabilistic intensification and diversification are moves for TS, neighbourhood, tabu move different attributes and the

candidate (tabu\_list) list length, aspiration level, stopping rule, description of basic TS and description of PM\_TABU.

#### I. Neighborhood

In heuristic search the neighborhood is most important aspect. Neighborhood can be applied as per requirement of the given problem. It is defined by applying the move function, in moving function is done by replacing or swapping the candidate list which provide best solution. According by Math world, it is defined as to move the point which is a set of distance without leaving the set. It proved when new solutions need to exchange the node or edge with another node or edge. Neighborhood solution this is done by swapping and replacing us have several routs but the number of nodes is remaining same. In heurist, neighborhood perform best move for exchanging nodes. Its concepts are different in tabu search form other local search algorithm. Here dynamic in nature because neighborhood move is depending of constructive or destructive neighborhood. In constructive, the solution and result is constructive process then it is called constructive neighborhood and if the solution or result take destructive process then it is known as destructive neighborhood. In TS it is using dynamic nature to avoid the cycle in search space. Here we use short term memory for storing and eliminating the visited solution but long term memory are used to expand the neighborhood and also use for examine the unvisited regions.

### III. TABU SEARCH ALGORITHM

#### Tabu Search Algorithm

1. **begin TS**
2. TS\_list = [];
3. S = initial solution;
4. S\* = S;
5. **Repeat Step 2 to step 4**
6. Find the best admissible solution S1 belongs to Neighborhood of S
7. **if** f(S1) > f(S\*) **then** S\*:= S1;
8. S:= S1;
9. Update TS\_list TS\_list;
10. **Until** the process, stopping criterion;
11. **End;**



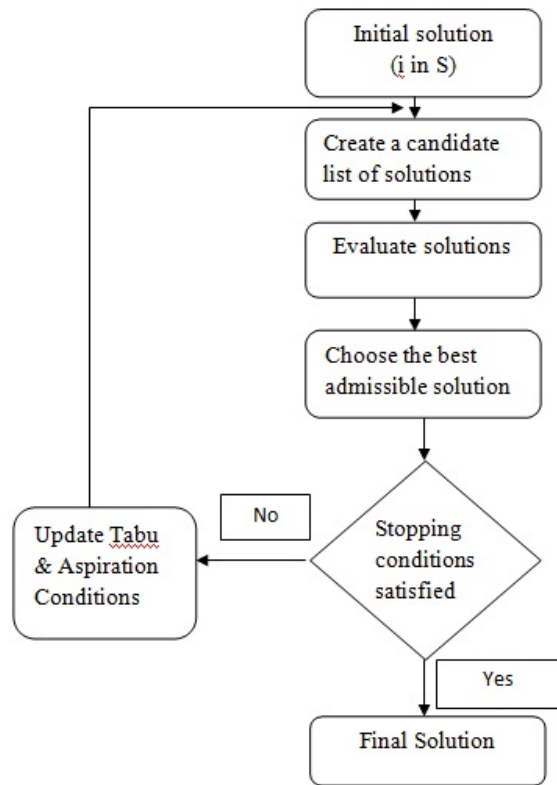


Fig. 3.1. Flow chart of TSA

#### IV. APPLICATION OF TABU SEARCH ALGORITHM

In TSA have several applications some of them travelling salesman problem (TSP), K- tree problem, VRP, OVRP, multi- trip routing and scheduling problem( MTRSP), container loading problem(CLP), preventive scheduling(PM) and job shop problem(JSP),etc.

##### A. travelling salesman problem

TSP is a most famous problem in computation mathematics for optimization research, because it is most popular and simple to explain and understanding but hardly difficult to find a possible optimal solution. TSP is a kind of NP-hard problem, that why very difficult to solve all possible Travelling salesman problem instances to find the optimality within minimum execution time.

TSP is defined as to calculate optimal cost route in a tree or graph (undirected graph) from an source or starting node and covering all the nodes in the graph or tree exactly once (except starting node) and further going to a stop at the starting node. It may be asymmetric or symmetric. First, asymmetric strategy, cost of the edge is dependent on the direction of travel such as cost of travelling from city X to city Y may be some or may be different from the cost of travelling from city Y to city X. Second, symmetric strategy the cost of a link or edge is independent of the direction of travel like the cost of travelling from city X to city Y is same when travelling from city Y to city X because of independent of direction in this strategy. Here is sample example, which is only

considering symmetric strategy Travelling Salesmen problems. Showing the following Figure 4.1 which showing a example of graph TSP with ten nodes. This graph is a symmetric graph of TSP. In the graph showing the numbers on the links are the weights of the edges which are connected from one node to another node.

##### Initial Solution

Graph 4.1 is showing the initial solution where the initial node 1 and applying the TSP, the travelling process start with node 1 and further visited only once for every node except node 1. The visiting process work in such way that there is an optimal cost finds the solution without any cycle (except starting node). By applying any local search, we can find the longest path with optimal cost. After that applying TSA to find the optimal solution and find that it gives best optimal solution which is showing figure 4.3. Now in below example we used first greedy algorithm to find the longest travelled path to get the initial solution the effect of finding the optimum solution for TSP increases as showing the figure 4.2.

##### Initial solution for Symmetric TSP

Based on heuristic tail solution is 81, we will use as initial solution for the input of tabu search (TSA).

##### Tabu search

##### At the starting edge (1, 2) swap move mechanism

At the starting in TSA, tabu\_list is empty. Random two edges are selected and selected edges will be no restriction to exchange them. At initial stage the moves are done without restriction and select best candidate list by moving each other. After that two new edges are added and exchanged by moving the best possible solution with some restriction. Here best tabu\_list which are node (1, 2) and node (4, 5) are exchange and these two edges are deleted and new two best edges are added which is (1, 4) and (2, 5). After deleting two edges the new tour length is 77 as shown the figure 4.3

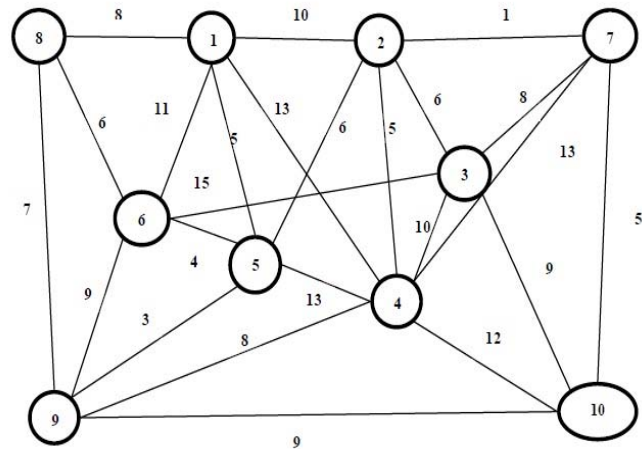


Fig. 4.1. Travelling salesman problem graph

Tour length 81

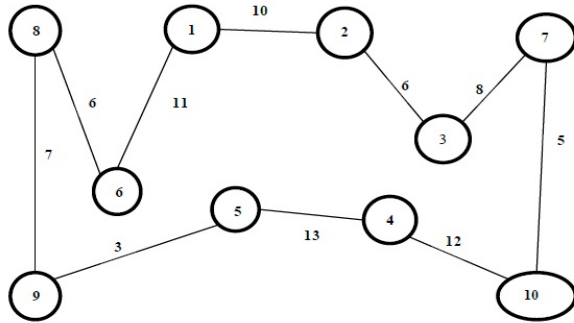


Fig. 4.2. Solution by greed algorithm

Tour Length 78

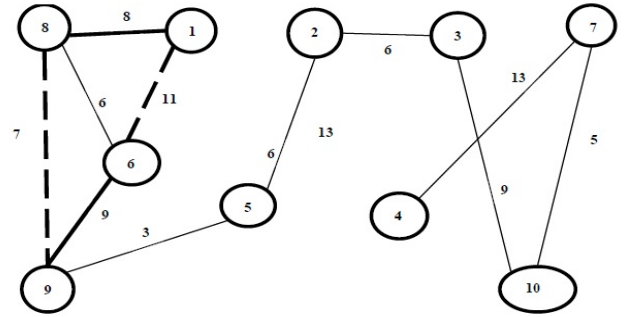


Fig. 4.5. Third iteration of tabu search

Tour length 77

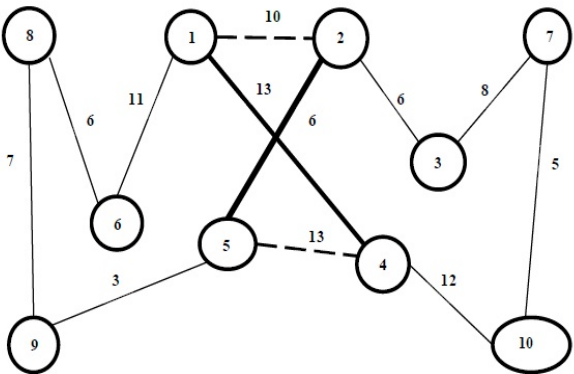


Fig. 4.3. First iteration of tabu search

In next iteration another two edges same mechanism are apply if the current solution and new solution are some or not perform better solution than current edges are not swap. But some constrain it give better solution then best solution will be updated with new solution.

Tour Length 79

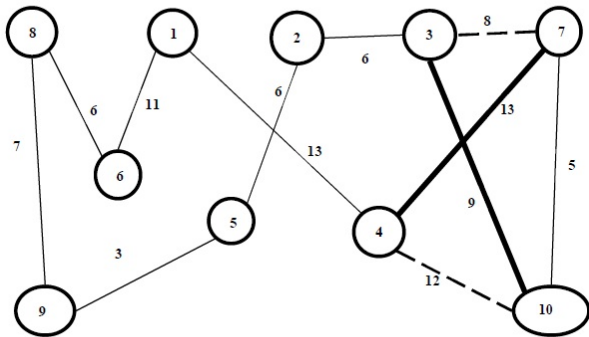


Fig. 4.4. Second iteration of tabu search

The iteration is repeated whenever stopping criteria is satisfied. When storing criteria are satisfied then fix the iteration before the process started. In this method there is no back drop process. In the example figure 4.4 and figure 4.5, the TSP considers best solution is 77.

### Consequence of TSP

Travelling Salesman Problem have been solved several manner by many researchers. Before apply the Tabu Search in TSP, it gives near optimal solution result or optimal result but after apply the TSA meta heuristic in TSP, it give always optimal result. Using TSA to solve TSP can be several or different outcomes which have done several research articles i.e. [3], [7], [8] & [14], comparative survey based on TS, TSP produce better results. It produced better result and effective solution for large test problem of TSP and the quality depends on length of each search and depends on the length of the each search. Several new methods have been applied on TSP while using TS, some of them are angle based TS, parallel adaptive tabu search, multi point tabu search [11] [12] [13]. TSA based, TSP have been solved VRP, OVRP and some researchers like Jose Brando et and all 1997 can improve the solution by using multi trip vehicle routing and scheduling in tabu search meta heuristic.

TABLE 1

Various problem short descriptions based on TS

S. No	Name of Problems	mechanism	Function and memory	Solution / future work
1.	Vehicle routing Problem (1999) By Gulary Barbaros oglu et.	Vertex exchange between different route, Euclidean distance, dynamic move,	Sympatric, Aspiration criterion, diversification, parallel computing, short term memory.	Best admissible solution, Application for company distribution.
2.	Open vehicle	Move, train	k- tree, NNH, MST,	Very good solution, may

	routing problem (2004) By. Gestao e Administracao publica et.	swap, lower bound, lowest tenure give better solution	influence, symmetric and asymmetric both, parallel processing	or may not admissible solution, random tenure give better solution than fix tenure		e maintenance scheduling (2001) By M. Gopalakrishnan et al.	based, tabu heuristic, flow chart, upper bound, all tabu search criteria,	adding dropping and swapping craft combinations, memory mechanisms, local heuristic, PM TABU	study, local heuristic and average optimality gap it can be reduced
3.	Multi trip vehicle routing and scheduling problem (1997) By Gestao e Administracao publica et.	Swap move consist of exchange two different route,	forward slack, negative forward slack, two approaches-sequential constructive and un routed orders is inserted one of the existing routes	Random factor, algorithm give better solution as compare to manual solution, improve the availability of vehicle	7.	Job shop problem (2005) By: Eugeniusz et al	Job shop problem, make span, path relinking, neighborhood	Job scheduling in PC, dynamic memory, tabu based advanced scheduling topological order, head and tail, tuning parameter,	i-TSAB and relinking provide very powerful tool for solving job shop problem, very good accuracy, obtainable quick time on PC.
4.	Container loading problem (2002) By A. Bortfeldt and et al	Heuristic, local and global optimum, or exchange,	Parallel TSA algorithm, achieve mean value utilization, min support, LIFO, local as well as global swap, package space, sort term memory, etc.	Parallel Tabu more powerful as tabu search, better performance, use multi search threads, can be solve WLP, there are future work with hybrid parallelization approach for meta heuristic.					
5.	Optimal PMU placement (2005) By: Jiangnanpeng and et al.	Move, initial PMU placement, set of candidate move, aspiration criteria, stopping criteria,	PMU optimum placement scheme, incidence matrix, simulation by IEEE 14 bus, new England 39 bus system, IEEE 57 bus system,	TS provide high accuracy and less computational effort, incidence matrix manipulate the integer numbers and fast conveniently network observability					
6.	Preventiv	VRP	Three move	Comparative					

## V. CONCLUSION

Tabu Search Algorithm (TSA) works well and provide optimal result. There is survey several different problem based on TS. It provides the basic as well as problem based solution for tabu search. How it can be applied and where it can be applied. The learner is also able to track and find the concept of TS and apply TS in several local based problems for finds the best admissible solution. It helps researchers which are working with combinatorial optimization and TSP, TSA, JOB SHOP PROBLEM, VRP etc.

## VI. FUTURE WORK

In future TS may apply in several areas such as Internet of Things, Deep learning and it can be simulated and make the best hybrid approaches to solve the most admission optimization problems.

## REFERENCES

- [1] Glover Fred, *Tabu Search – Part I*, ORSA Journal on Computing, Volume 1, Issue 3, pp. 190-206, 1989
- [2] Glover Fred, *Tabu Search – Part II*, ORSA Journal on Computing, Volume 2, Issue 1, pp. 4-32, 1990.
- [3] Yi He, Yuhui Oiu, Guangyuan Liu, Kaiyou Lei, *A parallel adaptive tabu search approach for travelling salesman problem*, Natural Language Processing and Knowledge Engineering, 2005, IEEE NLP-KE 2005, IEEE International Conference, pp. 796 – 801.
- [4] Meeran, S and Morshed, M S, *A Hybrid Genetic Tabu Search Algorithm for solving Job Shop Scheduling Problems*, Journal of Intelligent Manufacturing, Volume 23, Issue 4, pp. 1063 – 1078, 2012.
- [5] Gouhui Zhang, Yang Shi, Liang Gao, *A genetic algorithm and tabu search for solving flexible job shop schedules*, computational Intelligence and Design, 2008, ISCID 2008, International Symposium on ( Volume :1), pp. 369 – 372
- [6] Yajie Tian, Sannomiya N., Yuedong Xu, *A tabu search with a new neighborhood search technique applied to flow shop scheduling problems*, Decision and Control, 2000, 39th IEEE Conference ( Volume :5), pp. 4606 – 4611.



- [7] Laporte G. *The vehicle routing problem: An overview of exact and approximate algorithms*. *European Journal of Operational Research* 1992;59:45-58.
- [8] Fisher M.L. *Optimal solution of vehicle routing problems and minimum k-trees*, Report 89-12-13, Decision Sciences Department, The Wharton School, Philadelphia, PA, 1989.
- [9] H. Gehring, A. Bortfeldt, *A genetic algorithm for solving the container loading problem*, *International Transactions in Operational Research* 4 (1997) 401-418.
- [10] R. Morabito, M. Arenales, *An AND/OR-graph approach to the container loading problem*, *International Transactions in Operational Research* 1 (1994) 59-73.
- [11] B.K.A. Ngoi, M.L. Tay, E.S. Chua, *Applying spatial representation techniques to the container packing problem*, *International Journal of Production Research* 32 (1994) 111-123.
- [12] D. Pisinger, *Heuristics for the container loading problem*, *European Journal of Operational Research* 141 (2002) 143-153.
- [13] Y. Rochat, E. Taillard, *Probabilistic diversification and intensification in local search for vehicle routing*, *Journal of Heuristics* 1 (1995) 147-167.
- [14] G. Scheithauer, *Algorithms for the container loading problem*, in: *Operations Research Proceedings, 1991*, Springer, Berlin, 1992, pp. 445-452.
- [15] M. Gendreau, A. Hertz and G. Laporte, *New insertion and post optimization procedures for the traveling salesman problem*, CRT-708 Centre de Recherche sur les Transports, Universite de Montreal, Montreal, Canada (1991).
- [16] C.-N. Fiechter\* *A parallel tabu search algorithm for large traveling salesman problems* (1994)243-267.
- [17] JoseBrandao, Alan Mercer, *A tabu search algorithm for the multi-trip vehicle routing and scheduling problem*, *Elsevier in European journal of operation research* 100(1997) 180-191.
- [18] Eugeniusz Nowicki and Cxslaw smutnicki, *An advanced tabu search algorithm for the job shop problem*, *Springer Business media in the Neatherland*, 2005, *Journal of Scheduling* 8: 145-159.
- [19] M. Gopalakrisnan, S. Mohan, Z..He , *A tabu search heuristic for preventive maintenance scheduling*, *Elsevier, 2001, computers and industrial engineering*, 149-160.
- [20] Jiangnan Peng, Yuanzhang Sun, H.F. Wang , *Optimal PMU placement for full network observability using the tabu search algorithm*, *Elsevier, 2006, Electricla power energy system* 223-231.
- [21] A. Bortfeldt, H. Gehring, D. Mack, *A parallel tabu search algorithm for solving the container loading problem*, *Elsevier, 2003, parallel computing* 641-662.
- [22] Gulay Barbarosoglu, Demet Ozgur, *A tabu search for the vehicle routing problem*, *Elsevier, 1999, computers and operations research* 255-270.
- [23] Jose Brandao, *A tabu search algorithm for the open vehicle routing problem*, *Elsevier, 2004, in European journal of operation research* 552-564.