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Scatter Search Optimization for Multi Node Machining Fixture Layout

P. Maheandera Prabu, Dr.K. P. Padmanaban, R. Rajasekar,
R. Devaraja Vignesh, Dr.S.Navaneethasanthakumar
[1, 2, 3, 5,] *Department of Mechanical Engineering, SBM College of Engineering & Technology*
[4,] *Department of Industrial Engineering, Oklahoma State University Stillwater,*
Oklahoma 74078-5021, USA

ABSTRACT

Geometric problems during machining of a work piece have been an archaic and prominent problem in industries. This problem has been overcome by installation of clamps and locators. Clamps and locators are excellent solutions to minimize geometric error in work piece machining, but fixing the point of contact of clamps and locators on the work piece has a major impact on reduction of deformation. Optimization of fixture layouts has been a crucial topic under research because of the above reason. Lot of optimization techniques has been implemented in fixture layout. This particular article deals with implementation of scatter search methodology in fixture layout selection. Scatter search with randomized subset combination was used for solving a case study and deriving the layout with minimum deformation. The diversification generation was formed in such a way that it covers all possible layouts for improvement method. The case study chosen was a multi nodal machining problem, so after multiple iterations of subset formations a ranking method was used for finalizing the result which suits best for all machining nodes without any discontinuity.

Keywords *- Finite Element Method, Fixture layout, Objective Function, Optimization,* Scatter *Search,*

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I. INTRODUCTION

Undesirable perturbations during machining have been a very critical problem for a very long time. Accuracy of the expected final design is at stake because of this factor. As the time propagated, modern optimization methods came into picture and altered the austere scenario. When better optimization techniques entered in this field undesirable factors has been filtered and eliminated. 3-2-1 locating principle has been considered thus far as the best method for constraining degrees of freedom for any prismatic shaped work piece, mainly because this theory considers minimum number of fixture elements for providing maximum rigidity [1].

In the case study chosen for this article, in order to control the degrees of freedom two clamps and three locators are required. Clamps apply force in order to retaliate and reduce undesirable increase in displacements. Its basic purpose is to secure the part against the locators and clamps, however the force obtained from clamps are not expected to resist the cutting forces which are applied during machining. Locators which are placed on peripheral degree are primarily installed to counteract and nullify displacement in particular axes. All these supports must be positioned far away from each other in order to achieve maximum efficiency and accuracy while machining [1]. Accuracy is an indispensable factor in machining process [3]; this accuracy can be achieved only by positioning the supports in optimized positions.

The optimization of fixture layouts have been achieved through various non conventional optimization methods and implementations of many more techniques into this topic are underway. This particular article deals about optimization of fixture layouts by using scatter search methodology. The complete problem of displacement calculations, machining calculations and various steps of optimizations were handled by codes written in C++. A comparison with previous works has been done and consolidated results are given in this article.

II. REVIEW OF RELATED WORKS

Lot of research works has been conducted in fixture layout optimization area so far. All the basic requirements, criteria and computational methods for fixture machining and supports were explained in details in a dissertation by Zheng [1]. He has given a deep explanation about conventional Computer aided Fixture Analysis by doing so he has provided away for fixture stiffness to keep in pace with development of CAFD. He has also analyzed various dimensions of contact stiffness and elaborated Finite Element Analysis (FEA) Method to analyze fixture layout problems. Lee and Haynes developed computer software for analysis and design of fixtures [2]. It can lead the designer to the optimal design of fixture system which minimizes the total work done on the piece, the fixture force, the deformation index or the maximum effective stress. Lot of mathematical advancements in this area was done by Cogun who investigated the effect of the application sequence of clamping forces on the mounting accuracy of a work piece [3]. He also established that the selection of a rational sequence of clamping force is important for the control of work piece displacement under clamping forces.

Mathematical approaches for finding and analyzing the displacement values for a fixture layout has been discussed in various works. Kaya and Öztürk have analyzed various algorithms of group machining operations and they have also analyzed the dynamic machining conditions [4]. Finite Element analysis worked out as the best method for them in most cases. M. Vasundara et al have analyzed many alternative solutions for computation in place of FEA like Artificial Neural Networks (ANN) and Response Surface Methodology (RSM)[5].Krishnakumar and Melkote presented a machining fixture layout optimization technique that used genetic algorithm (GA) - a metaheuristic computational approach, to find a fixture layout that minimized deformation of the machined surfaces due to clamping and machining forces over the entire path [6]. Necmittin Kaya proposed a comparatively better way to analyze and present better results using GA. He improved the results of previous works by implementing wider range of search and fine tuning, by doing so he has improved the fitness of chromosomes in GA [7]. K. P. Padmanaban et al has implemented ACA (Ant colony Algorithm) for optimizing fixture layouts. In their article they have proved that the ACA-based continuous fixture layout optimization method exhibits the better results than that of ACA-based discrete fixture layout optimization method [8].Scatter Search (SS) was first introduced and implemented by Fred Glover et al, he explained the broad layout of the algorithm of scatter search and he also proposed a wide accepted template which is used for almost all scatter search problems up to date [9]. César Rego and Pedro Leao worked and presented a article on implementation of scatter search in graph theory based permutation problems, this article on implementation of SS in graph theory based permutation problem, this article tends to give a wider perspective on implementing SS in knapsack and combination based problems as well[10]. Juan Jose Pantrigo et al understood the flexibility of implementing scatter search in a broader area, they used scatter search to solve a widely acclaimed bench marked problem - The travelling salesman problem. Results and works done in all these above works seem to allude that the scatter search has a more definitive place in Fixture layout optimization [11].

III. SCATTER SEARCH CONCEPTS

Scatter Search concept enabled a way to cover all possible opportunities to attain better results with comparatively lesser runs and to attain wider coverage of both feasible and unfeasible results. Possibility of handling even unfeasible result is a merit for this search. Scatter search can cover wide grounds of applications and is a commendable metaheuristic optimization technique. The multiple stages of Subset combinations and formations have ensured betterment of new set of population formed. Adaptable Improvement method which depends on better objective functions is the crucial merit of this optimization technique.

Just like Genetic Algorithm, Scatter Search works on the basis of design variables and parameters in the problem rather than with actual parameters. Similarly, Scatter Search requires only objective function value, no derivatives or gradients are necessary. Both population type search and single node wise search can be implemented based on required flexibility in SS. The main merit of scatter search over GA is its methodology which has the tolerance to handle both feasible and infeasible solutions.

Algorithm of the Basic SS is given as follows:

1. Diversification Generation: Generation of Random set of layouts. Choosing a diversified set of layouts throughout the boundary limits is a quintessential way to handle this step.
2. Objective Function: The maximum displacement value on the machining part is to be considered as the objective function.
3. Improvement Method: Amongst the competition in a particular population the best set of results are identified and extracted based on objective function. The displacement here is an undesirable factor so minimization of objective function is the main concern based on which the improvement method is handled.
4. Reference Set Update: A Reference set is updated with diverse solutions for each run. Number of solutions in this set cannot exceed 20 at a time
5. Subset Combination: From the best results extracted from previous improvement methods a better set of layouts are combined.
6. Loop: Go to Step 1. All possible layouts can be covered if the numbers of iterations are increased, but comparatively lesser number of iterations is enough to achieve better results than other metaheuristic approaches.
7. Solution Combination: It is a problem specific algorithm step. There is no necessity to calculate the subset that has been previously calculated. In this step a new ranking method has been proposed for fixture layout optimization.

IV. FIXTURE LAYOUT OPTIMIZATION

4.1 Positioning Of Supports during Machining

Location of fixtures over machining part reduces any sort of unnecessary displacements by holding the machining work piece in required position. These fixtures fulfill their purpose by offering structural rigidity and reducing machining inaccuracy. Apart from providing proper fixture stiffness these supports also reduce geometric inaccuracies [3]. The main types of forces which must be considered while providing supports are machining forces and clamping support forces.

The basic way to start this analysis would be by analyzing machining and supports of a prismatic part. The common and most effective way used for determining the location of supports over a prismatic part is 3-2-1 principle. This method has proved to be effective because it provides maximum rigidity with comparatively minimum number of elementary data. This theory deals with degrees of freedom in a prismatic part and a way for minimum number of supports to counteract and restrict these degrees of freedom.

In the case study which is chosen for this article supports are provided for a 2D prismatic part [6]. For arresting the degrees of freedom totally five supports will be required- two clamps and three locators. Any supports provided more than those mentioned above will turn out to be redundant, on the contrary any supports provided lesser than mentioned above will lead to unnecessary displacement and inaccuracies. So the optimum amounts of supports are provided for extracting optimum result.

The locators are placed opposite to the axis of clamps so that the clamping forces will direct the opposite points of work piece towards the locators. The reactions derived from the locators must be positive all the time because the machining forces travel along with the machining surface, so in case the locators exhibit negative reactions for any layout that means there has been a loss of contact. This criteria mentioned above is a limitation factor for locators, whereas in the case of clamps, the clamping forces they exhibit must counteract with unnecessary displacement but they must never interfere with machining forces for any layout.

4.2 case study

The ultimate aim of this problem is to find the optimized positioning of locators and clamps which has lowest displacement value on the machining part. Number of locators and clamps, clamping force, machining force, material Properties and Friction factors are fixed, constant parameters dealt in this article hence they are not design parameter values and also optimization of these parameters are not concerned with in this article.

A 2D case study was chosen for implementing scatter search methodology. This case study is the widely considered preliminary work for most optimization problem in fixture layout area. This 2D case was chosen for its simplicity because of the first time trial of scatter search method on these grounds. This case study was first analyzed by Krishnakumar and Melkote[6]. Pictorial representation of the work piece along with the supports is represented in the figure 1.

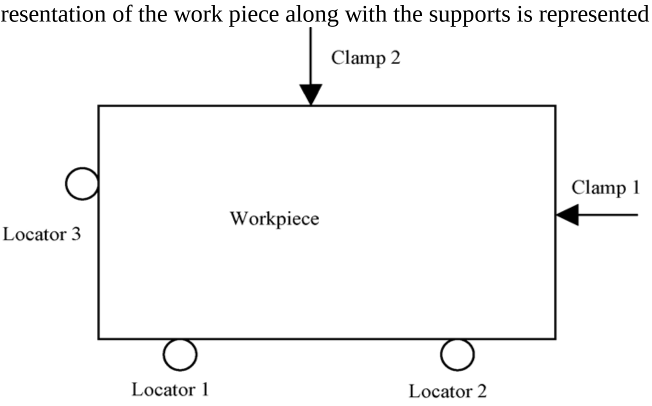

Figure .1: Representation of case study

Finite element analysis which is the powerful computational method for resolving the problems regarding fixture layouts is used for computing displacements in this chosen case study [4]. In order to use FEA for this problem and to easily compute all necessary factors, multiple nodal points and elements has to be created. After the basic FEA, computations for global stiffness matrix and force matrix are required. From these above data, displacement matrix could be calculated from which the objective value is derived, but all these computations must be carried out as a part in improvement method of scatter search. For this article all these computations were done through codes written in C++.

V. IMPLEMENTATION OF SCATTER SEARCH IN FIXTURE LAYOUT OPTIMIZATION

Scatter Search is a relatively new metaheuristic technique to be introduced in to fixture layout optimization, but fortunately the flexibility of this methodology has made the adaptability to this context possible [9]. After mapping the work piece into various elements and nodal points, the boundary limits of each supports are determined based on 3-2-1 principle as represented in the figure 2.

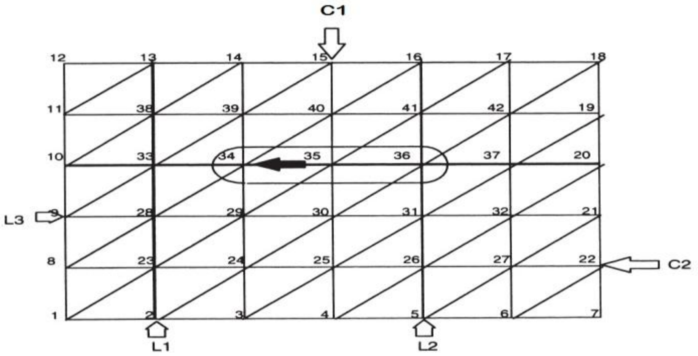

Figure.2: Case study split into elements

Work piece dimensions: Length=304.8 mm
Breadth= 254 mm
Sides of each triangular element (except hypotenuse) = 50.8 mm

Locators and clamps position constraints:

$$1<L1<4$$
$$3<L2<7$$
$$1<L3<12$$
$$12<C1<18$$
$$7<C2<18$$

Boundary Conditions:

The displacement is zero in vertical direction for locators L1 and L2
The displacement is zero in horizontal direction for locator L3
Material properties and cutting parameters
Work piece material= Steel
Young's modulus (E) = 206 X 10^9 N/m^2
Poisson's ratio (γ) = 0.3
Clamping force= 1779 N
Machining force F_x= 889.6 N
Machining force F_y= 889.6 N

The dynamic response of elements for a fixture layout can be effectively computed through FEM. Based on the positioning of locators and clamps and machining force applied, displacement matrix for each layout can be calculated. In this case study there are 60 elements. Using coordinate values of each nodes and area of each elements gradient matrix is calculated. Using young's modulus, an elasticity matrix is created. From gradient and elasticity matrices, element stiffness matrix is formed (6X6 matrix for each element)

$$[K^e]=A[B]^T[D][B] \qquad (1)$$

[K]- Element stiffness matrix
A -Area of triangular element
[B] [B^T] - Gradient matrix and transpose of the gradient matrix
[D]- Elasticity matrix

These individual element stiffness matrices of 60 elements are assembled and a global stiffness matrix of order 84 X 84 is obtained. Force vector matrix differs based on position of fixtures. From global stiffness matrix and force vector matrix displacement matrix is derived, from which objective values are obtained.

$$X=K^{-1}F \qquad (2)$$

[K]- Global stiffness matrix
[F]- Matrix of nodal force vectors
[X]- Nodal displacement Matrix.

Basically this problem is dealt in the same way a knapsack problem is dealt with [10]. In five different knapsacks of all possible nodal points on which the supports can be placed are packed. Combinations of one element from each knapsack will give us a possible layout. So in order to ensure that a diversified set of layouts are combined to form a set, extreme nodes of boundaries are chosen for first run. This is the first step of diversification generation. In each of these extreme layouts there are five positions for nodal points where supports have to be placed. From the knapsacks of all possible nodal point locations of five supports, random members can be selected and replaced as new members in respective slots. Hence a diversified set of solutions are created.

This diversified set of solutions created is the first set for reference update. Based on general standard of SS the maximum population of a set is limited to less than 20 members (20 sets of layouts). After the first iteration farther sets of solutions are formed using same random combination process.

The flow chart representing various steps of scatter search implementation in fixture layout optimization is represented below flow chart. The case study chosen was a multi nodal machining problem [6][7]. The cutting forces are applied on three continuous nodes. In the preliminary steps, subsets are formed and competitions are conducted solely based on cutting forces on single machining point alone.

Improvement method is adapted as per the problem requirements. For each set of fixture layout displacement matrix is computed as per FEA. The highest value possibly achieved in displacement matrix was considered as the objective function. A competition was conducted within the initial group of sets and best results were extracted based on lowest objective function (Objective function in nonetheless an undesirable displacement so minimized objective function is the basic criteria). Many stages of subset combinations are conducted and feasible and infeasible fixture layouts are dealt with in each turn of subsets.

This case study has been dealt with 90 numbers of iterations. After all the above iterations, a final set of solutions has been derived respectively for all three machining points. Although we have been forming subsets and running iterations based on individual machining nodes, we need a common fixture layout without any discontinuation in practical application. A way to do that has been discussed in solution combination step of the algorithm. As mentioned before Solution combination is a flexible [11] problem oriented step. In this article a particular ranking system has been tested for solution combination.

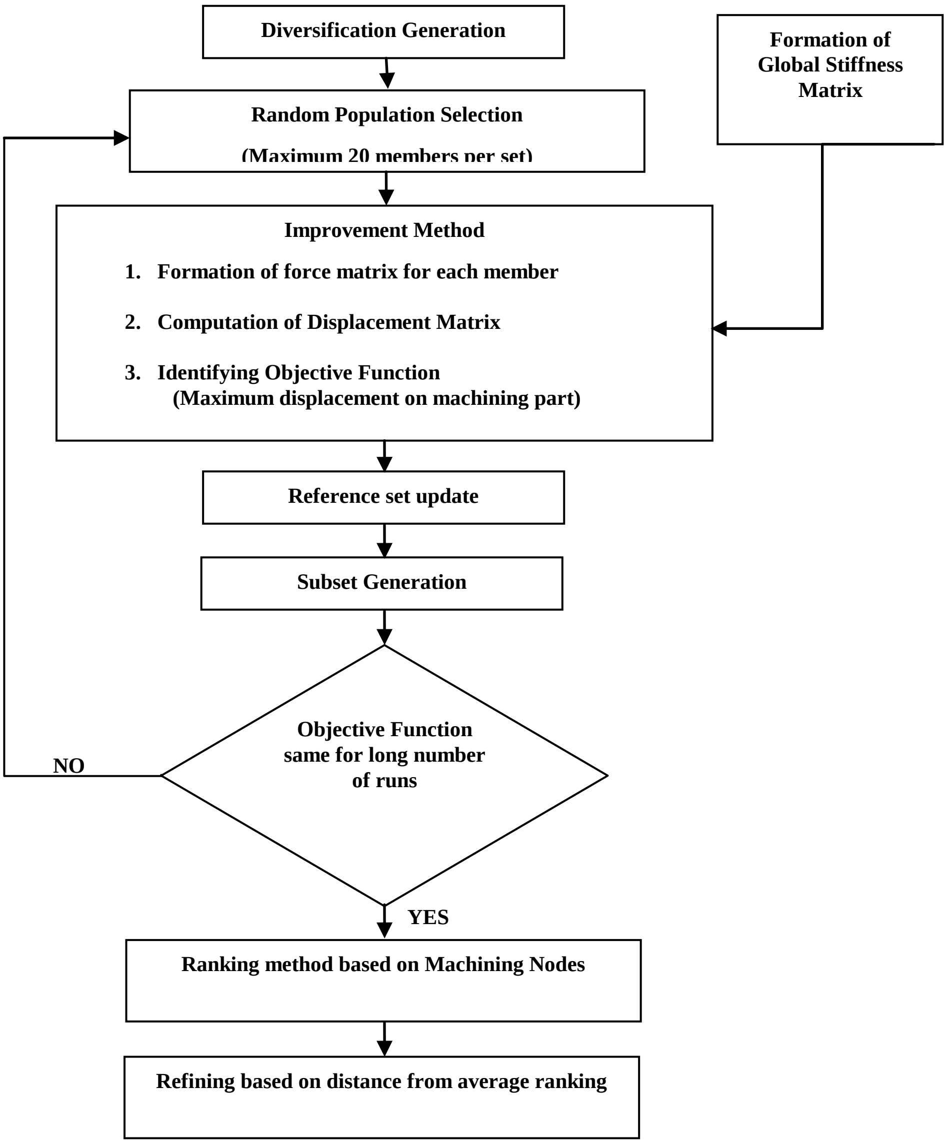

Figure.3: Flowchart representing scatter search in fixture layout optimization

After all iterations the final set of layouts are ranked within each group of machining points based on the objective function. The machining layout which is in better standing when compared to any other layouts is selected as the best optimized solution. For this case study, the final ranked set has 10 members and the search of the best result from final set is based on following steps:

5.1 *Analytical Representation of ranking method*

After many number of subset combinations, let us consider first five ranks in three groups. A general representation of problem is as follows. (This tabulation does not represent actual case study).

TABLE.1: Analytical representation of ranking method

Respective Ranks	**Best Layouts**		
	Node 34 (Group 1)	**Node 35 (Group 2)**	**Node 36 (Group 3)**
1	p	p	u
2	q	q	q
3	r	t	x
4	s	r	p
5	t	v	t
6	u	u	s

1. ***Cross check for existence*****:**

In the first step the first member of group 1 is checked for existence in other two groups- In this case ‘p’ is cross checked for existence in other two groups, p is present in first and fourth position in group 2 and 3 respectively. On the other hand, fourth member of group 1-‘s’ is not present in group 2 and third member of group 3-‘x’ is not present in other two groups. So automatically layouts s and x loose the possibility of becoming the best layout.

2. ***Average computation:***

The average ranking for each member is computed. Let us consider two examples for this case

Example 1: Layout ‘p’ is first member in group 1 and 2. It is fourth member in group 3. So the average ranking for this member is

1+1+4 = 6; 6/3 = 2;

Example 2: layout ‘q’ is second member in all three groups. So the average rank of this member is 2.

3. *Distance from average:* Individual distance of each member (group wise) from average rank is calculated. Let us consider same examples for this case.

TABLE .2: Analytical representation of ranking method – Distance measurements

Member	**Average Rank**	**Distance from group-1**	**Distance from group-2**	**Distance from group-3**
p	2	1-2= -1	1-2= -1	4-2= 2
q	2	2-2= 0	2-2= 0	2-2= 0

Table.2: Shows both member p and q has same average rank value, but member p has more distance from average rank in group-3 which makes q as a comparatively better layout.

In above table p and q has same average rank. In some cases a member which has comparatively bad average rank may be better than a layout with good average rank based on this group wise distance. The best layout can be refined from this average ranking system.

VI. COMPARISON WITH OTHER APPROACHES

Genetic algorithm has been the main optimization technique so far to be used in fixture layout design. Scatter search is a relatively new topic in this context. Best works done by genetic algorithm so far has been proposed by Krishnakumar & Melkote and Kaya. Kaya has arrived at his best result with nearly 150 iterations for the same case study. In this article work the total number of iteration run is 100 (Sum of the iterations run in all three machining nodal point groups-90 + Solution combination using ranking method-10). In order to compare the runs done in scatter search with GA, the fitness value of each run of scatter search has been noted down and the results of run are displayed in Table 3 and comparison is also done with work of Krishnakumar & Melkote and Kaya.

TABLE.3: Comparison with other approach based on objection function

Supports	Krishnakumar & Melkote	Necmittin Kaya			Scatter Search Approach								
					Node 1			Node 2			Node 3		
					Run 1	Run 2	Run 3	Run 1	Run 2	Run 3	Run 1	Run 2	Run 3
L1	50.4	124.8	131.4	138.9	101.6	101.6	101.6	101.6	101.6	101.6	101.6	101.6	101.6
L2	101.6	40.3	56.4	56.3	254	254	203.2	254	254	254	254	203.2	254
L3	101.6	58.3	75.4	98.7	203.2	50.8	203.2	203.2	50.8	203.2	50.8	203.2	203.2
C1	50.8	6.9	16.7	6.4	254	50.8	101.6	254	50.8	101.6	50.8	101.6	254
C2	152.4	291.3	249.2	220.1	50.8	203.2	152.4	50.8	203.2	152.4	203.2	152.4	50.8
OF	**0.0393**	**0.0272**	**0.0287**	**0.0293**	**0.02907**	**0.02991**	**0.03098**	**0.02887**	**0.02992**	**0.03098**	**0.02992**	**0.03008**	**0.0301**

L1- Position of Locator 1 (mm)
C1- Position of Clamp 1 (mm)
L2- Position of Locator 2 (mm)
C2- Position of Clamp 3 (mm)
L3- Position of Locator 3 (mm)
OF- Objective function (displacement- mm, fitness value in GA term)

The best result obtained by Kaya has not been achieved but this article work is about basic implementation of scatter search in fixture layout. Incorporation of this method has produced a comparatively better result than Krishnakumar & Melkote. This result has been achieved in nearly 3/5th of the total runs conducted by Kaya. The convergence graph of scatter search method in this case study has been represented below (Iterations run as per average values in three machining nodes alone, solution combination is not shown)

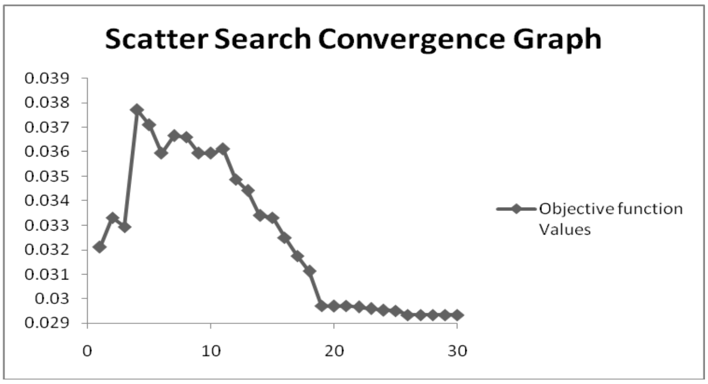

Figure.4: The Convergence Graph of Scatter Search implemented in case study

VII. CONCLUSION

Introducing a new metaheuristic technique into fixture layout optimization was the main intention of this article. The flexibility of the scatter search methodology allows it to be malleable as per the main problem described. One efficient way to implement the scatter search in fixture layout optimization was discussed. GA has been very prominent and benchmarked optimization technique for fixture layout optimization. A case study has been analyzed using scatter search and the result has been compared with previous works in same context. A better result than latest works in GA is being worked on. The betterment of this method in future works is likely to produce better results. The random selection process and well defined improvement method will produce wonderful results in lesser number of iterations and in most cases this method avoids repeated computation of sets which has been previously analyzed. This factor will reduce lot of computation time. The ranking method used in solution combination part of scatter search will give a well analyzed result. This method will facilitate a lot if more number of supports came into scenario. Nonetheless, fine tuning of the nodal elements will give far better results. More number of iterations and subset formations has to be done for fine tuning and also in case of machining, the case study seems like machining is done in a lean, straight line alone and also the point of concentration is mainly on machining nodes. These factors will be taken care of and much better results will be produced in future works.

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