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State of the art of nesting

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Abstract - *Over six decades of cutting and packing research termed nesting, a number of algorithms and techniques have been developed by the researchers in the field. Beginning from the earliest research in the field by Gilmore and Gomory (1961), which proposed a solution for one dimensional nesting problem. The research works then moved on to two dimensional nesting problems from regular orthogonal parts to highly irregular part nesting, irrespective of complexity in the geometry of parts and sheets. Approaches ranging from linear programming, Genetic algorithms, simple heuristics, CNA etc have helped to generate very effective solutions. This paper attempts to review and discuss the advancements of the solutions and techniques developed so far. The field of nesting, impacts upon several different industries and motivates many areas of research. Study on this field of nesting might help and encourage further research and greater comparison between these and future methods.*

Key Words: **Nesting, Orthogonal parts, Irregular parts Genetic algorithm, heuristics, CNA**

1.INTRODUCTION

Sheet metal parts are widely used in daily life and engineering field. In today's highly competitive industrial environment, it's very important to cut down the production cost. As the material cost is the major portion of the cost involved in producing sheet metal component, efficient nesting of parts will minimize the trimming losses, scrap material and reduce overall production cost efficiently. Cutting stock problem is of interest within the wood, garment, sheet metal, Plastics, ship building, footwear and glass industries. The main objectives are to maximize space utilization and minimize computational time required. In addition to these requirements there are certain industry specific requirements which are normally considered as the material to be cut, the cutting method and cut quality

Also the task which is involved in the cutting stock problem includes clustering and nesting. Clustering is to specify collection of patterns that fit well together before nesting on to a given stock.Nesting process is to determine an arrangement of a number of 2-D parts on a 2-D material sheet so that usage of sheet material gets reduced. Nesting of parts on to the sheet can reduce the time for machine setup; sheet loading and it effectively reduce the material cost.

Researches about the nesting problems/automatic packing approaches has increased subsequently over the past 6 decades due partly to industrial competitiveness but also to greater academic interest. The works performed can be categorized into two, one dimensional problems and two dimensional nesting problems. One dimensional problem, say division of bars or rods into smaller lengths for fabrication, a specific operation or sale. Two dimensional problems are which include orthogonal parts (rectangular) and irregular parts .So far up till 20th century greater attention was given to 2-D orthogonal problems.

Table 1. Nesting Solution Characteristics

Nature of Approach	Part Geometry	Flexibility
Heuristic Bottom left Bottom left filling BFLF CNA QLM IBH NFP Hybrid, meta – heuristic Genetic algorithm Parallel GA	Accurate	Accuracy - dictated
Simulated annealing Tabu search Iterated local search Cuckoo search	Discretized Semi discretized	Solution time- dictated

Table 2 . Nesting problem Characteristics

Part Shape	Degrees Of Freedom	Criterion
Orthogonal Arc , splines (linear)	Translation Rotation No Specific Restricted Complete Angle Mirroring	The length covered Centre of rotation % Empty area
Freeform		Nested profile length

2. LITERATURE REVIEW

2.1 Earliest Recognized Works

The earliest recognized works in the field is considered to have begun by Gilmore and Gomory[1] (1961), used linear programming to solve the one dimensional problems optimally. After many years of researches on the one dimensional problems, irregular packing problems were conducted by Albano and Sapuppo[2] (1980). Their approach relied on the two dimensional problem using NFP (No-fit polygon) nesting algorithm along with a profile simplification method to reduce complexity in geometry. No fit polygon considers two polygons without intersecting at the feasible positions.

2.2 Recognized Works Year 1990-2000

Marques, Bispo and Sentieiro[3] (1991) used grid approximation approach in the nesting process to reduce complexity. With simulated annealing search tool to control compaction, it produced good results in 24 hours time duration for the provided data sets with an approximate density of 69 % in the selected length of sheet.

Fujita, Akagi and Hirokawa[4] (1993) in the early months an approach consisting GA combinational search with combination of a local minimization function for nesting was proposed by them. Here a hybrid GA crossover operator used to create a nest via local minimization function, the method then attempts to place these shape pairs in bottom left fashion. The approach was more specifically appropriate for convex shapes to reduce time delays incurred due to complexities in identifying shape intersections.

Oliveria and Ferreira[5] (1993) proposed two approaches for the case. Both the approaches were based on simulated annealing algorithm. Approach was based on a raster representation of the shapes. This approach allows faster generation of solutions but due to inherent approximation in the raster representation it suffers from inaccuracy. Approach 2 uses a polygon- based representation where overlaps in the solutions were identified and resolved using D-functions. Second approach provides feasible and much more accurate results than the later one but performs 5 times slower than the first but still failed to solve overlapping.

Dowsland and Dowsland[6] (1993)- proposed identification of overlaps in a nested solution using simple geometric techniques. They also put forwarded several new algorithms which use these techniques. Computational results of the various methods were also discussed and presented. Jostle algorithm, one of the method proposed by them produced excellent results when an existing nest was tried to get improved. Jostle algorithm was able to find the nested solution within much less time.

Han and Na[7] (1996) for nesting of different irregular shaped parts in rectangular sheets a two stage approach was proposed. Approach utilizes neural networks and simulated annealing algorithms in the two stages .First layout is generated by a self layout learning algorithm based on neural networks .Then the efficiency of the layout is increased by simulated annealing algorithm by randomly translating and rotating the parts. But the approach fails when a large number of variables is involved in the problem since neural networks depend on training of a network

Jakobs[8] (1996) proposed work aimed at the stamping /punching operations in the sheet steel industry uses a GA approach to improve orthogonal results of an earlier work on rectangular packing by Baker, Coffman and Rivest. Jakobs used rectangular orientation and places them using the orthogonal method followed by a compaction phase. Compaction continues until no further movement of shapes towards the bottom left of sheet occurs. It is a step by step bottom left algorithm.

Dighe and Jakiela[9] (1996) added geometrical developments to the previous work of Smith (1985). Main aim was to cope up with irregular polygons. Their approach avoids overlapping to a higher extend and generates solutions using GA. In the initial stage clusters of shapes in appropriate and closely packed positions were developed. In the later stage GA was applied to for best fit cluster arrangement. The generated solutions are further evaluated by area of rectangular enclosure around the clusters.

Bounsaythip and Maouche[10] (1997) extended the works of Fujita, Akaji and Hirokawa (1993). They utilized the evolutionary algorithm which improves on the results from problem of the previous work. Proposed algorithm was functional in a specific textile industry for cutting cloths in the form of strip of user defined length across the sheet. They assured to have achieved high density during runs. The nesting is again said to be performed in two levels or stages. The first stage uses comb approach which finds the minimum bounding rectangle for two shapes and then to search through all possible combinations an evolutionary algorithm is used in the upper level.

A.Ramesh Babu and N. Ramesh Babu[11] (1999) - In the view of many limitations of mathematical models to handle a large number of parts for nesting in multiple sheets, specific heuristics was developed in this approach for nesting regular shaped parts in different types of sheets. Other heuristic approaches greatly adopted a fixed deterministic rule and followed a sequence dependant approach and did not give global optimum solutions for nesting problems. In this approach a hybrid approach consisting of a heuristic and genetic algorithm for different rectangular parts in several rectangular sheets of different sizes is proposed. Genetic algorithm is proposed to develop the optimal sequence of sheets for nesting of different parts and then nesting of parts in the sheet is done by means of heuristic algorithm with bottom left filling technique. Comparison was made with Jakobs (1996) to analyze its effectiveness.

2.3 Recognized Works Year 2000-2010

Oliveira, Gomes and Ferreira[12] (2000) Better results were produced with no-fit polygon algorithm for an irregular nesting problem. Could effectively overcome problems generated by previous researchers in the fabric cutting /textile industry. New benchmarks were produced for almost all problems in the field. Based on the minimum bounding rectangle or minimum length was aimed by the algorithm. Generated an outline polygon for all shapes which were already nested on to a sheet. Generation of no-fit polygon for the next shape to be nested was done by using the polygon. The nesting of new shapes in a non-overlapping position touching at least one other shape already on the sheet, which allows profile addition of shapes before next processing.

Hopper[13] (2000) Combined Bottom left and Bottom left fill approaches with an added Genetic algorithm was proposed for both orthogonal and irregular nesting problems. She was the first practitioner in this research area who tried to fix numerous problems from different areas. Based on her results Hopper has added nine new polygon based problems. Approaches made by many authors and their work information were gathered including results.

S.K. Cheng, K.P.Rao[14] (2000) proposed an algorithm to improve the effectiveness in nesting process by combining Compact Neighbourhood Algorithm (CNA) with GA to optimize large scale nesting processes by taking into account all multiple orientation constraints.CNA considers relationship between the number of neighbours and sharing space between them. It yields higher packing density when compared with the orthogonal and hexagonal approximations. Genetic algorithm is used to optimize generated layouts. The new algorithm can handle the problem of nesting two dimensional flat patterns of shapes containing line segments and arcs. To decrease the huge search space , a clustering process is first operated to collect the patterns . After clustering a grouping process is operated to remove all internal boundaries so that a much faster computational speed can be achieved during the subsequent steps.

A.Ramesh Babu and N.Ramesh Babu[15] (2001) proposed a combination of heuristic and genetic approach to solve the cutting stock problem with the objective of minimizing the wastage of sheet material. For nesting of 2D parts on 2D sheets a discrete form of representation was utilized to represent the complex part geometries and sheets. The proposed approach includes a heuristic algorithm to arrange multiple 2D shaped parts in multiple 2D shaped sheets in a sequential manner, with bottom left strategy. Bottom left strategy implies that parts are to be located at bottom left most acceptable positions on the sheets. The next part of approach is a genetic algorithm, which is used to generate the best sequence of sheets and parts along with their best possible orientations. It is to make the process independent and quick; the designed geometry is converted to discrete form. Genetic operations like coding of string, reproduction, initial population, evaluation of fitness function, crossover and mutation attempts to give out an optimal solution. Effectiveness of this approach was demonstrated with reference to different approaches previously put forward by Jakobs, Jain and Chang, A.Ramesh Babu and N .Ramesh Babu. Those researches were best suited for nesting of rectangular parts in rectangular sheets, orthogonal edged parts in a single rectangular sheet and in single and multiple rectangular sheets respectively. In the newer approach, employing modern heuristics nesting of variety of parts in a variety of sheets was made possible. Accuracy level of this approach is much higher than other approaches but the time consumed in generating the optimal results is on the higher side.

Jeffrey .W.Herrmann and David.R.Delalio[16] (2001) came up with dynamic nesting, an approach which was specifically meant for shearing operations. Dynamic nesting problem, presents a dynamic programming solution and discusses a linear programming relaxation .This approach periodically considers the specific orders to be punched in the next period and creates customized nest for those orders, however to make the nesting decision before they generate the actual nesting layout they simplified the layout problem by considering only the area that each part requires and the total usable area of sheet. The dynamic nesting approach assumed that parts will fit on to a sheet if the total area is sufficient. Number of sheets required for a nest is at least the total area of nested parts (necessary inter part spacing included) divided by the usable sheet area. They used a pseudo polynomial dynamic programming algorithm to solve nesting problem for each group

Gomes and Oliveira[17] (2002) proposed a nesting algorithm called shape ordering heuristics which Can be considered as an extended approach to nesting algorithm put forward by Oliveira, Gomes and Ferreira (2000) with the introduction of improved concept of inner fit rectangle which can be considered as an interior no fit polygon for a shape to be nested and the geometry of the sheet on to which nesting is to be done and generated. The intersection points and vertices of inner fit rectangle with no fit polygons of shapes already nested and which are to be nested, generates feasible positions which are non-overlapping for the given shapes. The journal also introduces a new dual exchange heuristic for manipulation of the order of shapes which needs to be further nested on to the sheet. The initial ordering criteria's for developing better solutions over a number of iterations includes longest lengths, random, greatest area etc.

Tai-His Wu, Jeng-Fungshen[18] (2003) –hybrid heuristic algorithms were proposed for the nesting of two dimensional rectangular parts in multiple plates. A new heuristic nesting algorithm, IBH was presented by modifying the nesting algorithm of Babu and Babu (1999). IBH was then embedded in simulated annealing algorithms. Apart from solving packing problems involving rectangular parts ,the proposed algorithms was also extended directly to the nesting of parts with irregular shapes .while packing irregular parts only clusters formed by two objects are considered to ensure that the embedding rectangles with good utilization ratio could be found in reasonable time. But the effectiveness of nesting was much lower than Babu and Babu Approach in most cases .

T. F Lam and W.S.Sze[19] (2007) approach worked out on the basis of the fact that most of the nesting algorithms were limited to regular blank shapes such as rectangular or simple polygon shapes. When the blank shapes are irregular, initial conversion to approximate manageable shapes are performed before nesting process. A series of algorithms were presented like Minikowski sum hull by edge copying method, decomposition of blanks to convex parts, nesting of a pair of convex and concave blanks and part layout formation of nested pairs. For nesting, in general Minikowski sum tool was utilized for computational geometry. It was used to sum up the polygons graphically. The method is simple and efficient, but is limited to polygons with straight line edges only

Heng Ma and Chia - Cheng Liu[20](2007) – incorporated a novel encoding scheme and greedy method for placing parts .Encoding scheme denotes occupancy of the parts and the vacancy of material sheet by semi discrete strip segments with an equal width and utilizes real-number co ordinates on each segments for presenting the occupancy and vacancy. The greedy method operates in an iterative fashion by generating a part sequence and searching for the best position and orientation of each part in the part sequence .The part sequence is generated by a genetic algorithm with appropriate operators.

Wen-Chen Lee, Heng Ma, Bor- Wen Cheng[21] (2008) – In the proposed method a quick location and movement algorithm (QLM) has been put forward to solve the nesting problem for irregular shaped parts on irregular shaped sheets. The approach is closely related to Babu and Babu Approach, which considers the situation like internal features, defective regions in the parts and sheets .The Heuristic algorithm, QLM tries to solve the nesting problem within two levels. In the first level the irregular part shapes to be nested are transformed in to polygons with the use of a cluster of straight lines and in the second level those polygons are embedded in circles and moved to good initial position, then gradually rotated with respect to its centre to find the final optimum position in a step by step manner. Here cutting tools and limitations of the available technologies are not considered while developing the approach which questions its applicability.

2.3 Recognized Works Year 2000-2010

K.Siva Saravanan, A.Rajasekhar and N.Ramesh Babu [22](2012)- A combination of genetic and heuristic approach is put forward by the researchers. Method proposed includes Concepts of Analytical geometry and semi discrete form of representation proposed previously by Ma and Liu (2007) with a modified GA tool for generating a predetermined sequence of parts. The proposed technique assures to reduce the time required for nesting. Approach considers a single coordinate system to track and represent the part position on the sheet. The work also proposes a new idea of three step collision checking algorithm containing centre distance check, vector interaction and semi discrete check by utilizing the analytical geometry and semi discrete representation schemes for the same. Chances of obtaining optimal solution is higher since ,instead of random selection of initial population being fed is replaced by predetermined set of population .The approach shows its effectiveness by comparing with modified Babu and Babu approach(2001)with the reduced processing time.

Alexandros Siasos, George –Christopher Vosniakos[23] (2014)-this work proposes a hybrid GA-heuristic approach of 2-D irregular parts which is applicable to solve the cutting stock problem which is applicable to solve the cutting stock problem in a textile composites industry. A new heuristic namely Bottom-Left-Fill-Left (BLFL) was employed which is an extended form of former bottom left fill technique. In this technique, initially the shapes are represented im an accurate vector model in 2D. Then the vector model generated is transformed into an equivalent bitmap image which is defined as raster shape transformation in the approach. In the next stage it is converted to a simplified polygon shape then later in to a high definition polygon representation. After generating these high defined polygons by two BFLF stages, nesting happens. In the initial stage a near optimum position is identified by placing the shape at the lowest left empty area of nesting sheet. Precise positioning of shapes follows this stage to eliminate the positioning errors that might have occurred in the initial stage. Later a genetic optimizer has been used which utilizes a genetic algorithm which does the optimization part by generating new shape placement sequences.

K.Ramesh, N.Baskar[24](2015)- Proposes a simple genetic algorithm for optimizing nesting of sheet metal parts. The solution here is meant to be applicable specifically for blanking operation. Approach provides a usual GA technique that includes random generation of initial chromosomes, filtering them out through the fitness function and thereby using the genetic tools like crossover and mutation new chromosomes i.e. part sequence and orientations are meant to be generated. The solution cannot fit well for highly irregular shapes, for bulk quantity of shapes. Parts surely have a chance to overlap with pure simple GA technique alone. The work does not promise or add anything to the previous research works

Table 3. Research Works and different Approaches followed

Researcher	Year	Approach	Remarks
Gilmore and Gomory	1961	Linear programming method	Dealt with one dimensional problems only
Albano and Sapuppo	1980	No Fit Polygon for irregular packing problem	Profile simplification to reduce complexity in geometry
Marques, Bispo and Sentieiro	1991	Simulated annealing approach to reduce complexity	Approximate density of 69% was achieved for the given length
Fujita, Akagi and Hirokawa	1993	GA combinational search and local minimization function	Appropriate for convex shapes to reduce time delays
Oliveria and Ferreira	1993	Simulated annealing algorithm	Faster solutions but suffers inaccuracy
Dowsland and Dowsland	1993	Jostle algorithm	Produced excellent results when an existing nest was tried to get improved
Jakobs	1996	GA to improve orthogonal parts	Specific to stamping /punching operations
Dighe and Jakiela	1996	Complex genetic algorithm	approach avoids overlapping to a higher extend
Bounsaythip and Maouche	1997	Genetic algorithm	Extended work of Fujita, Akaji and Hirokawa (1993)
A.Ramesh Babu and N.Ramesh Babu	1999	Combination of a Heuristic and Genetic algorithm with bottom left	Approach meant for different rectangular parts in

		filling.	several rectangular sheets of different size.
Oliveira, Gomes and Ferreira	2000	No Fit Polygon	Proposed for irregular parts nesting
Hopper	2000	Genetic algorithm with bottom left filling technique	Proposed for both orthogonal and irregular nesting problems
S.K. Cheng, K.P.Rao	2000	Combination of compact neighbourhood algorithm and GA	Faster computational speed
A.Ramesh Babu and N.Ramesh Babu	2001	Combination of a Heuristic and Genetic algorithm with bottom left filling.	Approach meant for different irregular 2-D parts in several multiple 2-D sheets of different size.
Jeffrey .W.Herrmann and David.R.Delalio	2001	Dynamic Programming algorithm	Specific to sheet metal punching ,it considers specific orders to be punched later and produces customized nests
Gomes and Oliveira	2002	Shape ordering heuristics	Manipulation of the order of shapes which needs to be further nested was made possible
Tai-His Wu, Jeng-Fungshen	2003	IBH algorithm embedded in SA algorithms	Proposed to utilize unused areas in material plates further
T. F Lam and W.S.Sze	2007	Minikowski sum tool	Limited to polygons with straight line
			edges only
Heng Ma and Chia - Cheng Liu	2007	Greedy method and semi discrete representation, part sequencing using GA	Iterative method
Wen-Chen Lee, Heng Ma, Bor-Wen Cheng	2008	QLM algorithm	2 level approach that includes shape conversion of irregular part to be nested and for finding the optimum position in the sheet.
K. Siva Saravanan, A.Rajasekhar, N.Ramesh Babu	2012	Combination of Genetic and Heuristic approach	Semi discrete representation scheme is utilized
Alexandros Siasos, George-Christopher Vosniakos	2014	Hybrid GA heuristic algorithm	Developed for cutting stock problems in a textile composites industry
K.Ramesh , N. Baskar	2015	Simple GA	Meant for blanking operation

3. CONCLUSIONS

The advancements in the field of Nesting through these years have been tremendous. This paper tries to study those advancements, which would definitely help further researches to find and study the case performances and discuss experimental results that demonstrate their ability to find good solutions. With the objective to reduce cost incurred due to material losses in different industries and much needed effectiveness in the potential solutions, future works on nesting are very important. The works which are limited to certain industries are to be extended to find its application in the other industries.

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