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INVESTIGATION OF MESH GENERATION METHODS APPLIED TO UMBILICAL CABLES AND FLEXIBLE PIPES 2D TYPICAL GEOMETRIES

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Abstract. *The Finite Elements Method (FEM) is a consolidated technique in solid mechanics simulations and great part of its results precision is dependent on a good quality mesh representing the problem domain. There is a large variety of methods and algorithms to generate computational meshes for this analysis, but they are not applicable to all geometry. Some complex geometry formed with curves and holes require the use of specific methods to meet its features and, therefore, if no suitable algorithm is implemented, it is commonly developed a low quality mesh.*
This work proposes an investigation of mesh generation methods to meet the typical geometries presented in Umbilical Cables and Flexible Pipes internal components, carefully selecting the more suitable algorithm to be used with FEM finality. A brief research on the state of the art of 2D mesh generation is presented based on previous published reviews and other separated methods, followed by a discussion about viability of applying the selected algorithms to the specific problem. At the end, it is verified there are multiple methods that meet the application necessities for separated types of geometries, but few can be used to generate high-quality meshes reaching all kinds of geometries exposed here.

Keywords: *Mesh Generation, Computational Mechanics, CAGD, FEM, Umbilical Cable, Flexible Pipe*

1. INTRODUCTION

1.1 The Context of Offshore Industry

Flexible pipes and umbilical cables have vital importance in Offshore Industry. It is through them that various tasks of this business are done, like extraction of oil and gas from subsea wells and transmission of hydraulic and electric power. They are employed on connecting the floating production system (FPS) to the oil well and this can require some thousands of meters of pipe. Thus, these structures are imposed to extreme environments and they must resist high stresses arising from its weight, from static and dynamic loads, from internal fluid flows, and from temperature changes.

The project of these devices is very complex, therefore, in the case of umbilical cables; each application demands a new design, becoming difficult to make them such as catalog products. In order to design them, the project is performed for a specific situation and the product is developed based on fabrication and material features, likewise it is based on many configurations of loads. Calculating these loads is not an easy task and it is usually adopted software to assist on the structural simulations. Software such as ANSYS™, NASTRAN™ and ABAQUS™ are globally used in mechanical simulation, however they are too generic and its large amount of tools may turn the system not suited enough to these cables and pipes. This raises the necessity of this Industry to develop proper software to optimize its specific projects.

1.2 Umbilical Cables and Flexible Pipes Models

These devices are compound by many sub-structures that form internal components and layers as shown in Fig. 1. These have many different behaviors inside the cables and pipes such as increase stress resistance, isolation functionalities, fluid transportation and signal and power transmission. Figure 1 shows examples of an umbilical and a flexible pipe. These devices present typical internal components known as: Interlocked Carcass, Plastic Jacket, Pressure Armor, Helical Armor, Anti-wear Layer, Fillers, Electric and Optical Cables. Figure 2 shows other examples of these components.

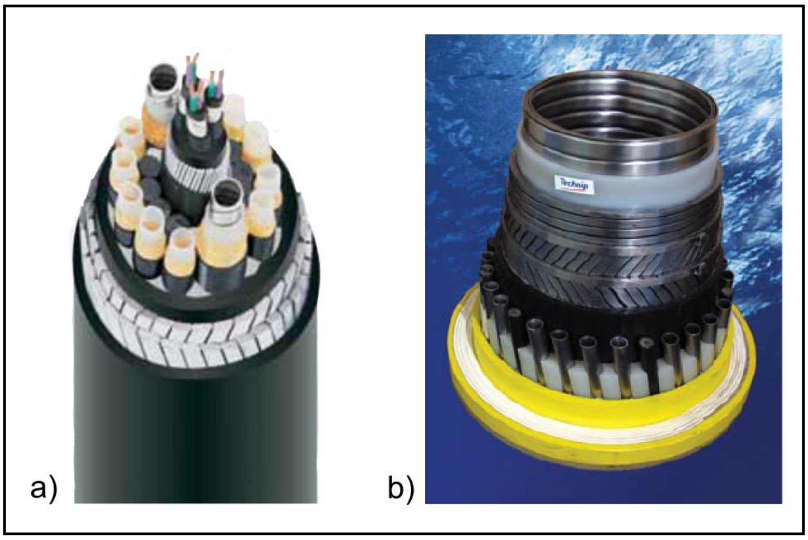

Figure 1. a) Chemical Injection Control Umbilical. Extracted from Prysmian Deep Water Umbilicals Catalog (2015). b) Flexible Pipe. Extracted from Technip Flexible Pipe Catalog (2015).

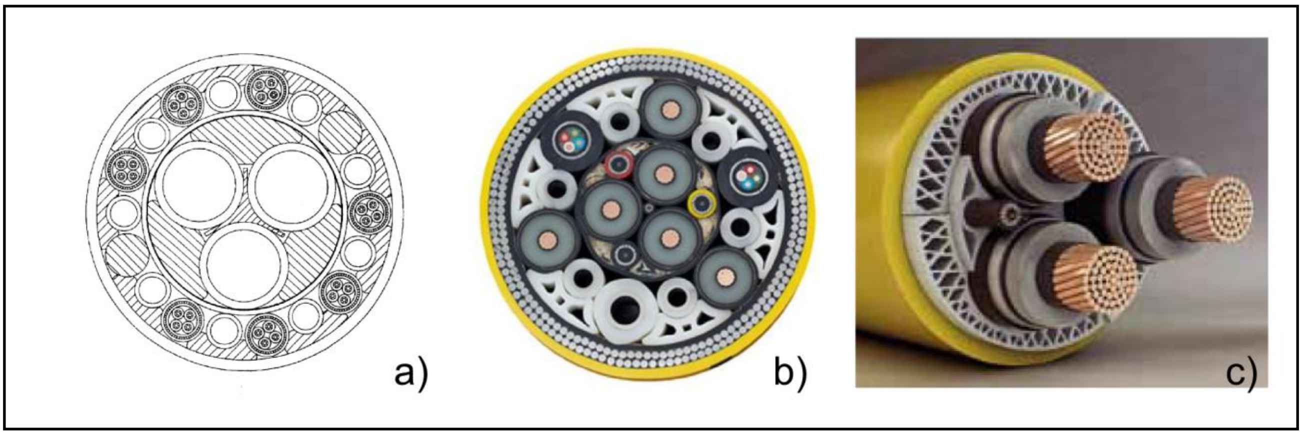

Figure 2. a) A model of hydro electric control cable. Extracted from Haxton (1999). b) A power umbilical cable of Nexans™. Extracted from Nexans Official Website (2015). c) High-voltage subsea cable of Akker™. Extracted from Akker Soluitions - Power Cable Catalog (2015).

1.3 Finite Elements Method Application

Structural simulations of umbilical cables and flexible pipes are commonly done by specific software in order to improve the design process. Knapp, *et al.* (1991) propose a methodology and a computer program to aid these device design, but they were very limited at geometry design, based only on circles, arcs and rings. They use structural simulation with finite element method (FEM) to calculate the loads and the contacts between the internal elements. The program has been upgraded to a commercial tool known as CableCAD. Provasi, *et al.* (2010) developed a tool to design these devices using FEM too, but it does not have an integrated generic mesh generator, thus, it depends on its own created simple meshes. This work implemented a proper simple mesh generator with a few variety of geometric forms. Other commercial program that enable the design and structural simulation of cables and pipes is the UmbiliCad. It has been developed by Ultra Deep™ and allows the creation of various internal components geometry; however it cannot create generic geometries. It has geometry limitations and allows only the creation of rings, circles, rectangles and circle interpolated forms (Bakke, 2009). There is also a program widely assimilated in Offshore Industry to allow structural umbilical cable load simulations, called Uflex and developed by Marintek. This tool has no user interface, and the user must prepare its input in a text file with all the information needed to the simulation. It is needed to draw the geometry in the input file by coding and it becomes a laborious task. However the program has automatic mesh generation methods to create meshes from any geometry entered by the user. Its methods mix up triangles and quadrilaterals in its meshes depending on the geometry of the component in the umbilical cable or flexible pipe cross-section (Marintek, 2010).

Developing an automatic mesh generator algorithm is not an easy task. Creating good quality elements is necessary to grant the performance of the algorithm. In order to grant a major control over the simulation results in FEM software, it is necessary that the program gets the control of the created meshes having its own mesh generator module. There are a lot of mesh generation methods in the literature but not all of them can be used on general geometries with curved boundaries and curved holes.

1.4 Motivation

Good results in structural simulation by FEM require a good quality mesh. In order to develop a tool for creating mesh from generic geometries, it is necessary to find the most suited method to meet the specificities of umbilical and flexible pipe cross-section geometries. Defining the more suitable algorithm grants the performance of a tool that generates the mesh for FEM software. Developing FEM software for umbilical and flexible pipes structures hereafter, building an automatic mesh generator module is an important task. As shown in Fig 2, these umbilical components present fillers with complex geometries. Additionally, other specific features like geometries of hoses and armors make specific requirements for mesh generation. These characteristics are exposed on Section 4 and on Section 6.

2. OBJECTIVES

This work aims to investigate automatic mesh generation methods, defining the most suitable algorithm to create a mesh on 2D geometries of umbilical cables and flexible pipes cross sections. The selected method must comply with the specific requirements of these typical geometries and it must generate a mesh focused on finite elements method application.

3. METHODOLOGY

Task proceedings are divided on definition of initial hypotheses of a generic mesh generation method. Sequentially, initial excluding criteria are defined to select methods into the group of articles and works found. After that, the chosen methods were submitted to a detailed evaluation in grading new criteria. The new analysis focuses on particular characteristics of the selected methods and of the articles presenting these algorithms. When the grades are set, it is defined the suitable method for this work motivation.

4. INITIAL METHOD AVALIATION CRITERIA

A brief research about methods found in the literature is developed here. A mesh generation method will be called as generic if the algorithm complies with the 2 general hypotheses listed below:

A) The orientation of the boundaries must not limit the mesh quality;

Some domains may present rectangular like boundaries or boundaries close to other regular geometries. Because of that, there are some mesh generation methods that use this feature to grant high quality elements, however they are extremely dependent on the inclination angle of the domain figure.

B) It must be not necessary to search for mathematical parameterizations between the boundaries.

Some mesh generation methods are based on the equations that form the domain boundaries, limiting the possibilities of application of the method to only specific geometries.

During the algorithm general evaluation it was used a list of initial considerations to select the pre-candidates to be the chosen method. They are divided in 2 criteria: the general criteria and the specific criteria. The general criteria are listed as:

1) The generated elements must be close to the reference elements
2) Quads must be convex
3) Quad mesh must present a majority of nodes with valence 2 and 4 (valence is the number of edges connected to the node).
4) The article must present the method and not only mentioning it.

The specific criteria are defined based on features presented in umbilical cables and flexible pipes. These criteria are listed below:

1) The mesh must be formed only by quadrilaterals or only triangles in order to create a homogeny mesh (all-quads or all-triangles).

As long as this text final purpose is FEM simulation, creating homogeneous mesh offers better control of numerical calculation results. Heterogeneous meshes mixing different types of elements must be carefully manipulated. Commonly, this must allow the user to control the kinds of elements that will be applied to each region of the divided domain. Besides, to maintain good results, each kind and size of the elements must be allocated in a proper region. The user should know previously how will be the form of the simulation result. It is very usual the creation of distorted elements in heterogeneous mesh. Variation of element types in the same mesh is common for memory economy purposes.

2) Regular geometries such as circles, rings and rectangles must have meshes close to structured.

Meshes are classified as 3 types:

- Regular or Structured
  Nodes topologically standardized with nodes of valence 2 and 4 (valence is the number of edges that connect to the node).

- Irregular or Non-Structured
  Mesh having irregular nodes, with nodes of valence 3 or bigger than 4.

- Semi-Regular or Semi-Structured
  Can be considered as a set of smaller regions with structured meshes connected with each other.

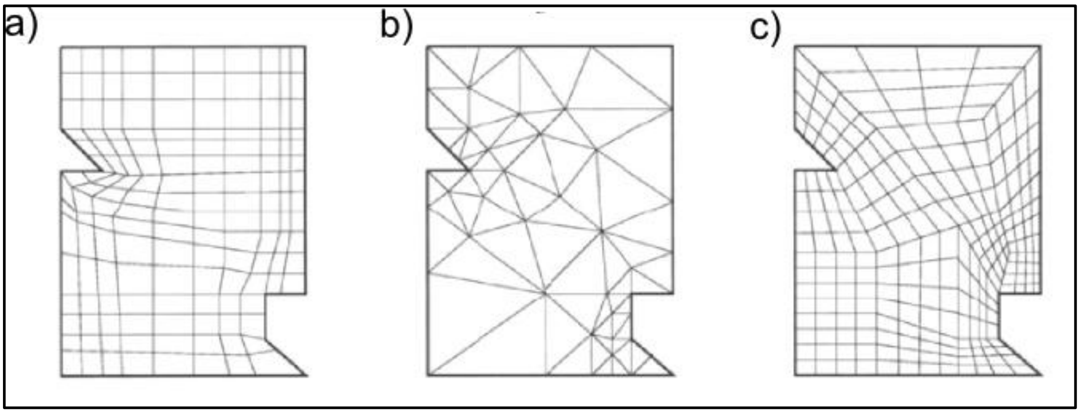

Figure 3. a) Structured mesh example; b) Non-Structured mesh example; c) Semi-Structured mesh example. Extracted from Sack and Urrutia (1999).

The cross-section of those devices usually presents regular geometries, because hoses and plastic jackets are generally represented by rings; electric cables can be represented by circles, besides helical armors can be represented by also circular or rectangle geometries.. A structured mesh grants better numerical results in FEA (Finite Element Analysis), so the closer the mesh is to a structured one, better will be the numerical results.

3) Regions of smaller distance between boundaries must not generate distorted elements.

The method should allow the creation of small high-quality elements along corners and tight regions of the domain. Having distorted elements at these regions can generate less precise results. The quality of the mesh depends on the quality of its elements that are measured by comparison with the fundamental element (A square for quadrilateral elements and an isosceles/equilateral triangle for triangular elements).

4) The method must handle figures with curves, holes and voids.

As shown in Fig. 2, geometries of hoses and fillers have voids and holes. These need to be handled normally by the algorithm, allowing good quality elements even with voids or without them.

5. A BRIEF RESEARCH

There are many kinds of mesh generation methods of 2D and 3D geometries in the literature and classify then is not an easy task. Some works propose organization for most kinds of methods by grouping them by methodology approach and by element type. These review works were published between 10 to 20 years of intervals, suggesting that the methods have been upgraded through time. It is widely known that this field of study is constantly revisited because the researchers usually create new algorithms or propose modifications on classical ones.

The review of Ho-Le (1988) divides that time algorithms by the type of geometry manipulation approach and by the type of data input. The author defines 4 groups of mesh generation methods:

- **Mesh topology first:** refinement methods that need a coarse mesh already created. The author limited his attention on this group because it is dependent of others.

- **Nodes first:** the methods create nodes inside the domain first and then connect them with each other. Algorithms based on the classical Delaunay criterion belong to this group.
- **Adapted mesh model:** The mesh is created based on the adaptation of grids or pre-modeled regular meshes to the domain. The classical quad-tree method is this kind of group. Problems such as bad adaptation of boundaries, bad formed elements and non-automatic processes are frequent in this group.
- **Geometry decomposition:** Here the nodes and the elements are created simultaneously, providing a better positioning of nodes, since each element created is constantly checked with other ones. This group represents the beginning of the development of advancing front method.

Ho-Le made this research in the same time that other important studies about this area have being developed. A more recent work is Owen (1998) and at that time the mesh generation methods started to become more consolidated. The author organizes the algorithms by the type of element generated and many articles exemplify different approaches. In case of triangles, the groups are based on algorithm type as:

- **Quad-tree:** A grid of squares of many sizes is adjusted to the domain in a way that the squares cross its boundaries. This procedure tends to generate a mesh with bad elements near curved boundary. The work of Yerry and Shephard (1984) is an example of a kind of this algorithm. Figure 4 shows an example of mesh created with this procedure and it can be noted bad-shaped elements near the curved loops. Geometries like the ones shown at fillers are leaning to present bad-shaped triangles.

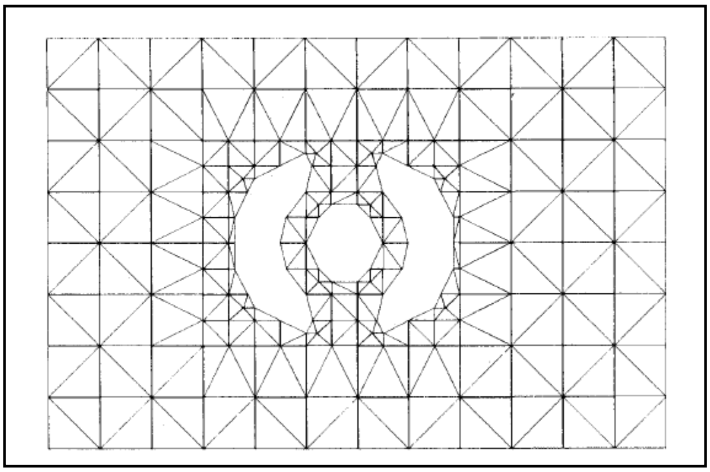

Figure 4. Mesh model created by quad-tree. Extracted from Yerry and Shephard (1984).

- **Delaunay triangulation:** Accordingly to Owen, methods based on the Delaunay triangulation criterion define a group. It is a sequence of procedures to connect point cloud nodes with each other, creating triangles from the Voronoi Diagram. This approach consider the Voronoi regions such as represented in Figure 5 by the areas limited by dotted lines, and the interconnection of the nodes inside these regions showed by the bold lines.

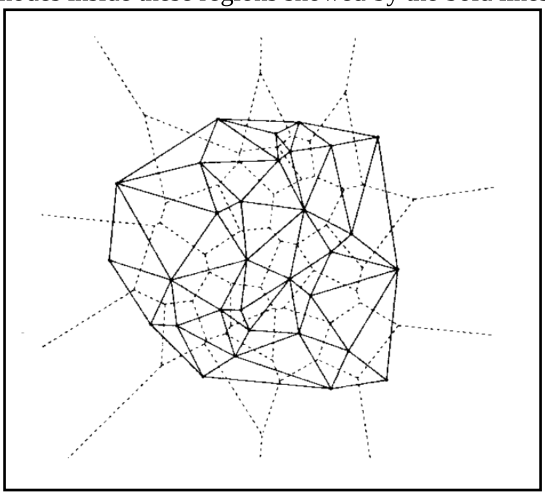

Figure 5. Delaunay Diagram. Extracted from Farin, *et al*. (2002).

The Voronoi Diagram is built having initially a set of points or a point cloud. Then, lines dividing equal distance regions are drawn in order to limit regions which its points are closer to one specific node (a point of the initial set) than to any other node from this set, forming in this way the Voronoi Regions. So the nodes from the set are connected each other building triangles. For a directed explanation about Voronoi Diagram see Farin, *et al*. (2002). There are a lot of algorithms adopting this group in the literature and they are commonly created with different procedures of adding new nodes to the domain to smooth it. In addition, it is used to verify the created triangles processing repeatedly the Voronoi triangulation as new nodes are added to the domain.

- **Advancing front:** This consolidated method is implemented in well-known software such as ANSYS™ and ABAQUS™. This group has been developed along decades since 1980 and is in constant upgrade. The algorithm is based on creating rows of triangles initially from the external and internal boundaries. Moreover, the rows proceed filling up the interior regions of the domain as shown in Figure 6.

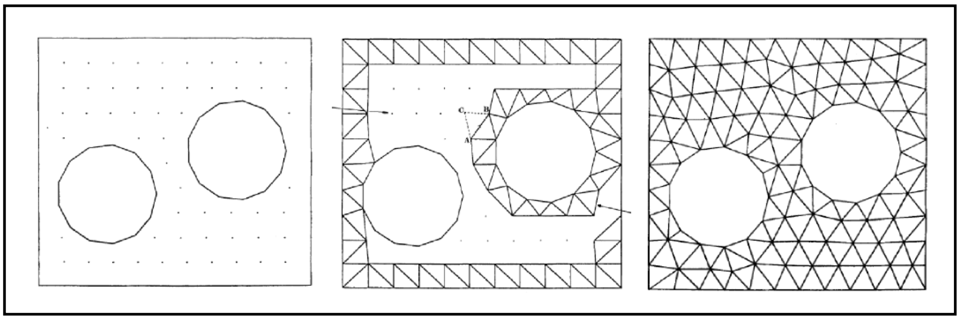

Figure 6. Advancing front algorithm sequence. Extracted from Lo (1985).

Owen proposes a classification of direct and indirect groups of quadrilateral mesh generation methods. Here the attention was focused on only direct algorithms because they create the mesh without a first coarse one, while the indirect methods need it. The groups were defined as follows:

- **Geometry decomposition:** The domain is divided in smaller regions to simplify the discretization. Baehmann, *et al.* (1987) proposes a method following quad-tree method with a process of treatment of bad-shaped quads. Figure 7 shows examples of steps of this method. This algorithm violates the first hypothesis of this text because the quality of boundary elements is dependent of the orientation of geometry curves, showing it is very suitable for straight lines boundaries but not so well for curved lines.

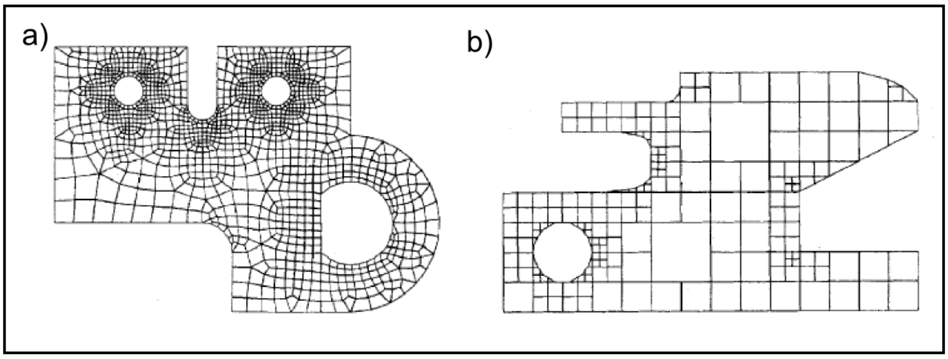

Figure 7. a) All-quad smoothed mesh. b) A coarse mesh of quad-tree process. Both extracted from Baehmann, *et al.* (1987)

- **Medial axis:** This group proposes the division of the domain, too. Nevertheless, it is featured by defining the medial axis of the geometry. Tam and Armstrong (1991) is one of the first works using this procedure. The complex task of finding the medial axis of all regions of the geometry are done by applying the Voronoi Diagram concept and breaking all the boundaries into very small line segments. Figure 8 shows steps of this meshing procedure.

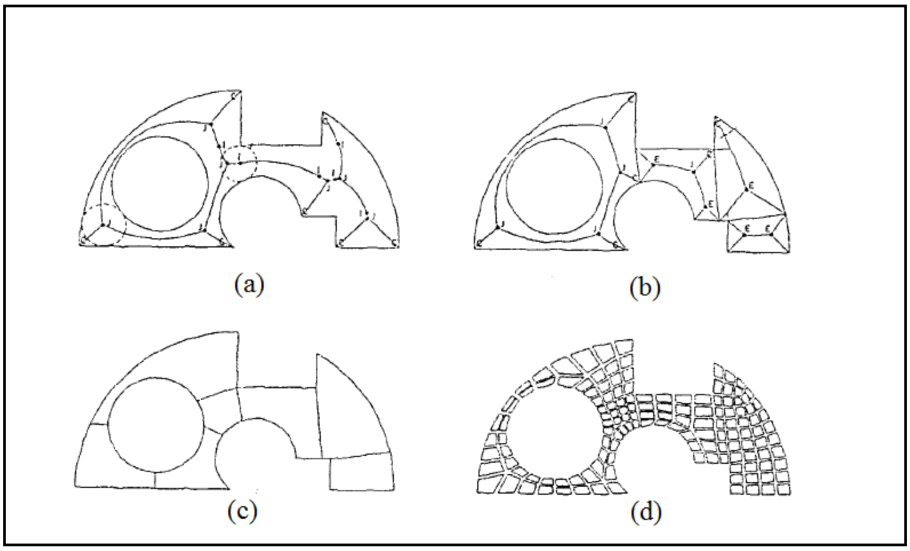

Figure 8. a) Domain with the medial axis. b) Removing concavities. c) Domain sub-division. d) Element creation by sub-regions. All extracted from Tam and Armstrong (1991).

- **Advancing front:** This is the same case as triangle advancing front with the difference of adding only quads to the domain. Blacker and Stephenson (1991) developed an adaptation of this group that is named paving. Known software as FEM, Nastran™ and Patran™, incorporate this method. Figure 9 shows a model of the method progression.

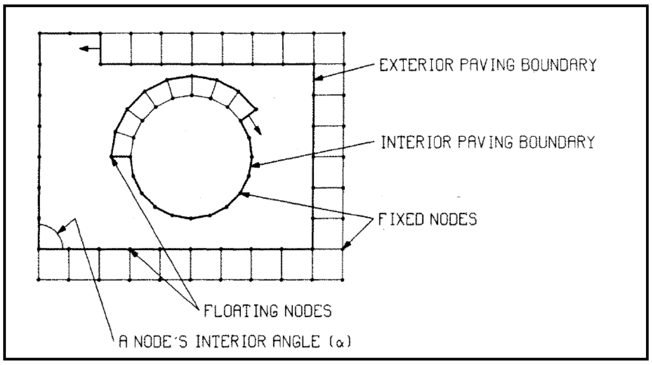

Figure 9. Model of the filling up process in paving method. Extracted from Blacker and Stephenson (1991).

Other minor revisions of mesh generation methods were found on literature. Fenwick (2005) presents her own method including Delaunay criterion and additionally made a simple research about the current triangle and tetrahedral mesh generation methods. The author divides them in two groups: Convex Hull and BRep methods. The first produce meshes from lists of nodes and line segments, the latter represent a modern way to list geometric information, so the methods need to handle only the given boundaries of the figure and apply processes of interior node creation. The BRep methods followed Owen's classification of triangles and tetrahedral elements.

Another mesh generation research found is Bommes, *et al.* (2012). However, there are cited methods about 3D elements and mesh post-processing smoothing algorithms in majority. These approaches diverge of this text goal.

Other single methods were found in the literature, but all were modifications of some group exposed here. Developing a detailed analysis of the methods and articles presented on the researches of Ho-Le and Owen already became a satisfactory overview of most used algorithms, allowing the selection of a suitable method for our problem.

6. ANALYSIS OF THE METHODS

6.1 Pre-selection Criteria

The first evaluation of the found articles is the fulfill of initial general hypothesis, of general and specific criteria. As the compliance was done with binary evaluation (yes or no), it was made a table of all methods and articles found on bibliographic review. In Appendix A, there is a table that represents the evaluation of all articles found.

After the first general analysis of all methods found, there were 11 algorithms that met the first requisitions, as it is shown in Tab. 1. The next filtering was developed with a detailed analysis of the methods besides the grading in six new criteria for each algorithm. These criteria were chosen to promote clearer algorithms and the simpler computational methodology. Each one received a grade between 0 and 4 for each criterion, as can be seen in Tab.1. It is important to notice the mesh generation method step of transforming boundaries in sequential line segments was not considered as another criterion. None of these articles explain this step with considerable details, making their comparison based on this step an impracticable task.

The criteria are listed as:

A) Versatility with the possible application geometries

The method must cover generic planar geometries. Examples within its article assist in the grade determination.

B) Figures with near-regular geometries result in near-structured meshes

The method must generate near-structured meshes at regular geometries (for instance rings, circles and rectangles).

C) Method with detailed explanation

It is necessary to evaluate the clearness of the method explanation. All the mesh generation method steps are verified. Bad explanation may result in low grades.

D) Simple coding

Measurement of the complexity on development of software to implement the method.

E) The method manages the creation of new nodes, in order to guarantee high quality elements

The level of control of the method in generation of new nodes is verified. Some methods can adjust new nodes while create them, improving the mesh quality. This process is more effective than only adjusting the nodes positions after the mesh generation process.

F) The method trends to generate better numerical results in FEM analysis

As the previous, this criterion is relative to numerical results after FEM analysis. Quadrilateral elements provide a marginal gain in these simulations in comparison to triangles. This criterion will add the grade 0, if it generates triangular elements or 1, if it generate quadrilateral elements. It is important to point that most mesh generation methods, especially these of triangular elements, adopt less rigorous procedures to manage the element quality. This occurs because their approach is focused on computer graphic model generation; therefore distorted elements have less effect on final results of this type of application than on FEM analysis.

The grades applied to the methods, by each criterion except (F), follow the crescent order bellow:

0 - The algorithm does not meet the criterion;
1 - The algorithm meets weakly the criterion;
2 - The algorithm meets the criterion but needs large adaptations;
3 - The algorithm meets the criterion but needs small adaptations;
4 - The algorithm meets the criterion well;

6.2 Algorithm Evaluation Discussion

After a detailed evaluation of the pre-selected algorithms it becomes possible to enumerate the principal features of each one and how it could contribute to the problem solution. It is noted that various articles presented the methods in a superficial way, omitting some essential method steps. This occurs because there are indications to others references in these articles or the author simplifies some part of his text. The simple citation of steps and not a good explanation is observed more often. Table 1 shows the final evaluation of the methods. Their grades are listed by criterion and each article is indicated by which version of algorithm it is referred. Some articles present the same method, but each one has its own particularities.

In the work of Talbert and Parkinson (1990) it is explained superficially one method step called node visibility that is essential to the sub-division of the domain in smaller convex regions, and this contributed to lower grades in method explanation. Nowottny (1997) presents its version of domain subdivision. Some details of the algorithm are omitted, but its examples provide high quality mesh on regular geometries. Tam and Armstrong (1991) also omit their algorithm phase of dividing the domain in smaller convex polygons. It is important to notice that the domain subdivision method, as it has been presented so far, cannot reallocate generated nodes during the mesh generation process, resulting in low grades for criterion (E). Likewise Talbert and Parkinson (1990), the work of Choi (2011) also apply the methodology of dividing the domain in sub-regions but does not explain how to create the splitting lines to separate the regions. It is not said how to manage geometries with holes and internal voids and the example of geometry shown in the article is very simple. These limitations in method explanations indicate low grades for the method understanding criterion, i. e., the (C) criterion.

Zhu, *et al.* (1991) proposes the creation of quadrilaterals from triangles as they are created on the mesh and it used the advancing front algorithm presented by Peraire, *et al.* (1987) as base. However the authors do not explain in details the step of creating the background mesh which is an essential item to the algorithm. Some method measurement parameters are defined by the background mesh. The step of union of the created triangles to form quads is also little detailed. In case of the article of Peraire, *et al.* (1987), there is a poor explanation of the background mesh too, mentioning that this background mesh is received by the algorithm as a input from the user, that generates the necessity of searching for the proposed method of advancing front detailed in other works, in order to find automatic ways of processing this essential step of the method. The advancing front version of Ma and Zhao (2014) has a particularity: The internal voids are connected to the external boundary in order to create only one loop for the entire domain. This unique loop is projected to domain inner regions, generating new elements. However, the author did not detail the steps after the element creation. Verifications such as intersections and proximity between elements are essential to guarantee high quality elements in this method. Therefore, this article got medium grade on criterion (C).

Another important criterion is (A). The problem with generic geometries is seen in the algorithm proposed by Rebay (1993). It is presented 2 methods in this work, granting that generics geometries can be met with great efficiency; however the examples in the article are very limited by showing only simple curved boundaries and circular holes. There are indications that those algorithms cannot grant to create structured meshes even on regular geometries. Lo (1985) shows generic examples in the text, however the algorithm is little flexible. A grid of points is inserted in all the domain including the internal voids but the author does not explain how to disregard the nodes created outside the domain. Additionally, inserting nodes as a rectangular grid generates the same problem seen in quad-tree method: bad quality elements along curved boundaries will be created, suffering the orientation problem. Joe (1995) proposes a very generic algorithm but it is not well explained. It got difficult to evaluate the validity of the generality of geometries handled. The algorithm provided in his article is given without detailed comments and explanations of the loops and variables.

Table 1. Initial selected articles evaluated.

Element Type	Method	Article	A	B	C	D	E	F	Total
Triangular Element	Delaunay	(Rebay, 1993)	3	1	2	4	1	0	11
	Advancing Front	(Lo, 1985)	1	3	3	3	3	0	13
	Advancing Front	(Peraire, *et al.*, 1987)	3	2	2	3	3	0	13
	Advancing Front	(Pirzadeh, 1993)	3	2	2	2	3	0	12
Rectangular Element	Advancing Front	(Zhu, *et al.*, 1991)	3	3	1	2	2	1	12
	Advancing Front	(Ma and Zhao, 2014)	3	4	2	3	3	1	16
	Medial Axis	(Tam and Armstrong, 1991)	4	3	2	1	3	1	14
	Paving	(Blacker and Stephenson, 1991)	4	4	3	3	4	1	19
	Domain Subdivision	(Talbert and Parkinson, 1990)	3	3	2	2	2	1	13
	Domain Subdivision	(Choi, 2011)	3	2	2	2	2	1	12
	Domain Subdivision	(Joe, 1995)	3	2	2	2	2	1	12
	Domain Subdivision	(Nowottny, 1997)	4	4	2	2	2	1	15

7. RESULTS

After a detailed evaluation of these methods, paving excelled in the way of meeting generic geometries close to the ones proposed here. Not only this algorithm has consolidated his usage nowadays, as known FEM commercial software implement paving and other mesh generation methods. The tools ANSYS and ABAQUS have advancing front in their mesh creation modules, while PATRAN has incorporated paving and medial axis algorithm, all being references in the CAE market.

The advancing front method is presented by Peraire, *et al*. (1987) and by Lo (1985), was used by Pirzadeh (1993) and it has been upgraded since 1980 decade. Although, the works using advancing front presented here do not explain well the algorithm, becoming necessary to make a specific literature search to find other publications about this algorithm. Specific searches would be coherent if this present work were focused on specific methods, which is not the case. The medial axis presentation article lacks some detailed information too, as so it demands more complex programming to be implemented in comparison to advancing front and paving algorithm.

The paving method is a derivation of advancing front and was firstly proposed by Blacker and Stephenson (1991). This selected article presents a detailed explanation and suitable examples, which resulted in high grades on criteria. The indication that this algorithm can handle generic geometries and the tendency of creating structured mesh on regular geometries makes this method a useful tool to be incorporated in a mesh generation module of CAE software, in order to simulate umbilical cables and flexible pipes structures.

8. CONCLUSION

This work has presented a brief review about mesh generation methods and did an evaluation of these algorithms in order to apply it to specific geometries such as these exemplified here. That detailed evaluation selected the paving method as the most suitable algorithm. This selection was endorsed by it presentation having the best compliance with the formulated criteria and by its best adaptation for the application requirements.

9. ACKNOWLEDGEMENTS

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11. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.

12. APPENDIX A

	Hypothesis		General Criteria				Specific Criteria			
Article	**A**	**B**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
(Azarenok, 2012)		X								X
(Baehmann, Wittchen, Shephard, Grice, and Yerry, 1987)	X							X		
(Baerentzen, Gravesen, Anton, and Aanaes, 2013)								X	X	X
(Blacker and Stephenson, 1991)										
(Shi, Zhang, Loh, Bradley, and Wong, 2005)								X	X	
(Bykat, 1976)								X	X	
(Cavendish, 1974)									X	
(Cavendish and Wixom, 1975)						X		X	X	
(Chae and Jeong, 1997)								X		
(Chew, 1993)								X	X	X
(Choi, 2011)										
(Johnen, Ernst, and Geuzaine, 2014)						X		X	X	
(Fenwick, 2005)								X	X	
(Haber, Shephard, Abel, Gallagher, and Greenberg, 1978)		X							X	
(Lai, Hu, and Martin, 2009)		X							X	
(Joe, 1995)										
(Jones, 1975)		X			X	X				X
(Klein and Straiβer, 1995)		X	X					X		
(Liang and Zhang, 2013)	X		X					X	X	
(Lindholm, 1983)			X					X		X
(Lo, 1985)										
(Lohner, Parikh, and Gumbert, 1988)						X				
(Ma and Zhao, 2014)										
(Marcum and Weatherill, 1995)						X				
(Nowottny, 1997)										
(Miranda and Martha, 2014)		X								
(Lee, Pennington, and Shaw, 1984)	X							X		
(Peraire, Vahdati, Morgan, and Zienkiewicz, 1987)										
(Phillips, Mitchiner, Blacker, and Lin, 1988)						X				
(Pirzadeh, 1993)										
(Rebay, 1993)										
(Ruppert, 1992)								X	X	X
(Sadek, 1980)			X						X	
(Schöberl, 1997)			X						X	

(Sheffer and Üngör, 2001)						X				
(Shewchuk, Mesh Generation for Domains with Small Angles, 2000)						X				
(Shewchuk, 1996)						X				
(Takayama, Panozzo, Sorkine-Hornung, and Sorkine-Hornung, 2013)						X				
(Talbert and Parkinson, 1990)										
(Tam and Armstrong, 1991)										
(Tracy, 1977)						X				
(Unruh and Anderson, 1992)						X				
(Wördenweber, 1983)						X				
(Atalay, Xu, and Ramaswami, 2009)	X							X	X	
(Yerry and Shephard, 1984)	X							X	X	
(Zhu, Zienkiewicz, Hinton, and Wu, 1991)										