COMPUTER AIDED PROCESS PLANNING FOR AUTOMATED FIBER PLACEMENT

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ABSTRACT

This article presents a state-of-the-art software for Computer Aided Process Planning (CAPP) in the context of Automated Fiber Placement (AFP). A ply level optimization is performed by the exploration of process planning parameters, namely layup strategies and starting point. The virtual layup of these plies enables the measurement of geometry-based defects such as gaps, overlaps, angle deviation and steering. To quantify these different scenarios, measurements which describe the instances and severity of these defects are established through maximum allowable thresholds. Measurements are combined with a weighting process enabled by the Analytical Hierarchy Process, where relative importance are defined then used to generate normalized scores for each ply candidate. Then, subsequent ply scenarios can be strategically generated to reduce the instances and severity of the defects. Process planning represents an essential stage of the AFP workflow. It develops efficient machine processes based upon the working material, composite design, and manufacturing resources. The current state of process planning requires a high degree of interaction from the process planner and could greatly benefit from increased automation. Therefore, CAPP was developed around the list of key functions which were identified as benefiting the most from automation.

Keywords: Layup strategies, Automated Fiber placement, Process Planning, Carbon Fiber Composite

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1. INTRODUCTION

The goal of the Computer Aided Processes Planning (CAPP) software is to implement and appropriately automate the process planning functions identified in the down selection process based on the work presented in [1]. This is performed to benefit the rapid prototyping design phase of composite laminates along with the ply level optimization to reduce geometry related fiber defects. The following sections present the fundamental algorithms of the CAPP module. Additionally, the implementation of these algorithms through a graphical user interface (GUI) is presented. The methods laid out will ultimately aid in the identification of an ideal starting points and layup strategy to reduce fiber defects.

2. PLY LEVEL OPTIMIZATION

The creation of the best layups can be approached as an optimization problem. In order to perform this optimization, it is necessary to quantify and score the generated layups. For this approach, a ply level optimization was performed. Each ply was individually tailored in order to minimize its objective function. The latter enabled quantification of the resulting plies according to the following sets of inputs and outputs.

The inputs were two common process planning functions :(1) starting point, and (2) layup strategy selections. These were two of the functions that were identified from the process planning survey as benefiting from some automation. Additionally, these have a very direct effect on the resulting ply and subsequently manufactured structure. The outputs are the defects directly resulting from the geometrical relationship between the tool surface and the created plies. The defects chosen here were gaps and overlaps, angle deviation, and fiber steering. Fiber steering can be directly measured from the geometry of the created fiber paths and may lead to several other defects such as puckers, wrinkles, and folds.

The remainder of this section will define the techniques used for summarizing defects for use with the objective function, and how an iterative approached is utilized to optimize the objective function for reducing those fiber defects.

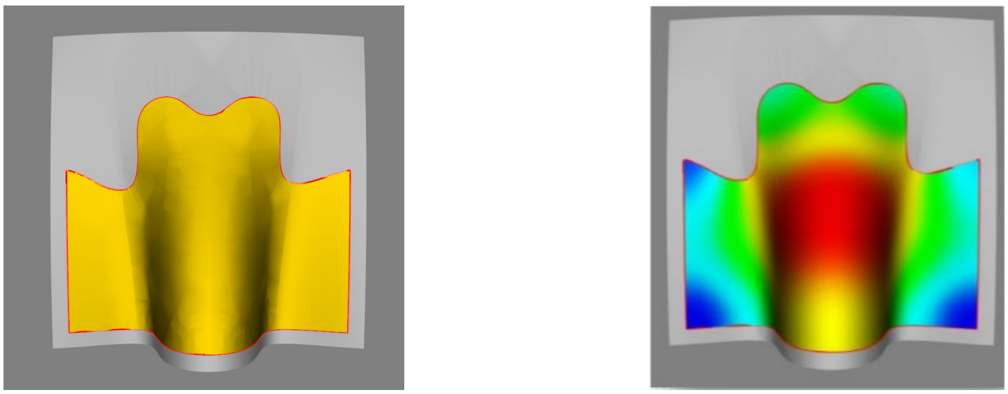
2.1 Defect Instances and Severity

Process planning works to minimize defects and unwanted features that will develop based on the chosen process planning parameters. Currently, there are techniques in place that are able to measure these defects in a case by case basis but lack the ability to summarize the defects on a ply-wide scale, as well as on a laminate wide base. Additionally, there is no system to compare the presence of defects on a common scale where they may be used to generate a logical, overall ranking for a generated scenario depending on the requirements set forth by the process planner.

In order to summarize these features, two aspects of their presence must be considered. Many manufacturing and design processes set a maximum instance value for each feature. An instance threshold measures total amount of defects above a certain threshold. These limitations are imposed to reduce the propagation of more defects and to improve the manufacturability of the laminate. The other measurement used by process planners is severity. The severity threshold of the defect finds the amount by which the defects exceeded the threshold set forth. This measures how significantly certain defects will affect the overall laminate and will demonstrate if there are many small defects or several large defects. The Instance measurement functions as an indicator of commonality of the features for the given ply, while the Severity measurement of the feature uses the threshold to find the sum of the instances as they occur in the ply.

2.2 Creation of Ply Scenarios

The CAPP's initial function is to find the starting points for different tool surfaces and associated ply boundaries and then export these to the Vericut Composites Program (VCP) software. Finding the correct starting point is a critical function of process planning. However, finding a good starting point can be a tedious and difficult task that benefits greatly from automation. To help reduce the time for this task the CAPP module finds an array of starting points for each ply.



(a) Split Surface　　*(b) HKS Result*

Figure 2.1 Starting point selection process

The CAPP module performs the following three steps in order to identify the starting points. The surface is split along the ply boundary so only the area inside the surface is analyzed as in Figure 2.1a, performs the Heat Kernel Signature (HKS) analysis on the area inside the ply boundary, Figure 2.1b. The HKS calculation essentially applies heat to the surface and monitors head dissipation. Finally, an array of potential starting points is created where the HKS is the "hottest". The final array of starting points is visualized in Figure 2.2, where the orientation of the starting point array will be controlled by the fiber angle set forth in the basic ply definition. The process is relatively simple but reduces the time it takes for process planners to find initial starting points.

Each starting point will have a specific layup strategy associated with it. The available layup strategies correspond directly to those used by VCP and can be selected or deselected by the process planner.

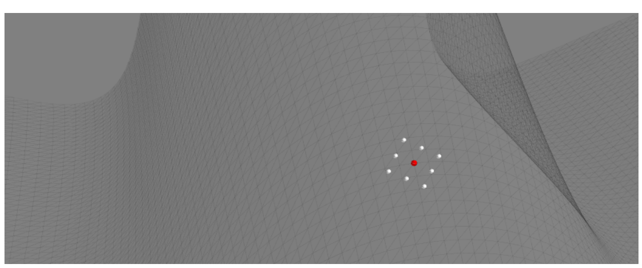


Figure 2.2 Central Starting point and resulting grid

2.3 Comparison and Ranking

The Analytical Hierarchy Process (AHP) provides a method for creating an overall ranking of many features through a series of pair-wise comparisons. These comparisons are then used to develop a relative weight for each of the fiber defect variations.

	Gap Instances	Overlap Instances	Angle Dev. Instances	Steering Instances	Gap Severity	Overlap Severity	Angle Dev. Severity	Steering Severity
Gap Instances	1.0	3.0	1.0	4.0	3.0	2.0	4.0	1.0
Overlap Instances	0.3	1.0	2.0	1.0	4.0	5.0	2.0	6.0
Angle Dev. Instances	1.0	0.5	1.0	2.0	2.0	6.0	5.0	3.0
Steering Instances	0.3	1.0	0.5	1.0	3.0	7.0	2.0	1.0
Gap Severity	0.3	0.3	0.5	0.3	1.0	3.0	4.0	3.0
Overlap Severity	0.5	0.2	0.2	0.1	0.3	1.0	2.0	2.0
Angle Dev. Severity	0.3	0.5	0.2	0.5	0.3	0.5	1.0	4.0
Steering Severity	1.0	0.2	0.3	1.0	0.3	0.5	0.3	1.0
Sum of each column	**4.7**	**6.6**	**5.7**	**10.0**	**13.9**	**25.0**	**20.3**	**21.0**

(a)

	Gap Instances	Overlap Instances	Angle Dev. Instances	Steering Instances	Gap Severity	Overlap Severity	Angle Dev. Severity	Steering Severity
Gap Instances	0.21	0.45	0.18	0.40	0.22	0.08	0.20	0.05
Overlap Instances	0.07	0.15	0.35	0.10	0.29	0.20	0.10	0.29
Angle Dev. Instances	0.21	0.08	0.18	0.20	0.14	0.24	0.25	0.14
Steering Instances	0.05	0.15	0.09	0.10	0.22	0.28	0.10	0.05
Gap Severity	0.07	0.04	0.09	0.03	0.07	0.12	0.20	0.14
Overlap Severity	0.11	0.03	0.03	0.01	0.02	0.04	0.10	0.10
Angle Dev. Severity	0.05	0.08	0.04	0.05	0.02	0.02	0.05	0.19
Steering Severity	0.21	0.03	0.06	0.10	0.02	0.02	0.01	0.05
Avg. of Each Column	**0.22**	**0.19**	**0.18**	**0.13**	**0.10**	**0.05**	**0.06**	**0.06**

(b)

Figure 2.3 (a) AHP Matrix filled with input from Process Planner; (b) AHP Matrix processed to retrieve final rankings

	Weights
Gap Instances	22.3%
Overlap Instances	19.3%
Angle Dev. Instances	18.0%
Steering Instances	12.9%
Gap Severity	9.5%
Overlap Severity	5.5%
Angle Dev. Severity	6.2%
Steering Severity	6.3%

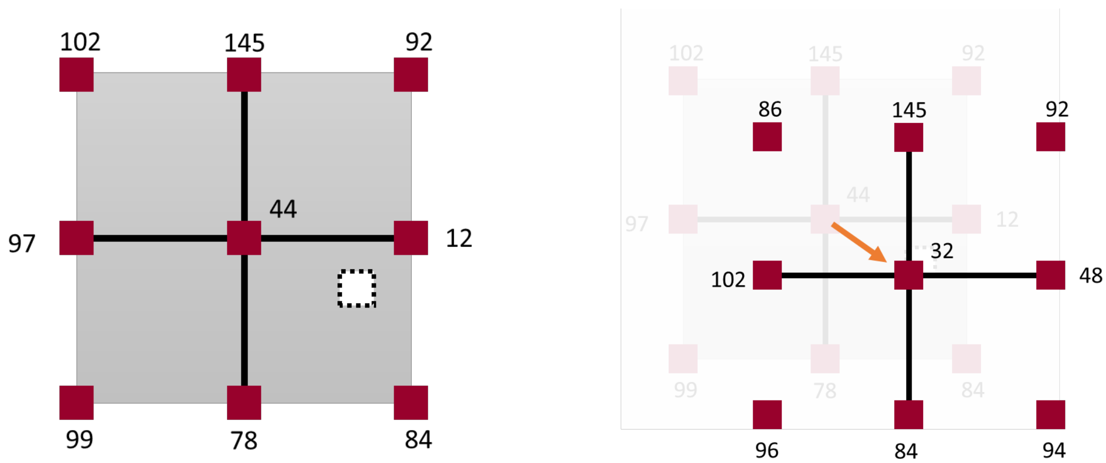
Figure 2.4 Resulting defect weights

The value of relative importance between each pair of defects were entered into the upper half of the matrix and signifies how much the column is preferred over the row criteria. By doing this, the bottom half of the matrix is automatically computed as the inverse values of the upper half as seen in Figure 2.3a. From there, the sum of each column is computed and divides the value in each column to achieve Figure 2.3b. The final weights of Figure 2.4 are achieved by averaging the values of each column in Figure 2.3b. These final weights represent the relative importance of each type of defect and are utilized in the objective function.

2.4 Iterative Optimization Approach

Due to the time required to compute the ply from the specified inputs, it is not currently feasible to test every possible pair of inputs over the entire domain of the tool surface, so instead an iterative approach is used. Each ply is initially defined by a ply boundary and ply angle. These provide the basis for the defined plies of the laminate; therefore, the ply boundary and ply angle can be used to create several variations of ply parameters. These input variations for each ply create what is known here as ply scenarios and serve as the inputs to our objective function.

The objective function utilizes the values defined in the previous section. The summary of the ply's defects and the selection of the defects to prioritize were combined to create a normalized value quantifying each scenario. The chosen rankings apply weights to the fiber defects, such that the more highly ranked defects impart the most to the overall value. Therefore, it is necessary to minimize our objective function in order to produce the ply with the lowest amount of the prioritized defects.



(a) Initial array with scores

(b) Next iteration

Figure 2.5 Starting point optimization

The first step of the optimization begins with the starting point array created from the HKS results, where the ply scenarios are scored using the resulting defects and weightings as in Figure 2.5a. Following iterations operate on new ply scenarios which are generated using the starting point and layup strategy with the lowest score as in Figure 2.5b. Iteration to the optimal ply solution can be stopped after reaching an acceptable amount of defects, or when a certain length of time has elapsed in computing each round of ply scenarios.

3. COMPUTER AIDED PROCESS PLANNING

The CAPP software is broken down into three major functions. First, the software helps to create several ply scenarios by locating starting points with potential layup strategies and presents the resulting geometrical fiber defect instance and severity measurements. The second portion allows the process planner to define the relative importance of defect types in order to create an overall ranking of the defect set that is used for the ply level optimization. The final function presents final scores for each ply scenario and organizes them by starting point and the chosen layup strategy. These scores can be used to decide if a satisfactory solution has been reached or if additional iterations should be performed. Minimizing the ply's overall score, or objective function, indicates that a solution has been reached which adequately minimizes the prioritized defect types. These functionalities are defined as the three "Majors" of the software and are described in the following sections. However, before continuing into the description of the CAPP itself, it is important to discuss how the CAPP module has been integrated into a higher-level workflow for the reduction of fiber defects and their impact on a laminate's structural properties. The following section describes the inter-software communication that occurs to achieve this overall laminate optimization of which the CAPP is a part of.

3.1 Inter-software Communication

The purpose of inter-software communication is to leverage well developed functionality that is contained within pre-existing tools. Utilizing these other tools enables abstraction and new functionality of their methods. The CAPP software takes a similar approach, utilizing several other software solutions, namely Collier Research's Central Optimizer (CO) and CGTech's Vericut Composite Programming (VCP). The flow of communication is presented in Figure 3.1.

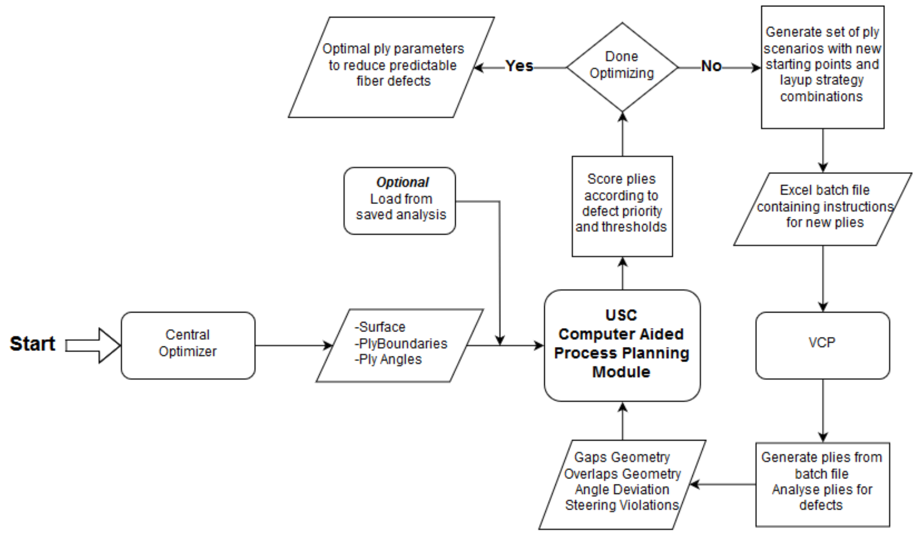


Figure 3.1 Software flow diagram

The flow diagram presents the CAPP's relationship with the other software and which types of data are shared during each step to achieve the laminate optimization. The process begins with the CO, which passes the basic laminate definitions to the CAPP. These laminate definitions contain the tool surface on which the laminate will be constructed as well as the ply boundary and ply angles that define each individual ply in that laminate. The CAPP takes this laminate definition and constructs and enters the ply level optimization loop with VCP. Here, different laminates are iterated upon to minimize the prioritized defects. VCP enables this iteration by building the geometry of the ply scenarios supplied by the CAPP and identifying the resulting geometric defects. After a sufficiently optimized laminate has been generated, the process planning results can be used to continue the laminate design phase.

The remaining sections of this chapter present the software interface and explain the CAPP's own software workflow. The goal is to gain a better understanding of the CAPP module, and how it can incorporate the optimization scheme defined in the previous chapter in order to benefit the laminate design process.

3.2 Batch Processing of Ply Scenarios

Once the ply scenarios have been initialized, the CAPP module can create a VCP batch file which contains their ply definitions. This batch file is imported into VCP where the specified starting points are investigated with their associated layup strategies. VCP generates the plies from these ply scenario definitions and finds the defects present. The gaps, overlaps, angle deviation, and steering angle defect results are included in a report that is imported back into the CAPP module. These results are utilized by the workflow in Major 1, 2, and 3.

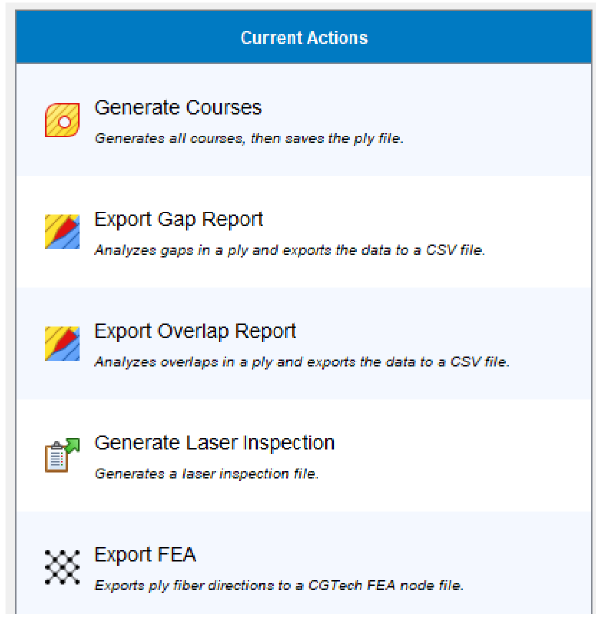
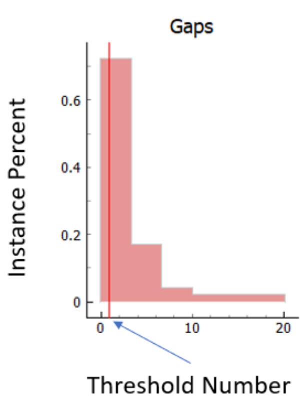


Figure 3.2: VCP Batch Functionality Manger

3.3 Major 1: Extraction of Toolpath Information

The defect data is presented in a series of histograms which help visualize the distributions of the defects to assist in the selection of the best possible thresholds. The graphs can also be used to identify the threshold by dragging the red line associated with the threshold. There is a graph for each defect that shows the amount and magnitude of the defect, such as in Figure 3.3a.

Major 1 develops the set of instances and severity measurements for each feature of interest. The operator sets the maximum threshold values for the gap, overlap, angle deviation, and curvature steering defects as presented in Figure 3.3b.



	Threshold	Instance	Severity
Gap	1 in^2	0.468	0.946
Lap	1 in^2	0.209	0.514
Angle Deviation	10 deg	0.396	0.860
Steering Radius	400 in	0.459	0.336

(a) Graph representing gap defects

(b) Feature Threshold Value table

Figure 3.3 Thresholding operations

3.4 Major 2: Defect Prioritization and Ranking

In Major 2, an operator will apply their expertise in deciding what defects are the most important to prevent. This section is dependent on the use case and different rankings for each defect may vary. A series of default options streamline the matrix creation process if the operator wants to specifically target a defect type or wants to create their own custom rankings. By utilizing any of these options the final rankings will automatically adjust to the choice selected. The three preset default options with their corresponding final rankings can be seen in Figure 3.4.

	Rankings
Gap Instances	20.0%
Gap Severity	20.0%
Overlap Instances	20.0%
Overlap Severity	20.0%
Angle Deviation Instances	5.0%
Angle Deviation Severity	5.0%
Steering Instances	5.0%
Steering Severity	5.0%

(a) Coverage

	Rankings
Gap Instances	3.3%
Gap Severity	3.3%
Overlap Instances	3.3%
Overlap Severity	3.3%
Angle Deviation Instances	40.0%
Angle Deviation Severity	40.0%
Steering Instances	3.3%
Steering Severity	3.3%

(b) Fiber Angle

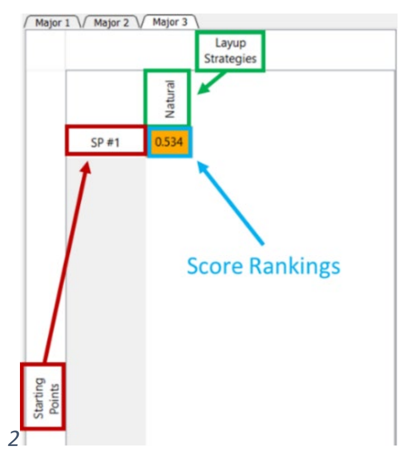
	Rankings
Gap Instances	3.3%
Gap Severity	3.3%
Overlap Instances	3.3%
Overlap Severity	3.3%
Angle Deviation Instances	3.3%
Angle Deviation Severity	3.3%
Steering Instances	40.0%
Steering Severity	40.0%

(c) Fiber Steering

Figure 3.4: AHP default rankings

3.5 Major 3: Propagation and Solution Optimization

Major 1 has generated a normalized set of instance and severity measurements for each feature of interest. Major 2 provides a method for creating an overall ranking of many features with a series of pair-wise comparisons through the Analytical Hierarchy process. Major 3 combines the data into a single normalized score for each ply scenario. The lowest score will identify the best starting point and layup strategy of that iteration according to the thresholds and preferences used.



(a) Interface sections

Starting Points	Layup Strategies: Natural	Limited steering
SP #1	0.534	0.546
SP #2	0.551	0.562
SP #3	0.542	0.537
SP #4	0.536	0.540
SP #5	0.548	0.218
SP #6	0.083	0.083
SP #7	0.082	0.083
SP #8	0.084	0.220
SP #9	0.082	0.082

(b) Multiple analyzed ply scenarios

Figure 3.5: Major 3 Interface

The intuitive display, Figure 3.5, clearly shows which starting points are the best by color coding them on a scale from red, being worst, to green, being best. When creating the next iteration of starting points, the CAPP module will select the starting point and strategy with the lowest score. Through multiple iterations the best scenario can be located with minimal effort.

4. CONCLUSION AND FUTURE WORK

In this work, a Computer Aided Process Planning software (Figure 7.1) has been developed. Additionally, a comprehensive list of layup strategies, fiber defects, and discrete process planning functions were cataloged and organized. The software was developed around these concepts of composite design and was specifically focused on the selection of layup strategies and their starting points. The automation of the software took place in a series of optimization iterations which developed ply scenarios based upon select layup strategies and recommended starting points near the surface's geometric center. The optimization used the resulting geometrical defects detected during virtual planning of the ply layups through VCP. The workflow of the CAPP module was documented in a series of tutorials and demonstration videos (link to CAPP Demonstration). These resources were intended to bring a user with little knowledge of process planning up to a sufficient understanding to operate the CAPP module and the relevant batch processing functionality of VCP.

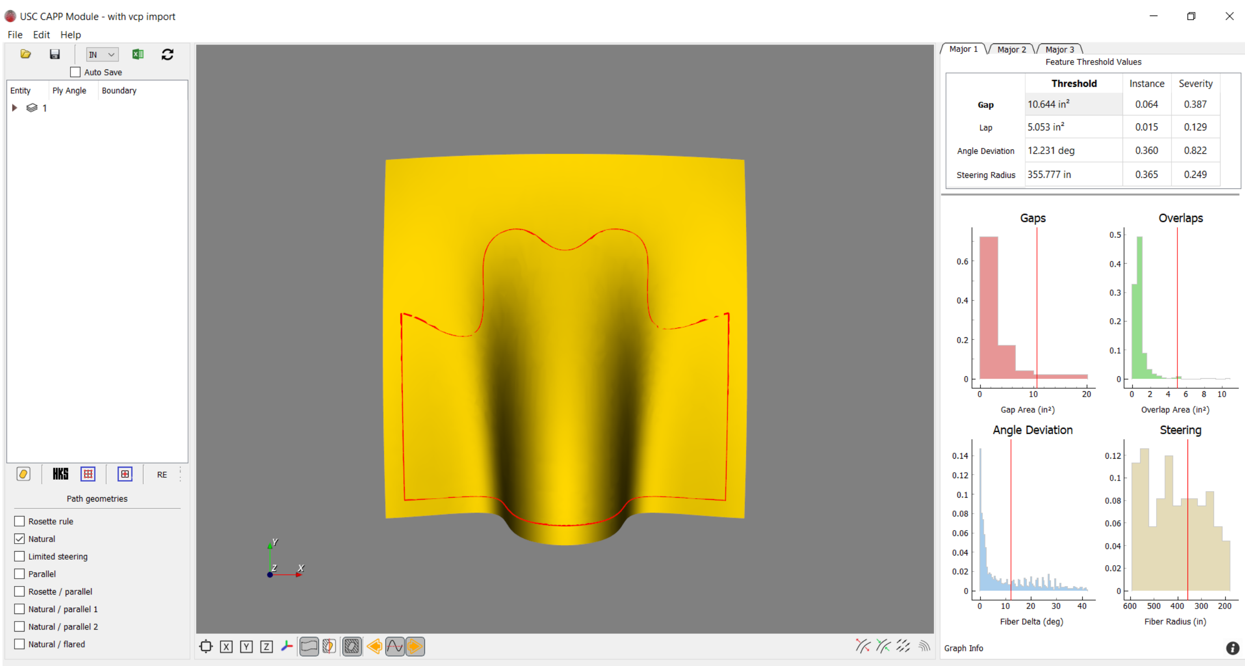


Figure 4.1: Snapshot of CAPP Module interface

Future work on the CAPP software would be the inclusion of additionally process planning functionality. The current state of the software focused on the set of geometrically detectable fiber defects, which represents a small subset of the defects set forth. Many of the defects may have factors in not only the surface geometry, but sources such material imperfections, machine capabilities, and most importantly the processing parameters. These parameters would include things such as compaction pressure, heating temperature, feed rates, and many others.

Incorporating defect detection models which utilize these other sources of information about the layup process, would enable much more of the process planning to occur before any manufacturing must be performed. Such a closed loop process in the process planning phase enables more rapid iteration of part design in order to account for the possible issues that may arise during manufacturing, where aspects such as material and machine operating cost must be considered.

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