AUTOMATION OF AFP PROCESS PLANNING FUNCTIONS: IMPORTANCE AND RANKING

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ABSTRACT

Process planning represents an essential stage of the Automated Fiber Placement (AFP) workflow for developing a useful and efficient machine process 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. To identify the more difficult and time-consuming phase of process planning, it is important to discretize it, developing a list of its key steps and functions. Under the NASA Advanced Composites Project (ACP) a Collaborative Research Team (CRT) of industry members of the Advanced Composites Consortium (ACC), including Aurora Flight Sciences, the Boeing Company, Collier Research, Inc. and Spirit AeroSystems is developing a design for manufacturing (DFM) analysis tool. As a part of that development activity, a ranking process was performed through a survey of the DFM CRT members who possess practical process planning experience in the composites manufacturing industry. The process planning survey collected general input on the overall importance and time requirements for each function, in addition to which functions would benefit most greatly from semi-automation or full-automation.

1. INTRODUCTION

Process planning is the stage of the AFP process which creates a manufacturing plan based on the working material, composite design, and manufacturing resources. Process planning (Figure 1) is one of the most critical and user-interactive portions of the AFP process. In this step, a process planner will use a multitude of different functions to prepare the design for layup by the machine. To use these functions, a process planner must use his knowledge of the part being made, the tool being laid up on, and the machine.

The economic impacts of process planning for AFP arise from the time consumed to program the machine prior to manufacturing, in addition to labor and material cost that may result during manufacturing due to poor and/or inefficient programming. Therefore, an improvement of this stage would allow for a more cost efficient and faster manufacturing pace to be set for the industry. In order to improve AFP process planning, we must first identify and discretize the functions that make up the process planning stage. By defining these individual functions, their

SAMPE Conference Proceedings. Charlotte, NC, May 20-23, 2019. Society for the Advancement of Material and Process Engineering – North America.

total contribution to the result can be interpreted and steps taken to automate the most important and time-consuming functions.

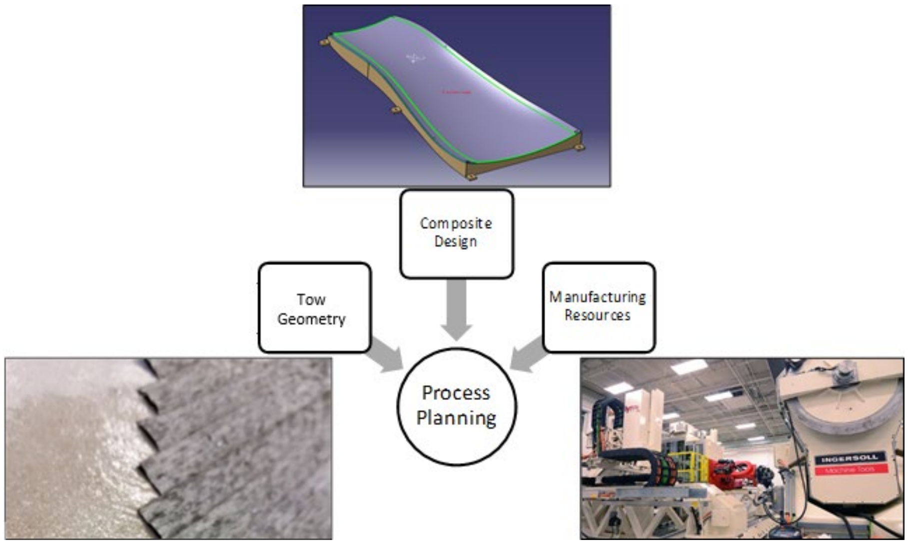


Figure 1. Process planning flow chart.

2. PROCESS PLANNING FUNCTIONS

The process planning functions in this paper were specifically chosen from a down selection process that took place after collecting input from process planners with industry experience in aerospace composites manufacturing. These individuals provided guidance of the challenges they face and the decisions they make during the process planning portion of AFP which consume the most time and have the largest effect on the laminate. The functions that were the most difficult and time consuming were then selected as the candidates to further investigate for automation. Overall, the input given by these industry expert process planners helped to form a roadmap of functions that any process planner will have to face at some point during machine programming and helped form an idea of the challenges required to automate the most critical of these functions.

2.1 Boundary Creation

The boundary (Figure 2) is the general border where the layup must end. It separates the furthest point the process planner wants the layup to be allowed to go from the point where the machine may be damaged by collision with obstacles on the mandrel such as holes, bumps, or vacuum bag openings.

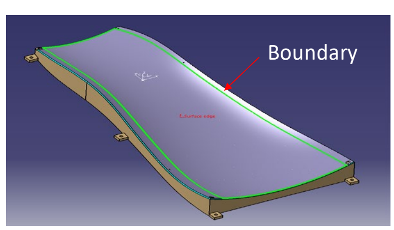


Figure 2. Schematic of an example part boundary.

2.2 Starting Point

The starting point (Figure 3) indicates from where the computational material coverage strategy will initiate. The starting point can change depending on the complexity of the mandrel, the complexity of the part's geometry, and how much roller coverage there will be at a certain point. The starting point has an influence on the computation of the center path for the machine.

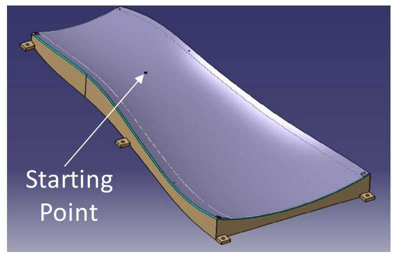


Figure 3. Schematic of an example starting point.

2.3 Tow Width Definition

The tow width definition (Figure 4) is the width of the tow that can be modified within the software to account for any error between the manufacturer's tow width specification and the actual width of the tow. The error in the tow width is usually found by the process planner when they verify the dimensions of the tow and find a difference between the specified width and the actual.

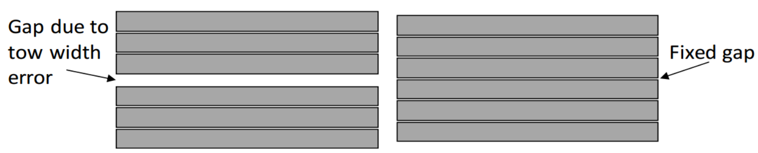


Figure 4. Schematic of an example tow width definition.

2.4 Layup Strategy

The layup strategy (Figure 5) is the general strategy required for a specific part to be laid up on a given surface. These strategies will change based on both the part being laid up and the tool being laid up on [1].

2.5 Steering Constraints

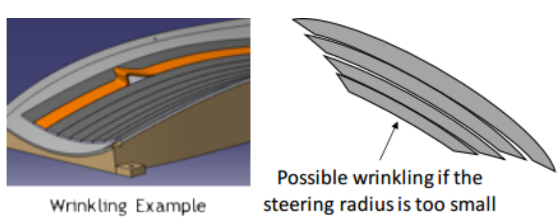


Figure 5. Schematic of example steering constraints.

Steering constraints (and violations) are the restrictions a process planner will set on any steering necessary during the layup process. These constraints include the steering angle and radius and will vary largely, depending on the path algorithm chosen for the part being fabricated and the curvature of the tool being laid up on, in addition to the composite's width and material properties [2,3].

2.6 Interband Offset

An interband offset (Figure 6) is an offset that is placed in between courses during a layup. This offset will be used mainly to prevent any gaps or overlaps that may occur during layup, and especially while steering, but can also be used for any specific part geometry.

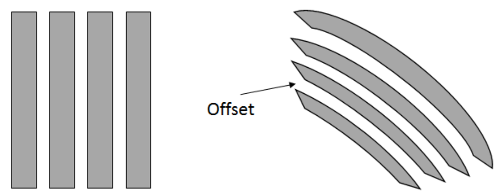


Figure 6. Schematic of interband offset example.

2.7 Stagger Shifts

A stagger shift (Figure 7) is when a process planner staggers two similarly oriented plies by shifting the top ply with respect to the bottom ply. A stagger shift is usually used when gaps or overlaps are present in a ply so that these defects do not propagate to a subsequent ply oriented in the same direction.

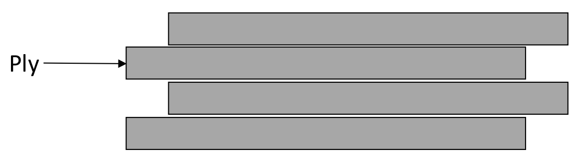


Figure 7. Schematic of typical stagger shifts.

2.8 Boundary Coverage

Boundary coverage (Figure 8) is when the material cannot perfectly meet up with the edge of a part when laying up at angles that are not normal to the boundary, resulting in a gap or an overlap on that edge. The three common scenarios a process planner chooses from are a 100% gap-0% overlap, a 50% gap-50% overlap, or a 0% gap-100% overlap. This is especially important for internal boundaries as well (ply drops).

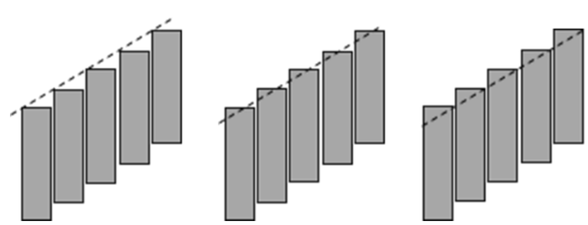


Figure 8. Boundary coverage (0%, 50%, 100%).

2.9 Dog Ear Addition

A dog ear (Figure 9) is additional material that is laid up at any corner of a part due to not being able to layup perpendicular or parallel to that corner. Every machine has an absolute minimum tow length that it can layup which causes dog ears to be present. The process planner will choose whether to implement these dog ears in the layup.

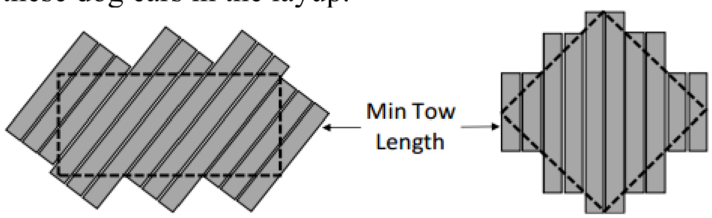


Figure 9. Schematic dog ear additions.

2.10 Uni/Bi-Directional Layup

Uni-directional and bi-directional layups (Figure 10) are the difference between laying up a course in one or two directions. Different parts will benefit more from one or the other depending on the part's geometry and the off-part motion due to the complexity of the mandrel.

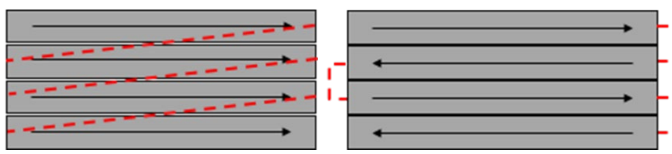


Figure 10. Schematic of Uni/Bi-Directional layup.

2.11 Off-Part Motion

Off-part motion (Figure 11) is the amount of movement the machine must make between laying up courses while off the machine. The most efficient off-part motion will vary from machine to machine and from part to part.

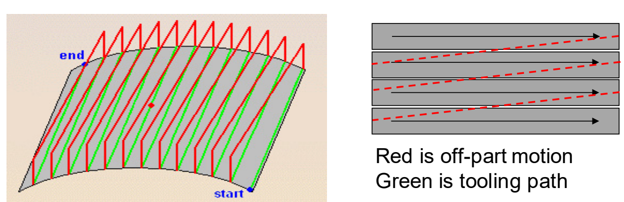


Figure 11. Schematic of example off-Part motion.

2.12 Feed Rates

The feed rates are the layup, add, and cut zone speeds for tow placement while laying up a part. These speeds determine how quickly or slowly the machine will layup and at what rate the machine will start layup and cut material during the layup process. This function will target identification of optimal feed rates based on the selected layup strategy.

2.13 Axes Weights

The axes weights (Figure 12) are how the different machine axes are weighted at any point throughout a layup. Assigning a higher weight to an axis indicates that it will generate more of the machine motion during travel. In weighing the axes differently throughout the layup, a process planner can create a more efficient layup depending on the necessary layup strategy and the complexity of the tool. Properly weighing the machine axes is rather important in the post processing stage.

Figure 12. Image of McNair AFP machine indicating axes weight directions.

2.14 Angles of Tilt

The angle of tilt for the machine (Figure 13) is what defines the tilt of the head of the machine during layup. The tilt of the machine's head will vary depending on the geometry of the part and the complexity of the mandrel being laid up on in order to maximize roller coverage. This function is based on machine configuration and investigates extreme opposed tilts.

Figure 13: Image of McNair AFP head showing typical angles of tilt.

2.15 Course Efficiency

The course efficiency (Figure 14) of a part is how efficiently the courses are laid up due to their dimensions, which is usually reviewed before or during simulation. Course efficiency investigates where partially empty courses can be eliminated by merging with other partially empty courses. However, merging courses must not interfere with the imposed course stagger which intends to minimize coincident course edges through the laminate.

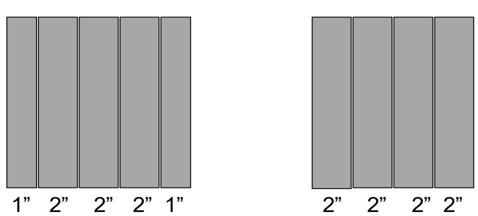
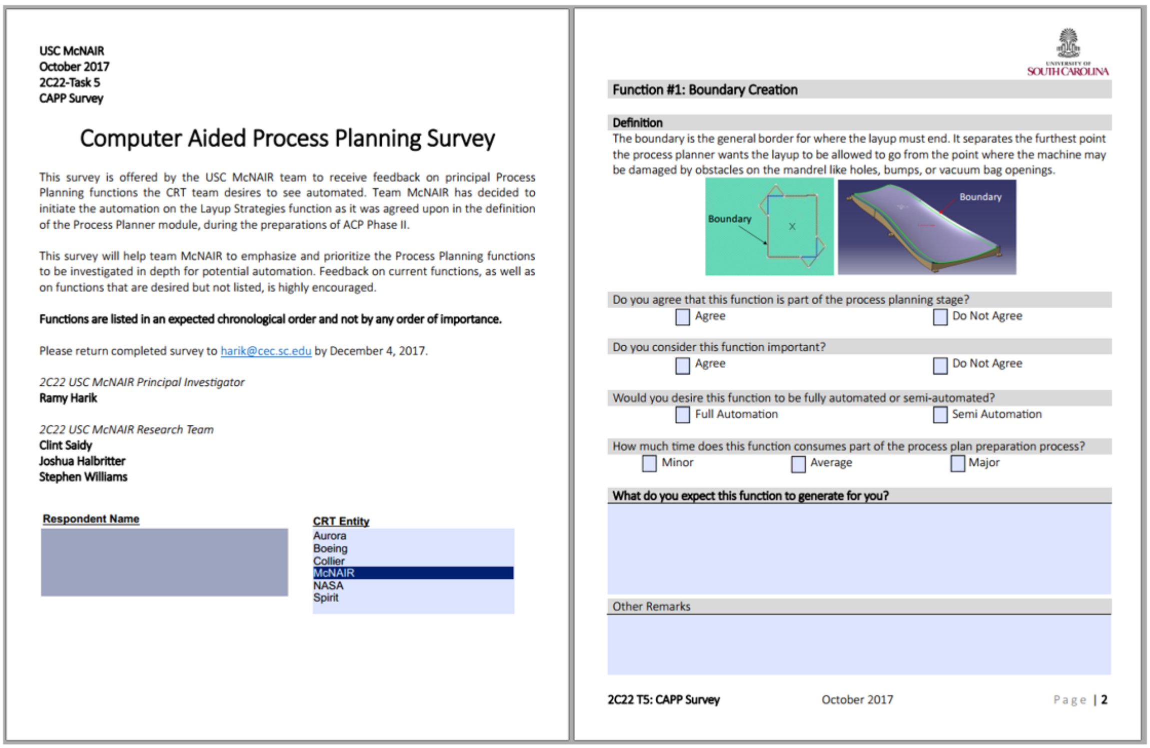


Figure 14. Schematic of course efficiency examples.

3. PROCESS PLANNING SURVEY

The Computer Aided Process Planning (CAPP) survey was developed and distributed to receive feedback on the principal process planning functions from the ACC CRT industry partners with AFP process planning experience. The functions on the survey were rated for their relevance and importance, expectations for automation, and time consumption during the process planning stages. Additionally, an open-ended question allowed the CRT members to define the expected output of the function. The final goal of the survey was to help emphasize and prioritize the process planning functions to be investigated in depth and apply useful levels of automation.



USC McNAIR
October 2017
2C22-Task 5
CAPP Survey

Computer Aided Process Planning Survey

This survey is offered by the USC McNAIR team to receive feedback on principal Process Planning functions the CRT team desires to see automated. Team McNAIR has decided to initiate the automation on the Layup Strategies function as it was agreed upon in the definition of the Process Planner module, during the preparations of ACP Phase II.

This survey will help team McNAIR to emphasize and prioritize the Process Planning functions to be investigated in depth for potential automation. Feedback on current functions, as well as on functions that are desired but not listed, is highly encouraged.

Functions are listed in an expected chronological order and not by any order of importance.

Please return completed survey to harik@cec.sc.edu by December 4, 2017.

2C22 USC McNAIR Principal Investigator
Ramy Harik

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Respondent Name

CRT Entity
Aurora
Boeing
Collier
McNAIR
NASA
Spirit

UNIVERSITY OF SOUTH CAROLINA

Function #1: Boundary Creation

Definition
The boundary is the general border for where the layup must end. It separates the furthest point the process planner wants the layup to be allowed to go from the point where the machine may be damaged by obstacles on the mandrel like holes, bumps, or vacuum bag openings.

Do you agree that this function is part of the process planning stage?
☐ Agree ☐ Do Not Agree

Do you consider this function important?
☐ Agree ☐ Do Not Agree

Would you desire this function to be fully automated or semi-automated?
☐ Full Automation ☐ Semi Automation

How much time does this function consumes part of the process plan preparation process?
☐ Minor ☐ Average ☐ Major

What do you expect this function to generate for you?

Other Remarks

2C22 T5: CAPP Survey October 2017 Page | **2**

Figure 15. Snapshots of the survey information page and sample function.

The survey was distributed to the ACC CRT industry partners on November 2, 2017 and collected throughout the month of December 2017. Surveys were returned from Aurora, Boeing, Collier and Spirit. A total of five surveys were returned, with a total of nine contributing experienced aerospace industry AFP engineers (Table 1).

Table 1. CRT entity survey participation.

CRT Entity	Total Surveys Returned	Total Contributors
Collier	1	1
Spirit	2	2
Aurora	1	2
Boeing	1	4

4. CAPP FUNCTION SURVEY ANALYSIS

The survey analysis identifies the key points that were presented by each survey and summarizes the voting results for each question. Each of these comments helps to clearly identify the inputs and outputs expected from each function. The results of the survey are presented through the tables included in Section 4.

4.1 Quantitative Assessment

A quantitative summary of the survey is presented in Figures 16 through 19. Figure 16 assesses if the respondent believes that the function importance to the process planning work-flow and Figure 17 if automation is desired for the said function. In Figure 18 the importance of the function is assessed and in Figure 19 the estimated amount of time the function currently consumes in the process planning work-flow.

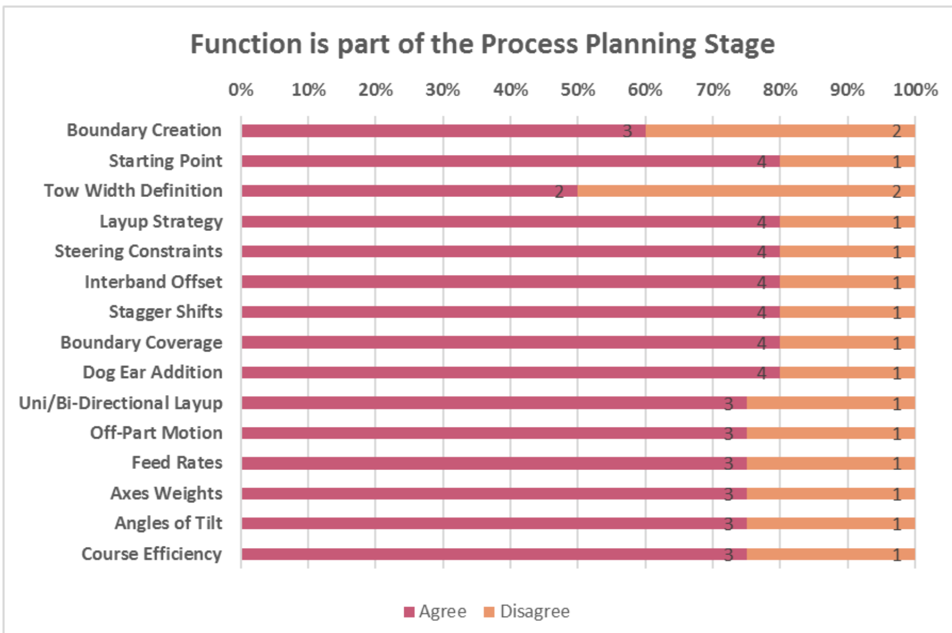

Figure 16: Graph of Function importance to process planning phase

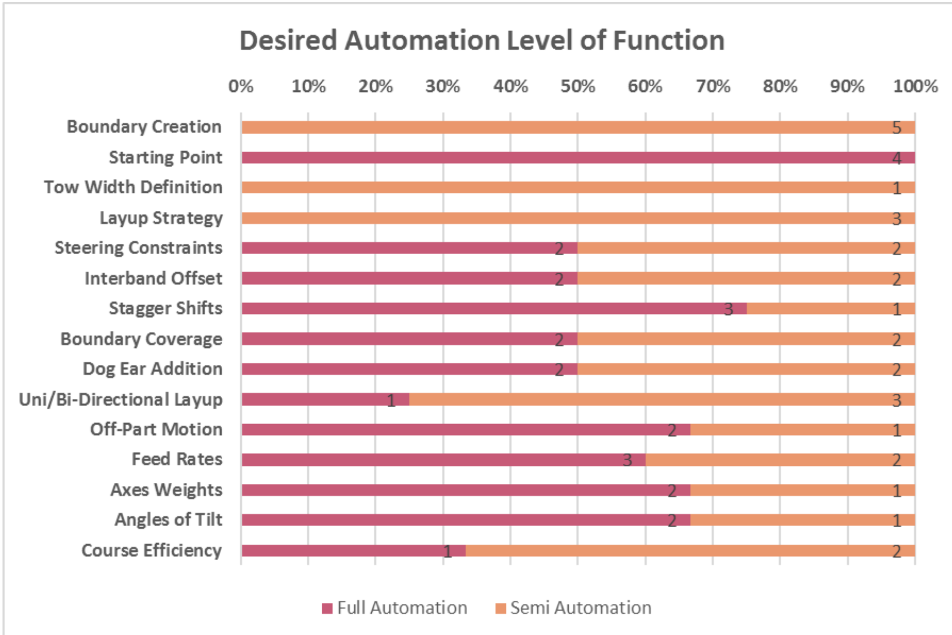

Figure 17. Graph of desired level of automation of each Function.

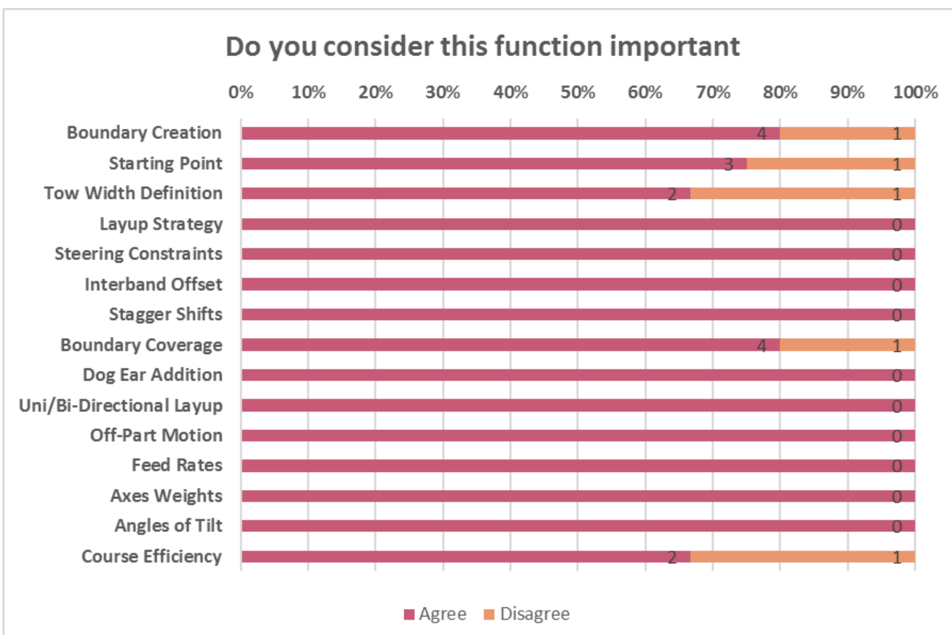

Figure 18. Function Importance.

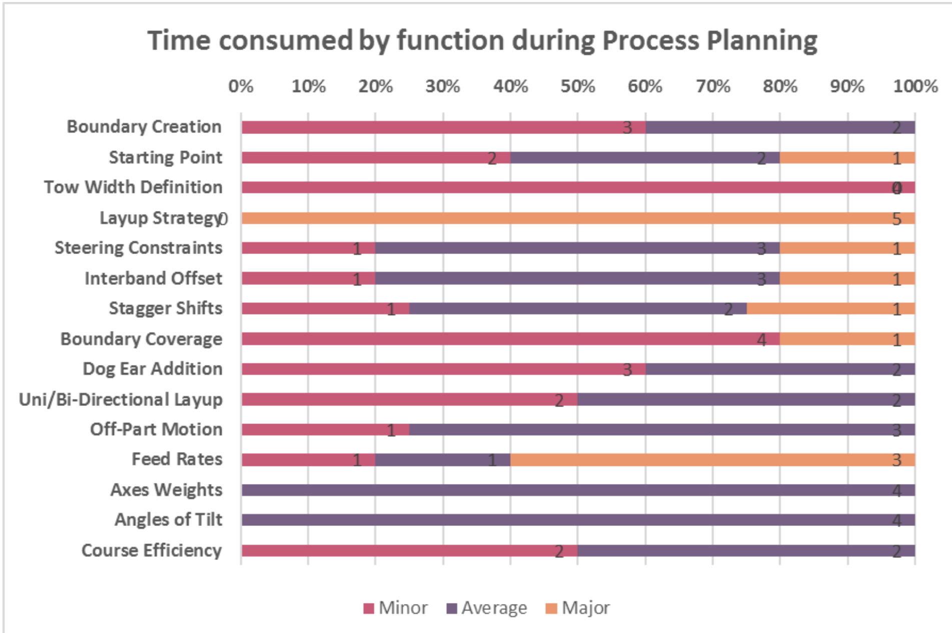

Figure 19. Time to complete function.

4.2 Prioritization of Process Planning Functions and Grouping

By comparing the voting results from the survey, we were able to generate a list of functions supported by their decided importance (Figure 18). Only functions that were deemed important by each of the surveys were included in the down selection, presented below in Table 2.

Table 2. Prioritizing functions (only functions with complete agreeance from Figure 18 were reviewed).

Functions (voted importance)*	% of Process Planning Agreeance (votes)
Layup Strategy (5 Y – 0 N)	80 % (5)
Dog Ear Addition (5 Y – 0 N)	80 % (5)
Stagger Shifts (4 Y – 0 N)	80 % (5)
Steering Constraints (4 Y – 0 N)	80 % (5)
Uni/Bi-Directional Layup (4 Y – 0 N)	75 % (4)
Off-Part Motion (4 Y – 0 N)	75 % (4)
Feed Rates (4 Y – 0 N)	75 % (4)
Axes Weights (4 Y – 0 N)	75 % (4)
Angles of Tilt (4 Y – 0 N)	75 % (4)

Based on the above result, we can clearly distinguish between three groups of process planning functions:

- Group 1: Process Optimization Functions listed below in Table 3
- Group 2: Toolpath Optimization Functions listed below in Table 4
- Group 3: Miscellaneous Functions listed below in Table 5

4.3 Process Optimisation Functions

The group of functions that ranked the highest in term of priority for automation are shown in Table 3. We describe the function number, the function title, the expected output, as well as the additional received remarks.

Table 3. Group 1: Process Optimization Functions.

#	Function Title	Expected Output	Additional Remarks
4	Layup Strategies	▪ Provide a set of metrics for each layup strategy relevant to defect likelihood ▪ Optimize based on user priorities such as angle deviation, steering, gaps/laps, etc.	▪ Determined by engineering with some input from numerical control programming ▪ Choose the strategy that minimizes through-thickness deviation
9	Dog Ears	▪ Modify ply boundaries to account for additional material placement ▪ Determine optimal dog ear strategy by structural analysis	▪ Accept default dog ear method defined by process planning if they are not engineering dependent
7	Stagger Shift	▪ Reduce coincident laps/gaps through laminate thickness through modification of the starting point	▪ Consider the importance of reducing the feature that stagger shift is attempting to minimize ▪ Combine stagger shift functionality with the start point function
5	Steering Constraints	▪ Dynamically vary the acceptable steering radius over the surface depending on local curvature ▪ Recommend minimum steering radius based on geometry and layup orientation	▪ Only suggest minimum steering radius as guideline, since the surface curvature will alter the effects of in-plane curvature
2	Starting Point	▪ Minimize steering error, gaps, overlaps, and angle deviation, in addition to meeting course stagger requirements by placement of the starting point	▪ Finding proper placement varies by path generation algorithm, and can be a tedious, but process critical action

4.4 Toolpath Optimization Functions

The group of functions that ranked second in terms of priority for automation are shown in Table 4.

Table 4. Group 2: Toolpath Optimization Functions.

#	Function Title	Expected Output	Additional Remarks
10	Uni/Bi-Directional Layup	▪ Select the fastest method by default, but retain the user's ability to force a specific method ▪ Account for the speed of specific machine axes required during method selection	▪ Account for tool access, potential collisions, and current machine status during method selection
11	Off-Part Motion	▪ Select route which connects courses to produce fastest possible time ▪ Affects part quality at the start and end of courses, and determines the approach and exit settings from each course	▪ Selection of routing should account for the status and potential tooling collisions ▪ Depends on the Uni/Bi-directional setting chosen
12	Feed Rates	▪ Generated as a function of the part geometry, material properties, and machine capability ▪ Optimized down to the course level	▪ Affects process reliability and sensitivity to working conditions
13	Axes Weights	▪ Find weights which result in fastest times, and identify the limiting axes for specific part geometries ▪ Identify which weights result in the best layup accuracy	▪ Necessary to avoid axis limits and singularities during layup ▪ Selection of weights are more of a numerical control programming responsibility
14	Angle of Tilt	▪ Recommend machine tilt in areas where machine-tool collisions are present ▪ Adjust machine lead and lag to optimize compaction for surface contours and to reduce material bridging	▪ Improve laminate quality through angle of tilt

4.5 Miscellaneous Functions

The group of functions that had lower automation priority for the process planner are shown in Table 5.

Table 5. Group 3: Miscellaneous Functions.

#	Function Title	Expected Output	Additional Remarks
1	Boundary Creation	▪ Optimized ply boundaries for boundary coverage and dog ear generation ▪ Account for user input for the generation of machine boundaries	▪ Size boundaries for laminate specifications to account for ramping to subsequent plies ▪ Enforce engineering rules regarding overstuffing, but are limited to specific applications
3	Tow Width Definition	▪ Define tow width with respect to machine abilities ▪ Account for steering and contour when deciding tow width	▪ No automated tools exist to determine optimal tow width for a given geometry and path generation algorithm
5	Interband Offset	▪ Account for course width deviation from nominal values that result from machine effects	▪ Most relevant to areas of course convergence, and the allowed offset must follow engineering requirements
8	Boundary Coverage	▪ Monitor over/under-fill created by boundary coverage strategies ▪ Consider primarily around interior boundaries, and predict its effects on ramping for subsequent plies	▪ Effects proportional to width of tows/tapes, more relevant when material width exceeds 3.81 cm (1.5 in)
15	Course Efficiency	▪ Driven by starting point and stagger shifts, so updates to those parameters are necessary to modify course efficiency ▪ Recommend most efficient course width depending on geometry and roller width	▪ Diminishing impact as ply size increases relative to the chosen course width

5. CONCLUSIONS

Process planning is a fundamental methodology that enables rapid manufacturing and certification of composite structures. This paper presents a clear understanding of the process planning functions for AFP. These functions are tedious and require expert knowledge that is often not perpetuated. Moreover, these functions can profit from automation to enhance accuracy. Sixteen process planning functions were defined and illustrated. An industry survey provided to subject matter experts in academia and industry was performed. Process planners from NASA, Boeing, Aurora, Spirit, Collier and the McNAIR Center completed the survey and the detailed findings were tabulated. The perceived importance, automation and time requirements of the functions were discerned from the data and were ranked and grouped into functions of similar concept such as process optimization, toolpath optimization and miscellaneous. Details are documented for each of the groups, including the expected output and additional remarks. This effort is a precursor to a more elaborate effort for the generation of a process planning automation software.

6. ACKNOWLEDGEMENTS

The material is based upon work supported by NASA under Award Nos. NNL09AA00A and 80LARC17C0004. The authors express their gratitude to Alex Cowdry and Timothy Holifield from Aurora Flight Sciences. Jeron Moore, Brice Johnson, Sayata Ghose, and Jessica Hughes from The Boeing Company. Trevor Angell and Troy Wampler from Spirit Aerosystems. Stephen Williams, undergraduate researcher at McNAIR supported this work.

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Aeronautics and Space Administration.

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