THERMOPLASTIC AIRCRAFT MANUFACTURING MODEL

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ABSTRACT

A manufacturing process to produce 80 single aisle sized thermoplastic composite aircraft a month is presented. Within the Hi-Rate Composite Aircraft Manufacturing (HiCAM) program a baseline aircraft fuselage was designed and modeled based on the Boeing 787 one-piece barrel build, but scaled down to a single aisle aircraft. Key Performance Parameters (KPPs) of recurring cost, non-recurring cost, and weight are calculated from the model. The outcome of this simulation indicated a prohibitively high non-recurring cost, so the thermoplastic team modeled the manufacturing flow for a panelized fuselage concept. The minimum success criteria is a 30% cost reduction and less than two percent increase in weight compared to the baseline aircraft. Automated Fiber Placement (AFP) is used to layup skins, stamp forming is used to make body frames, stringers, and passenger door surround parts. In the model, Co-Fusion was used to consolidate the skin while simultaneously welding on stringers to make stiffened panels. Additional welding technologies were considered to minimize fastener use and a vertical build concept was used for final assembly to reduce factory size. This manufacturing concept for a thermoplastic aircraft indicated a 39% cost and 12% weight savings compared to the baseline. Additional trade studies were conducted using Northrop Grumman's Automated Stiffener Forming technology to make stringers and stamp forming instead of AFP to make skins.

Keywords: thermoplastic composites, thermoplastic welding, discrete event simulation, manufacturing model

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1. INTRODUCTION

Commercial aircraft take a long time to build; this duration contributes significantly to the cost of the aircraft. To encourage new ideas on how to manufacture airplanes less expensively NASA launched the Hi-Rate Composite Aircraft Manufacturing (HiCAM) consortium [1]. Several Tier 1 and OEM organizations as well as universities are part of the HiCAM consortium. The goal of HiCAM is to establish how to build an airplane faster, lighter, and less expensively than the current state of the art. To evaluate if a new manufacturing process meets this goal, it must be compared to the HiCAM baseline aircraft. The HiCAM baseline aircraft is a single aisle aircraft built in a single barrel configuration using qualified thermoset autoclave cure composite materials [2]. New build processes have been proposed that revolve around new materials systems: Next Generation Thermosets, Resin Infusion, and Thermoplastics. This paper focuses on the Thermoplastic manufacturing model and the quantification of this model.

Manufacturing models portray all the operations needed to build an aircraft. Manufacturing models are compared to each other based on their Key Performance Parameters (KPPs). The HiCAM KPPs are: recurring cost (RC), non-recurring cost (NRC), factory area, and weight. In addition, the unit cost can be derived from the RC and NRC assuming a program lifetime of 3,600 aircraft as: NRC divided by 3,600 plus RC. RC account for labor and composite materials. NRC include equipment, tooling, and factory construction cost which is assessed by the square foot [3].

Most important to making a manufacturing model is the creation of a manufacturing process flow showing discrete blocks where some amount of work will happen in the same physical location. An example of a manufacturing process flow is shown in Figure 1. Each block in the process flow becomes a station in the manufacturing model. Process activities at each station within the manufacturing model must include activities that occur at the same physical location in the factory. As an example, in the flow below a vacuum bag leak check and the autoclave cure are two activities that can happen at the same station (466 Fuselage cure) since the autoclave is needed to do the leak check. However, caul install and bagging needs to be a separate station (467). For each station there is a set of activities associated with that station. Activities are the actions carried out to build the aircraft.

Manufacturing models are created with two different levels of fidelity: the first is an activity level model (ALM) which is a static model consisting of several linked worksheets within the same Microsoft Excel workbook. The main worksheets are: stations, activities, equipment, area, size, and material. The stations worksheet is where all the costs and durations from the supporting worksheets are summed together to provide station level costs and durations to the discrete event simulation. Discrete event simulation (DES) is the second stage of manufacturing modeling; providing a higher level of fidelity than the ALM and is used to generate the KPPs. In the ALM each station has a duration associated with it; the DES adds variability (using a perturbation function) to the time a station takes to complete and handles queuing and blocking behaviors. In this way the factory flow is stress tested to see if the process flow reliably produces 80 airplanes per month (APM). The DES is cycled several times and because of the variability it is possible that a different number of airplanes are made each month. The modeler ensures that no fewer than 75 APM is ever produced and that the overall average is 80 APM or greater. If the DES does not reliably produce an average of 80 APM then an additional station replicate (s) needs to be added into the DES by the modeler. The ALM provides an initial estimate for the number of station replicates needed for each station. With the necessary number of station replicates validated the DES can then calculate the KPPs to include the impact of the variability in the process time. This variability often results in longer station durations which may result in more station replicates being needed which means additional people, equipment, and factory floor space are needed.

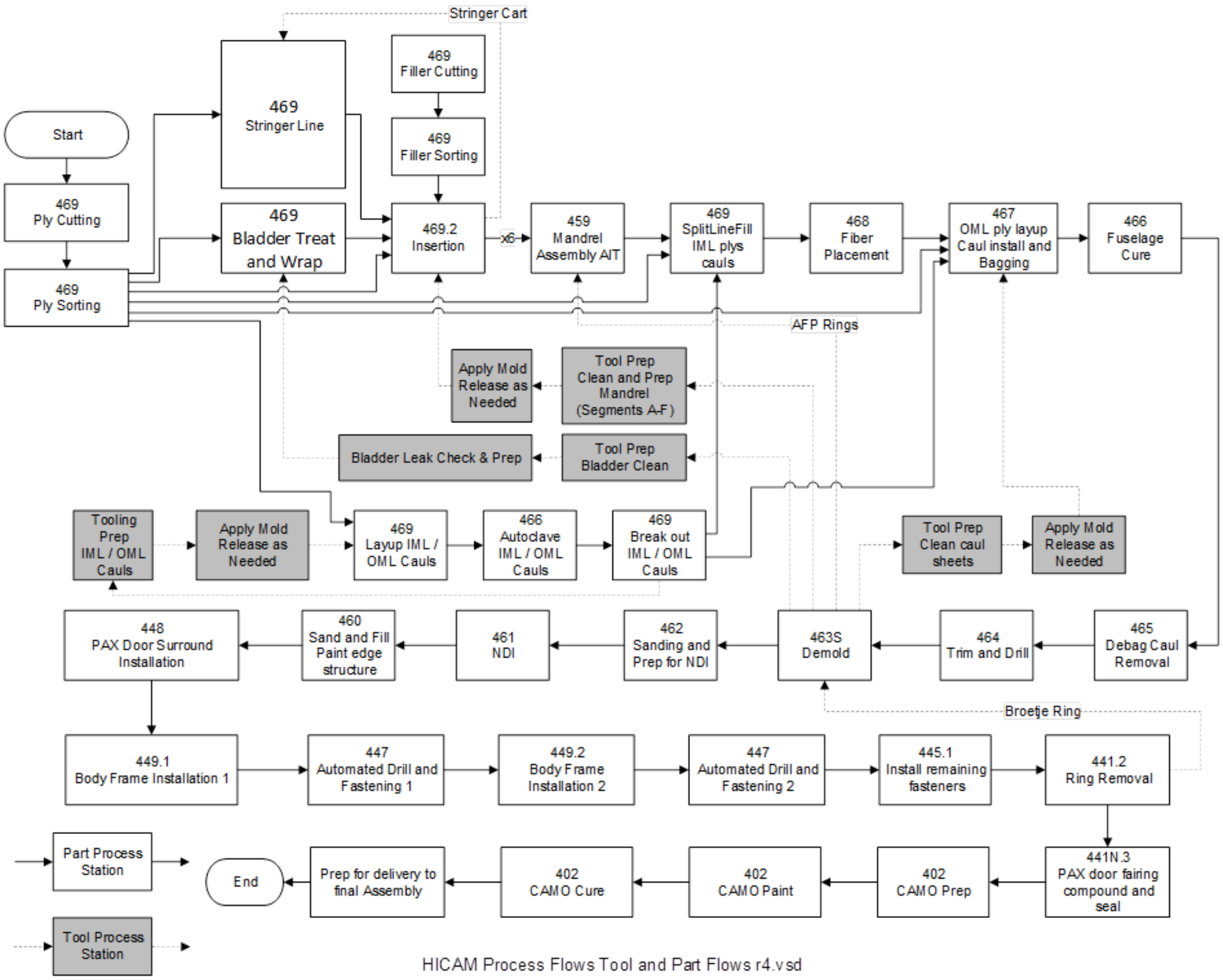


Figure 1. Baseline Fuselage Manufacturing Flow

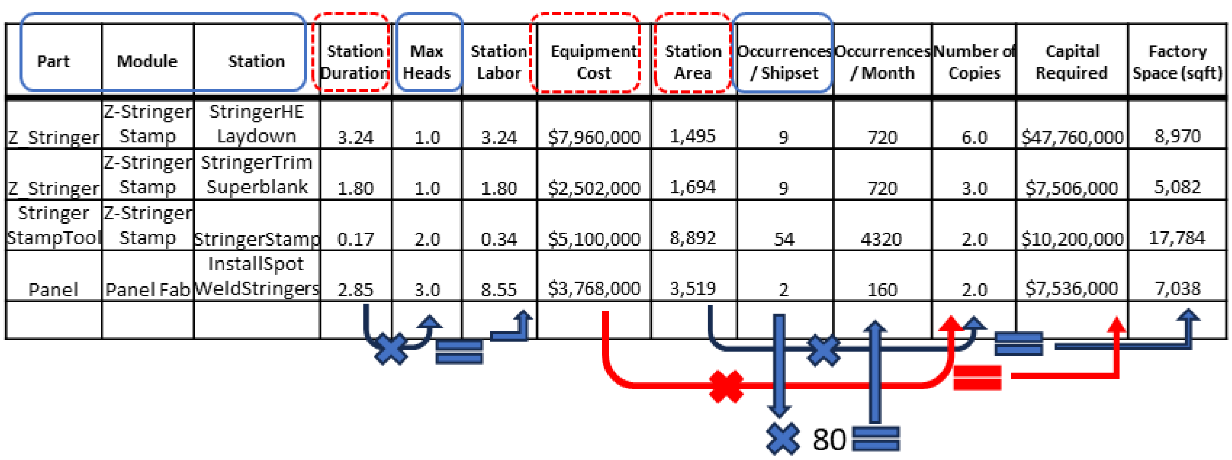
The KPPs for the fuselage of the baseline aircraft as well as the thermoplastic manufacturing proposal are shown in Table 1 [4]. Some key characteristics of the airplane fuselage design (that the baseline and all proposed build proposals must include) are: a barrel section 4 m in diameter and 8.5 m long, 14 body frames, 50 stringer lines, 18 windows, and 2 passenger door surround (PDS) structures. The scope of HiCAM excludes systems, bulkheads, floors, control surfaces, and many other features present on a real aircraft, but this simplification is sufficient to demonstrate the potential of any new manufacturing process. The HiCAM success criteria for KPPs are a cost reduction of 30% per aircraft and 2% lighter than the baseline. The thermoplastic fuselage meets both of these criteria.

Table 1. Key Performance Parameters for Baseline and Thermoplastic Fuselages

	Thermoset Baseline	Thermoplastic	Reduction
KPP: Non Recurring Cost	$2,640,000,000	$1,825,119,788	31%
KPP: Recurring Cost	$ 840,000	$ 433,969	45%
KPP: (m^2)	75,252	55,192	34%
Weight (kg)	785	693	12%
Unit Cost	$ 1,573,333	$ 940,947	39%

2. METHODS

The Stations worksheet of the ALM collects data from other worksheets in the ALM and sums up the station duration, equipment cost, and factory floor space needed for each station. Figure 2 shows key features of the Stations worksheet. Columns with the solid outline are data entered by the modeler. Columns with the dashed outline sum up information from other worksheets in the ALM and provide that summation on the Stations worksheet. Part, Module, and Station are identifiers that must be matched in the Activities, Equipment, and Area worksheets for the data from those worksheets to be correctly summed in the Stations worksheet. As an example only lines in the Activities worksheet with the Part, Module, and Station labeled as Z_Stringer, Z-Stringer Stamp, and StringerHELaydown will be summed to count towards the Station duration for the StringerHELaydown station. The same is also true for the Equipment and Area worksheets.



Part	Module	Station	Station Duration	Max Heads	Station Labor	Equipment Cost	Station Area	Occurrences / Shipset	Occurrences / Month	Number of Copies	Capital Required	Factory Space (sqft)
Z_Stringer	Z-Stringer Stamp	StringerHE Laydown	3.24	1.0	3.24	$7,960,000	1,495	9	720	6.0	$47,760,000	8,970
Z_Stringer	Z-Stringer Stamp	StringerTrim Superblank	1.80	1.0	1.80	$2,502,000	1,694	9	720	3.0	$7,506,000	5,082
Stringer StampTool	Z-Stringer Stamp	StringerStamp	0.17	2.0	0.34	$5,100,000	8,892	54	4320	2.0	$10,200,000	17,784
Panel	Panel Fab	InstallSpot WeldStringers	2.85	3.0	8.55	$3,768,000	3,519	2	160	2.0	$7,536,000	7,038

Figure 2. Key fields on Stations worksheet in Activity Level Model

Max Heads is how many people are needed to work the station. In HiCAM this is entered by the modeler with input from the subject matter experts working the project. Occurrences per Shipset is how many times that station needs to run to complete all the operations that are needed to build one airplane. Figure 2 indicates StringerHELaydown must run nine times to laydown enough material to make all the stringers for one airplane. Given the requirement of 80 APM, the Occurrences per Month is simply Occurrences per Shipset multiplied by 80. The remaining fields are either summations from other worksheets or are calculated as shown in Figure 2. Sation Duration is the sum of the duration for all non-parallel activities associated with a given station. If two activities happen at the same time in a station then these activities are worked in parallel. The activity of lesser time needs to be marked as a parallel activity so its flow time is not counted towards station duration. A cumulative labor column (not shown in Figure 2) is used to store the total labor hours. Cumulative labor and material cost go together to make the recuring cost KPP. Labor is assessed at $250/ hr and composite material is assessed at $22.7/ kg. Design and stress engineering provide the weights of all finished components. The subject matter experts work out how much excess material is needed in the part fabrication process and assign a scrap rate to each part family to determine the total amount of material that needs to be purchased. Additionally, any purchased parts, such as metal fittings and fasteners are accounted for as part of the material cost.

The Number of Copies (meaning quantity of station of replicates) column is calculated in the following way. To calculate the number of station replicates needed the Occurrence per Month is multiplied by Station Duration. Then this time is divided by the available time within a month, which is defined as 441 hours (7 hrs/ shift, 3 shifts/ day, and 21 workdays per month). The number is rounded up to the nearest whole number. A result of 2.1 rounds up to 3. Equipment cost is a summation of the cost for the total number of pieces of equipment and tools required per station which is recorded in the Equipment worksheet. In the Area worksheet each station is assigned an area and some justification for how that area was determined. Areas for the thermoplastic model were determined by producing a factory layout containing the correct number of station replicates and using representative equipment sizes based on part size. Capital Required is the product of equipment cost multiplied by number of copies. To determine an estimate of the NRC KPP, the Capital Required column is summed and added to the product of square footage cost and the summation of the Factory Space column. HiCAM uses $4,682 /m^2 ($435/ sq ft).

3. RESULTS

The thermoplastic fuselage manufacturing flow caters to advantages of thermoplastics: rapid part fabrication and using welding to build up to integrated sub-assemblies before starting the large scale final assembly. The manufacturing flow for the thermoplastic fuselage is shown in Figure 3. There is the main flow for building the skin panels, including adding the stringers to the skin and assembling the panels into a barrel. In addition, there are independent flows for each part family: stringers, body frames, window frames, PDS edge frames, PDS intercostals, and PDS Sills. In comparison to the Baseline fuselage manufacturing flow the thermoplastic approach differs significantly in the following areas: panelized build approach, Out of Autoclave (OoA) Consolidation, making of body frames and the PDS parts instead of having them as purchased parts, welding instead of fastening as a primary means of joining, and a vertically oriented final assembly process instead of a horizontal approach.

The panelized build approach reduces the amount of time specialized equipment is tied up on the part in comparison to the full barrel approach. In the baseline process Broetje rings and mandrel segments stay with the fuselage during the majority of stations in the manufacturing process. This drives many replicates of these pieces of equipment (61 Broetje rings, 252 mandrel segments) creating a large non-recurring cost (805 million dollars). OoA Consolidation is faster than autoclave cure and has a slightly lower equipment cost. For the make versus buy decision on body frames and PDS components the cost savings opportunity was unknown, but what it did allow was control over part design to facilitate the preferred assembly conditions. Welding over fastening is perhaps the most significant implication of using a thermoplastic material instead of a thermoset material. Elimination of drilling holes and adding fasteners offers a large time savings opportunity and eliminates operations that are often subject to rework or repeat inspections. However, there is increased risk of welding versus fastening as a joining strategy from a certification viewpoint. Neither the potential for less rework nor the certification risks are assessed as part of the KPP generation process. The vertical orientation for major assembly is an untested idea; it does reduce the square footage of area used in the factory, but the amount of non-recurring cost that is factory floor space compared to tooling and equipment is low (200 million out of 2 billion dollars). Vertical assembly works well with the proposal to join the body frames into 360° rings and then welding the skin panels to the frames as opposed to the traditional method of building a barrel and then adding frames segment by segment. However, a horizonal attitude during assembly is acceptable with the same proposed set of activities.

Elements that are unique to the thermoplastics fabrication plan include: Panel AFP, Install and Spot Weld Stringers, Install Windows PAX Cauls, Co-Fusion, stamp forming, body frame join and frame inspection. Skin Support Assembly and Skin Splice Weld are stations unique to the thermoplastic assembly process.

The Panel AFP station is where skin plies are laid down using laser assisted thermoplastic AFP. Laser heating is needed to raise the temperature of the thermoplastic composite above its melt temperature to around 330ºC to get enough tack. Research so far has shown that the thermoplastic material itself does not limit the laydown speeds; rather the limitations are how fast the equipment can move and how much heat energy can be delivered to the nip-point. The rate for AFP of thermoplastic skins in the HiCAM project is estimated to be 10 kg/hour. 10 kg/hr assumes thermoplastic material can be laid up at the same linear rate as thermoset material, but since the areal weight of the thermoplastic material is lower than the baseline thermoset material then the overall deposition rate in kilograms per hour is also lower.

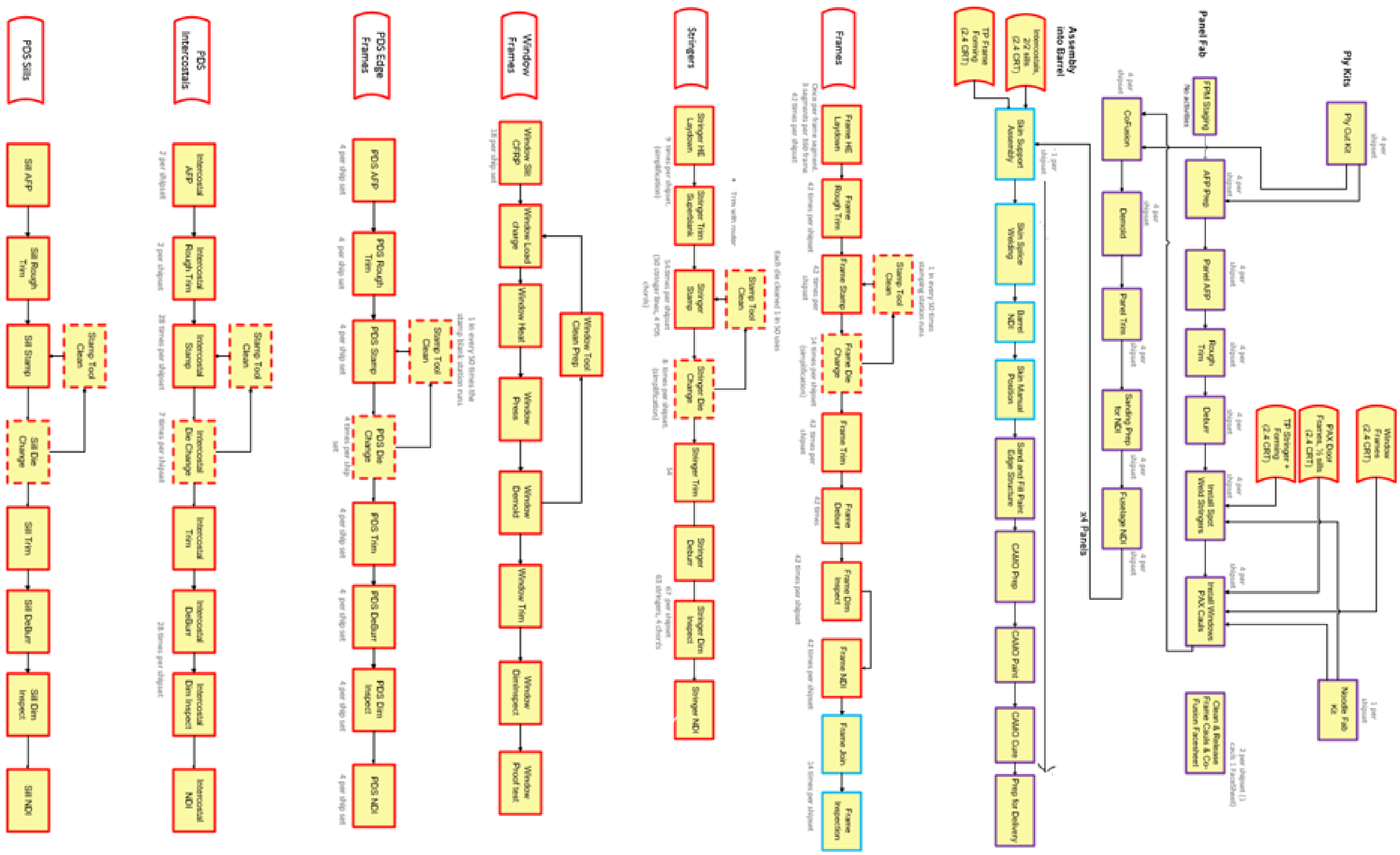


Figure 3. Thermoplastic fuselage manufacturing process flow

Figure 4. Robotic spot welding of stringers

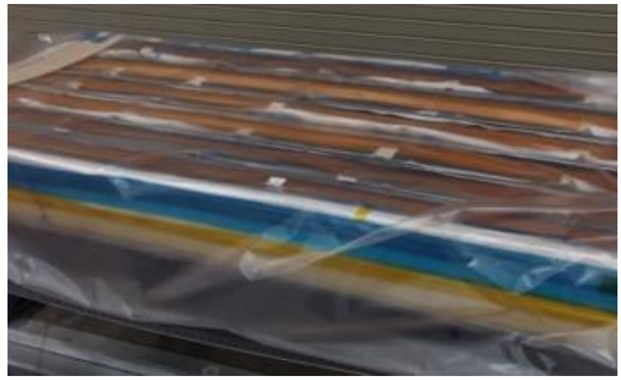
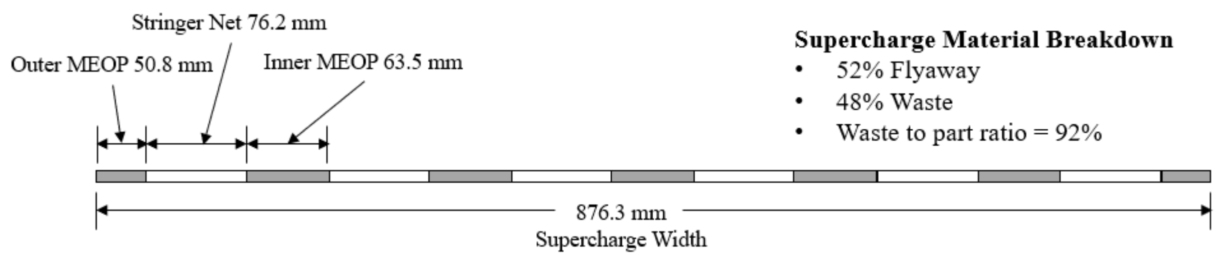


Figure 5. Stiffened skin panel bagged for Co-Fusion

In the Install and Spot Weld Stringers station; an automated means of adding stringers to the skin is proposed. The stringers are fully consolidated and can be handled with pick and place equipment. Stringers must be added in the correct location. To do this the pick and place robots coordinate their position based on unique features in the skin and the tool holding the skin. Stringers are spot welded in place so that the skin can travel to additional work locations before the stringers are fully welded to the skin during Co-Fusion. A two robot system is envisioned as seen in Figure 4. One robot holds the stringer while spot welding it to the skin, and the second robot holds the end of the stringer to keep it in the correct position. This arrangement was inspired by a Fanuc automation brochure [5]. Window frames and PDS Sills are added in a second pick and place station so they can be welded to the skin with Co-Fusion rather than with an additional welding process. Metal cauls are also added to create smooth interfaces in locations where the body frames will be welded to the skin. Composite parts are spot welded into place like stringers and cauls are held with spray tackifier.

Co-Fusion is analogous to thermoset cocure. Co-Fusion is a Spirit AeroSystems patented process that consolidates the skin while welding additional thermoplastic components onto the skin [6]. Co-Fusion uses heated tooling, and an insulation system to protect the vacuum bag from the high temperatures (370^{o}C) needed to consolidate the thermoplastic composite. Insulation along with thermal isolations zones in the tooling allows conventional bagging materials to be used saving time and money compared to thermalimide bags and high temperature sealant tapes that are not as reliable or easy to handle. The end result of Co-Fusion is a stiffened skin panel that will be trimmed, deburred, and inspected prior to being moved to the final assembly area.

Stamp forming is used to make a wide variety of stiffening elements for the thermoplastic aircraft. Stamp forming is an attractive process because of its short cycle times (on the order of minutes) and the high degree of surface and dimensional control afforded by a matched metal die molding process. As can be seen in Figure 3 the manufacturing sequence to make stamp formed parts is to make the blank with AFP, rough trim the blank to features needed to align and hold the blanks during stamping, stamp the part, perform final trim, deburr, dimensional inspection and NDI. Stringers are prepared from a supercharge to increase the laydown efficiency during AFP by avoiding short courses where the equipment starts and stops so often it does not get up to full speed. The downside to a supercharge is the large amount of wasted material. Figure 6 shows six stringer lines are nested within a supercharge. The engineering definition of the stringer needs about 76.2 mm of material. As is customary in composites fabrication excess material is included for part handling and machining down to net dimensions. 50.8 mm of manufacturing excess over part (MEOP) is provided for in the stringer blanks on the outside edges of the supercharge while stringers within the central part of the supercharge share 63.5 mm of MEOP. Six stringers each of 76.2 mm width is 457.2 mm of material. Compared to the overall supercharge size of 876.3 mm only 52% of the material put down goes onto the airplane.



Supercharge Material Breakdown
- 52% Flyaway
- 48% Waste
- Waste to part ratio = 92%

Figure 6. Configuration of stringer supercharge

Stringers serve as an interesting part to review in terms of how they are modeled in the ALM. The first station in Table 2 is Stringer HELaydown (high energy laydown); supercharges are made with six stringer lines each. Since there are 50 stringer lines and four PDS chords made on the stringer equipment then this station must run nine times to make enough parts for one aircraft. The equipment cost covers the AFP and overhead laser projectors. StringerTrimSuperblank uses a robotic trim and drill operation to extract a stringer line blank from the supercharge. The robotic trim and drill equipment as well as a vacuum lift are accounted for in equipment costs. This station runs nine times per shipset as well. StringerStamp is the actual forming operation. StringerStamp runs 54 times per aircraft. The nine supercharges after trim become 54 stringer line blanks. Each blank might still have more than one part in it. This station assumes two load/unload stations each with A & B positions so four blanks can be loaded into the stamp cell. Correspondingly, there are four ovens, two robots to shuttle blanks from the load station to the oven, from the oven to the press, and from the press to the unload station, and two operators to keep the stamping cell filled with product. The factory floor layout of the stamp forming station is shown in Figure 7 (dimensions are in feet). The stringer Stamp Cell is costed as one piece of equipment to include all the components just discussed and shown in Figure 7 as well as a die cleaning and repair station. The die shuttle system is responsible for moving dies from overhead storage to the preheat station as well as from the preheat station to the press. Some amount of commonality is assumed between stringers such that 20 different dies plus a final trim operation create 63 stringers. Stringer dies are estimated to be $451,600 each. Each of the four PDS chords are assumed to be unique, requiring their own die. Each PDS chord die is estimated at $239,000 each. 63 stringers and four chords make up the 67 occurrences per shipset documented in Table 2. The cost of the press cell system is estimated at 5.1 million dollars.

Table 2. ALM section for stringer fabrication

Part	Module	Station	Alternate	Station Duration	Max Heads	Station Labor	Equipment Cost ($)	Station Area	Occurrence / Shipset	Occurrence / Month	Copies	Capital Required ($)	Factory Space (sqft)
Z_Stringer	Z-Stringer Stamp	Stringer HELaydown	0	3.24	1.0	3.24	7,960,000	1,495	9	720	6.0	47,760,000	8,970
Z_Stringer	Z-Stringer Stamp	StringerTrim Superblank	0	1.80	1.0	1.80	2,502,000	1,694	9	720	3.0	7,506,000	5,082
Stringer Stamp Tool	Z-Stringer Stamp	StringerStamp	0	0.17	2.0	0.34	5,100,000	8,892	54	4320	2.0	10,200,000	17,784
Stringer Stamp Tool	Z-Stringer Stamp	Stringer DieChange	8	0.17	1.0	0.17	-	-	8	640	1.0	-	-
Stringer StampTool	Z-Stringer Stamp	Stamp ToolClean	50	1.00	1.0	1.00	1,000,000	800	1.08	86.4	1.0	1,000,000	800
Z_Stringer	Z-Stringer Stamp	Stringer Trim	1	0.55	1.0	0.55	6,712,256	1,661	32	2560	4.0	26,849,024	6,644
Z_Stringer	Z-Stringer Stamp	Stringer Trim	2	0.54	1.0	0.54	6,712,256	1,661	16	1280	2.0	13,424,512	3,322
Z_Stringer	Z-Stringer Stamp	Stringer Trim	3	0.53	1.0	0.53	6,712,256	1,661	4	320	1.0	6,712,256	1,661
Z_Stringer	Z-Stringer Stamp	Stringer Trim	4	0.52	1.0	0.52	6,712,256	1,661	2	160	1.0	6,712,256	1,661
Z_Stringer	Z-Stringer Stamp	Stringer Deburr	0	0.30	2.0	0.60	198,250	1,080	67	5360	4.0	793,000	4,320
Z_Stringer	Z-Stringer Stamp	Stringer DimInspect	0	0.42	1.0	0.42	415,000	960	67	5360	6.0	2,490,000	5,760
Z_Stringer	Z-Stringer Stamp	StringerNDI	0	0.33	1.0	0.33	2,192,000	840	67	5360	5.0	10,960,000	4,200

The StringerDieChange station is broken out as a separate station to control how often it runs. The equipment, floor space, and operators for this station are all accounted for within the StringerStamp station. Table 2 shows StringerDieChange uses the Alternate column in the ALM. Since the value in the Alternate column is not zero Simio knows that there needs to be a conditional statement to determine if the time for the die change operation is tallied when the StringerStamp station runs. StampToolClean also uses the Alternate Column. The idea is the die only needs to go to a dedicated cleaning station once every fifty stamping cycles. Instead of tracking each unique die and how many part cycles it has seen; the StampToolClean station runs once every fifty times the StringerStamp station runs. To get 1.08 occurrences per shipset, fifty four times per ship set is divided by the Alternate value of fifty.

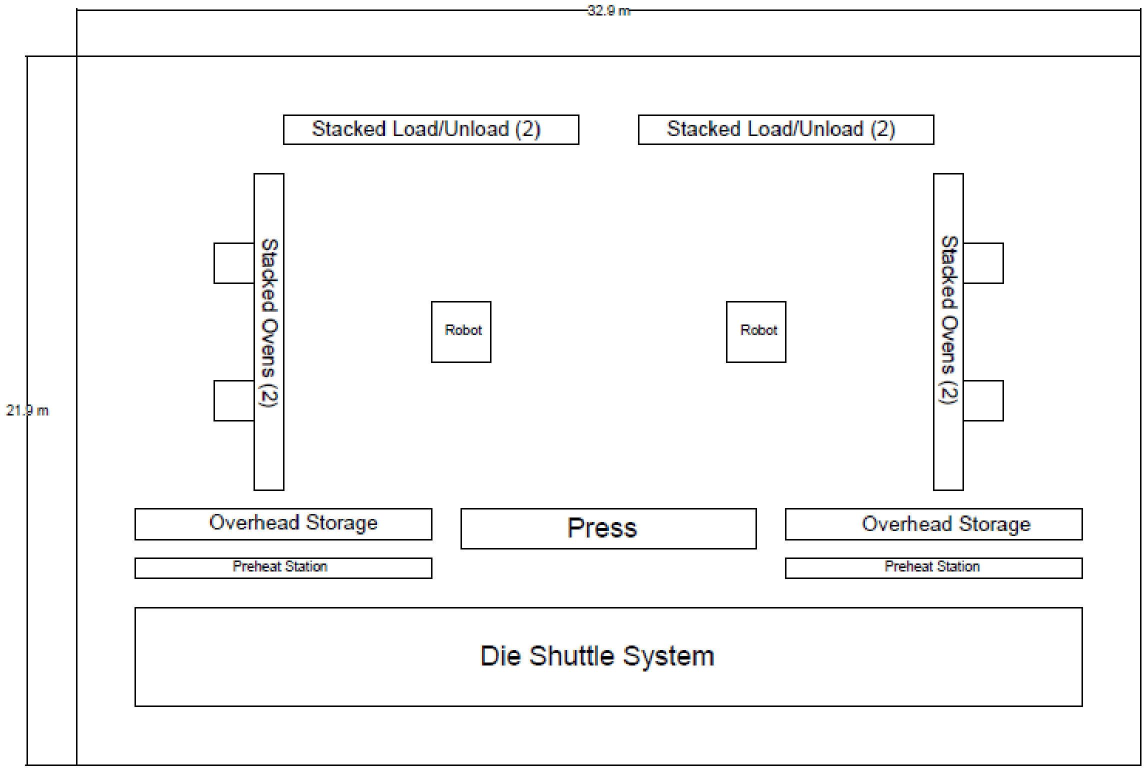


Figure 7. Stringer Stamp Form Cell Layout

There are four different types of Stringer Trim operations; each with a unique number of times it needs to run and a unique trimming length. The Alternate column is used to assign a unique identifier to each type of Stringer Trim operation so that when the DES runs it does not see four different stringer trim stations; rather it knows the correct amount of time and number of times that trim operation needs to run. The total number of stringer trim operations, 54, matches the number of times the StringerStamp station runs. 54 formed blanks go into the StingerTrim station and get turned into sixty individual parts. A 5-axis gantry is assumed for the trimming equipment. Mill fixtures are designed such that multiple different formed blanks can use the same mill fixture to cut down on the number of tool setups.

Stringer deburr, dimensional inspect (DimInspect), and NDI all run once per part, so sixty-seven times per aircraft. StringerDeburr is a manual operation needing a basic worksurface, hand tools as well as a downdraft table. During dimensional inspection the stringer surface profile, hole locations, and angles between the flange and the web will be checked. A vision capture or optical scanning system was assumed as opposed to a coordinate measuring machine or FaroArm. Stringers go through ultrasonic inspection. A special pass-thru setup matching the cross-section of the stringer is used. In addition to the inspection equipment a transfer system to facilitate the safe loading and unloading into and out of the NDI cell is included in the station equipment cost. On average 123 hours per shipset (9% of total hours) is spent on the SkinSupportAssembly station. The major functions that occur at this station are: loading of 360° frames into the fuselage assembly tool (FAT), loading up four skin panels around the frames, welding the skin panels to the frames, and building the passenger door surround. Figure 8 shows a concept for the fuselage assembly tool. The tool holds the body frames which have been joined into a 360° ring. Skin panels are brought to the frames in the FAT. Figure 9 represents welding equipment that will need to be integrated into the FAT. There are welding end effectors for each shear tie on the frames. The end effectors are pneumatically actuated to provide clearance when loading the frames into the FAT and then to apply pressure when welding the skins to the frames. Once all four skin panels are loaded into the FAT a cinch belt is applied around the skins to react the pressure. The welding end effectors are activated sequentially to progressively close any gaps.

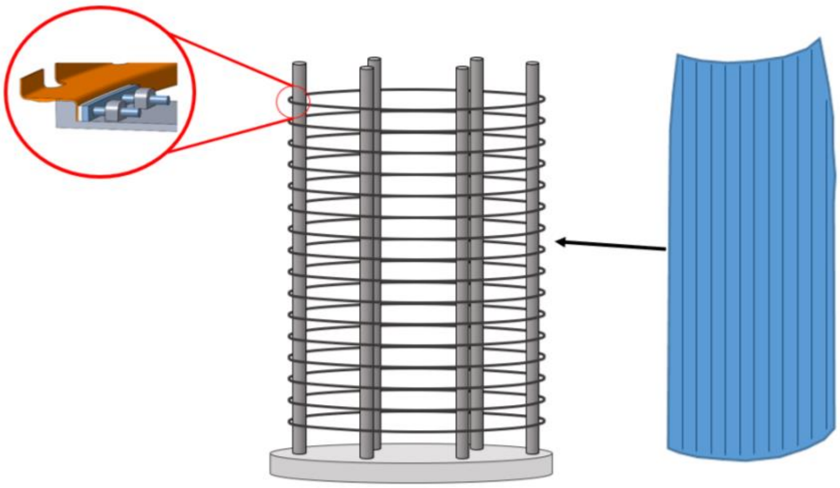


Figure 8. Fuselage assembly tool

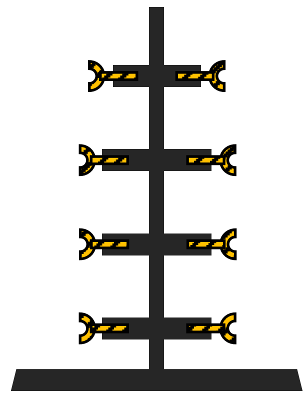


Figure 9. Frame welding equipment

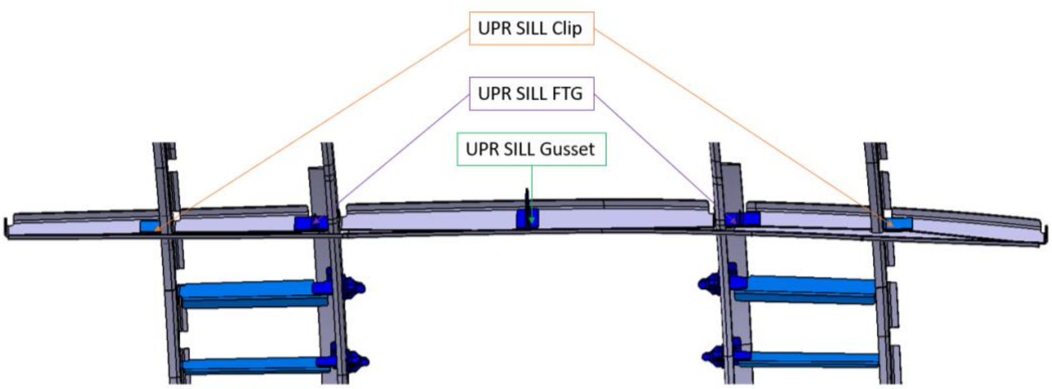


Figure 10. Placement of outer sill components onto inner sill at frame intersections

The inner half of the door sill is Co-Fused to the skin however the intercostals, and the outer sill components are added to the fuselage during this station. The sills are joined to the skin using a slip knife welding concept patented by Spirit AeroSystems [7]. Induction welding is used to join the intercostals to the skin and to body frames. Intercostals are fastened to the titanium door stop fittings on the edge frames. Where the frames intersect with the door sill, the outer sill components are added to serve as a clip that gets welded to tie the frames to the door sill. The assembly of sills and frames is shown in Figure 10. This completes the assembly of the passenger door surround.

The fuselage is lifted off the FAT and transferred to the SkinSpliceWeld station. The seams between each skin panel are welded shut using the hot knife method mentioned previously. At this stage in the program the joint is modeled as a scarf joint pending the verification of weld strength. The welding equipment is mounted on a vertical post and the fuselage is placed on a turn table enabling each splice to be presented to the welding equipment (Figure 11). To reorient the fuselage to the horizontal position trunnion assembles are installed in the door surround and connected to a crane with web belts. A concept for the maneuver is given in Figure 12. Additional lifting provisions may be needed to distribute the weight of the fuselage more evenly through the fuselage. The remaining discussion will walk through two examples of using the ALM as a tool to make manufacturing trades.

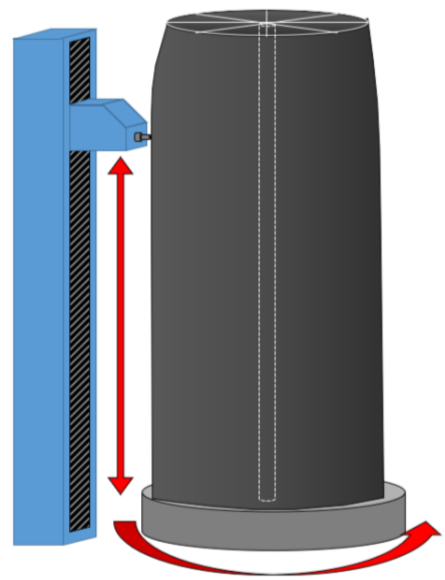


Figure 11. Skin Splice Assembly Fixture

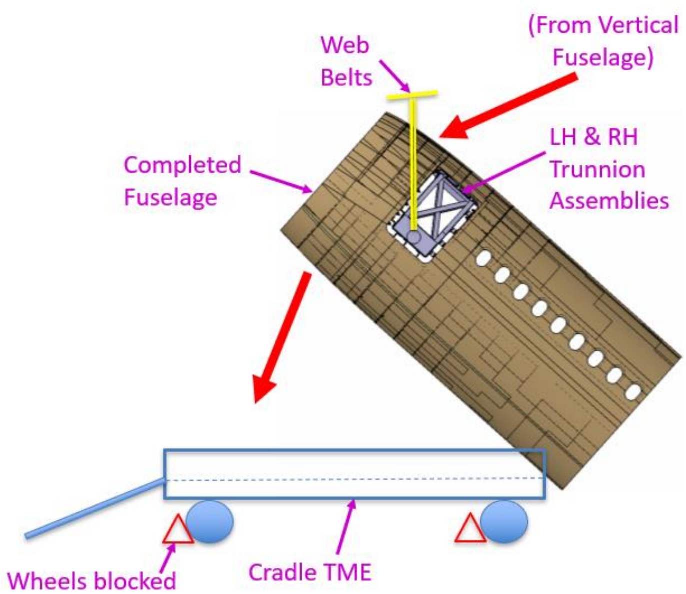


Figure 12. Fuselage positioning from vertical to horizonal

An alternative to consolidating and welding the skin panels with Co-Fusion is to use stamp forming to make the skin panels and conduct a welding operation separate from consolidation to add on the stringers. For purposes of the manufacturing model the risk level of out of autoclave consolidation offered by Co-Fusion and stamping large structures is equivalent. ALMs were built for stamping three and six skin panels and joining into a barrel in addition to a three panel Co-Fusion concept. The resulting KPPs in comparison to the HiCAM baseline aircraft are given in Table 3.

Table 3. KPP Summary Comparing Co-Fusion and Stamp Forming

KPP	Baseline	Savings Compared to Baseline		
		Co-Fusion	Stamp Skins (6 panel)	Stamp Skin (3 panel)
Recurring Cost	$ 763,994	48%	49%	52%
NRC	$2,022,833,711	26%	21%	27%
Unit Cost	$ 1,325,892	39%	37%	41%

A three and six panel model for stamping was prepared because the risk level as a function of size of a skin panel which can be stamped is difficult to accurately assess. The expense in presses and dies large enough to stamp one third of the fuselage skin is far beyond any existing equipment. In addition, the difficulty in supporting, transferring, and accurately locating a molten blank during a stamp forming process certainly increases with size. Three panels were considered possible but six was chosen as a more likely situation. According to Table 3, the Stamp Forming concept is a superior choice if only three skin panels are needed. If stamp forming needs six panels while Co-Fusion can stick to three panels then the methods are about equal with the Co-Fusion model having a unit cost $20,000 less than the stamped skins model. Stamped skins offer a labor savings compared to Co-Fusion. As the panel count increases more setups and teardowns must be performed leading to more copies of stations and thus more capital expenditure. The breakdown of labor and non-labor costs are further explored in Table 4.

Table 4. Stations most changed by choice of skin fabrication

Model	Station	Number of Copies	Labor Hours (per month)	Non-recuring Cost
Co-Fusion	Co-Fusion Consolidation	3	2366	$12.8M
	Pick & Place Stringers	2	2477	$10.6M
	Skin Support Assembly	10	8336	$415M
	Skin Splice Welding	2	578	$95.4M
Stamped Skins (6 skin panels)	Stamp Skin	1	240	$7.61M
	Pick & Place and Weld Stringers	3	3269	$17.7M
	Skin Support Assembly	11	9672	$456M
	Skin Splice Welding	3	934	$143M

Table 4 helps to show how exciting the stamp forming process is: 240 labor hours over a month compared to 2366 hours needed for Co-Fusion consolidation. This advantage is partially reduced by the need to weld on stringers in a separate operation. The combined hours of stamping and welding on stringers is still less than the combined hours of Co-Fusion consolidation and placing stringers. Table 3 shows stamped skins is more expensive than Co-Fusion because of the non-recurring costs. Table 4 shows the stamped skins concept needs additional Skin-Support Assembly and Skin Splice Welding station copies compared to Co-

Fusion. As seen in the non-recuring costs column these two stations are disproportionality heavy in capital costs.

Northrop Grumman's Automated Stiffener Forming (ASF) process is used to make thermoset stringers for the Airbus A350 [8]. Preliminary estimates for adopting ASF for thermoplastics have been made. ASF is a ply by ply manufacturing process and results in a fully consolidated thermoplastic part. ASF is uniquely designed for high aspect ratio parts and can control the pitch, roll, and yaw of the part making it well suited to fabricating stringers for the forward most compound contour section of the HiCAM aircraft. Figure 13 shows the principal components of an ASF machine. Figure 14 indicates the stations used to prepare a manufacturing model for forming of stringers by ASF.

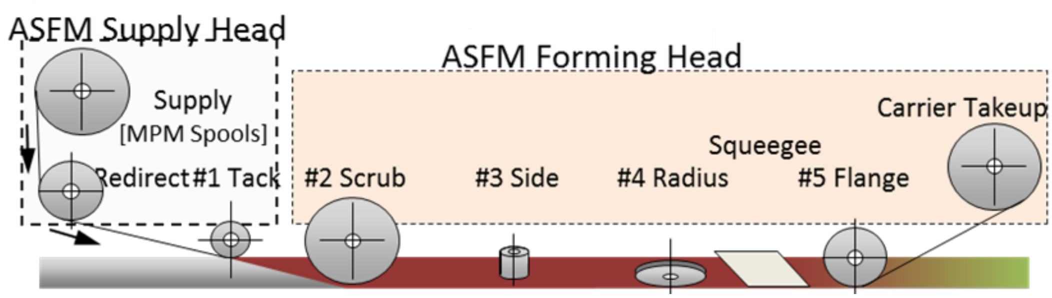


Figure 13. Typical thermoset stringer forming process

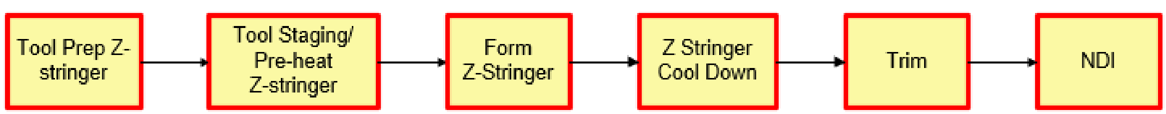


Figure 14. Manufacturing process flow for ASF stringer forming

A comparison of the time and cost for ASF versus stamp forming to make stringers is given in Table 5. Under the current modeling assumptions ASF is clearly a better technology. Compared to stamp forming ASF is still an immature process for thermoplastic stringers. Dimensional inspection and deburr stations are excluded from the ASF manufacturing flow; future trades between ASF and stamp forming would look to experimental evidence to justify the continued exclusion from the ASF flow and also consider if changes could be made the stamp form process flow. The forming step in stamp forming is much faster than with ASF, however stamp forming needs a blank built by AFP. The material laydown rate for ASF is currently higher than that for AFP, and the supercharge concept has a high buy to fly ratio. Assuming ASF and stamp forming can both meet HiCAM program inspection and performance criteria than future manufacturing models will use ASF as the technology of choice to make stringers.

Table 5. Stringer Manufacturing Costs

Fabrication Method	Labor Hours/ Shipset	Capital Costs
Stamp Form	218.75	$ 253,408,560
ASF	147.94	$ 88,176,240

4. CONCLUSIONS

A framework for which to quantitatively compare and assess commercial aircraft manufacturing strategies has been presented. The manufacturing process flow for a thermoplastic fuselage was presented and using the Activity Level Model and Discrete Event Simulation tools the Key Performance Parameters of the thermoplastic manufacturing model are evaluated against the manufacturing model for the HiCAM baseline aircraft. The thermoplastics model offers a 12% weight reduction and a 39% saving in unit cost. In the thermoplastic manufacturing model large investments in automation are made to decrease touch labor. Although the capital investment is high the labor savings pay that back. Labor is reduced by 45% compared to the baseline. The ALM manufacturing model was used to compare Co-Fusion and Stamp Forming as methods of Skin fabrication. Both methods have relatively equivalent KPPs, but it depends on the number of panels used to build up to the full barrel. The labor hours and non-recurring costs determined from discrete event simulation were used to compare stamp forming and automated stiffener forming to make stringers. ASF has superior KPPs but the technology is currently a higher risk than stamp forming.

5. REFERENCES

1. “Hi-Rate Composite Aircraft Manufacturing (HiCAM) Project Overview.” Apr. 2022, https://www.nasa.gov/wp-content/uploads/2022/07/hicam-overview-apr-2022.pdf.
2. The Boeing Company, Spirit AeroSystems, NASA, "Baseline Fuselage Barrel Definition Report (P0-1.01 Deliverable Item 4.9.13)," 2021.
3. The Boeing Company, Spirit AeroSystems, NASA, "Key Performance Parameters (KPPs) Report (Deliverable Item 4.9.10)," 2021
4. Spirit AeroSystems, NASA, " P1.TPC.TDA.01 – Thermoplastic Quantitative Assessment Report (Deliverable Item 4.9.1)," 2023.
5. https://www.fanuc.eu/it/en/industrial-automation/aerospace
6. (USA Patent No. 10828880 B1, 2020)
7. (USA Patent No. 10703049 B2, 2020)
8. Mason, Karen. “Spar Forming Simplified.” *CompositesWorld*, 2 Apr. 2019, www.compositesworld.com/articles/spar-forming-simplified-.