ATK'S RADIAL AIRFRAME FORMING PROCESS ASSESSMENT

A Senior Project submitted

In Partial Fulfillment

of the Requirements for the Degree of

Bachelor of Science in Industrial Engineering

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By

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Abstract

ATK's Radial Airframe Forming Process Assessment

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The purpose of this project was to provide ATK with a solution to increase efficiency in the R-02 radial forming center so that it could meet the increase in demand projected for the next 5 years. In addition, give ATK projected dates of when new machines would need to be implemented to be able to keep up with the demand. The system was analyzed through time studies to identify areas of possible improvement and eliminate any non-value added activities. Cycle times of each activity were used to simulate the current state of the system using ProModel software. Changes in operations were considered to optimize machine and operator's levels of efficiency. These changes and possible improvements resulted in an increase in machine's efficiency to 91% and operator's efficiency to 98%, which consequently produce 19% more throughput. With a higher throughput, the R-02 center will only need 5 out of the 6 forming machines that ATK had originally planned for 2017, resulting in a present worth value savings of $2,730,000.

Acknowledgements

The author wishes to thank all of those who directly and indirectly contributed to this project. Special thanks to the lead Industrial Engineer of Alliant Techsystems (ATK), Monty Rashwan, who continuously collaborated with detailed data pertaining to this project and facilitated the written approval to use the company's information. Another contributor who helped build the simulation model for the system under Dr. Sema Alptekin's supervision was Industrial Engineering student Andrew Balberchak. Last but not least, Dr. Sema Alptekin, who was the technical advisor for this project on both quarters and the academic advisor for the last quarter.

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Introduction

The initiative for this senior project began with a three month Industrial Engineering internship focused on continuous improvement for the new aircraft production center at Alliant Techsystems Inc. (ATK). It was observed that a number of workstations in the current facility suffer a significant percentage of downtime and non-value added processes that can and should be eliminated. The improvement of these processes is crucial to meet the expected increase in the number of ship sets that the plant has scheduled for the next 5 years: to progressively increase from a rate of one ship set a month to twelve ship sets per month by 2017. The intern, decided to analyze the current state of radial forming (R-02), one of the many work centers at which he spent several weeks doing work measurement and performing time motion studies. The company would benefit from this by identifying the amount of time spent on both value added and non-value added activities involved in the production of the airframe parts.

Problem Statement

The current rate of production of the radial forming center at ATK will not meet the requirements for the increase in demand of years to come. The R-02 work center is already constantly behind schedule or barely meeting the demand at the current rate of production. The range of number of parts produced in a given day can vary from as low as no parts up to twelve parts per day. This high variance in production might be due to the fact that there is only one forming machine in place at the moment. The purpose of this project is to decide if another forming machine will be needed and by when.

Main Objectives

- Analyze time motion studies taken of the radial forming process.
- Design a simulation model that accurately represents the manufacturing process.
- Study the current state of the radial forming (R-02) work center.
- Improve the throughput of the R-02 work center by identifying and reducing downtime as well as non-value added activities.
- Properly allocating resources for a leaner manufacturing system.
- Re-design the simulated model with applied changes to identify improvements.
- Decide on the possible implementation of additional radial forming machines.
- Estimate date of implementation if additional machines are to be installed.

The decision must be made if the increase in productivity through the aforementioned approach is enough to meet future demands, or if a new machine must be installed to increase total throughput. In either case, it is the goal of this project to come up with a set of strategies that will help ATK meet the future demand for radial airframes.

Approach

The recorded time studies of the multiple activities involved in the radial forming process are used to identify activities that need improvement and to point out the bottlenecks in the system. The data are also used to simulate a system, using ProModel software, that accurately represents the product flow in the work center.

Once the locations that cause major queue and bottleneck in the system have been identified, the system is then considered for possible changes including but not limited to:

number of operators, shifts, priority of activities, and implementation of new machines. The following Industrial Engineering applications learned throughout the years at Cal Poly are used:

- ❖ IME 223 Work Design & Measurement → Time Studies to collect data.
- ❖ IME 303 Project Organization & Management → Work Breakdown Structure
- ❖ IME 326 Engineering Test, Design & Analysis → Define standard times of operation, standard deviation, and distribution values.
- ❖ IME 410 Inventory Control Systems → Prod. Planning Concepts (Kaizen & Muda)
- ❖ IME 420 Simulation → Use ProModel to track activities, use of resources, and cost.

The scope of this project entails all the activities that take place at the radial forming R-02 station. The processes that happen before entering and after leaving this work center are not be considered. Perhaps a simulation model of the entire facility and all of the work centers could be pursued in the future upon the company's request, but it's not in the scope of this project. Cycle times used for simulating the models are based on the recorded time studies and scheduled shifts of the operators; distance between locations is disregarded.

The simulated model was shared with the lead industrial engineer for the Airbus A350 program for validation and verification of the modeled system. Once the model was approved and the necessary changes were made, then a series of what-if analysis and projections followed. A statistical analysis was also performed using the current data to identify if there is a significant difference in throughput when implementing an additional

machine. Using the throughput results, a coherent projection for the increase in number of machines are made based on the gradual increase in required ship sets.

In addition, a cost analysis and economic justification are performed once the number of machines and required date of implementation are established. The results of these analysis and projections will be shared with ATK and the Lead Industrial Engineer for possible implementation.

Background

Alliant Techsystems (ATK) is a leading aerospace and defense contractor company that manufactures composite parts for aircrafts and propulsion systems. The company was formed as a result of Honeywell Inc. transferring their defense business in 1990. ATK entered the aerospace industry in 1995 by acquiring the aerospace division of Hercules Inc. and has become a leading supplier of aerospace products since then. The company has been awarded multi-million dollar contracts with leading aerospace companies like Boeing, Airbus, and Lockheed Martin amongst many others.

ATK's new composite manufacturing facility in Clearfield, UT, opened in August 2011 and it houses the production line for composite frames for the new Airbus A350. The Aircraft Commercial Center of Excellence (ACCE) building is dedicated to producing high-rate composite manufactured parts. The initial and current production has a rate of one ship set per month, which consists of 700 parts. The ACCE facility is expected to hit future production level of 10,000 parts, or over 12 ship sets a month. A fourth of the parts in the ship set are radial frames of various dimensions.

Given the complexity of the parts, wide variety of sizes and dimensions, some radial frames take much longer to form than others. In order to accurately measure production rates and throughput, the company uses ply meters as a unit of measure instead of the quantity of parts produced. The same strategy will be used for this project in order to accurately measure throughput.

Literature Review

In order to get a solid understanding of all the concepts surrounding the scope of this project, an extensive research for the relevant topics was performed. This literature review provides a basis for these topics and aims to review critical points that will provide context for the reader. The topics discussed in this review are airframe manufacturing, manufacturing composite materials, simulation models in a manufacturing system, and validation of simulation models,

Airframe Manufacturing

The aircraft industry is characterized by the complexity of manufacturing high value-added products that are made in relatively small quantities. (Ericksson 2011) Products in this industry have long development periods and extremely high development costs.

European aircraft industry demands for reduced development and operating costs, by 20% and 50% in the short and long term, respectively (Degenhardt 2006)

Nowadays, all major aircraft projects involve various kinds of global cooperation. The industry has developed into an intricate and very complex web of suppliers creating truly global supply chains. The high-technology requirements require a high level of research and development. In no other industry is there more of inter-dependence and cross-fertilization of advanced technology than in the aerospace sector. (Ericksson 2011)

Aircrafts, whether military or commercial are assembled in many countries, but few of them have the capability to design, develop and produce an entire aircraft. Technology used in modern aircraft is extremely demanding due to the high levels of functional performance, reliability, safety and efficiency required at the system level. (Ericksson 2011)

In airframe manufacturing, new automated manufacturing processes are being implemented to help reduce touch labor, improve quality and consistency, and meet demanding throughput requirements. Technologies such as automated fiber placement, tape laying and robotic material deposition are being used on an increasing variety of components. Some experts believe that within the next decade "more than 75% of composite parts will be manufactured with an automated fiber placement, tape laying or robotic deposition process instead of hand layup, which will drive demand for new systems." (Peck 2010)

Manufacturing Composite Materials

Composite materials have been successfully replacing the conventional materials in many structural applications. Major virtues of composite materials include higher specific strength and stiffness, better corrosion and wear resistance among many other things. (Chung 2004) In addition to consumer products such as skis, golf clubs, and tennis rackets "composite structural elements are now used in a variety of components for automotive, aerospace, marine and architectural structures." (Gibson 1994)

According to Ronald Gibson, "military aircraft designers were among the first to realize the tremendous potential that composite materials with high specific strength and high specific

stiffness, since performance and maneuverability of those vehicles depends so heavily on weight.” (Gibson 1994)

In the past, performance and weight saving have historically been the key drivers behind the adoption of composites for the aircraft structures. Nonetheless, competition in the aerospace industry keeps growing and composite structures must compete in cost with metal structures. "Composites applications in commercial aircraft have been steadily increasing as material costs come down, as design and manufacturing technology evolves, and as the experience with composites in aircraft continues to build.” (Gibson 1994)

The aforementioned techniques of polymeric composites are, for the most part, manufactured by hand lay-up due to its flexibility. Hand lay-up is the process of manually stacking up plies of composite material, layer-by-layer, with different orientations and compressing them together assisted by a vacuum bag. The composite stacking is then sent to the autoclave where the part is cured, which is what gives it the strength and stiffness it needs. “The mechanical properties are directly influenced by the stacking sequence, fiber volume fraction and morphology, as well as the cure process.” According to Gutowski, the most important manufacturing process of composites applied to aerospace industry is the hand lay-up of prepregs and autoclave cure. (Avila 2005) The simulated model considered for this project will represent a hand-lay-up station where radial airframe parts are manufactured out of composite materials.

Simulation Models in a Manufacturing System

Manufacturing systems is one of the largest and most useful application areas in which simulation modeling is used. With a thorough analysis and adequate design, simulation modeling can be a valuable tool to improve and make a manufacturing system more efficient. Simulation can help address several specific issues involved in a manufacturing environment, which will be described in detail further on. "A simulation model is a surrogate for actually experimenting with a manufacturing system, which is often infeasible or not cost-effective" (Law 1999) According to Fowler et al, there have been numerous efforts to use modeling and simulation tools and techniques to improve manufacturing efficiency over the last four decades. There has been considerable progress made due to simulation models and many manufacturing system decisions are made based on models' results. Experts believe that "there is a need for pervasive use of modeling and simulation for decision support in current and future manufacturing systems. There are several challenges that need to be addressed by the simulation community to realize this vision." (Fowler 2004)

Simulation can help address various specific issues in manufacturing, for example, identifying the need for equipment and personnel in a given workstation. Through simulation, a model of a system can return the quantity of machinery necessary to run the system based on a desired output.

For purposes of this project, a manufacturing-oriented simulator such as ProModel is needed in order to have the right modeling constructs that are specifically focused on manufacturing and material handling scenarios. A manufacturing-oriented simulator is a

simulation package designed to model a manufacturing system in a specific class of systems. (Umeda 1992) The major advantage of a simulator like ProModel is that the amount of time required designing and developing a model is reduced considerably because the software is already programmed to build scenarios of a manufacturing environment.

Law and McComas mention the following issues for which simulation can provide a solution in manufacturing: (Law 1999)

- Identify requirements for transporters, conveyors, and other support equipment
- Evaluation of the effect of a new piece of equipment on an existing manufacturing system
- Evaluation of capital investments
- Performance evaluation by throughput, time-in-system, and bottleneck analysis.
- Evaluation of operational procedures through production scheduling

It's important for the simulation analyst to determine if the model is an accurate representation of the system being studied, in other words, if the model representing the system is valid or not. An important aspect to consider before developing a model and for validation is to define what will be the performance measures for evaluating the current system. Common performance measures estimated by simulation include throughput, time in the system, queue sizes, times in queue, and utilization of equipment and personnel. For this project, simulation will serve useful to help set a standard to evaluate performance in throughput, time in the system and bottleneck analysis. Also, it'll help to briefly discuss issues like evaluating operational procedures through production scheduling.

It's extremely important for the appropriate probability distribution to be used in any

given process so that the output data is relevant and adequate for analysis. "In order for an estimate to be statistically precise and free of bias, the analyst must specify for each system design of interest appropriate choices for length of simulation run, number of independent simulation runs, and length of the warm-up period, if one is appropriate" (Law 1999)

Law et al recommend that at least three to five independent runs for each system design be performed and to use the average of the estimated performance measures from those individual runs as the average of the performance measure. The ideology behind this strategy is so that the overall estimate is more statistically precise than only one run of the model (Law 1999).

Manufacturing systems that require modern high technology such as the aerospace industry can be very complex. One factor that results in high complexity is the use of multiple part types manufactured in the same facility with numerous manufacturing steps in the process. This complexity requires constant maintenance, which results into downtime and high cost of setting up the machines and transitioning from one setting to another. A simulation model serves as an instrument to give an accurate estimate of the manufacturing system behavior. (Fowler 2004)

The process of simulating manufacturing systems involves the following phases and steps, which will serve as a roadmap for the modeling portion of the project. (Breakdown from Fowler et al.)

A. Model Design:

1. Identify the issues to be addressed.
2. Plan the project.
3. Develop conceptual model.

B. Model Development

4. Choose a modeling approach.
5. Build and test the model.
6. Verify and validate the model.

C. Model Deployment:

7. Experiment with the model.
8. Analyze the results
9. Implement the results for decision-making.

Validation of Simulation Models

According to Sargent, "simulation models are increasingly being used in problem solving and to aid in decision-making. The developers and users of these models, the decision makers using information obtained from the results of these models, and the individuals affected by decisions based on such models are all rightly concerned with whether a model and its results are correct. This concern is addressed through model verification and

validation." (Sargent 2005)

The verification and validation of a model can be simple or very ambiguous depending on the model and system studied. The difference between the two aforementioned terms is that verification is concerned with the correct output data based on a specified input, while validation checks the consistency and accuracy of the model with the real application. An example of validation would be reviewing outputs with end-users to ensure that results are reasonable. For this project, the model could be validated by verifying the output results from the simulated model with real output numbers from management. If the results are similar and the simulated model accurately represents the reality of the system, then it can be said that the model is indeed valid.

In his *Verification and Validation of Simulation Models* journal, Sargent suggests that several versions of a model need to be developed prior to obtaining a satisfactory valid model. The substantiation that a model is valid, in other words performing model verification and validation, is considered to be a part of the total modeling process.

There are several validation techniques to check the true validity of a model, however, for the scope of this project the following will be considered: event validity, face validity, predictive validation, and traces. The definitions below summarize Sargent's techniques for validation that will be used to validate the model for this project.

Event Validity: The events of occurrences of the simulation model are compared to the

occurrences of the real system to identify similarities. For example, comparing the average total parts built on a given work shift.

Face Validity: Operators familiar with the system and knowledgeable enough to identify the behavior of the model will be asked to compare and validate for accuracy.

Predictive Validation: "The model is used to predict (forecast) the system's behavior, and then comparisons are made between the system's behavior and the model's forecast to determine if they are the same." (Sargent 2005)

Traces: The behavior certain entities in the model are followed through the model to determine if the model's logic is correct. For example, tracing the tools through the different stations and validating the true routing pattern.

Methodology

As part of my internship, I was part of a rotational program and performed process improvement on different departments at ATK's Clearfield facility. For this project, it was decided that only one workstation of the entire facility would be closely observed and that was the R-02 (radial forming) workstation, which suffered the most down time.

The methodology in pursuing this project followed a six-sigma approach: the concept of DMAIC (Define, Measure, Analyze, Improve, and Control). The flowchart, Figure 1 on the right represents the DMAIC methodology for a simulation process.

Define: After becoming familiarized with the forming process of making radial frames for the Airbus A350 airplane, the system was analyzed and areas for potential improvement were identified. A clear set back was noticed in observing the process, and it was that the forming machine was constantly down and the rate of production was low.

Measure: Time studies were performed on this particular manufacturing line for a total of 30 parts. Average times and standard deviations were calculated from the recorded time studies for each of the activities in the forming process and used for the simulation of the

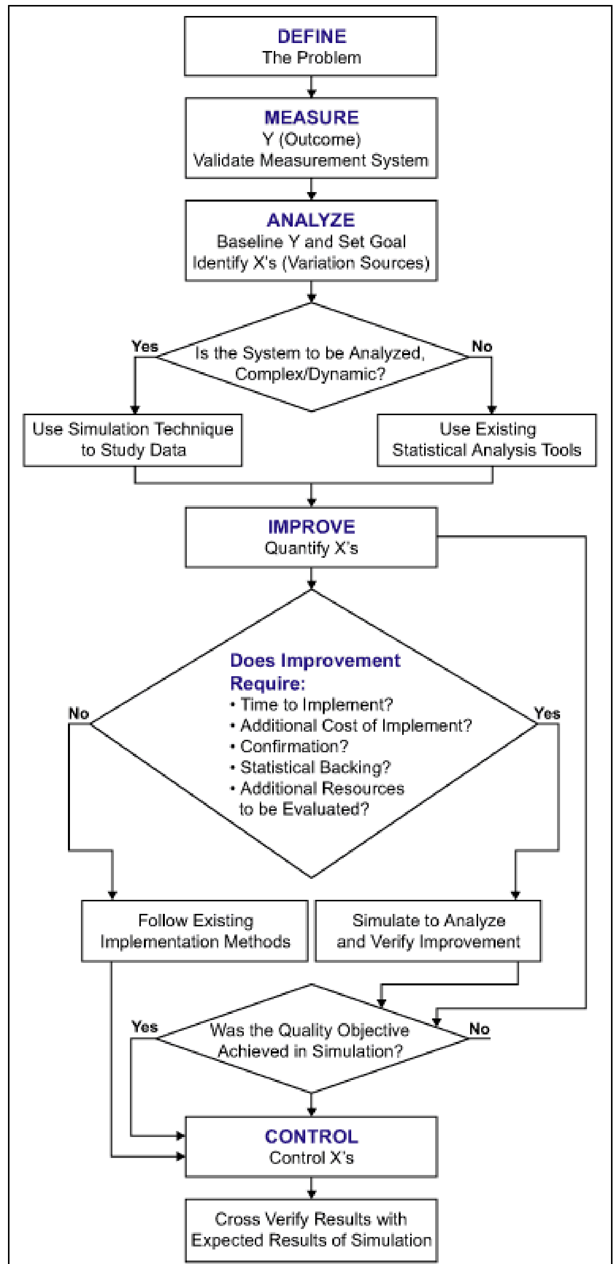

Figure 1 - DMAIC Methodology for Simulation (www.isixsigma.com)

system.

Analyze: Once the system was simulated, the statistical output given by ProModel was analyzed and shared with ATK. Projections for the total throughput at a monthly basis were performed according to the results of the simulated model. Based on the increase in demand that ATK will face in the near future, projections were made to identify until when the current system will meet the demand.

Improve: Once it was identified that the system based on the current resources cannot meet the required demand for radial parts, the following alternative scenarios were considered in a random order:

- Will adding more operators to the system increase the rate of production?
- Should the machine be running around the clock (24/7)?
- Will an additional machine increase the rate of production?
- If an additional machine is added, can it operate under the same number of operators?

The above what-if scenarios were analyzed using ProModel and the resulting data were compared to the current state of the system. An economic analysis was performed and the return of investment along with the overall improvement in throughput of all scenarios was projected to present ATK with various possibilities. The control portion of this methodology will depend on ATK's decision to implement the suggested solution and continuously update the model with updated data to monitor the progress.

Design

The simulation model was designed as an exact replica of the radial forming work center in order to accurately represent the system, with the same layout and including all of the individual workstations that are part of this work center. Figure 2 below gives a visual representation of how the parts flow through the system at the radial forming room.

Simulation Logic

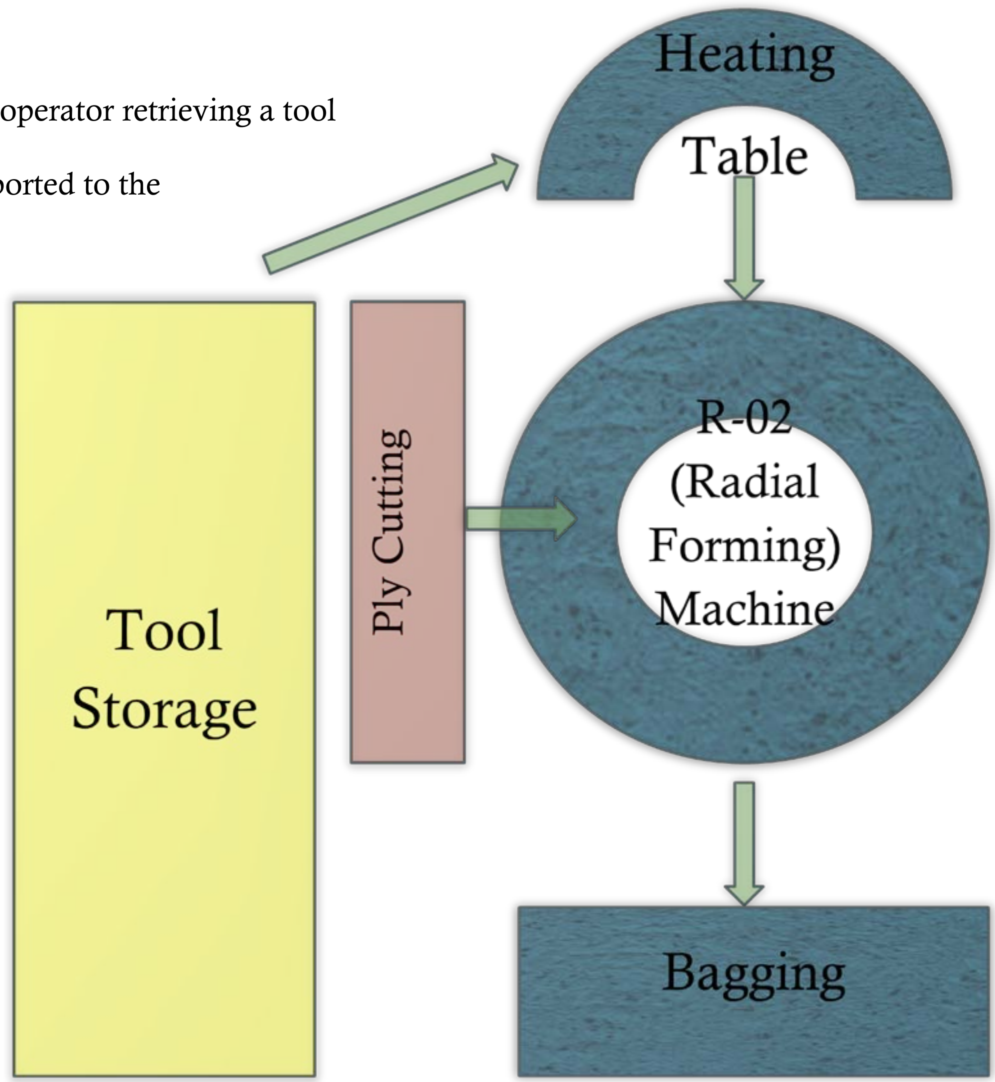

Figure 2 - R-02 Process Flow

The simulation begins with an operator retrieving a tool from storage. The tool is transported to the heating table using a forklift crane. The tool is then laid on the heating table and the heating process begins with an average time of 9.5 minutes per operation. Once the tool is heated, it is then conveyed over to the R-02 (Radial Forming) machine. The operator then begins to lay plies of composite material on to the tool; this process is more complex and cannot be assigned one single average time and standard deviation

because it is widely variable depending on the type of part being built.

Since there are a large number of combinations of type of parts that can be built varying in length and thickness, ATK measures the parts on *ply meters*. *Ply meters* is the overall length of composite material used to build that particular part. It's important to clarify that in order to make the simulation of this system less complex, while still very close to the true system, certain assumptions and generalizations were made.

Parts were categorized as "S" (Small), "M" (Medium), and "L" (Large) based on the number of ply meters used for that part under the following ranges:

- "S" Small: 0 – 35 Ply Meters
- "M" Medium: 36 – 130 Ply Meters
- "L" Large: 131 – 300 Ply Meters

Based on these assumptions, the average time to build (or form) a part was calculated from the recorded time studies.

Simulation Model Usability

The simulation model was created to serve as an analysis tool in production planning and to observe multiple scenarios by simply readjusting the data at no cost. The user of this model can easily modify standard times and the distribution of various parts built by using the macro tool in ProModel. This is an extremely powerful tool that can be constantly updated to the current state of the system and project throughput with quick adjustments to the algorithm. Appendix B shows instructions on how to modify the model's data based on updated states of the system, including: mean times of forming a tool, standard deviations, percent distribution for the type of part being built, and number of ply meters per tool.

Data

The process of building radial frames at R-02 was observed for a total of 30 radial frames of different sizes. Time studies were used to time every single activity involved in the process described in the "Design" section of this report. Before collecting the data, a template was built with the detailed activities involved in each process. The average times (in minutes) to build all of the 30 parts timed are given below broken down into individual activities.

Refer to Appendix A for raw data set of individual parts.

Table 1 - Total Recorded Times

Set-up	Retrieve tool	**108.0**
	Heat tool	**281.0**
Uptime	Load tool	**48.0**
	Unload	**38.0**
	Hand lay, form, remove poly	**1722.0**
	Machine lay/form/compact plies	**347.0**
	EWI, Virtek, paperwork, buyoffs	**93.0**
Downtime	**Downtime**	
Programming	EWI / Impressa/virtek Issues	**103.0**
	Machine programming	**129.7**
Machine	Machine E-stop	**5.0**
	Machine Feeder jam	**0.0**
	Machine supply head	**0.0**
	Machine rollers	**5.0**
	Machine sensors	**0.0**
	Machine Maint. /Setup	**0.0**
	Remove, replace, rework ply	**16.0**
Material	Material Defective	**1.0**
	FPM ply, scrape, trim, add mat'l	**131.3**
	Material with FOD	**0.0**
	Material Expired	**0.0**
Stop & Wait	Stop tool search	**7.0**
	Stop & Wait (Tool)	**12.0**
	Stop & Wait (Material unavailable)	**180.0**
	Stop - material change out	**8.0**
	Stop move tools in & out	**0.0**
Admin	No work Break/extended	**78.0**
	Meetings / Visitors / Training	**32.0**
	Idle - not working	**0.0**

Data Analysis

In performing the data analysis, the first step was to calculate the machine and operator's levels of efficiency based on the uptime & downtimes recorded in the time studies. Machine efficiency was calculated on Equation 2 using the recorded averages of the time studies and yielded 85% of uptime (efficient) and 15% downtime as seen on Figure 3.

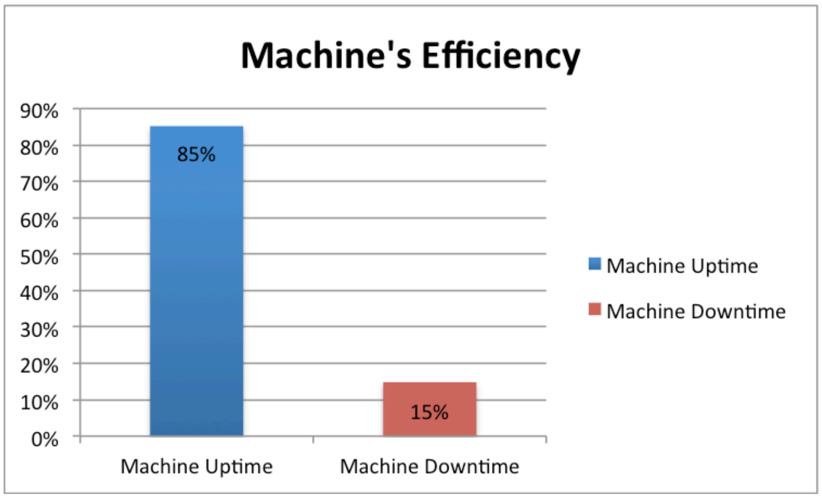

Figure 3 - Machine's Production Efficiency

Operator's efficiency was calculated on Equation 3 using the recorded averages of the time studies and yielded 88% of uptime (efficient) and 12% downtime as seen on Figure 4. It's important to note that this efficiency ratio is based on the operator working on the machine, not one specific operator.

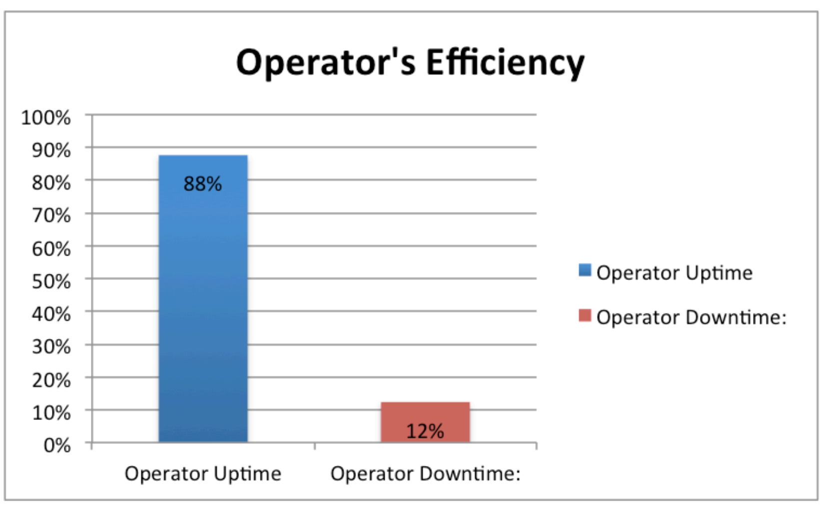

Figure 4 - Operator's Production Efficiency

Next, individual causes of both machine and operator downtimes were identified, shown in Figures 5 and Figure 6 respectively. The major causes for the machine's downtime, each contributing nearly one third of the total machine downtime are as follows:

1. FPM ply, Scrape, Trim, Add Material	34%
2.Machine Programming	33%
3.EWI / Impressa / Virtek Issues	27%

The major causes for operator's downtime are given below:

1.Stop & Wait (Material Unavailable	57%
2.No Work / Extended Breaks	25%
3.Meeting / Visitors / Training	10%

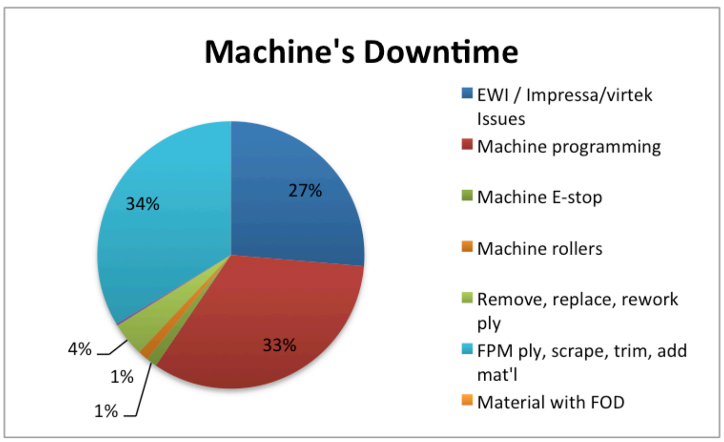

Figure 5 - Causes of Machine Downtime

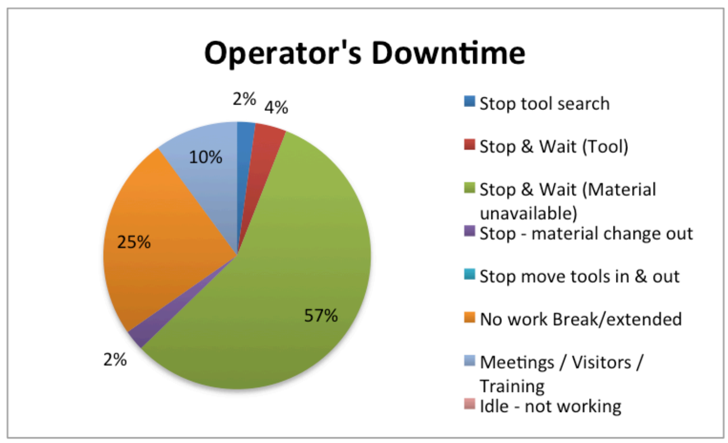

Figure 6 - Causes of Operator Downtime

In order to get a visual representation of the major activities causing downtime, a Pareto chart was constructed for both machine's and operator's total downtime. See Appendix A.

Average times and standard deviation were calculated for each size of the parts built using JMP software. The following are mean times and standard deviation (in minutes) for building each part. Refer to Appendix A for the full data set of time studies for each part and the output of JMP software.

Table 2 - Process Times (JMP Software)

Part Size	Mean Lay-Up Time / Ply Meter	Std. Deviation	Mean Ply Meters
S	3.35	1.29	25
M	1.10	0.45	60
L	0.83	0.12	150

This data was used as a baseline to run the simulated model using ProModel software for the lay up activity at R-02. Along with these mean times and std. deviations of the processes, an efficiency analysis was performed to obtain the true run time of the forming process. The R-02 radial forming machine operates for a 12-hour shift on a daily basis, for a total of 360 hours of machine availability. See Equation 1. Since the machine itself will not be running at 100% efficiency and it's also dependent on operator's efficiency, each individual efficiency level must be analyzed separately.

Simulation Model Result (Current)

As previously stated, the current total machine run hours is 360 per month, with an 85% machine efficiency and 88% operator efficiency for a total of 269 hours of productive run time. See Equation 4. This production time was used to run the simulated model and predict throughput in total number of finished parts for a month. The simulation model projected a total of 340 finished parts for a given month. This number of finished parts is the

average of 5 replications in the simulated model to get a statistically sound prediction. See Table 3.

Table 3 - Current total part throughput per month.

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Location Summary (Rep. 1)

Name	Scheduled Time (Hr)	Capacity	Total Entries	Average Time Per Entry (Min)	Averag e Co...	Maximu m Con...	Curr ent...	% Utilization
RO2 Radial Forming	269.00	1.00	340.00	46.60	0.98	1.00	1.00	98.16
Ply Receiving	269.00	999,999.00	80,900.00	5,913.74	29,641.9(	60,229.00	60,190	2.96
Heating Table	269.00	1.00	341.00	45.68	0.97	1.00	1.00	96.50
Bagging	269.00	1.00	339.00	46.73	0.98	1.00	1.00	98.16
Pallet Loading	269.00	5.00	338.00	95.70	2.00	5.00	3.00	40.08

Sensitivity Analysis

Another useful tool of ProModel used is the resource utilization chart. Through this tool, the model gives a percentage of the level of utilization of a given resource. For this system, the operator's utilization was taken into consideration. *Note:* not to be confused with operator's efficiency. Considering the current system, which has 3 operators working in the R-02 room, operator's utilization resulted in a rough average of 60%. See Figure 7.

Figure 7 - Current Operator Utilization

Therefore, the first sensitivity analysis was considered by reducing the number of operators to 2 instead of 3, however, this raised the utilization level to 85% and reduced the number of parts produced. See Figure 8. Hence, the number of operators is to stay at 3 since the main goal is to increase throughput.

Figure 8 - Two Operator Utilization

Once it was established that the number of resources would stay the same, the second and most important sensitivity analysis performed was the change in total production time. In order to improve the total production time of the system, certain improvements must be made, which will potential increase the machine and operator's levels of efficiency.

Suggested Improvements

When observing the system, important relevant data was recorded to make changes in operating procedures and increase production efficiency. An operator's efficiency can be significantly improved through the following:

1. Cross-training operators so that whenever idle or free, they prepare the material to be used in R-02 and find the tool that will be used for the next part to be built.
    a. The major cause of operator's downtime is operator stopping work to get material, search for tools, and/or waiting for unavailable tools. This can and should be completely eliminated by having another operator have the material and tools ready to go in a just-in-time fashion.
    b. The current system resulted in a 60% operator utilization, which indicates that 1 out of the 3 operators will constantly be free to help with preparing the material and obtaining tools.
    c. Through this change implementation and cross-training all operators to assist the operator in the R-02 machine, operator's downtime can be reduced by 200 minutes.
2. Scheduling operator's breaks so that the R-02 machine always has an operator working on the part.
    a. The current state of the system with 3 operators allows for them to have constant breaks without interrupting the production in the R-02 machine.
    b. It was noticed that operators would take breaks simultaneously and leaving the R-02 machine idle the entire time.

c. Rotating operators' breaks will completely prevent overlapping breaks, reducing operator's downtime by an average of 78 minutes.

The machine's efficiency can increase through the following:

1. Assigning an engineer to be solely responsible of the R-02 machine's technical issues.
    a. The R-02 forming machine constantly presents issues that completely stop production and need the expertise of an engineer to fix those issues.
    b. The intern noticed that every time this happened, it took a significant amount of time to locate an engineer that could fix the issues.
    c. If an engineer is assigned and available to immediately resolve the problems, an approximate 50% of the downtime caused by machine programming issues can be eliminated; approximately 168 minutes.

When implementing the aforementioned improvements, the system could benefit from a potential machine efficiency of 91% compared to the current 85% level and a potential operator efficiency of 98% compared to the current 88%.

Results

Changing the system through the suggested improvements will make sure that the system operates at a higher efficiency. The increase in machine and operator's efficiencies will have a significant impact in total throughput. When the system is modeled again with the suggested changes, the simulation yields a new throughput of 405 parts per month, as seen in Table 4.

Table 4 - New potential throughput

Report1 × | Report2 ×

Location Summary (Rep. 1)								
Name	Scheduled Time (Hr)	Capacity	Total Entries	Average Time Per Entry (Min)	Averag e Co...	Maximu m Con...	Curr ent...	% Utilization
RO2 Radial Forming	321.00	1.00	405.00	46.69	0.98	1.00	0.00	98.19
Ply Receiving	321.00	999,999.00	94,300.00	7,235.47	35,426.0:	70,125.00	70,125	3.54
Heating Table	321.00	1.00	406.00	45.80	0.97	1.00	0.00	96.54
Bagging	321.00	1.00	405.00	46.73	0.98	1.00	1.00	98.26
Pallet Loading	321.00	5.00	403.00	98.35	2.06	5.00	3.00	41.16

These suggested improvements have already been discussed with the lead industrial engineer at ATK, who has been constantly updated on the progress of this project. Both the current model and the improved model with the suggested changes have been validated as realistic.

As a result of the increase in throughput, from the current state of 340 per month to the potential 405 per parts per month, fewer machines will be needed to meet the demand. The current system would require a total of 6 R-02 machines by 2017 to meet the demand of 12 ship sets per month. The new system with the implemented changes will only need a total of

5 machines to produce the 12 ship sets per month requirement. Table 5 shows the total machines that would be required under both the current and proposed system from now until September 2017.

Table 5 - Number of machines required to meet demand

Date:	Current	Potential
13-Sep	1	1
14-Mar	1	1
14-Sep	1	1
15-Mar	2	2
15-Sep	2	2
16-Mar	3	3
16-Sep	4	4
17-Mar	6	5
17-Sep	6	5

Radial forming machines (R-02) have a cost of $4 million, so the economic benefit of having to implement one less R-02 machine by 2017 at $4 Million dollars, has a net present worth value of $2,730,000 in savings for ATK. Refer to Equation 6 for present worth value calculation.

Conclusion

The analysis and process improvement suggestions made for the current state of the radial forming center (R-02) lead to higher efficiency levels of both the machine and the operators. Machine operating efficiency is predicted to increase from 85% to a potential 91% and operator efficiency from 88% to a potential 98% with the aforementioned improvements. Simulation, as the core tool of this project, helped make predictions of the total throughput in both number of parts and ship sets capable to be produced by the current and the proposed system based on real production times.

ATK should implement the suggested changes, which have already been validated by the lead industrial engineer as true potential improvements. A triple bottom line is achieved through the proposed system. ATK will meet customer's demands in time and increase production efficiency without jeopardizing the employee's allowances. Throughput for the radial forming center would be maximized with a 19% improvement and the number of machines required would be 5, as opposed to the 6 that ATK had originally planned for. This has a present worth value savings of $2.7 million dollars.

Continuous improvement strategies along with simulation's ability to test multiple scenarios and quickly predict total throughput for a given month were the major contributions in the assessment of the R-02 radial forming center.

Equations

Equation1:

$$\frac{Total\ Machine\ Hrs}{Month} = \frac{Available\ Hrs}{Work\ Shift} x \frac{Work\ Shift}{Month} = \frac{12\ Hrs}{Work\ Shift} x \frac{30\ Work\ shifts}{Month} = 360\ Available\ Hrs$$

Equation 2:

$$Machine's\ Efficiency = \frac{Uptime\ Machine\ Activities}{Total\ Machine\ Run\ Time}$$

$$= \frac{(48 + 38 + 1722 + 347 + 93)}{(48 + 38 + 1722 + 347 + 93 + 103 + 129.7 + 5 + 5 + 16 + 1 + 131.3)} = \frac{2248}{2639} = .852$$

Equation 3:

$$Operator's\ Efficiency = \frac{Uptime\ Opertor\ Activities}{Total\ Operator\ Time} = \frac{(48 + 38 + 1722 + 347 + 93)}{(48 + 38 + 1722 + 347 + 93 + 7 + 12 + 180 + 8 + 78 + 32)}$$

$$= \frac{2248}{2565} = .876$$

Equation 4:

$$\frac{Actual\ Production\ Time}{Month} = \frac{Total\ Machine\ Hrs}{Month}\ x\ \frac{Machine's\ Eff.}{Rate}\ x\ \frac{Operator's\ Eff.}{Rate} = 360\ Hrs\ x\ 0.85\ x\ 0.88 = 269.2\ Hrs$$

Equation 5:

$$\frac{Potential\ Production\ Time}{Month} = \frac{Total\ Machine\ Hrs}{Month}\ x\ \frac{Machine's\ Eff.}{Rate}\ x\ \frac{Operator's\ Eff.}{Rate} = 360\ Hrs\ x\ 0.91\ x\ 0.98 = 321\ Hrs$$

Equation 6:

$$Present\ Worth\ Value = Future\ Value\ x\ \left(\frac{P}{F}\right) = Future\ Value\ x\ \frac{1}{(1+i)^n} = 4{,}000{,}000\ \frac{1}{(1+.10)^4} =$$

$$4{,}000{,}000\ x\ .6830 = 2{,}730{,}000$$

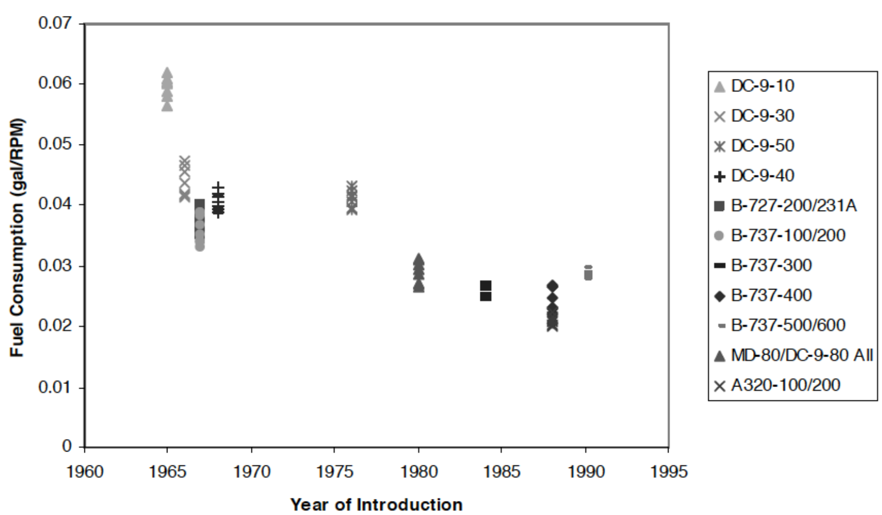
Social and Environmental Impact

The rate of production at any aerospace company has an indirect impact in aviation air pollutants; by helping to put in operation lighter and more modern aircrafts, they influence the level at which the rate of pollutant emissions in aviation increases.

"The impacts of aviation emissions on the global atmosphere are expected to continue to grow. Increasing total fuel consumption and the potential impacts of aircraft engine emissions on the global atmosphere have motivated the industry, scientific community, and international governments to seek various emissions reduction options." (Lee)

ATK's manufacturing of composite parts for aircrafts helps replace high fuel consuming aircrafts with a lighter and more modern fleet that will indirectly help reduce the rate of CO2 emissions and other pollutants. Figures 9 and 10 provided by the Federal Aviation Administration show a historical trend reflecting how technological improvements have reduced the aircraft emissions of nitrogen dioxide, carbon dioxide, carbon monoxide, lead and sulfur dioxide.

Figure 9 - History of Aircraft Fuel Consumption



A faster rate of production in ATK's manufacturing of composite airframes will result in faster delivery to their customers and hence faster implementation of more fuel-efficient aircrafts. Implementing the suggested changes in the R-02 radial forming station at ATK would yield a faster rate of production, satisfying the customer’s needs and having positive influence aviation’s carbon footprint.

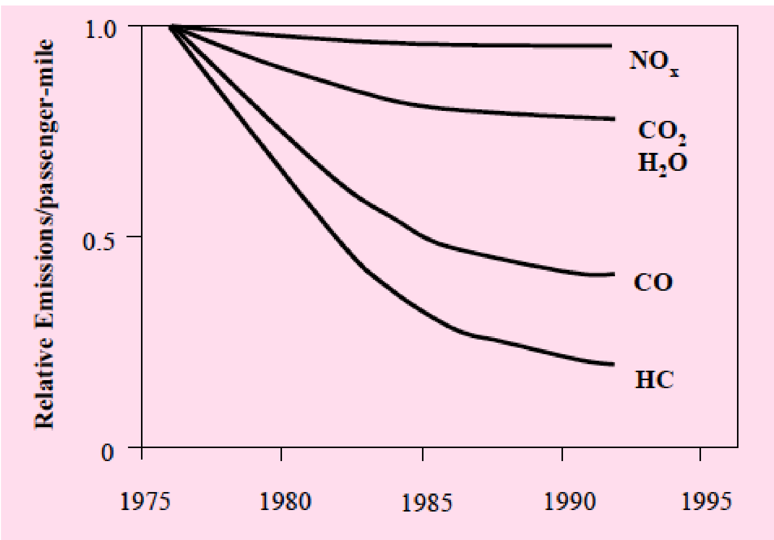


Figure 10 - History of Aircraft Pollutant Emission

Appendix A

Table 6 - Time Statistics building "Small" parts

Summary Statistics	
Mean	3.3572981
Std Dev	1.2951865
Std Err Mean	0.5287577
Upper 95% Mean	4.7165129
Lower 95% Mean	1.9980833
N	6

Avg. Time to build "S" part: 3.35 minutes

Std. Deviation "S" part: 1.29 minutes

Table 7 - Time Statistics for building "Medium" parts

Summary Statistics	
Mean	1.1001061
Std Dev	0.4563534
Std Err Mean	0.1046947
Upper 95% Mean	1.3200614
Lower 95% Mean	0.8801508
N	19

Avg. Time to build "M" part: 1.1 minutes

Std. Deviation "M" part: 0.45 minutes

Table 8 - Time Statistics for building "Large" tools

Summary Statistics	
Mean	0.835324
Std Dev	0.1221043
Std Err Mean	0.0546067
Upper 95% Mean	0.9869366
Lower 95% Mean	0.6837114
N	5

Avg. Time to build "L" part: 0.83 minutes

Std. Deviation "L" part: 0.12 minutes

Figure 11 - Pareto of machine downtime

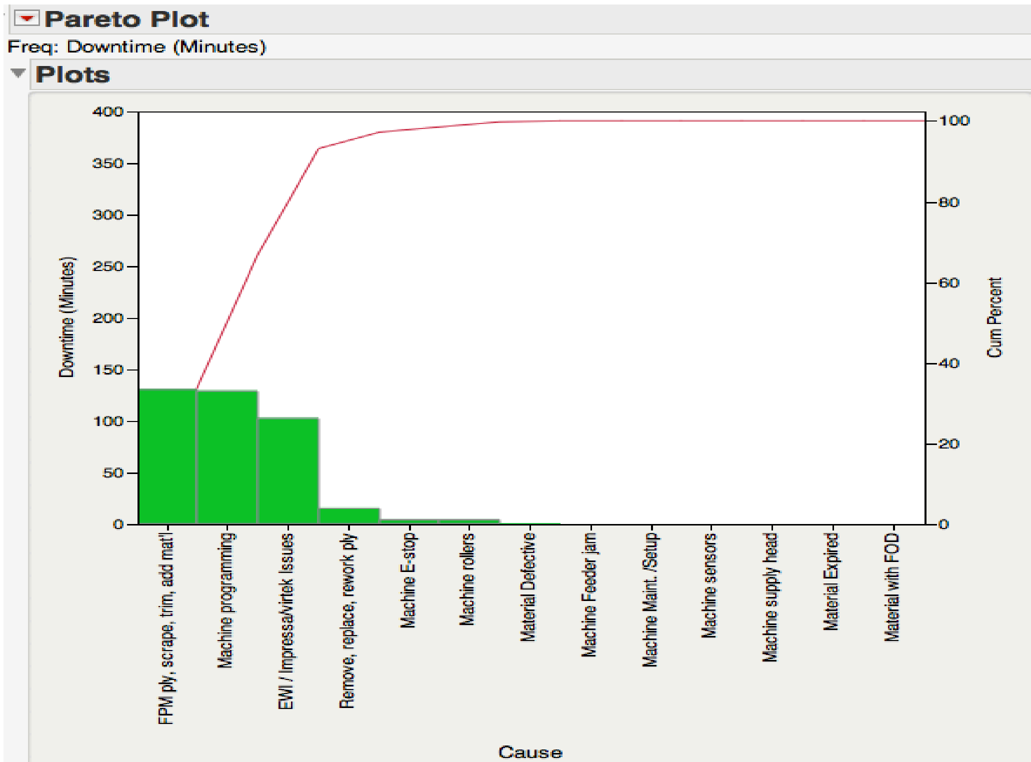


Figure 12 - Pareto of operator downtime

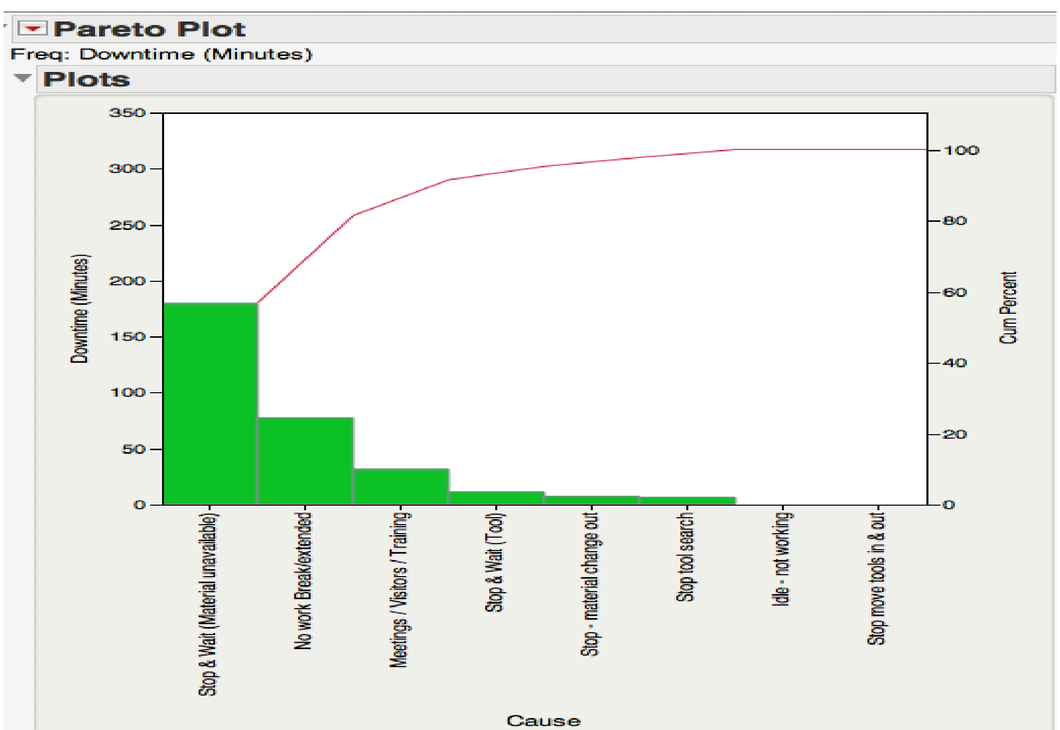


Table 9 - Time

	Date	7/24	7/24	7/25	7/25	7/30	7/31	7/31	7/31	8/1	8/1	8/2	8/2	8/2	8/2	8/2	8/2	8/3
	Parts	P30	P31	P32	P33	P34	P35	P36	P37	P38	P39	P40	P41	P42	P43	P44	P45	P46
		M	M	M	M	L	S	S	S	M	L	M	M	M	S	M	M	M
	Part Length (Mtr's):	**2.80**	**2.80**	**4.50**	**4.60**	**6.80**	**0.80**	**0.80**	**0.80**	**4.80**	**6.80**	**4.80**	**4.60**	**4.70**	**1.10**	**4.70**	**4.70**	**2.50**
	Ply Meters	**119.00**	**86.00**	**103.00**	**129.00**	**330.00**	**31.00**	**28.00**	**29.00**	**126.00**	**391.00**	**107.00**	**103.00**	**129.00**	**23.00**	**129.00**	**105.00**	**83.00**
	Number of Plies	**41**	**30**	**22**	**27**	**47**	**47**	**40**	**38**	**26**	**56**	**23**	**22**	**27**	**24**	**27**	**22**	**34**
	Number of Techs	**1.4**	**1.4**	**0.9**	**1.0**	**1.6**	**1.4**	**0.9**	**1.1**	**1.6**	**1.6**	**1.3**	**1.4**	**1.3**	**0.9**	**1.0**	**1.0**	**0.9**
Set-up	Retrieve tool	4.0	3.0	2.0	3.0	3.0	2.0	3.0	5.0	3.0	4.0	4.0	3.0	4.0	4.0	5.0	6.0	4.0
	Heat tool	5.0	6.0	7.0	12.0	11.0	7.0	11.0	7.0	6.0	20.0	8.0	18.0	12.0	8.0	15.0	6.0	8.0
Uptime	Load tool	4.0	2.0	0.0	2.0	2.0	1.0	1.0	1.0	1.0	3.0	3.0	1.0	1.0	0.0	2.0	1.0	1.0
	Unload	1.0	1.0	1.0	1.0	2.0	1.0	2.0	1.0	2.0	2.0	2.0	1.0	1.0	2.0	1.0	1.0	1.0
	Hand lay, form, remove poly	117.0	53.0	36.0	49.0	163.0	37.0	15.0	52.0	95.0	209.0	25.0	34.0	33.0	19.0	55.0	33.0	35.0
	Machine lay/form/compact plies	31.0	19.0	7.0	10.0	23.0	9.0	7.0	13.0	18.0	25.0	7.0	8.0	9.0	5.0	9.0	9.0	7.0
	EWI, Virtek, paperwork, buyoffs	3.0	4.0	3.0	8.0	0.0	4.0	1.0	5.0	0.0	5.0	3.0	4.0	4.0	3.0	7.0	3.0	0.0
	Downtime																	
Programming	EWI / Impressa/virtek Issues	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Machine programming	1.7	7.0	14.0	2.0	11.0	4.0	7.0	0.0	3.0	9.0	5.0	0.0	0.0	2.0	2.0	4.0	3.0
Machine	Machine E-stop	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Machine Feeder jam	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Machine supply head	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Machine rollers	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Machine sensors	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Machine Maint. /Setup	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Remove, replace, rework ply	1.0	0.0	0.0	0.0	6.0	0.0	3.0	0.0	4.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Material	Material Defective	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	FPM ply, scrape, trim, add mat'l	1.3	1.0	5.0	2.0	5.0	4.0	5.0	8.0	17.0	19.0	1.0	1.0	0.0	0.0	10.0	2.0	4.0
	Material with FOD	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Material Expired	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Stop & Wait	Stop tool search	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.0	0.0
	Stop & Wait (Tool)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.0	0.0	0.0	0.0
	Stop & Wait (Material unavailable)	0.0	0.0	8.0	9.0	2.0	4.0	5.0	8.0	6.0	24.0	4.0	5.0	4.0	4.0	6.0	6.0	0.0
	Stop - material change out	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Stop move tools in & out	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Admin	No work Break/extended	2.0	0.0	0.0	29.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	27.0	0.0	0.0	0.0	0.0	0.0
	Meetings / Visitors / Training	0.0	10.0	0.0	2.0	0.0	0.0	0.0	1.0	0.0	2.0	1.0	0.0	2.0	0.0	1.0	0.0	0.0
	Idle - not working	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

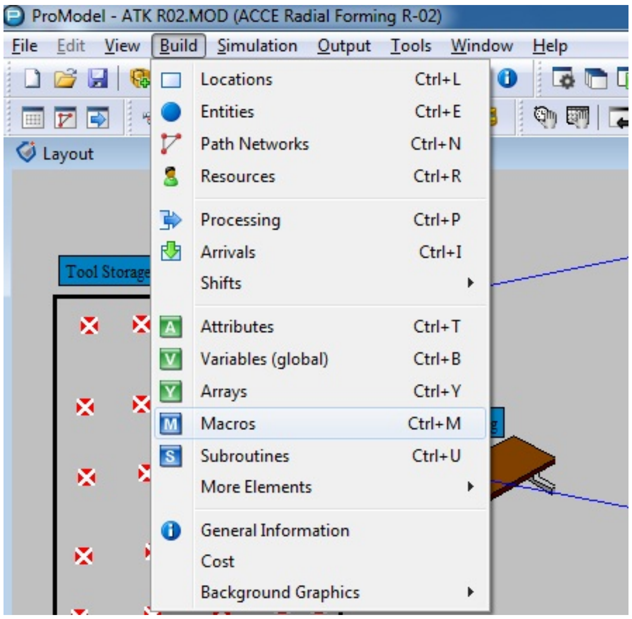
Table 9 - Raw data continued..

8/3	**8/3**	**8/6**	8/6	8/6	8/6	8/7	8/7	8/7	8/7	8/7	8/7	8/9
P47	**P48**	**P49**	P50	P51	P52	P53	P54	P55	P56	P57	P58	P59
L	**L**	**L**	**S**	**S**	**M**	**M**	**M**	**M**	**M**	**M**	**M**	**M**
5.50	**5.70**	**5.70**	**0.70**	**0.75**	**3.20**	**3.20**	**3.20**	**3.20**	**3.20**	**3.20**	**3.20**	**2.50**
134.00	**156.00**	**156.00**	**11.00**	**34.00**	**39.00**	**79.00**	**79.00**	**66.00**	**69.00**	**76.00**	**79.00**	**106.00**
24	**27**	**27**	**18**	**24**	**12**	**24**	**24**	**20**	**21**	**23**	**24**	**43**
1.4	**1.3**	**1.4**	**0.8**	**1.3**	**1.3**	**1.0**	**1.2**	**1.1**	**1.1**	**1.0**	**1.3**	**1.1**
4.0	5.0	4.0	3.0	3.0	3.0	3.0	3.0	4.0	2.0	4.0	4.0	4.0
19.0	14.0	20.0	2.0	3.0	5.0	8.0	6.0	8.0	7.0	9.0	8.0	5.0
2.0	2.0	1.0	2.0	2.0	2.0	1.0	2.0	2.0	1.0	1.0	2.0	2.0
1.0	1.0	1.0	1.0	1.0	1.0	2.0	1.0	2.0	1.0	1.0	1.0	1.0
46.0	51.0	80.0	23.0	52.0	51.0	50.0	38.0	30.0	41.0	58.0	42.0	100.0
14.0	18.0	16.0	6.0	10.0	7.0	7.0	7.0	7.0	5.0	10.0	8.0	16.0
2.0	2.0	1.0	4.0	3.0	6.0	3.0	2.0	7.0	2.0	1.0	0.0	3.0
15.0	0.0	0.0	0.0	88.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.0	7.0	5.0	4.0	3.0	8.0	5.0	3.0	7.0	0.0	7.0	4.0	0.0
0.0	3.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7.0	2.0	9.0	0.0	2.0	4.0	3.0	3.0	2.0	3.0	4.0	3.0	4.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
19.0	2.0	8.0	0.0	1.0	12.0	15.0	9.0	5.0	5.0	4.0	3.0	2.0
0.0	8.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	1.0	0.0	18.0
0.0	0.0	0.0	5.0	0.0	3.0	0.0	0.0	0.0	0.0	0.0	5.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

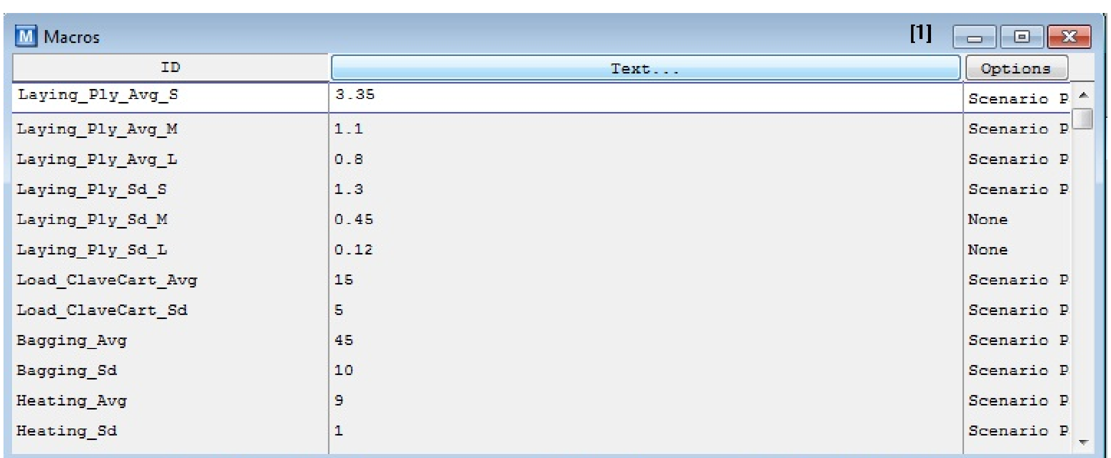
Appendix B

ProModel macros application allows the user to easily edit the core data that runs the simulated model of the system. The following steps indicate how to edit: means, standard deviations, and part size distribution.

Build →"M" Macros
(this will pop up a window to edit means and std. deviations of the lay up process)



The pop up window gives the current established mean times for laying a ply meter of a S, M, and L part. Simply edit the column on the right ("Text") to the corresponding mean or std. deviation with the desired value.


Macros [1]

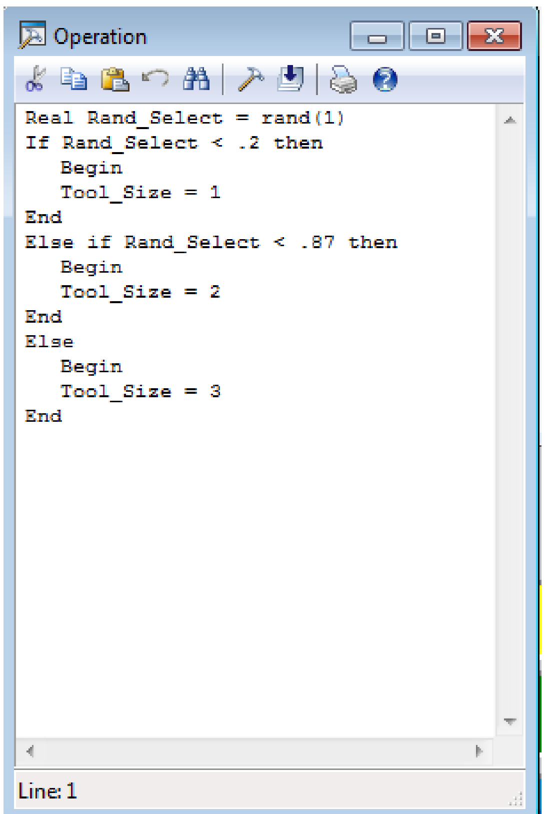
ID	Text...	Options
Laying_Ply_Avg_S	3.35	Scenario P
Laying_Ply_Avg_M	1.1	Scenario P
Laying_Ply_Avg_L	0.8	Scenario P
Laying_Ply_Sd_S	1.3	Scenario P
Laying_Ply_Sd_M	0.45	None
Laying_Ply_Sd_L	0.12	None
Load_ClaveCart_Avg	15	Scenario P
Load_ClaveCart_Sd	5	Scenario P
Bagging_Avg	45	Scenario P
Bagging_Sd	10	Scenario P
Heating_Avg	9	Scenario P
Heating_Sd	1	Scenario P

To edit the part size distribution from the current one, the user must pull up the processing window (also under: Build → Processing) and open up the operation window where the type of tool is defined:

“S” Small parts are defined as: Tool_Size = 1 (currently 20%)

“M” Medium parts are defined as: Tool_Size = 2 (currently 67%)

“L” Large parts are defined as: Tool_Size = 3 (currently 13%)



Bibliography

Avila, Antonio F., and David T.S. Morais. "A Multiscale Investigation Based on Variance Analysis for Hand Lay-up Composite Manufacturing." *Composites Science and Technology* 65.6 (2005): 827-38. *Www.sciencedirect.com*. 21 Jan. 2005. Web. 31 Oct. 2012.

Baker, Alan, Stuart Dutton, and Donald W. Kelly. *Composite Materials for Aircraft Structures*. Reston: American Institute of Aeronautics and Astronautics, 2004. Print.

Chance, Frank, Jennifer Robinson, and John Fowler. "Supporting Manufacturing with Simulation: Model Design, Development, and Deployment." *FabTime*. N.p., n.d. Web. 13 Nov. 2012. <www.fabtime.com/files/WSC96.pdf>.

Chung, Deborah DL. *Composite materials*. John Wiley & Sons, Inc., 2004.

Degenhardt, R., R. Rolfes, R. Zimmermann, and K. Rohwer. "COCOMAT—improved Material Exploitation of Composite Airframe Structures by Accurate Simulation of Postbuckling and Collapse." *Composite Structures* 73.2 (2006): 175-78. Print.

Deng, S., and Tsung-Han Yeh. "Using Least Squares Support Vector Machines for the Airframe Structures Manufacturing Cost Estimation." *International Journal of Production Economics* (2011): n. pag. *Science Direct*. Web. 1 Nov. 2012. <http://http://www.sciencedirect.com/science/article/pii/S0925527311000776>.

Eriksson, S. (2011) 'Globalisation and changes of aircraft manufacturing production supply-chains – the case of China', *Int. J. Logistics Economics andGlobalisation,* Vol. 3, No. 1, pp.70–83.

Federal Aviation Administration (FAA). "Aviation and Emissions a Primer." N.p., Jan. 2005. Web. Jan.-Feb. 2013. <http://www.faa.gov/regulations_policies/policy_guidance/envir_policy/media/aeprimer.pdf>.

Fowler, J. W. "Grand Challenges in Modeling and Simulation of Complex Manufacturing Systems." *Simulation* 80.9 (2004): 469-76. Web. 12 Nov. 2012. <http://www.thesimguy.com/GC/papers/scsgc-02.pdf>.

Gibson, Ronald F. *Principles of Composite Material Mechanics*. Boca Raton, FL: Taylor & Francis, 1994. 2012. Print.

Law, Averill M., and Michael G. McComas. "Simulation Modeling and Analysis 3rd Ed.

Averill Law and David Kelton, Authors © 2000 McGraw-Hill, 752 Pp." *Journal of Manufacturing Systems* 18.5 (1999): 382. Print.

Lee, Josung J. *Historical and Future Trends in Aircraft Performance, Cost, and Emissions*. N.p., Sept. 2000. Web. Jan. 2013. <http://www.southampton.ac.uk/~jps7/D8%20website/future%20trends%20in%20aircraft%20costs.pdf>.

Park, C. "Simultaneous Optimization of Composite Structures considering Mechanical Performance and Manufacturing Cost." *Composite Structures* 65.1 (2004): 117-27. Print.

Peck, Steven J. "Streamlining Automated Processes for Composite Airframe Manufacturing." N.p., June 2010. Web. 1 Nov. 2012. <http://http://www.vistagy.com/downloads/vsg_article_jec_feature.pdf>

Sanders, Daniel G. "The Current State-of-the-Art and the Future in Airframe Manufacturing Using Superplastic Forming Technologies." *Materials Science Forum* 357-359 (2001): 17-22. Print.

Sargent, Robert G. "Verification and Validation of Simulation." *Proceedings of the 2005 Winter Simulation Conference* (2005): <http://delivery.acm.org/10.1145/1170000/1162736/p130-sargent.pdf?ip=129.65.243.248&acc=ACTIVE%20SERVICE&CFID=140975305&CFTOKEN=96426356&__acm__=1352780498_eb07e6656b7765c4715ea430b9c1140c>

Umeda, Shigeki. "Validation and Verification of Simulation Models." *Validation and Verification of Simulation Models*. N.p., n.d. Web. 12 Nov. 2012. <http://dl.acm.org/citation.cfm?id=167311>.

Vinson, Jack R., and R. L. Sierakowski. *The Behavior of Structures Composed of Composite Materials*. Dordrecht [etc.: Springer, 2002. Print.