Model-Based Systems Engineering
for Composite Wing Production

Leon F. McGinnis
Professor Emeritus
School of Industrial and Systems Engineering
The Georgia Institute of Technology

August 20, 2018

Rev 02

Acknowledgements: This case is based on research conducted in the W. M. Keck Virtual Factory Lab at Georgia Tech and supported by the National Institutes of Science and Technology and by the Boeing Corporation. It has benefited from the participation of many individual researchers, particularly Dr. Tim Sprock, Dr. George Thiers, Dr. Doug Bodner, Dr. Russell Peak and Mr. Selcuk Cimtalay.

Table of Contents

Forward ii

Introduction 1

Composite Wing Product 1

Composite Wing Production Processes 3

Composite Wing Production Resources 5

  Composite Wing Fabrication Resources 5

    Layup 5

    Cure 6

    NDI 6

    Trim 7

    Paint and Seal 7

  Composite Wing Assembly and Material Handling Resources 8

  Manufacturing Resource Summary 9

Production System ConOps 10

Modeling Objectives and Scope **Error! Bookmark not defined.**

MBSE Method and Tools **Error! Bookmark not defined.**

Model Organization and Conventions **Error! Bookmark not defined.**

Mission and Stakeholder Needs **Error! Bookmark not defined.**

  Stakeholder Concerns **Error! Bookmark not defined.**

Production System Control **Error! Bookmark not defined.**

Conclusion **Error! Bookmark not defined.**

Notes **Error! Bookmark not defined.**

Forward

Model-Based Systems Engineering (MBSE) is a relatively new phenomenon that is transforming the way complex technical systems are designed. NASA JPL has been a leader in advancing MBSE through its application to the design of deep space missions, and today MBSE is becoming standard practice within DoD, as well as many major corporations, such as Boeing and Lockheed. The deployment of MBSE reduces the ambiguity that plagues document-based systems engineering, enables the integration and automation of a broad range of system analyses, and makes possible much more frequent critical review of system design and development decisions. It is making systems design and development faster, better and cheaper.

With the advent of Industrie 4.0, “the smart factory”, and “the internet of things”, production systems are becoming much more technical and complex. There is every reason to believe that the benefits of applying MBSE to space missions and aircraft programs also can be realized in applying it to the design and development of production systems.

This case study is one of a series intended to illustrate and promote the application of MBSE to production systems. The presentation of the case uses the semantics of discrete event logistics systems (DELS) developed over the course of several sponsored research projects performed in the W. M. Keck Virtual Factory Lab, beginning in 2007 and continuing today.

The work reflected in this case owes a large debt of gratitude to MBSE thought leaders, particularly Sandy Friedenthal, formerly of Lockheed, and the author of a leading textbook on the OMG Systems Modeling Language™ or SysML, and Dr. Chris Paredis, currently BMW Chair in Systems Integration at Clemson University. Any errors and/or omissions in this document are completely the responsibility of the author. Comments or questions may be directed to leon.mcginnis@gmail.com.

Composite Wing Production System (CWPS) Description

Introduction

Modern passenger airplane manufacturers are moving to composite materials for new airplane designs because of their lighter weight and corresponding reduction in fuel consumption, relative to traditional metal structures and skins. Conceptually, wings whose structural components are composite appear very similar to the older metal wings, but the production process is almost completely different.

A composite wing production system must fabricate all the major structural wing components from composite fiber material, often using part specific forms, or mandrels. These large but light weight, and somewhat fragile parts must be moved through the factory and various assembly and testing processes. Almost no process involved in producing these wings is like its counterpart for traditional metal wings.

This case study explores composite wing production for a large passenger airplane with wings that may reach to a length of 70 to 90 feet or more. All aspects of this case are hypothetical, and all the information presented has been taken from open sources.

Composite Wing Product

The aircraft wing has four key part types as illustrated below: the spars, ribs, and stringers, which provide the internal structure for the wing, and the skin, which provides the surface of the wing. In the discussion below, additional part types, such as posts, stiffeners, fittings, etc, are not included, in order to keep the discussion relatively easy to follow. Each part or assembly is the *product* of some production process.

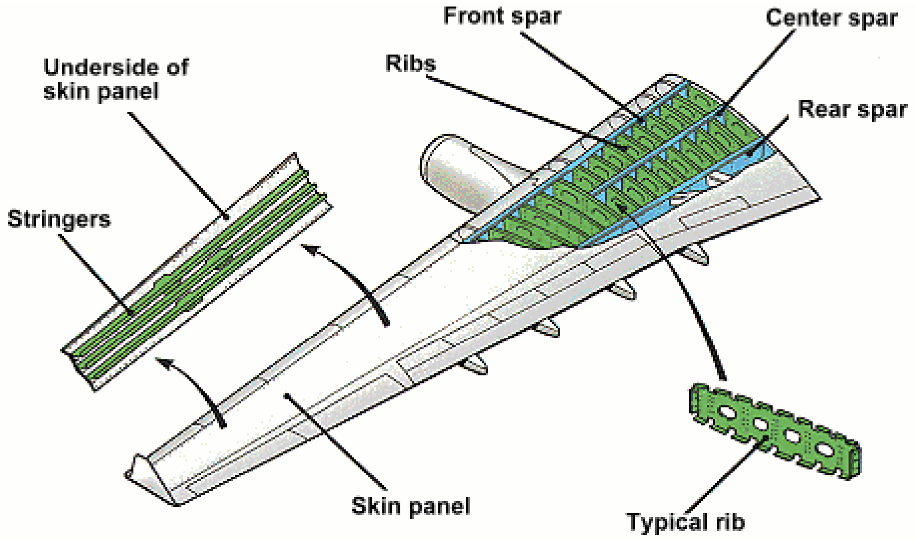

Figure 1 Wing Assembly

Source: http://www.qureshiuniversity.com/aircraftstructure.html

For our hypothetical pair of composite wings (port and starboard), suppose that on each side, there are three different spar types S1, S2, and S3, ten different rib types, R1 through R10, 15 stringer types, St1 through St15, and a single upper and lower skin, SU and SL. The engineering bill of materials (eBOM) for one wing (either port or starboard) might look something like the one shown in Figure 2 below.

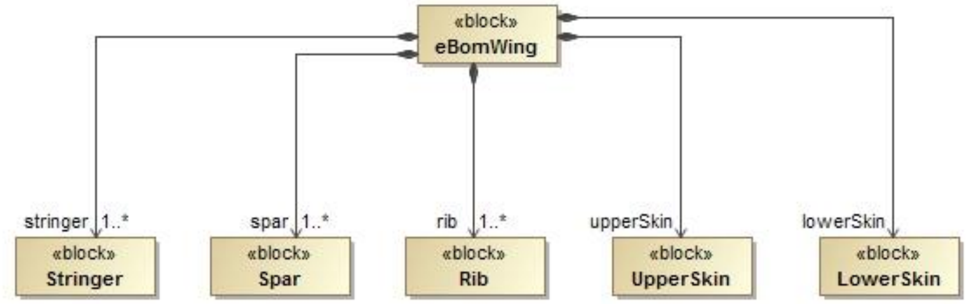

Figure 2 Engineering Bill of Materials

In this highly simplified eBOM, the Stringer, Spar and Rib blocks actually represent three different spar types, ten different rib types, and fifteen types of stringers. Because there are two distinct wings—port and starboard—the number of parts is doubled.

The eBOM describes the wing assembly as designed, but a different view is need for manufacturing. A manufacturing bill of materials (mBOM) will reflect the strategy for actually producing the wing parts and assembling them. If we assume the parts are produced in a single manufacturing step or process, then the mBOM might look like the one shown in Figure 3 below. This mBOM reflects a manufacturing plan where the spars and ribs are first assembled into a "ladder", the stringers are attached to the skins, the lower skin (with stringers) is assembled with the ladder to form a "lower wing assembly", and finally the upper skin (with stringers) is attached to the lower wing assembly to form the completed wing assembly.

This mBOM implies a hierarchy of fabrication ("fab") and assembly processes. The intermediate assemblies in this case are the two skins with stringers, the ladder, and the lower wing assembly. These assemblies are "products" in the sense that they are the result of a distinct production process, and then become input to some subsequent production process. Note that this is not necessarily the only feasible strategy for producing the wing—other subassemblies might be defined. For example, the lower skins might be fabricated in several parts and then assembled with the ladder and the upper skins might be fabricated in several parts for joining with the lower wing assembly.

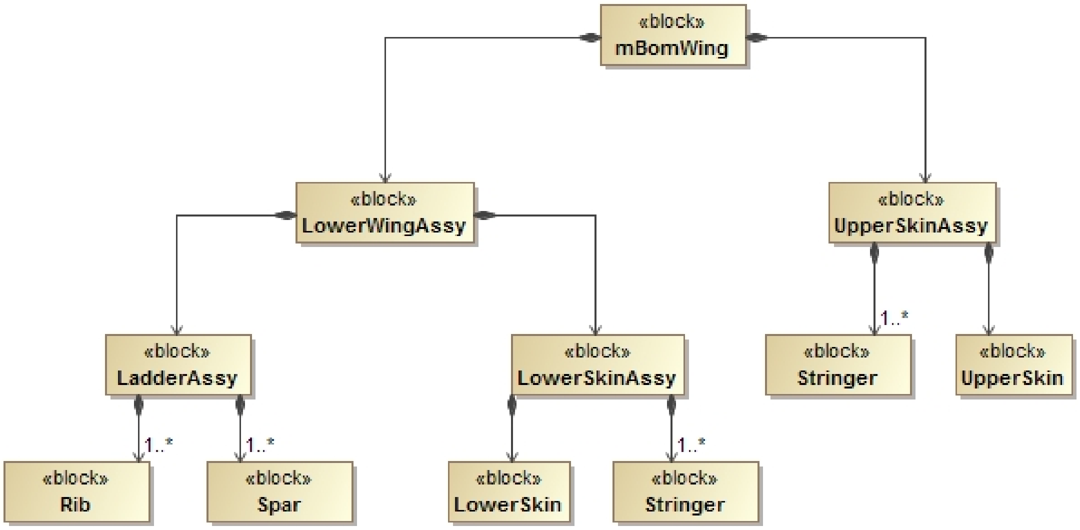

Figure 3 Manufacturing Bill of Materials

Composite Wing Production Processes

It's important to identify the wing production process steps, because eventually they must be assigned to specific manufacturing resources that are organized into workstations or cells. Figure 4 illustrates the set of manufacturing activities necessary to produce the wing as described in the mBOM of Figure 3. Note the two different kinds of activities—fabrication and assembly.

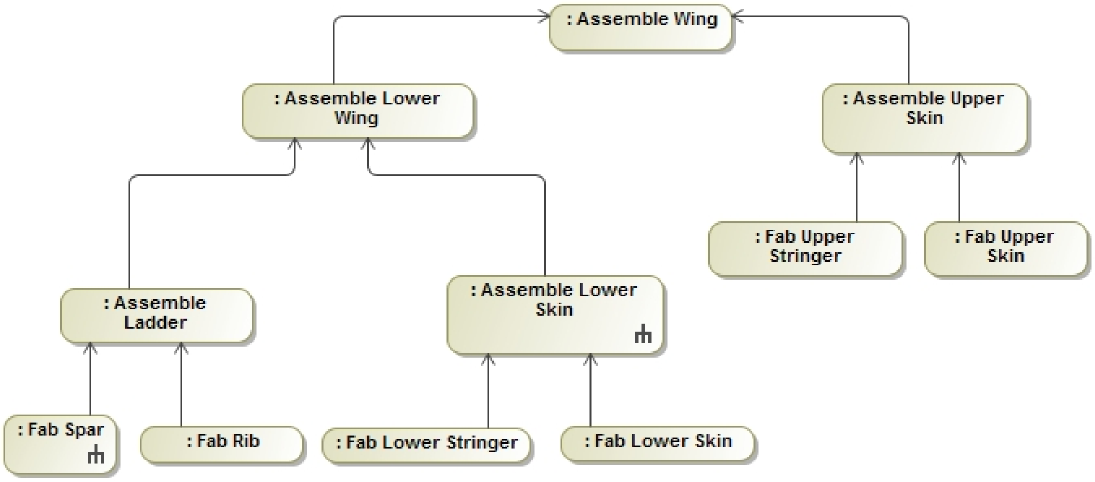

Figure 4 Wing Production Processes

Each of the processes in Figure 4 might be further decomposed into a sequence of process steps. For example, the process "Fab Spar" might be decomposed into the process steps shown in Figure 5. The "rake" symbol in the Fab Spar process of Figure 4 indicates that there is a view of the process that reveals more detail, in this case the view shown in Figure 5.

Figure 6 Spar Fabrication Processes

Similarly, the individual assembly processes can be further decomposed. As an example, the assembly of the lower skin and stringers would require the steps shown in Figure 6. Again, the rake symbol on Assemble Lower Skin in Figure 4 indicates there is a more detailed view, which is shown in Figure 6.

Figure 5 Lower Skin Assembly Process

It also is important to reiterate that all these figures are actually a very simplified view of the production process. It is not a single spar part and rib part coming into the Assemble Ladder process; rather there are three different spar parts and ten different rib parts. Also, there is a specific process plan and specific manufacturing instructions defined for each of the different parts of each part type. So in total, we would have:

- 3 spar fab processes
- 10 rib fab processes
- 15 stringer fab processes
- Upper skin fab process
- Lower skin fab process

or a total of 28 fabrication process plans for each of two wings. Altogether, we have approximately 114 individual fabrication processes, assuming each part type has roughly six individual process steps. Also, we have the five assembly processes, with all of their sub-processes. The number of individual process specifications could easily reach to 150 or more, for each wing in the two-wing ship set.

Trying to visualize all of these processes at one time probably would not be very effective, because of the number of individual processes and flows between processes. It is probably more effective to use aggregated process models, with disaggregated views as necessary, as illustrated in Figures 4-6.

Within this collection of 56 unique part types, there are some important characteristics. The skins will have a specific shape, so they must be fabricated on a part-type-specific mandrel. The same is true for the spars, the ribs, and some of the stringers. Some stringers will have a “hat” shape, which requires layup on a part-type-specific form. Other stringers have a “blade” shape, and layup can be performed on a flat table. Stringer may vary from 10 feet or less to as much as the full length of the wing—up to 80 feet or more for a modern airliner.

Spars will generally be as long as the wing. Depending on the design, some spars actually may be fabricated in two or three sections, which then are assembled to form the complete spar.

At this point, we have only a high-level description of the part types and process types involved in producing the wing. In order to describe the production system for producing the wing, we need some additional information.

Composite Wing Production Resources

There are three primary categories of production resources for the CWPS: fabrication resources which transform composite fiber from its tape form to the final part form; assembly resources which enable individual parts to be joined to form the wing assemblies; and material handling resources which support both fabrication and assembly.

Composite Wing Fabrication Resources

The design of the CWPS requires identifying the specific manufacturing resources to be used, how much of each resource is needed, and how those resources are organized in the CWPS facility. Consider the fabrication processes first. What has been identified for fabrication processes are:

- Layup: composite material, usually in sheet or roll form, is arranged in layers on a form, or mandrel, according to detailed specifications as to length, orientation, number of layers, etc. for each specific part type
- Cure: the "green" part is placed in a vacuum bag and transferred to an autoclave where a specific temperature and pressure profile causes the composite layers to bond and harden
- NDI (non-destructive inspection): the cured part is inspected to insure that there are no flaws, such as delamination, bond failure, etc.
- Trim: the part is trimmed to remove any excess material at edges
- Paint: the part is painted
- Seal: the painted part is given a sealer coating

Specific production resources will have to be identified to execute each of the required processes.

Layup

There are automated machines capable of the layup process, as illustrated in Figure 7 below. These *advanced fiber placement*, or AFP machines lay down narrow strips of composite fabric, .25 to .5 inches in width, and can dispense fiber from multiple reels, or *tows,* simultaneously. These kinds of processes are very effective for large composite parts, but have some limitations with regard to size (small parts) or shapes (internal corners, e.g.). Thus, some composite parts fabrication may require using manual layup, and operators with appropriate training, tools, and workspace. In general, different layup technologies are characterized in terms of "pounds per minute" of material, and feature-based limitations.

Figure 7 Automated Lamination Machine
https://www.glassdoor.com/Photos/Aurora-Flight-Sciences-Office-Photos-IMG971891.htm

Cure

The curing process requires an autoclave, and in production, sufficient autoclave capacity will be require to accommodate both the sizes of fabricated components and the rates at which components must be cured. For a large-scale production system, such as might be needed for producing long haul passenger aircraft wings, autoclaves might be custom designed, and determining the mix of autoclave sizes could be a major investment decision. Figure 8 illustrates an autoclave being manually loaded with parts. In general, the autoclave capacity is stated in terms of effective volume, based on the set of parts to be cured.

Figure 8 Manually Loading Autoclave

https://www.ainonline.com/aviation-news/aerospace/2014-02-10/boeing-and-airbus-partnerships-proliferate-asia

NDI

There are a variety of technologies for NDI, and some are available for automated inspection of large parts, as illustrated in Figure 9. Small parts or specific area inspections of larger parts might be accomplished with manually operated inspection tools. The capacity of an NDI technology would

Figure 9 Large Area NDI Automation

https://pinetteemidecau.eu/en/testing/ndt-ndi-systems generally be stated in terms of an area-based rate, e.g., meter^2/minute. For smaller parts, the inspection time might be based on features other than area.

Trim

For large composite parts, the trim process may be automated, as illustrated in Figure 10. However, for small parts or parts with complex geometries, manual trimming may be required, using appropriate hand tools. The rate at which a particular technology can perform the trip process is driven by part features, such as total edge length plus other features, such as holes.

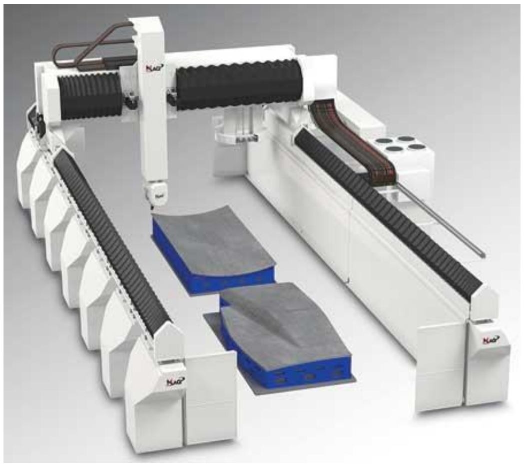

Figure 10 Automated Trim Cell

http://www.mfgnewsweb.com/archives/4/37203/General-oct12/New-5-Axis-MillTrim-Gantry-for-Large-Parts.aspx

Paint and Seal

Painting and sealing of composite wing parts typically will involve applying the paint or sealer materials with a spray. As with other processes, there may be automated resources appropriate for large parts and/or simple geometries as illustrated in Figure 11. However, some manual resources may be more effective for small parts or parts with intricate geometries. For a given technology, the rate capacity for painting or sealing will generally be expressed in area/time, although for some parts, features may also may contribute to process time.

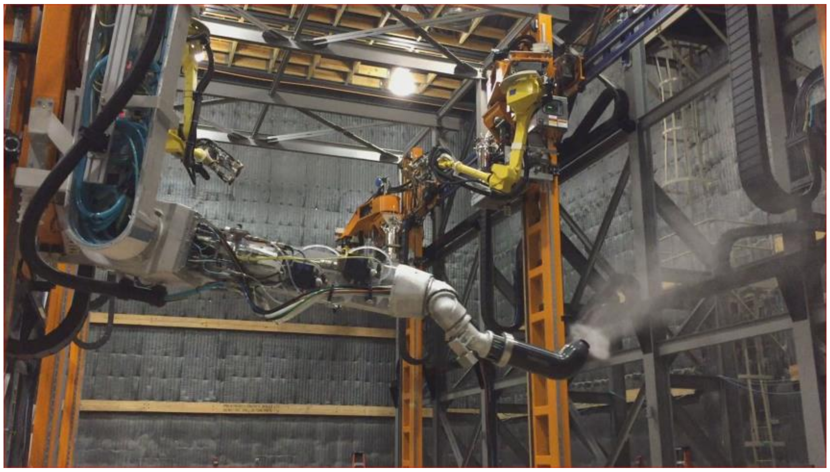

Figure 11 Large Component Painting Automation

http://www.encoreautomation.com/aerospace/aerospace-painting/

Composite Wing Assembly and Material Handling Resources

Many traditional assembly processes can be automated, such as hole drilling for fasteners, laying down beads of bonding or sealing material, etc. But because aircraft wings are such large objects, perhaps the most important aspects of assembly automation is automated material handling and positioning. Figure 12 illustrates the use of robots to position large parts for automated assembly.

Figure 12 Robotic Parts Positioning for Assembly

https://www.usatoday.com/story/todayinthesky/2015/06/02/boeing-says-wing-production-has-started-for-737-max-jets/28372587/

One goal in producing composite wings is to make the parts as large as possible in order to reduce the number of parts. This creates some challenges in moving the parts between manufacturing processes. Automated, or partially automated material handling is essential. Part movement may take place on the floor, using ground-based vehicles, or overhead, using cranes. Figure 13 shows a part being moved on the ground, while held in a fixture to facilitate transfer between workstations. Figure 14 shows parts being moved via overhead cranes.

Figure 13 Part Movement with Fixture

http://advancedmanufacturing.org/picking-pace-aerospace-production/

Figure 14 Part Movement via Overhead Crane
http://www.oobject.com/category/aircraft-factories/

In both figures 13 and 14, part-specific tooling is required to support the assemblies during movement.

Another significant issue is the storage of these large parts between production operations. If wing production operations cannot be perfectly synchronized, some temporary accumulation of parts may be necessary between operations. For example, the assembly of a wing skin and its stringers requires that all the parts be available. The fabrication of stringers may only be done in a single workstation, so if, say, a lower wing assembly requires four stringers, then a batch of four (possibly different) stringers must be accumulated prior to the assembly operation. Similarly, an autoclave will hold a batch of parts, which must be accumulated prior to starting the autoclave cycle.

Manufacturing Resource Summary

This presentation has illustrated only some of the possible manufacturing resources required in producing composite wings; a full exposition is not the intent. What should be clear is that in making the transition from the eBOM to the mBOM to the specification of the production system, specific manufacturing resources must be identified that have the inherent capabilities to perform all the manufacturing processes implied in the mBOM. It is rather challenging, in a time of rapid technological development, to be able to conceptualize and identify the manufacturing resources that might be best suited for a particular productions system, based on the details of the parts to be produced and the rates at which they will be produced. This kind of decision-making requires both experience and the ability to rapidly assess alternatives.

Production System ConOps

The composite wing production system is going to produce many wings over a significant period of time. A fundamental question in designing a production system like this is "What is the batch size for each production operation?" Is the concept of operation to produce complete "ship sets"—a kind of make-to-order approach—or are some parts or subassemblies produced in batches—a kind of make-to-stock approach? In what follows, we are assuming that the concept of operations is to produce complete ship sets, one at a time, through the entire production process. However, the option of batch production for some parts, such as stringers, should be investigated.

Producing complete ship sets does not imply there are no production batches. As pointed out above, batches of different parts—batches of ribs, batches of stringers, batches of spars—will be accumulated in front of the lower wing assembly process. Similarly, batches of parts will be accumulated in front of the autoclave.

Another aspect of production conops is how parts are assigned to specific wing sets. For example, a stringer might be fabricated according to a forecasted consumption rate, but only assigned to a specific wing when that wing is released to production.

It also is possible that batches of similar but slightly different stringers might be produced in a single setup of a layup table, in order to better utilize the table area.

With this concept of operations, an important consideration is the response to an inspection failure. Does an entire assembly wait in place for a repair or a new part to be fabricated?

System Summary

The Composite Wing Production System uses a variety of very specialized resources to transform bulk composite materials into wing sets ready to assemble to a fuselage. It is a critical element in the overall aircraft production system, and must perform to exacting technical standards and to a synchronized aircraft production schedule. Performance of the CWPS depends upon both the capacity of the resources in the CWPS and the control system that manages these resources. Making significant changes to either once the CWPS is in production will lead to significant unplanned costs and to disruptions in the aircraft production schedule. Thus, it is critical that the CWPS be specified in detail, and that its performance be estimated accurately before production starts.