Relational geometry in surface-driven modeling

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Abstract

Relational modeling technologies are crucial in the control of complex surface-driven models in the aviation industry. There has not been exploration of relational design using the 3D modeling package Siemens NX5. For this project, two accurate models of an airframe from a historic aircraft were created using different techniques that both utilized relational modeling. These two methods were datum-based and sketch-based modeling approaches, and the models were qualitatively evaluated against each other with respect to a major aircraft manufacturer's standards for computer modeling. In the Computer Graphics Technology curriculum at Purdue University, relational design techniques are based on the datum method, utilizing work planes in a skeleton structure to control the shape and position of components in an assembly. In contrast, the sketch-based method uses a single drawing file to control placement of components in an assembly using geometric primitives. The sketch method is a more modern process than the datum method, but both methods provide functional results. Advantages and disadvantages to each technique became apparent during testing; however, both methods offer the ability to maintain design intent and minimize rework due to relational modeling. The testing revealed that the datum method had a smaller total and per part file size, despite containing a greater number of parts. However, the sketch method was a more simple process to work with and featured significantly less parts, but took longer to load the model. The fact that both methods are used in industry make it a valuable tool for any design engineering student to learn, and integrating both methods into an engineering student's education can only enhance comprehension of modeling techniques. Also, adjusting curricula to meet the demands of industry adds value to graduates entering the workforce. This paper examines the background and application of relational modeling technology in the aerospace industry, reviews the research involved in this study, and discusses the results and potential applications for the future.

Introduction

Relational geometry is an essential part of the complex modeling strategies preferred in the aerospace industry today (Farcy, 2010). By creating relations between model structures, companies can improve the efficiency of the design process, and decrease errors caused during model revisions (Ma & Tong, 2003).

Currently, The Boeing Company designs aircraft from the outside in; meaning that aerodynamic surfaces are used to define the interior structures of the aircraft. However, these shells are often subject to change, and can vary drastically over the course of the design process due to engineering specifications, testing, and performance characteristics. Relational design plays a crucial role by allowing the design process to continue while the specific aerodynamic profile of the aircraft is finalized (Farcy & Siebenaler, 2010).

Case studies in the application of relational design by Barrett (2007) and Ma and Tong (2003) illustrated how effective associative geometry can be in change management. They both examine applications that allow simplified geometry to control more complex features. Hoffman and Joan-Arinyo (1998) examined this concept in the scope of geometric dimensioning & tolerancing (GD&T). GD&T is dependent on positioning and can generate errors when geometry is updated. This problem illustrates the need to be conscious of design intent to control change management. Vickers (n.d.) discussed structuring products using top-down strategies, which utilize the nesting of assemblies. This allows for the core structure to exist without having individual parts negatively affect the stability of the master structure.

The purpose of this research was to compare different methods of using relational geometry, in accordance with current Boeing modeling procedures for aircraft design. The application of the research was to begin development of a digital B-17F aircraft in Siemens NX5. The airframe models provided a test case for applying current modeling procedures in relational geometry. The research tested two methods, datum-based and sketch-based modeling approaches. In a top-down modeling strategy, datum-based modeling controls features with a series of work planes and mold lines that act as a functional backbone for the derived geometry (Huang, Tang, & Tang, 1999). This is the method currently employed by the commercial arm of the Boeing Corporation. Sketch-based modeling uses a single drawing that uses links to control the relationships between model features, and the primitive design elements contained in the drawing (Delph & Macri, 2010). This approach, using nested sketches, is currently in use in the defense sector of Boeing.

Historical information about the B-17 aircraft was gathered from three primary sources. The first source was legacy documentation from Boeing Corporation, consisting of the original drawings in the form of digital image files, and a copy of an original field service manual (BoeingAircraft Company, 1945). The field service manual contained specifications for critical structural placements, as well as, information pertaining to assembly. Additionally, measurements were taken of existing B-17 airframes. Information was also received during interviews with computer modeling experts at Boeing.

Modeling

Datum-based method.

Datum-based modeling is representative of commercial aircraft design at Boeing. For this research, a procedure was developed to mimic Boeing modeling processes in the Siemens NX5 software. Several sample models were created to test particular functions, as well as the relationships that are constructed when linking parts geometrically (see Figure 1). This test case illustrated a rib interacting with a support structure and a surface, similar to what would be seen in the final construction procedures. The geometry was attached to datum planes, and exposed to a series of adjustments to ensure that all components would update properly.

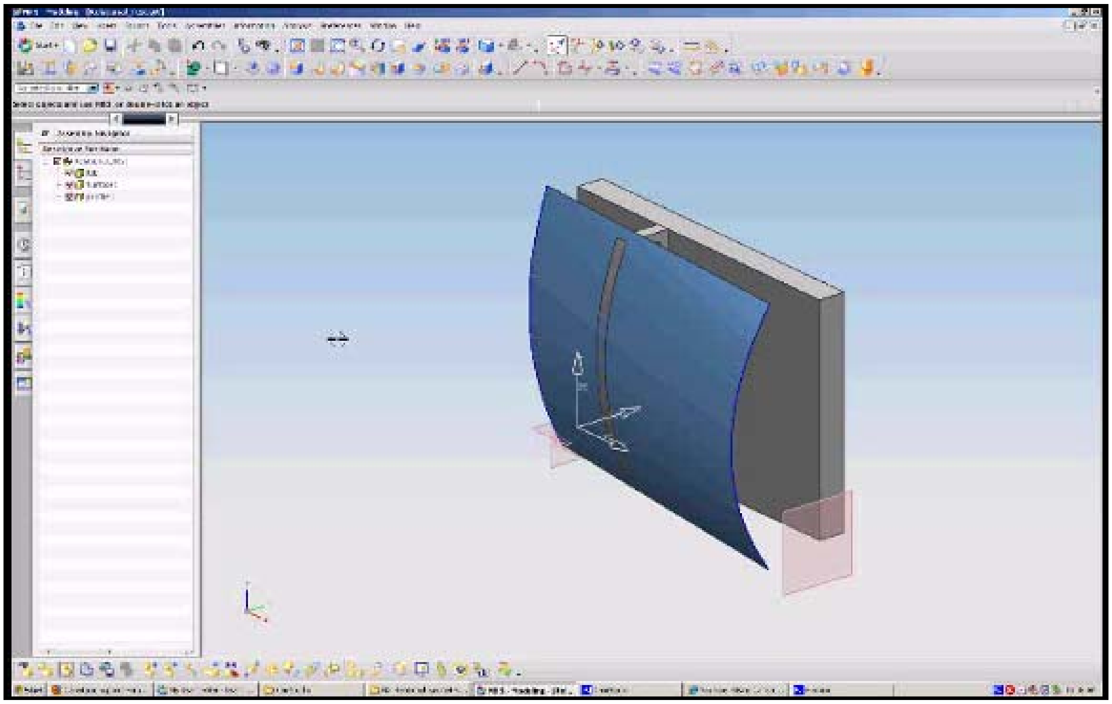

Figure 1. Datum-based test case

Once the test model was validated, work on the skeleton began based on the original manufacturing plans for the B-17. In the datum-based modeling strategy, Boeing uses a series of work planes to align key components such as ribs, stringers, and spars in a master assembly file (see Figure 2). The skeleton document is known as a Master Datum File (MDF).

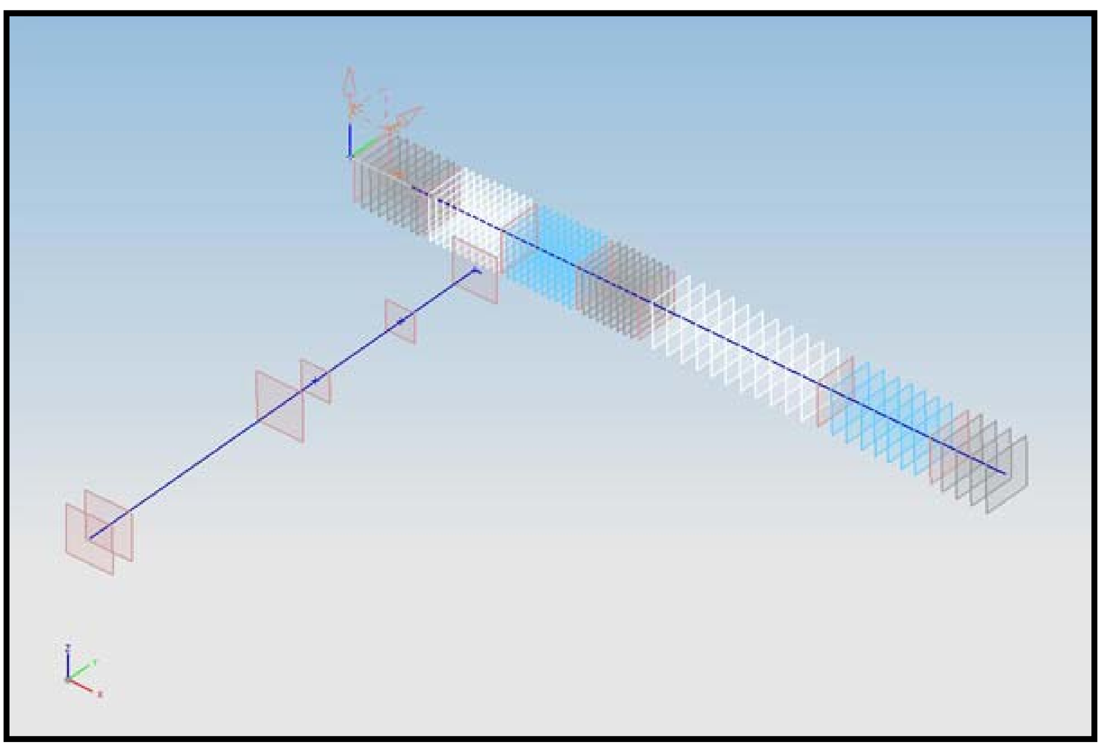

Figure 2. Datum planes in master datum file

The datums were used to isolate parts and features in order to control change management and reduce each component's impact on the entire assembly. Once the MDF was finalized work began on generating the shell of the aircraft. The working surface is known as a Master Datum Surface (MDS). The MDS is driven by the aerodynamics of the plane; therefore this surface is crucial to defining the structure of airframe models (see Figure 3). An exact recreation of the skin was not required initially because of the relational nature of this design.

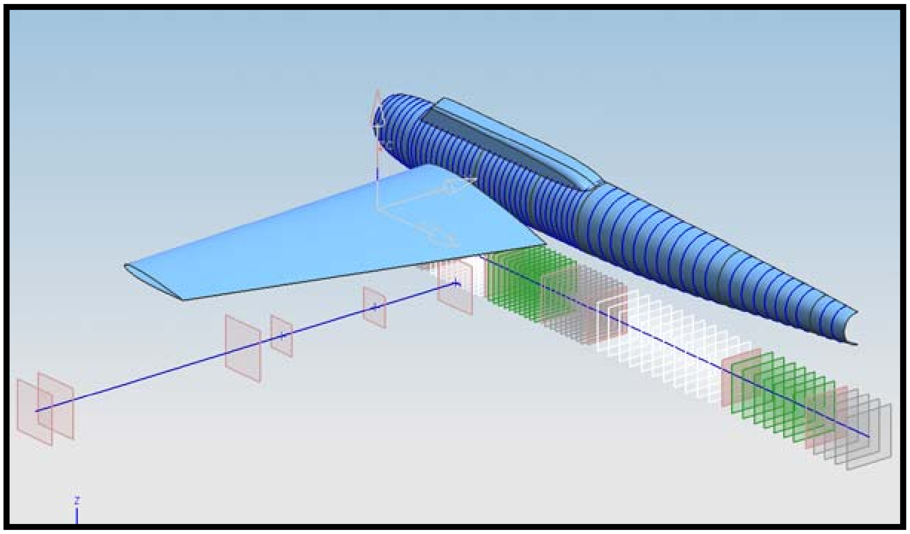

Figure 3. Master datum surface

After the MDS was completed to a rough size and shape, work on the airframe began. The key to modern aviation design, in this strategy, is relational geometry (Farcy, 2010a). The ribs were generated dynamically depending on the contour of the shell and the positioning of the skeletal planes along the fuselage (see Figure 4).

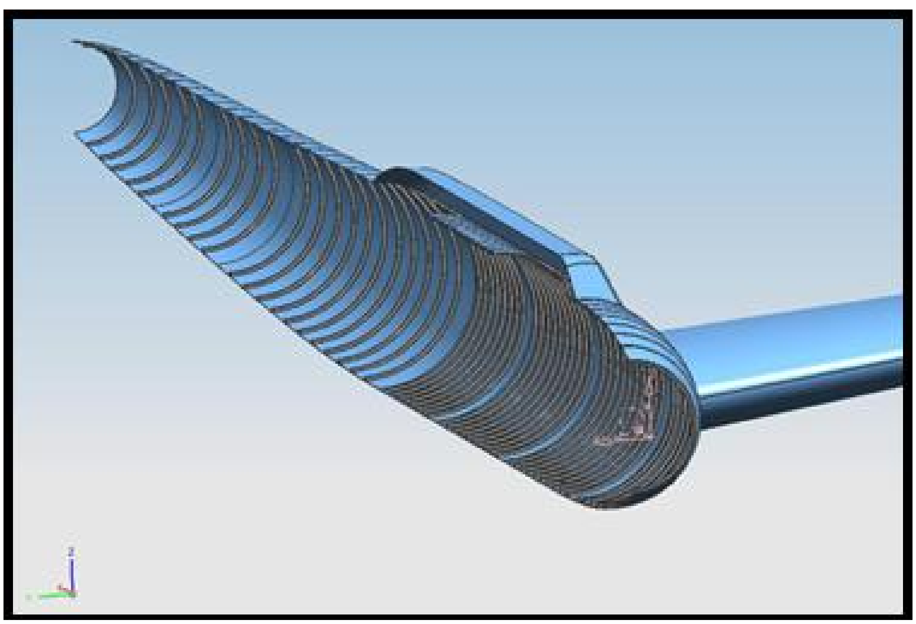

Figure 4. Datum-based airframe model

Each rib was created as a separate instance of a fully linked version. Thus using position independent copying allowed for a single rib design to be propagated down the length of the fuselage. Since existing links were maintained between the MDS and each part, new ribs only needed to be positioned based on a datum and the center axis of the fuselage.

Sketch-based method.

Sketch-based modeling is the preferred method of the defense arm of Boeing production. This strategy relies on 2D drawings that are known as Digital Design Files (DDF). Documents are linked to the DDF using the WAVE geometry linker, and parts are connected at the primitive level (see Figure 5).

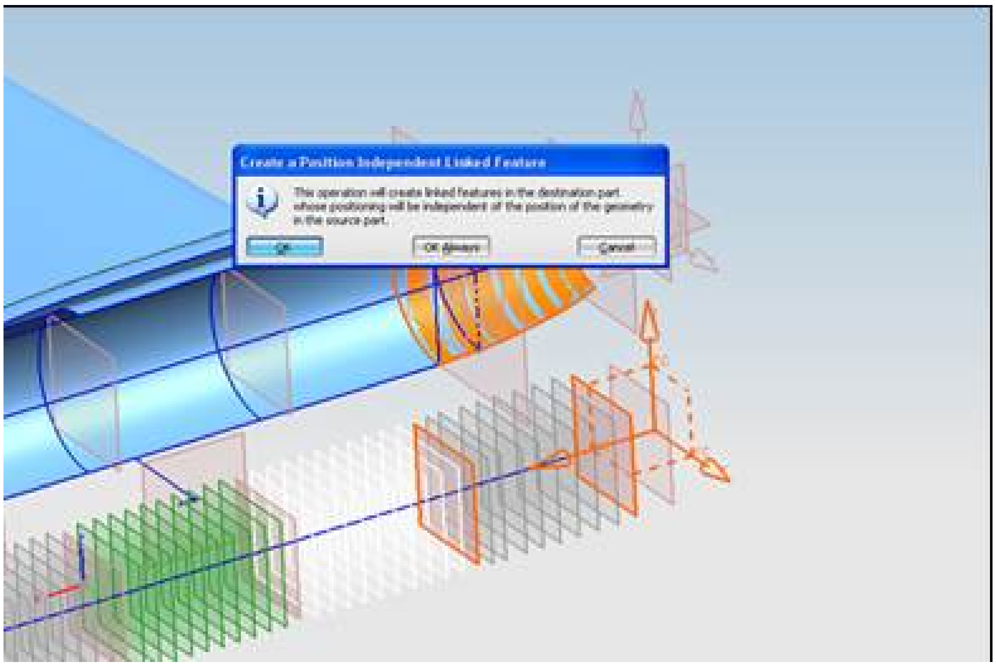

Figure 5. Sketch-based design file

Small dashes called ’tick marks’ are created on control geometry to indicate the direction that solids and surfaces will expand if adjustments are required to the dimensions of an individual part for the benefit of present and future designers (see Figure 6). This step is crucial to ensuring that design intent is maintained, and errors are not created due to poor modeling practices.

Using the sketch geometry, work surfaces and solids can be derived (see Figure 7). In this method, the entire 3D shape definition can be controlled by updating the 2D sketch contained in the DDF. Rib creation in the sketch-based modeling structure used a similar process to those in the in the datum-based method. A single rib instance was created using proper link structures, and then independent instances were created. The only difference is the ribs in this method reference the markers contained in the DDF for direction and positioning.

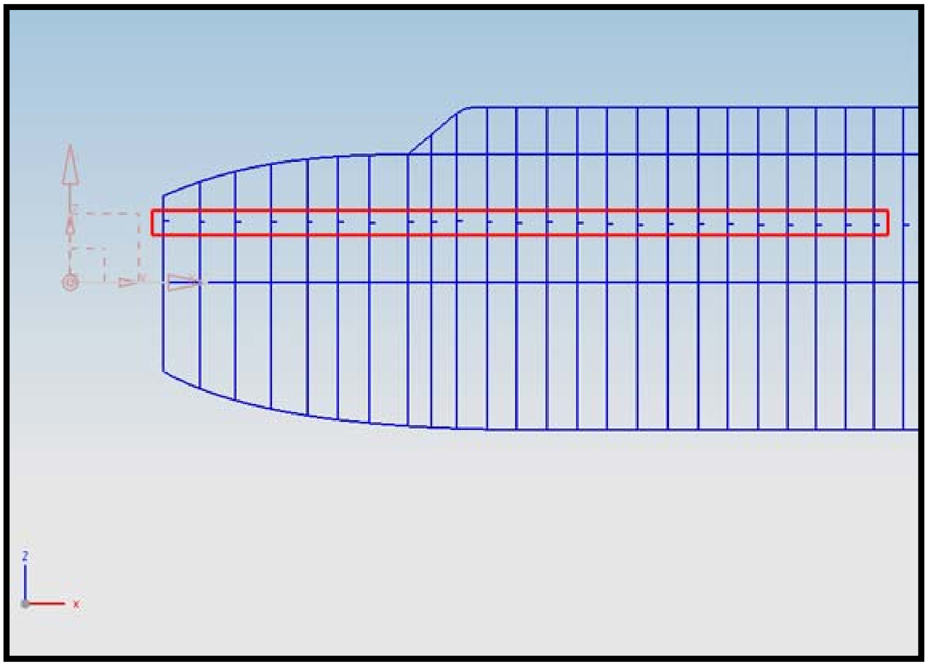

Figure 6. Sketch-based directional sketches

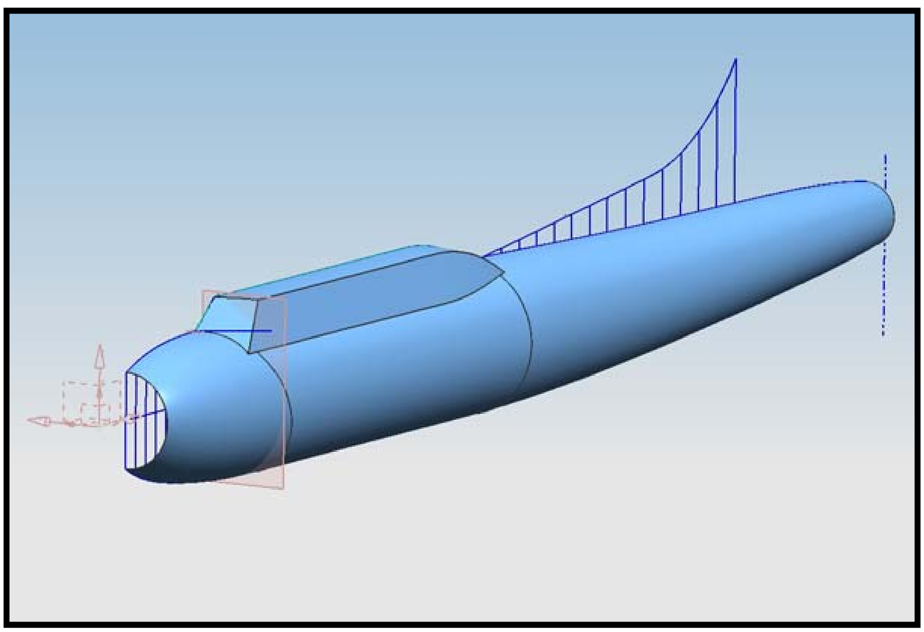

Figure 7. Sketch-based derived entities

Testing

With the completion of both fuselage models, comparison testing could was begun. Each model was put through a series of steps to observe the supporting geometry and the individual components as the geometry and locations were edited. The testing involved several different procedures for testing the models' flexibility. The first tests examined characteristics of the files. Criteria such as file size, load time, parts lists, and volume of links were examined. These indicators provide information on the efficiency of the modeling systems, and on the information density contained in each component.

The next set of tests involved physically altering part locations, dimensions, and instancing. The models were stressed by pushing and pulling components in relation to the fuselage's skin, and the ribs were added and removed. Also, the skin was replaced to test how well the models would adapt to new geometry, and if there would be any error in computation of new geometry or interface.

The final round of testing involved altering the entire assembly, using the product structure to move parts and assemblies. This test relocated parts and assemblies from one subassembly to another, and used the addition and removal of parts to test if the structure was built properly in the top-down modeling scheme.

The following information was tracked throughout the research testing:

- All errors that occurred
- Detailed logs of actions that generated error messages
- The scope of the error/impact on product structure
- Workarounds or fixes to repair the geometry to Boeing standards

Results

The first test was an examination of the characteristics of the files. The files were examined for individual size, number of parts per assembly, total size of the assembly, and total number of links created in the assembly (Table 1). Despite having fewer parts, the sketch-based method has a larger total file size, larger average file size, and a greater number of links between parts.

Table 1. File characteristics

	Datum-based	**Sketch-based**
Total File Size	37 MB	44 MB
Number of Parts	94	81
Average File Size	403 KB	557 KB
Number of Links	174	261

The second round of testing involved loading the models to examine system (CPU Time) and model time-to-display (Real Time). For each load test, two identical computers were booted, and then the NX software was started. Next, one of the assemblies was loaded onto each computer. The test data was extracted from log files inside of NX. Once the load times were extracted from the log files, the system was rebooted and the test re-run with the other assembly. The two load time tests showed that the sketch based method takes longer for the computer to resolve, and for an output to be displayed (see Table 2 and Figures 8 & 9).

Table 2. Load Test Data

	Datum Based			**Sketch Based**		
Count	**CPU Time**	**Real Time**	**Difference (Real-CPU)**	**CPU Time**	**Real Time**	**Difference (Real-CPU)**
1				8.796	19.097	10.301
2	7.626	16.384	8.758	8.609	17.901	9.292
3	7.718	16.588	8.87	8.484	18.366	9.882
4	7.594	16.993	9.399	8.734	18.041	9.307
5	7.844	17.485	9.641	8.531	17.984	9.453
6	7.719	16.415	8.696	8.577	17.691	9.114
7	7.594	16.306	8.712	8.781	17.71	8.929
8	7.72	16.712	8.992	8.594	18.07	9.476
9	7.782	16.555	8.773	8.703	17.771	9.068
10	7.844	16.531	8.687	8.969	19.98	11.011
11	7.735	16.344	8.609	8.703	17.945	9.242
12	7.891	17.664	9.773	8.735	17.953	9.218
13	7.687	16.61	8.923	8.703	19.493	10.79
Mean	7.7295	16.715583	8.9860833	8.6860769	18.30785	9.62176923
Std Dev	0.097543	0.4433225	0.3959434	0.1284163	0.736473	0.672869

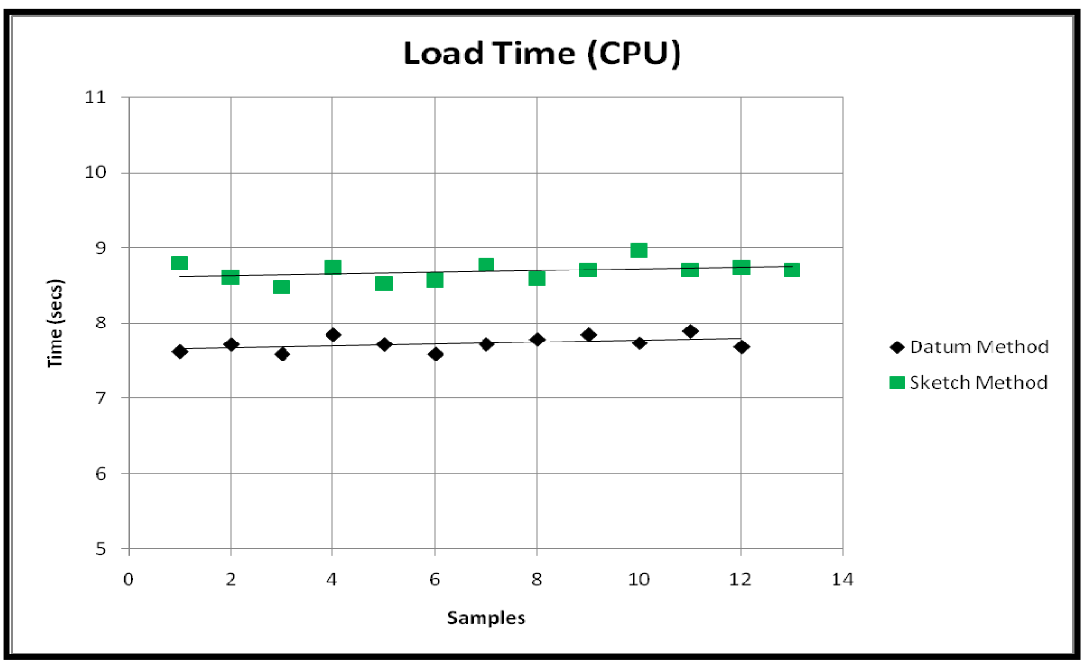

Figure 8. Model load time - CPU

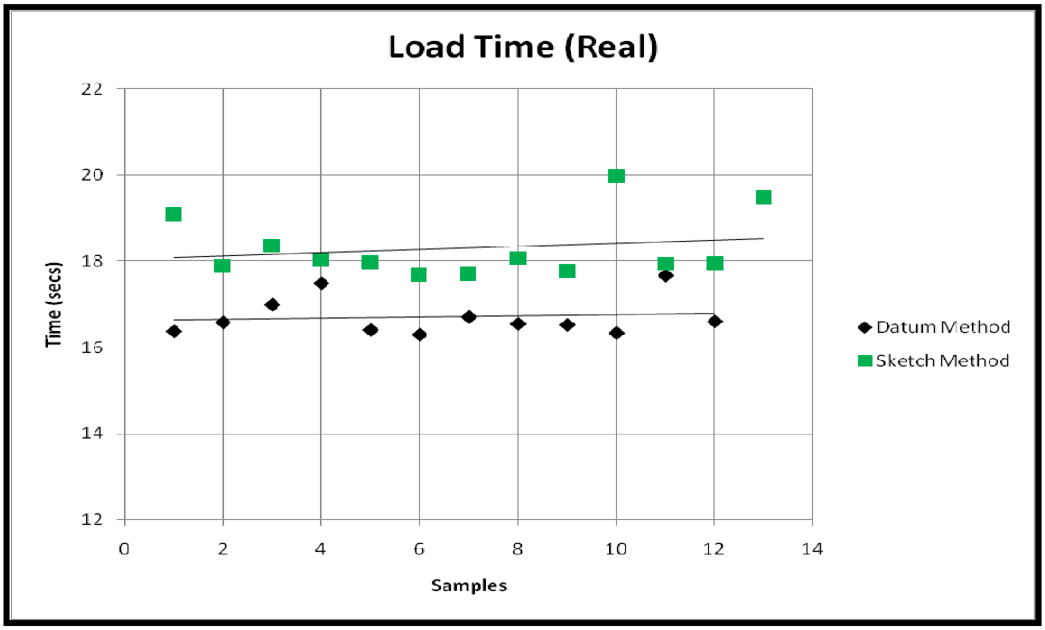

Figure 9. Model load time – graphical image

Next, information was collected from manipulating the models, including efforts to cause problems in the assembly. The only issues experienced involved minor errors in the update of ribs. On occasion, the rib geometry would flip from the interior of the fuselage surface without a clear cause (see Figure 10). This was classified as a minor error because the rib geometry could easily be fixed by switching the surface normal for the support plane of the rib. In addition, this problem occurred equally in the datum method and the sketch method.

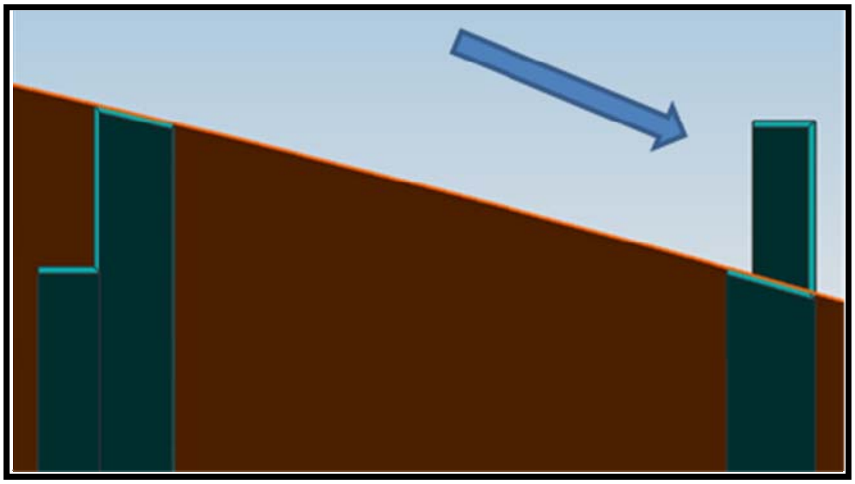
Figure 10. Rib regeneration error

All other tests executed equally well in both methods. These tests included adjusting the profile of the fuselage to identify any errors between the ribs, and fuselage. In Figure 11, alterations to the profile of the fuselage surface were used to try and create profile errors in the rib structures. Despite the changes, all rib structures were able to successfully update, but there were trim errors on occasion between the cockpit surfacing, and the master fuselage surface (see Figure 12).

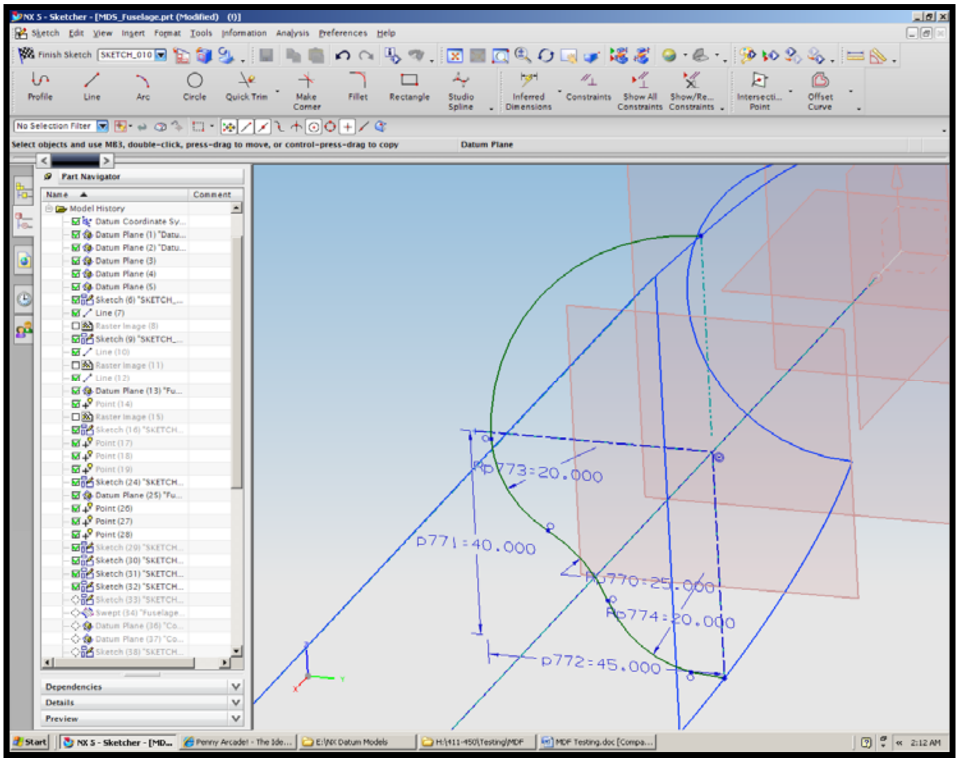

Figure 11. Rib alteration geometry

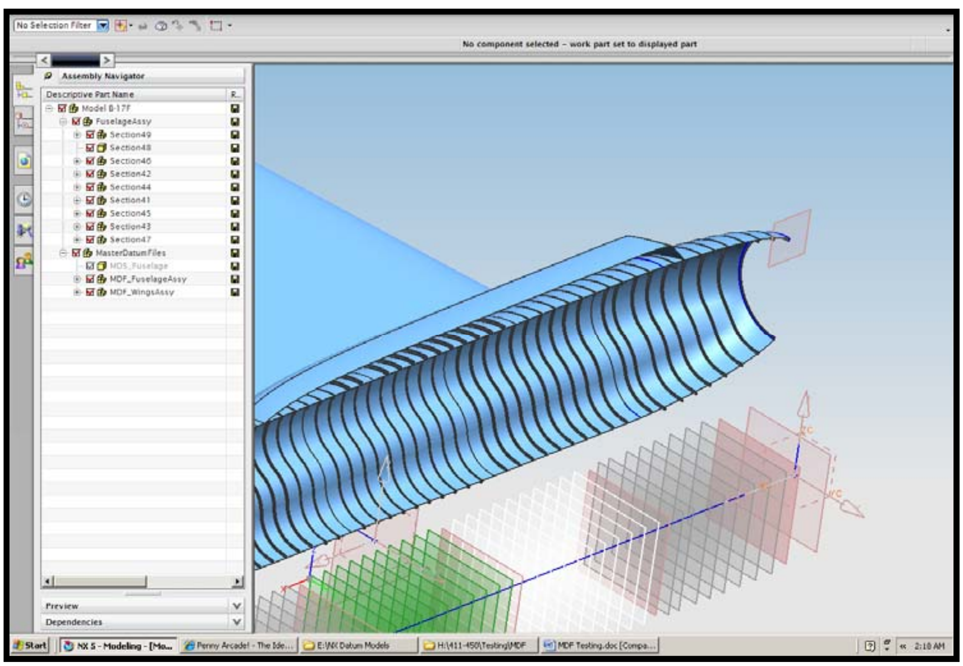

Figure 12. Trim error example

Altering the product structure had little effect on the stability of the model. Parts were moved from one assembly to another, swapped in place for new components, and deleted from the product tree all together. No errors were reported from this test, and none of the links between parts were broken.

Analysis

According to the load tests performed on the part files, there was an advantage to the datum-based method. The file inspection identified that the datum method had a smaller overall and individual part size compared to the sketch-based method despite the fact that the datum structure contained more individual part files. Statistical t-test analysis showed significant difference in load times between the datum-based and sketch-based method of 2.0x10-6 for the real load time and 3.5x10-16 for the CPU load time at the .05 significance level.

Physical evaluation of the models offered no conclusive difference between the datum method and the sketch method. Any errors experienced in one method also occurred equally in the other method. None of the errors that were experienced caused computational problems in the program, and were simple to repair. As a result, these tests validated the effectiveness of both modeling techniques.

The final tests involved editing the assembly in the product tree. Because of the top-down modeling structure, all components and subassemblies were not dependent on their position in the tree. Likewise, deleting parts from the history tree does not cause instability in the master assembly document. This result reflects the main benefit of a top-down modeling structure.

Conclusion

The file comparison tests and load time tests showed that because of its lighter weight and superior load times, the datum-based method is a more technically superior process. The analysis using the two sample t-test shows that the difference in load times is statistically significant in favor of the datum method, and from a file size perspective, the datum method holds an advantage over the sketch-based method.

However, the sketch-based method also has some advantages. The main benefit for the sketch-based method is its simplicity. By isolating control geometry to a single drawing, the modelers for this project found this process to be faster for modeling components, and less confusing to deal with. In the datum method there was a tendency for the modelers to get confused by the complexity of the product structure, and the mixing of links. The simplicity of the sketch-based modeling system is advantageous from this perspective.

The results of the model manipulation tests indicated that both processes are effective at creating and controlling geometry. Both methods performed equally well when contained geometry was manipulated, and any errors that occurred in the datum-based method also appeared in the sketch-based approach. Although further research is indicated, it appears that both processes contain benefits for the modeler. For assemblies of this size and complexity, the datum-based method is a more efficient process from a load time perspective. However, this may differ in assemblies of different scale or complexity.

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