Justifying the Automation of Engineering Design

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SUMMARY

The Joint Strike Fighter Programme has benefited from the development of a number of dedicated software tools that provide various levels of automation that assist the engineering design process in terms of time, cost and quality.

During the deployment of these applications, GKNAES has carefully monitored their productivity and obtained a set of usage metrics. These performance data are presented and discussed herein – a good case is made to justify the development costs and time saving when compared with the standard methods of data manipulation that were previously available.

Further observations and assessments are made in relation to the introduction of these toolsets into the everyday working environment of aeronautical engineers and designers. Whilst some resistance was initially encountered, once the benefits became apparent, more widespread acceptance immediately followed. Indeed, given the vast amount of data that has to be processed, any software that facilitated this in a user-friendly, rapid, and reliable fashion was guaranteed to produce efficiency gains in the short-medium term, and would ultimately be viewed in a positive light.

Keywords: Engineering Software, Design Automation, Knowledge-Based Engineering, KBE, CAD, CAE, Future-Trends, Structural Analysis.

1. BACKGROUND

In a previous paper [1] the authors explained the rationale for developing engineering software tools that automate elements of the aerospace structural design process. This paper will investigate whether one area of the JSF System Development and Demonstration phase has benefited overall by using such automated design and development tools. In particular, evidence will be provided of the cost and time savings attributed to particular toolsets, and some more general inferences will be drawn in relation to their role in effecting aircraft weight reduction.

2. INTRODUCTION

The vast cost associated with bringing a military aircraft from paper specification to type certification means it is vital for the manufacturer to “get it right” first time. Accordingly, more and more effort is expended nowadays than ever before in the areas of digital design, analysis simulation, and systems’ testing. This paradigm shift in working practice is well-illustrated in the burgeoning number of flight load cases that nowadays have to be considered for structural analysis and justification. This increase, from perhaps a few tens of load cases in the late 1940’s (DH106 Comet airliner [2,3]) to tens of thousands of load cases in the early 2000’s (JSF F-35) [4], is due to a number of factors[1], including mature computational capability.

The advent of mainframe computing and the introduction of nascent Finite Element routines in the 1960’s brought forth a much clearer understanding of load paths within a typical aircraft’s highly redundant structure, and a corresponding refinement of the structural design process. Significant emphasis was placed on understanding how loads developed throughout the flight envelope, particularly in the corners, with a corresponding ability to isolate the most critical load cases for analysis. This meant far more “up-front” work for the loads group in generating and validating a significantly reduced number of load cases to be used subsequently in detail stressing. Nowadays, all load cases, however

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[1] Developments in: regulations, gust properties, aeroelasticity/flutter, damage tolerant design philosophy, flight control systems, and powerplant performance, to name but a few.

insignificant, get analysed, partly because the computational capability exists, but also because the initial filtering of the most critical load cases is not performed in the same manner as previously. This is largely due to the prime contractor devolving responsibility and justification effort to its sub-contractors. Hence Tier-one suppliers to the aerospace industry face significant challenges in offering a service that is stable, respected, and based on the latest simulation technology, whilst delivering work that is on time, to cost, and of acceptable quality.

The structural design of the Lockheed-Martin F-35 Joint Strike Fighter (JSF) typifies this phenomenon - over 20,000 different static load cases (and more than 500 fatigue load cases) are used to size the structure of each variant. Each load case represents a particular flight configuration, enabling a highly detailed picture of the aircraft's structural response at every point in the flight envelope to now be considered at the initial design stage. Such fine resolution of the loads permits the designers and analysts to produce an efficient, weight-optimised structure capable of fulfilling all the operational requirements. (It is conceivable that the critical load on each bolt in a typical splice joint may be sized by a different load case!) However, the sheer volume of data that has to be manipulated and managed on a day-to-day basis starts to present difficulties of its own, and this provides the motivation and context for developing and using a variety of engineering automation tools.

3. SOME DEVELOPED SOFTWARE SOLUTIONS

Several tools have been developed by GKNAES that are currently in use in the JSF design effort. These tools include process specific applications, which have been designed to capture and automate a specific analysis or design process, and generic tools, which have been designed to automate or facilitate tasks that are common to many analysis and design processes. An example of a process specific application is one that automates the manual stress calculations of a structural item for a number of load cases, and outputs the critical margins of safety (MS). An example of a generic tool might be one that takes finite element results in one particular coordinate system and then transforms them into another coordinate system prior to further analysis.

Two examples of process specific tools will be described in this paper in more detail. These tools will be used as the basis for a case study to explore their benefits, as well as to examine the technical challenges and human issues associated with such engineering automation tools. Section 4 will address the methods of ascertaining the tangible benefits from the tools, including the capture and examination of tool usage metrics.

Tool 1: Stiffened Panel Analysis Tool (SPAT)

SPAT [5] is a stress analysis tool that incorporates a number of analyses commonly performed on panels and stiffeners in metallic integrally-machined structure on the JSF aircraft. The tool calculates MS values for static strength, buckling, post-buckling and stability failure modes of the panels and stiffeners. Input loading for the panels and stiffeners is defined from the coarse grid Air Vehicle Finite Element Model (AVFEM). Additional loading for stiffeners can be derived by the tool by redistributing panel pressure loading and post-buckling loading from the panels.

SPAT captures the analysis process as it would have been performed manually, but offers the following advantages:

- Enforces a consistent approach to the analysis performed by different analysts for similar structure.
- Enables a more accurate enveloping of loading conditions by allowing the analysis to be performed consistently for a large number of load cases, and finding the minimum MS, rather than performing a survey based on general criteria and manually performing the analysis for only a few load cases.
- Provides a visual representation of the geometry from the finite element model, the CATIA CAD model of the part, and the idealized analysis structure in a single display to enable analysis assumptions to be rapidly checked.

Although SPAT has had widespread use and a positive response from the engineers using the tool, the following issues have been identified:

- Although the tool simplifies the analysis process, it still requires the engineer to have a full understanding of the implications of altering the actual geometry and associated load paths and to evaluate the validity of any simplifications of analysis assumptions. There is a risk, particularly for inexperienced engineers, that the apparent simplification results in a disconnection between the engineer and the analysis being performed and the results from the tool may be used without the appropriate critical evaluation.
- The steps required to set up the data required for the analysis of stiffeners are significantly more complex than those required to perform the panel analysis. This has led to an apparent reluctance to use the stiffener analysis feature.

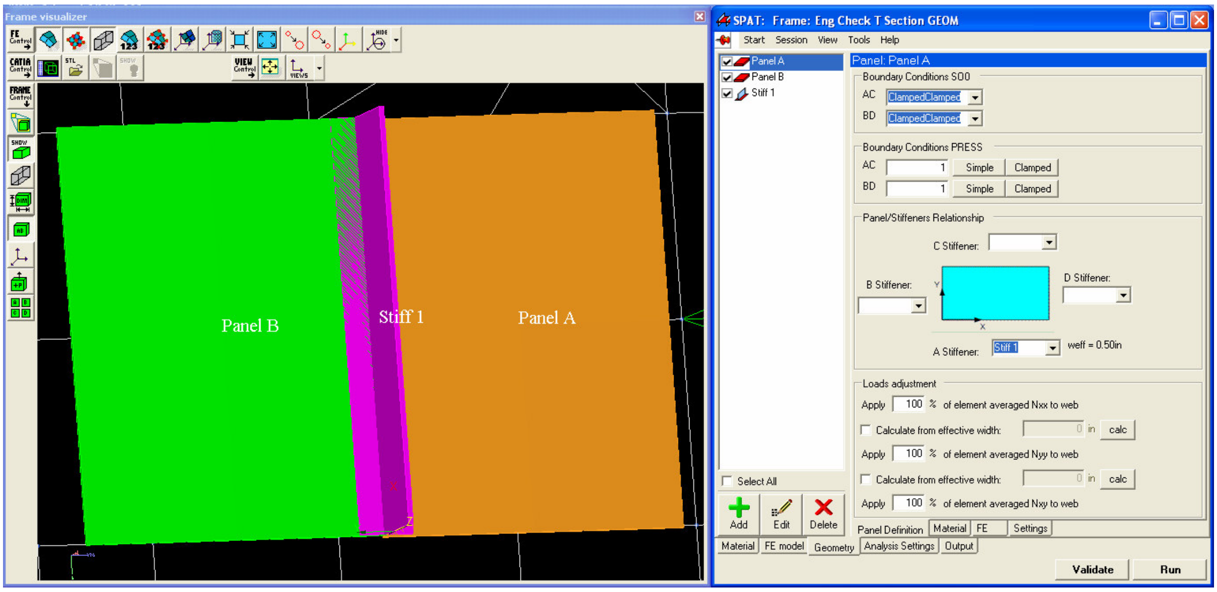

Figure 1. SPAT user interface showing visualisation window and data entry.

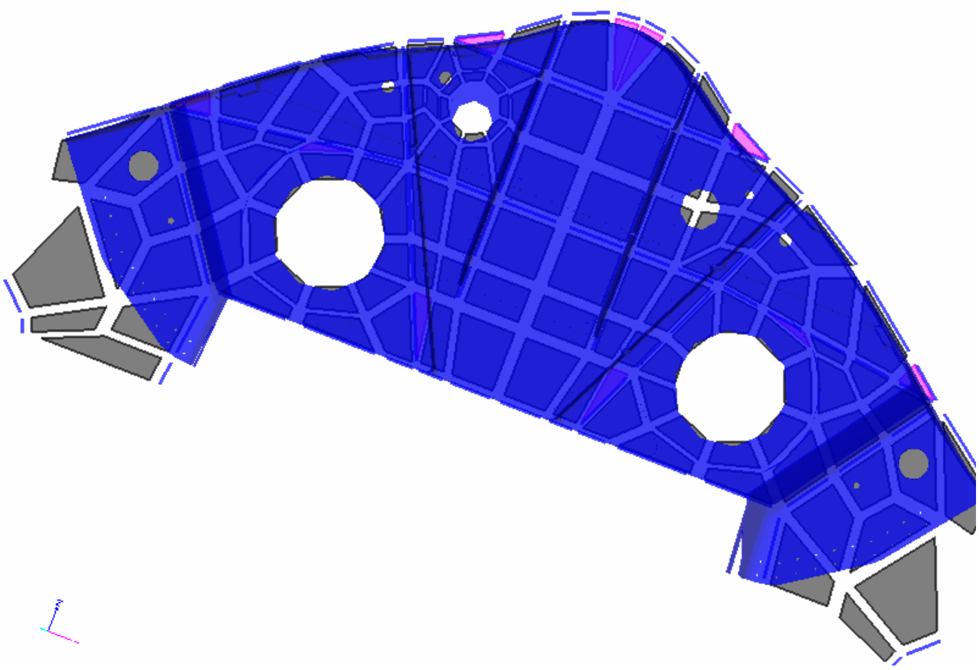

Figure 2. SPAT visualisation display showing FE mesh and CAD model overlay.

Tool 2: Bracket Analysis Tool (BAT)

Electrical wire harnesses on the JSF aircraft are supported using a series of brackets or studs along the harness length. These brackets or studs are generally common components and number in the thousands throughout the three variants of the JSF aircraft. Manually analysing each component in a harness run is routine and time consuming, so the engineer will typically determine the most critical component and perform a detailed analysis for only that component. Although this reduces the analysis time, the approach may introduce unnecessary conservatism into the design resulting in an overall heavier structure.

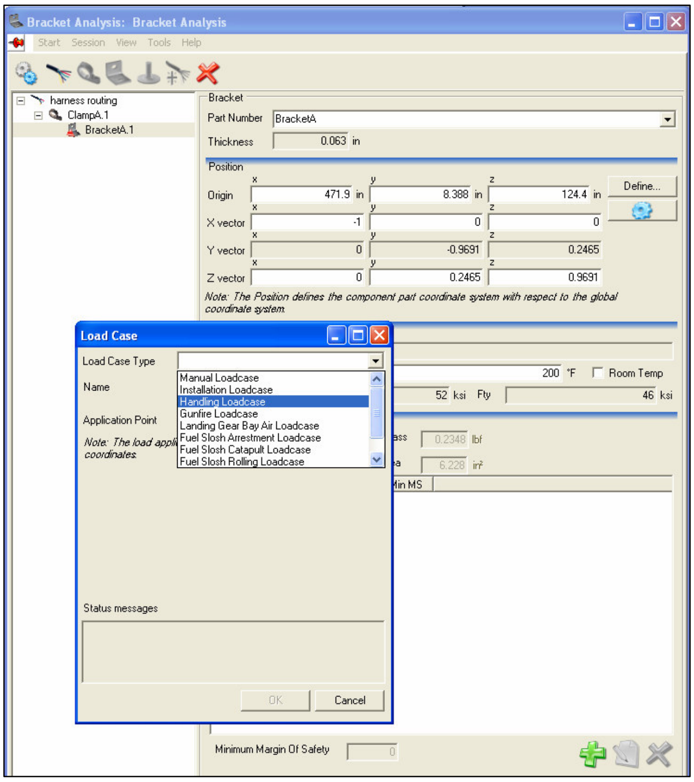

Figure 3. BAT user interface - data entry panel.

BAT [6] addresses this problem by simplifying the process of gathering the parameters required for the analysis of each component in an electrical harness run, including the location and orientation of each component. See Figure 3. BAT then performs the required analysis for each of the loading conditions at a number of analysis sections for each component within the harness run. The tool calculates the applied loads, interface loads, section stresses and margins of safety for each component. Critical MS values are found and reported.

The tool offers the following advantages over the traditional analysis method:

- A reduction in conservatism in the analysis, potentially resulting in weight reductions in the design.
- Capture of 'best-practice' for the analysis of these simple components, ensuring that consistent methods are used to perform the structural analysis justifications.
- A reduction in set-up time for analysis by allowing the analysis definition of common components to be specified once, and than centrally stored for subsequent use by multiple engineers.
- A reduction in potential error sources through:
  - centrally storing the analysis definition of common components, because these data can be validated once and then used for multiple analyses by multiple engineers.
  - directly linking the CAD model and the analysis tool, eliminating potential transcription errors, and allowing complex coordinate system transformations to be managed consistently and accurately.
- The ability to save all analysis inputs in one place so the analysis can easily be re-run in the event that design or loading changes are made.

The following limitations of the initial release of the application were identified by users and were key drivers for a second release developed to improve the usability of the tool.

- The tool was closely coupled with a particular CAD package, however much of the design data had not yet been migrated to that CAD package. Migration utilities had to be included in the second release to eliminate the need for manual migration.
- The original release of the tool did not anticipate the complexity of most harness assemblies, particularly with regard to forking, resulting in the need to break a forked harness into sub-components. The second release addressed this issue by adding provision for modelling forked harnesses, reducing the number of analysis files required, and reducing the overhead involved with keeping track of the location in the branched harness. See Figure 4.

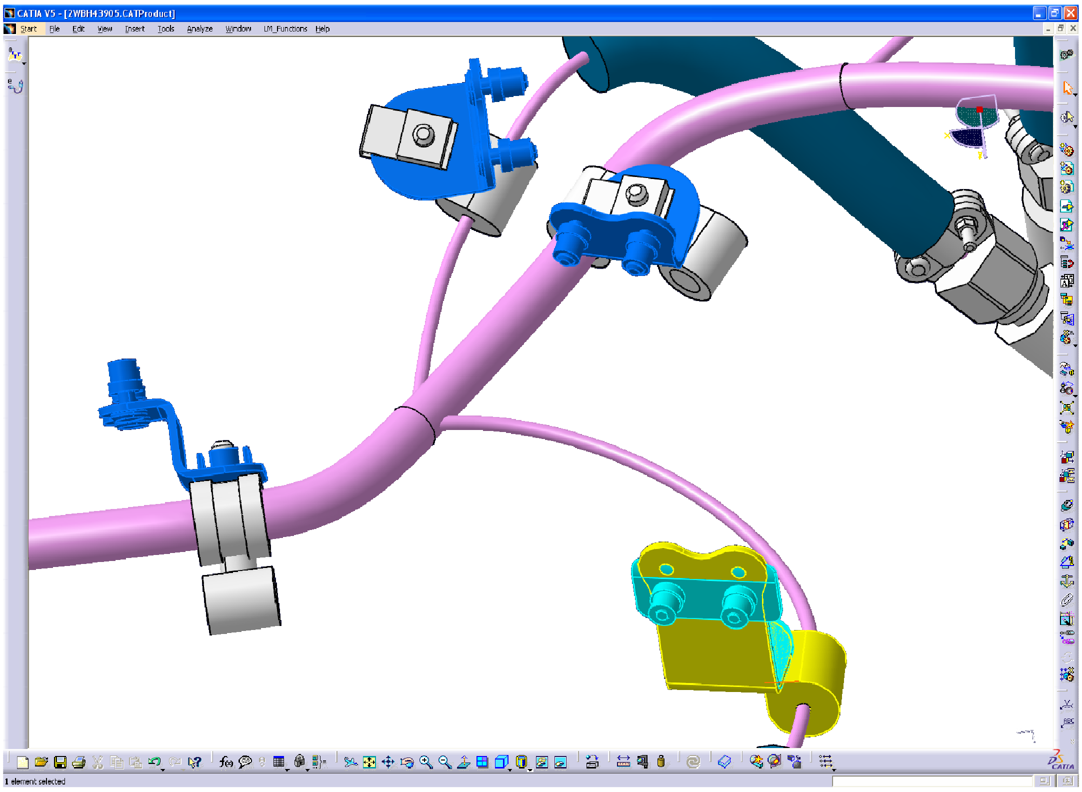

Figure 4. BAT example of a typical forked harness.

The issues identified for both of these tools highlight important considerations when planning new tools. Firstly, it is important that the automated analysis process is as transparent as possible and both input and output data is presented to the engineer in a way that simplifies validity evaluations. Secondly, for a good Return on Investment (ROI) to be realized, care must be taken to ensure that the complexity of user inputs is minimized. It is also important to be aware of changes in external tools and reduce close coupling where possible, without sacrificing the benefits of direct interaction with external applications such as CAD, FE and specific analysis tools. Where direct interaction with an external application is required, the software design should attempt to limit the coupling so updates can be more easily incorporated to support version changes or new tools. Finally, when planning the tool design, care must be taken not to underestimate how the task complexity can increase significantly when dealing with real-world data rather than simple test cases.

4. ASSESSING THE IMPACT ON THE ENGINEERING PROCESS

Measuring the usage of an application provides important information on the impact an application has on the engineering design process. It is also valuable for justifying the initial development investment, in furthering the case for new applications, and for funding the ongoing maintenance costs of legacy applications.

In both the SPAT and BAT applications described in Section 3, functionality was incorporated to record usage in terms of time, user and specific application events. A sample extract of the log file that records these details is shown in Figure 5 for the Stiffened Panel Analysis Tool. In this example the user starts the application, runs an analysis (1 panel, 1 stiffener and 572 load cases) twice then closes the application.

The log file is common for all instances of the application that are run on a local area network. Therefore multiple users contribute to a common file and application events are tracked by matching the session identification key. In the case of SPAT the key events include application start-up, shut-down and run analysis. Recording the application start-up and shut-down is important in eliminating erroneous application uses from statistical measurements. These events typically occur when a user starts the application unintentionally or out of curiosity, changes their mind part way through a session, or the application ends abnormally. Additionally, users will frequently re-run an analysis (as illustrated in Figure 5) making minor changes to the application inputs. The detail contained within the log file enables these events to be either eliminated or more accurately interpreted.

```
Time = 2006-08-17 13:12:18
       Session = 22e371ff-1e6c-4cc8-9647-1d007674d257
       User = Ima Engineer
       Event = Startup SPAT v2.1.33.0

Time = 2006-08-17 13:23:46
       Session = 22e371ff-1e6c-4cc8-9647-1d007674d257
       User = Ima Engineer
       Event = Analysis (Panels = 1 Stiffeners = 1 Load cases = 572)
       Run time = 00:01:42

Time = 2006-08-17 17:32:54
       Session = 22e371ff-1e6c-4cc8-9647-1d007674d257
       User = Ima Engineer
       Event = Analysis (Panels = 1 Stiffeners = 1 Load cases = 572)
       Run time = 00:01:21

Time = 2006-08-17 20:18:26
       Session = 22e371ff-1e6c-4cc8-9647-1d007674d257
       User = Ima Engineer
       Event = Shutdown SPAT v2.1.33.0
```

Figure 5. A sample extract from the Stiffened Panel Analysis Tool log file.

```
Time = 2006-10-27 13:56:10
       Session = 928f16c7-20c2-48bb-a102-814b34cdad6b
       User = Be Neat
       Event = Analysis (Panels = 5 Stiffeners = 16 Load cases = 2)
       Run time = 00:00:09

Time = 2006-10-30 14:19:59
       Session = f73ba4a6-8d27-4c66-acf5-8c006d610a7f
       User = Ann Other
       Event = Analysis (Panels = 1 Stiffeners = 0 Load cases = 1199)
       Run time = 00:01:29
```

Figure 6. An extract from the Stiffened Panel Analysis Tool log file.

The business case that justified development of SPAT was based upon an assumed number of panel and stiffener analyses, and an assumed number of load cases. The log file extract shown in Figure 6 illustrates the real-life variations that can occur in these quantities and hence the associated difficulties in estimating application usage.

Many other significant metrics can be extracted from an application log file. These include the number of users, what proportion of the target user base they represent, and which users push the performance of the application. Filtering the users that simply open then close an application can identify issues such as a lack of training or awareness within the user base. Similarly, identifying patterns of user behaviour can pinpoint issues such as functionality that is difficult to understand or an unfriendly user interface.

Tool 1: Stiffened Panel Analysis Tool (SPAT)

Two key periods of high activity are apparent from the distribution of usage in SPAT shown in Table 1 and Figure 7 and Figure 8. Quarter 4 2005 corresponds to a period of high activity associated with the JSF F-35B (STOVL) forward centre fuselage design which involved the analysis of major structural components including a bulkhead frame, two skin longerons, and various other stiffened panels. The other period of intense activity occurred in Quarter 2 2006, and corresponds to a major design effort for the JSF F-35C (CV) forward centre fuselage design that included frames, beams, integrally-stiffened fuel tank floor panels, etc.

Also apparent is the low number of stiffener analyses that were performed in comparison with the number of panels that were analysed. The main reason for this is that the majority of stiffeners are sized as panel-breakers and therefore only the geometric stability of the stiffener is critical. Since this failure criterion depends only on the geometry of the stiffener a carefully planned spreadsheet is more effective in calculating the necessary section properties than using SPAT.

The user base is dominated by a relatively small number of users, since 80% of all uses are completed by only 20% of the users. This may suggest that additional training or awareness of the application capability may be required in order to improve the distribution usage.

Table 1. SPAT summary usage statistics.

	Number of Panels Analysed	Number of Stiffeners Analysed	Average Number of Load Cases	Average Solution Run Time
User A	1795	1114	62	0.30 min
User B	1665	245	334	0.23 min
User C	795	859	32	0.18 min
User D	1100	0	2	0.20 min
User E	1014	0	283	1.62 min
User F	797	46	104	1.28 min
User G	803	0	134	0.58 min
User H	619	123	151	1.07 min
User I	738	0	42	0.62 min
User J	549	25	212	0.70 min
All Other Users (42)	2759	178	183	1.00 min
Total	**12634**	**2590**	**140**	**0.70 min**

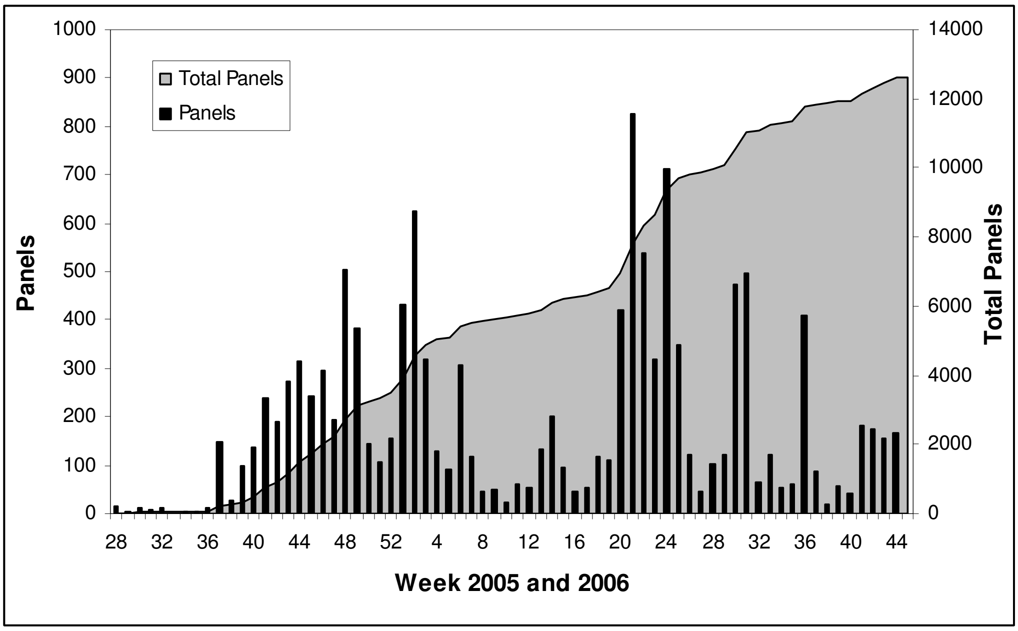

Figure 7. Summary usage data collected from SPAT for panel analysis.

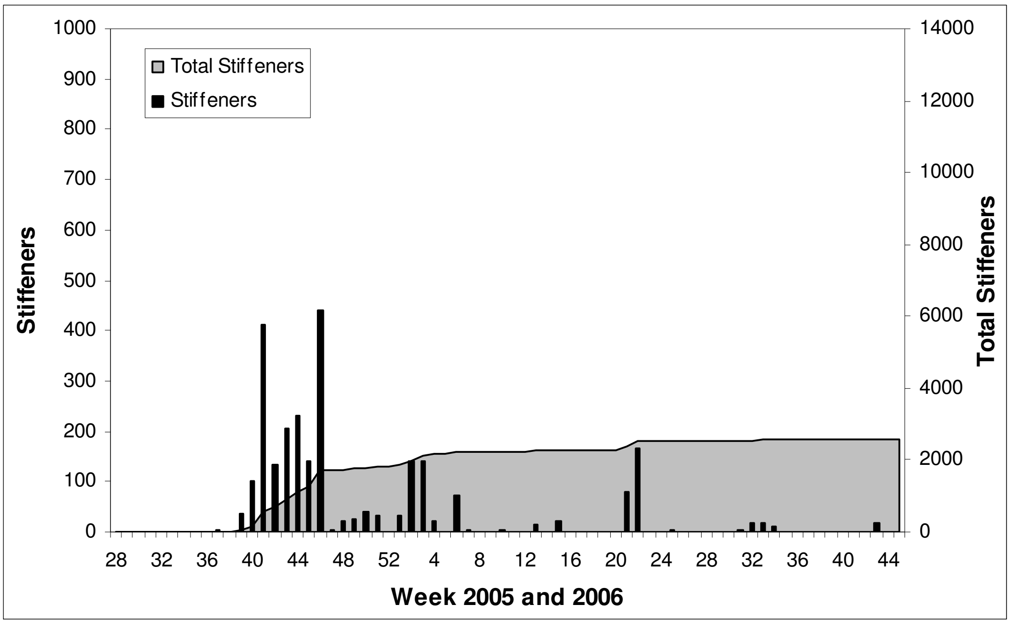

Figure 8. Summary usage data collected from SPAT for stiffener analysis.

The conventional time taken to undertake a panel or stiffener (static strength and stability) analysis was estimated at 2 hours per panel or stiffener. Typically this process would involve the following steps:

- Extracting geometric data from a CAD model.
- Identifying elements that represent the structural components.
- Surveying load case data and extracting critical cases.
- Transforming and averaging FE results.
- Determining material properties.
- Preparing input files and running external software programs.
- Extracting and summarising the results data.

Due allowance was made for the creation and reuse of spreadsheets and methods aimed at streamlining this [manual] process. Another assumption implicit in the estimate is that the time taken to use the application is small and is not included in the analysis. On this basis, the total estimated time to manually complete the recorded number of panel and stiffener analyses shown in Table 1 would be approximately 30,000 hours.

For comparison, a survey was conducted of the total number of panels and stiffeners that were actually analysed as part of GKNAES' contribution to the JSF programme. This suggested that 12 F-35B components (comprising 93 panels and 144 stiffeners) and 14 F-35C components (comprising 278 panels and 421 stiffeners) were analysed. Comparing these figures with those obtained from the application log files (see Table 1) it is clear that SPAT has been used heavily for iterative design improvement and weight optimisation.

Tool 2: Bracket Analysis Tool (BAT)

As was the case for SPAT, the periods of high BAT usage correspond to design activities in support of the JSF F-35B and JSF F-35C electrical sub-systems design effort. The usage data indicates that BAT has a small user base of which the majority of users have analysed a relatively large number of brackets. This usage is consistent with the intended user base and suggests that the application satisfies user expectations.

In the case of SPAT it was difficult to separate multiple re-runs of an analysis from new and distinct analyses. However, for BAT it is possible to review the number of new and distinct brackets that have been analysed. Interrogation of the cumulative log file showed that 1102 distinct brackets had been analysed in comparison with 3913 analysis runs. This suggests that users either changed inputs (geometry, loads, material properties, etc) between each run or made errors that required correction by re-running the application.

Table 2. BAT Summary usage statistics.

User	Total Number of Brackets Analysed	Average Number of Load Cases	Average Application Run Time per Bracket
User 1	246	15	
User 2	1480	17	
User 3	407	12	
User 4	806	16	
User 5	954	16	
Other Users (3)	20	9	
Total	**3913**	**14**	**24 mins**

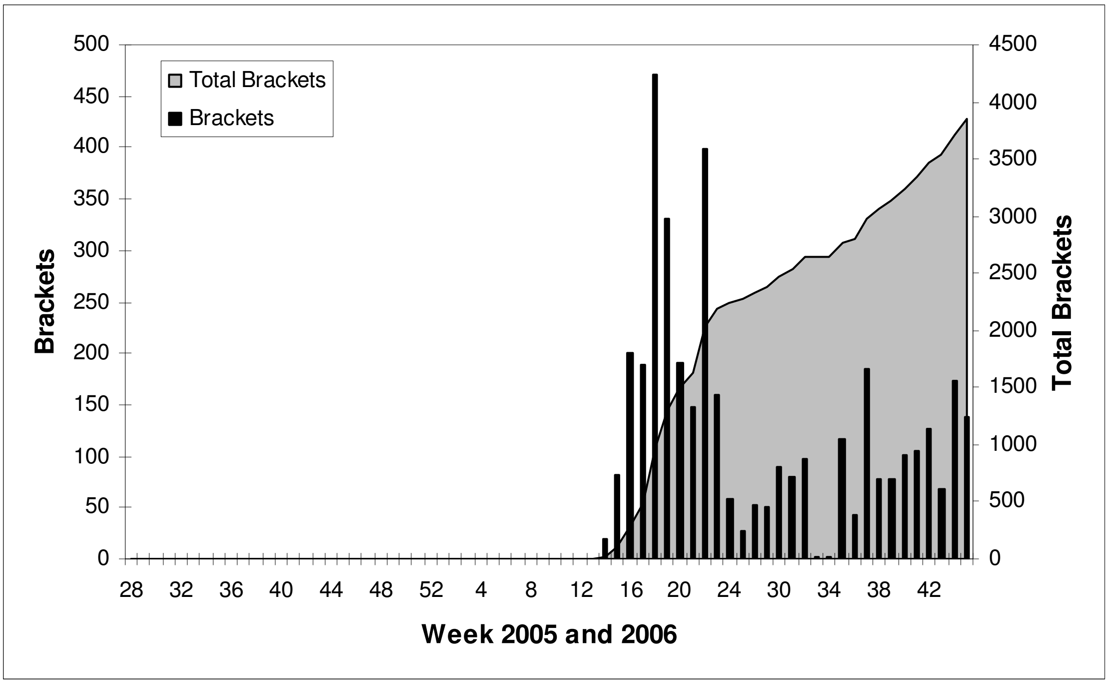

Figure 9. Summary usage data collected from BAT.

BAT simplifies the analysis process and enforces consistency thereby enabling the small user group to complete an abnormally large volume of work. Additionally, weight savings were achieved by analysing every single bracket within a system installation. Table 3 details the weight savings that have been achieved as a result of using BAT. These results assume that a manual analysis of a particular bracket type would size *all* the brackets in a particular wiring harness from a consideration of the worst case; in contrast, BAT is used to size *each* individual bracket according to its own discrete set of loads.

Table 3. Sample BAT weight savings.

Installation	Number of brackets with the same type	Total weight obtained using BAT (lb)	Total weight based on worst case bracket (lb)	Total weight saved (lb)
System A	13	0.523	0.584	0.061 (10%)
System B	35	0.721	0.918	0.197 (21%)
System C	17	0.216	0.260	0.044 (17%)

Although the above results indicate a relatively small weight saving relative to the whole aircraft, the percentage saving is significant.

5. RETURN ON INVESTMENT

Customers are always anxious to measure the performance of developed tools against the original business case. In a previous paper [1] the authors explained the rationale for estimating savings and the means by which a ROI can be calculated. Table 4 presents the estimates used to make the original business case prior to the development and deployment of BAT. This table also contains the actual values achieved to date where relevant.

Table 4. BAT return on investment analysis.

	Original Estimate	Actual [to date]
Time to analyse one bracket (conventional analysis)	10 hrs	
Average number of brackets per harness	10	
Number of harnesses per aircraft	105	
Number of aircraft variants considered	5	
Total number of brackets requiring analysis	5250	1102
Fraction of brackets actually analysed[2]	20%	50%
Actual number of brackets analysed	1050	551
Estimated time (conventional analysis)	10500 hrs	5510 hrs
Time to analyse one single bracket using BAT	0.4 hrs	0.4 hrs
Time to analyse one single harnesses using BAT	4 hrs	4 hrs
BAT development time	1000 hrs	1200 hrs
Total analysis time using BAT	3100 hrs	1640 hrs
Saving	**7400 hrs**	**3870 hrs**
Return on Investment [1]	**7.4**	**3.9**

At the time the data was collected, 1102 physical brackets had been analysed. On average each of these brackets had been analysed approximately 4 times because of loading or installation design changes. Therefore a factor[3] of 0.5 (50%) was applied to calculate the number of brackets that would have been analysed using conventional methods. The results in Table 4 demonstrate the initial investment is justified and that good progress is being made towards achieving significant savings, especially given that there is a large amount of work still to be completed. (It is noted that an ROI of 2.0 indicates a 100% saving in effort).

6. INTANGIBLE BENEFITS

Despite the obvious direct benefits due to savings in engineering hours there are a number of other less tangible benefits associated with engineering automation. The most important of these is the improved quality and consistency of engineering deliverables and hence the reduction in rework.

The work presented herein demonstrates the following benefits to the JSF Programme:

- *Schedule.* Like most present day military contracts, an aggressive design and development schedule typifies the JSF Programme. Faced with the burgeoning loads data that must painstakingly be interrogated, evaluated and analysed, and the associated time and cost overhead, any toolset that can compress this task will assist schedule – and therefore cost - adherence.
- *Consistency.* By using a dedicated analysis tool, with templated input and output, greater analysis consistency is obtained based on agreed company methodologies. This helps reduce the time spent in verification, checking, and correcting documentation errors.
- *Complexity.* A dedicated toolset can simplify or standardize a complex process, thereby minimizing scope for human error.

[2] Due to time and cost constraints the conventional analysis for subsystem brackets only considers the most heavily loaded components. The remaining components are sized based on this analysis.

[3] This factor incorporates the reduction associated with only analysing heavily loaded brackets and the increase associated with analysis re-runs.

- *Integration.* Rather than developing new packages for performing dedicated analysis tasks, much effort has been made to develop high level toolsets that interface with existing programme-approved engineering software. In this manner, the analyst is able to automate tasks seamlessly with full assurance that the end result derives from previously validated software.
- *Change Management.* Like all aerospace programmes, there will inevitably be changes during the project gestation – these may necessitate re-analysis with an associated time penalty.

7. INTANGIBLE COSTS

Notwithstanding the benefits that have been described in the above sections, some discussion is warranted concerning the "hidden" costs associated with the development, maintenance, and management of such dedicated engineering tools. In doing so, it must be remembered that such tools are developed as one-off, "turnkey" packages; in order to keep the initial development costs low no attempt is made to allow for generic upgrading.

Prior to release, any software tool developed for engineering purposes must undergo a series of rigorous tests in order to validate it, thereby ensuring the integrity of its input, process, and output. This work is carried out in part by releasing preliminary versions of the application to a limited number of users, and then assessing their feedback and incorporating any changes that may be required. A refined version is then released to another limited group of engineers for user acceptance testing; finally the initial release version is made available to the end users. Alongside this, documentation has to be compiled and delivered, and suitable training provided, which depends on the level of sophistication of the tool. Ongoing support must then be maintained for the lifecycle of a tool. This may involve version upgrades if changes occur to the original platforms for which the tool was initially developed.

Since many automation tools interact with existing COTS (Commercial Off The Shelf) software, problems are invariably encountered when a new release of a ubiquitous tool like CATIA happens. When CATIA V5 R14 rolled to V5 R16, some significant changes had to be made to SPAT in order to retain compatibility, and to interact with some of the new features available. Clearly there are costs associated with such changes; dependent toolsets will need to be upgraded, and this is a standard customer expectation.

During the design lifecycle of the JSF, currently projected to be 50 years, many new revisions of foundational design COTS software will be approved and used. Replication of results, using different software releases, is one important facet of structural analysis. Accordingly, there are unquantifiable costs connected with the continued use of dedicated automation toolsets – it is difficult to predict whether such turnkey packages will even execute in 20 years' time unless significant effort is expended in maintaining and updating these tools with each new release of COTS software. The decision to update or discard will ultimately come from the customer.

8. CONCLUSIONS

In this paper, the authors have sought to show that in terms of structural design and analysis the use of engineering automation software has produced some benefits to the JSF Programme. In particular, the use of SPAT and BAT has yielded efficiency gains greater than 300% compared with conventional analysis techniques. In addition, the use of these tools has enabled a more refined and weight-optimized structure to be designed than schedule constraints would otherwise have allowed. In terms of return-on-investment, it appears that the work involved in producing an engineering automation tool is definitely worth the effort, provided a convincing business case exists for its initial development.

The SPAT and BAT applications have both successfully provided substantial and measurable benefits for GKNAES. The estimated savings attributed to the use of SPAT and BAT are approximately 30,000hrs and 4,000hrs respectively. Since these applications are also deployed within Northrop Grumman and Lockheed Martin JSF programme teams, the true impact on the JSF programme is likely to be much higher.

In addition to the obvious benefits due to savings in engineering hours, there are number of other less tangible benefits associated with engineering automation. The most important of these is the improved quality and consistency of engineering deliverables and hence the reduction in rework. In the case of SPAT a complex and error prone process has been vastly simplified and the opportunities for inadvertent errors reduced. Likewise BAT has also improved consistency of output especially in the application and combination of bracket loads.

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