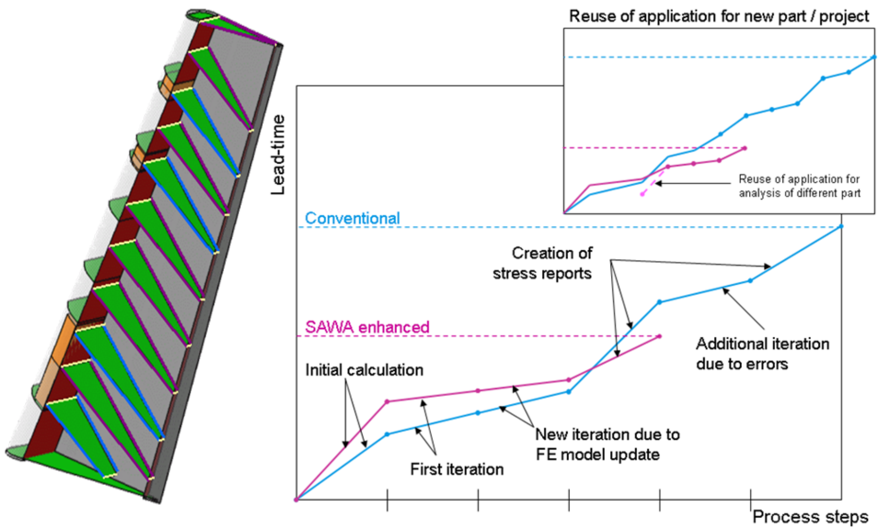
Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR

Executive summary

Improving aircraft component design through tool-chain automation



Problem area
The aerospace industry has entered a phase in which a large emphasis is put on cost and lead-time reduction. The supply chain of large aircraft manufacturers is challenged to supply advanced complex aircraft components in less time and at lower costs. At the same time, the suppliers are facing less economic and intellectual resources, increased competition, and less opportunity to transfer knowledge between consecutive programmes. To remain competitive, suppliers must respond to the challenge. They are actively looking for ways to keep ahead of the competition by enhancing their products in combination with improving the design and manufacturing processes. Since process improvement techniques, such as lean principles, are widely available to all companies, a supplier can only differentiate by capitalising on its expert knowledge.

Stork Fokker AESP designs and manufactures advanced complex light-weight structural components of aircraft and helicopters for the civil as well as military market. As supplier to the world's major aircraft integrators, including Airbus, Boeing, and Gulfstream, it also faces the above-mentioned challenge.

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Lead-time reduction

This report is based on a presentation held at the Aircraft Structural Design Conference: Challenges for the Next Generation – Concept to Disposal, Liverpool, UK, 14-16 October 2008.

Description of work
Stork Fokker AESP has identified the complete design engineering process, and in particular stress engineering, as one of the major parts of the development process in which exploitation of expert knowledge may lead to significant lead-time and cost reduction in the short and mid term. Stork Fokker AESP launched its Structural Analysis Workflow Automation (SAWA) concept to make their plans concrete. The key objective of SAWA is to increase stress analysis efficiency, which will contribute to lead-time reduction. NLR, with its long-standing and enduring relationship with Stork Fokker AESP with respect to stress engineering and supporting technologies, supports Stork Fokker AESP in the realisation of SAWA. Practical application of the knowledge based engineering (KBE) paradigm is considered the key to successful realisation of SAWA.

Results and conclusions
This paper describes the results of the first successful steps towards realisation of the SAWA objective. Stress-tool encapsulation and chaining significantly reduce the amount of non-creative work for stress engineers. Efficient application of these technologies enables the stress engineers to focus on the stress analysis problems at hand, and hence contribute to a more efficient design process. Based on observations and early experiences, KBE and stress engineers involved estimate a 40% to 60% lead-time reduction through application of skill-tool encapsulation and chaining technology. The paper also addresses the importance of the human aspects involved with the introduction and application of KBE technology in the industrial situation.

Applicability
The practical KBE technologies described in this paper are applied to, and evaluated in the context of stress analysis, but are definitely generic enough and certainly applicable to a broader spectrum of aerospace design activities.

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Improving aircraft component design through tool-chain automation

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Contents

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Abstract

The supply chain of aircraft manufacturers is challenged to supply enhanced and more robust aircraft components in reduced time and at lower costs. To remain competitive, aircraft structural component suppliers must respond to these challenges. Aircraft structural component design is an interdisciplinary activity, using complex computational methods. An important observation is that today's stress engineers spend a considerable amount of time on the operational aspects of these methods instead of on the actual design activities. This paper describes an innovative yet practical approach to enable engineers to focus on the design problem at hand. The approach is based on knowledge based engineering paradigms. Key assets are improvement of the aircraft component design analysis process and its computational methods and methodologies, and seamless embedding in an industrial situation. The key assets enable the supply chain to respond to the challenges. This paper also discusses the importance of the human aspects involved with the practical application of knowledge based engineering technologies.

Keywords: increase speed of design; allow rapid design changes; engineering methodologies; aircraft design analysis; knowledge based engineering

Introduction: Trends in Aerospace

The aerospace industry has entered a phase in which a large emphasis in aircraft development is put on cost and lead-time reduction. The supply chain of aircraft manufacturers is challenged to supply enhanced and more robust aircraft components in reduced time and at lower costs. Aside these goals set for the future, aerospace companies are facing less economic and intellectual resources, increased competition because of globalization and less knowledge transfer opportunities between consecutive programmes. Aerospace companies are actively looking for ways to keep ahead of the competition by improving their processes. Since most process improvement techniques, such as lean principles, are widely available to most companies, the only way they can differentiate is by focusing on the knowledge available inside the company.

Aircraft structural component design is an interdisciplinary activity, using complex computational methods. Today's stress engineers spend a considerable amount of time on operational aspects of these methods, instead of actual design activities. This article describes an innovative yet practical approach to enable engineers to focus on the design problem at hand. The approach is based on Knowledge Based Engineering (KBE) paradigms (Ref. [1], [2]).

The KBE approach is being realised by Stork Fokker AESP, as one of the key aerospace industries in the Netherlands, in collaboration with the National Aerospace Laboratory NLR, the aerospace research institute in the Netherlands.

The article will first show how the trends in industry are translated to challenges the stress department at Stork Fokker AESP BV is facing. Next, a KBE approach is presented, which has been developed to deal with these challenges. Finally, using an industrial case, the process of implementing the KBE approach in the daily stress engineering work will be discussed.

Stork Fokker AESP (SFA) develops and produces advanced complex lightweight structures for the aviation and aerospace industry. It excels in the design and production of box type structures, e.g., movables, empennages, and shell type structures, such as fuselage sections. A strong focus is on the continuous development and optimization of innovative material and manufacturing concepts, resulting in for instance Fibre Metal Laminates, which are applied on the A380 fuselage panels.

SFA has two engineering and production facilities in the Netherlands, and one engineering office in Bucharest, Romania. It supplies lightweight aircraft components and systems to leading European and American aircraft builders in both the civil and defense sectors, amongst which are Airbus, Boeing, Cessna, Dassault, Eurocopter, Gulfstream, Lockheed Martin, Raytheon and others. To remain competitive in the aerospace industry, SFA aims at being a knowledge-creating company, adopting knowledge based engineering as one of its core competences, thereby maintaining a strong relation with R&D institutes such as the National Aerospace Laboratory NLR.

The National Aerospace Laboratory NLR in the Netherlands is an independent technological institute which carries out applied research on behalf of the aviation and space sectors. NLR performs research to develop new innovative technologies for aviation and space travel, from a scientific perspective as well as for the application of this research in industrial and governmental sectors. NLR's clients include governmental authorities, large and small industries, and aerospace organizations - both in the Netherlands and abroad. NLR is a non-profit organization that carries out market-oriented and socially-relevant studies. NLR has two locations, one in Amsterdam and another about 100 kilometers to the northeast in Marknesse.

NLR has a long-standing and enduring relationship with SFA with respect to management and further development of validated and certified engineering methodologies and software supporting tools. NLR and SFA cooperate in several strategic research programmes to investigate the practical application of knowledge-based engineering technology to support and optimize the execution of stress-engineering methodologies.

Challenges for the engineering department

Responding to the trends in the aerospace industry, the engineering department of SFA strives for a significant reduction in lead time and in both recurring and non recurring cost. It is perceived that focusing on a qualitative better conceptual design and a leaner full-scale development process can achieve these goals.

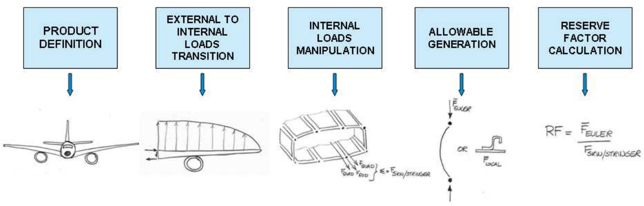

Figure 1. Basic steps in the stress analysis process

For the stress department, several challenges have to be overcome to achieve the state of ‘better and leaner’. Figure 1 presents a closer look at the stress process and helps to understand the challenges themselves and how SFA faces these challenges. The first step is to create an initial product definition, defining internal load paths based on external dimensions. Usually the aircraft integrator determines the external loading on the product, so the next step is to convert these external loads to internal loads. This step is usually executed using Finite Element Method (FEM) packages. A Finite Element (FE) model is a digital representation of the actual product. Subsequently, the applied load on the structural element should be calculated. This step entails a large amount of data reordering, combining FE data and product definition data, such as internal dimensions. Next the allowable load of the structure is calculated, via allowable methods, detailed testing or using legacy data. Finally, having determined the allowable load on the structural element, a reserve factor can be calculated.

To best perform their task, each discipline creates its own view on the product during the design process. Unfortunately, this typically involves non-value added work of transforming discipline specific product views in order to be used as input. It can be stated that in the stress process, most time is often spend on communicating information between disciplines and on manipulating data.

Because of the time-consuming process of analyzing a structure, it is not always possible to come up with multiple-concept solutions for a design problem. A more thorough evaluation of the design space during the conceptual design phase is needed to increase the quality of the solution.

Besides lead-time issues, the stress department also faces the challenge of reduced intellectual resources. The number of highly skilled lead stress engineers, who define the stressing guidelines and supervise the work of stress engineers, is becoming an issue. Not having sufficient time to thoroughly define the stressing methodology, more time is needed to supervise the individual stress engineers during their work, resulting in a vicious circle.

The different process steps can be executed using a large variety of software tools. The customer (aircraft integrator) often defines the tools to use. For instance each customer has its own set of allowable generation software. Hence, a requirement for the solution to the challenges stated above is that it must be customer independent. It should furthermore be possible to outsource stress work, without giving away Intellectual Property. Finally, the solution should promote the re-use of stress knowledge and tools.

The challenges can be summarized as follows:

- Reduction of the time spent for manipulating data.
- Increase of the span of control of lead engineers, so that they can supervise more engineers with less effort.
- Support for outsourcing of stress analysis activities while preserving the intellectual property of the information involved. Note that stress-engineering knowledge, including methodologies and skill tools, are part of SFA‘s business capital.
- Being workable and acceptable for all of SFA’s customers.
- Provision of supporting means independent from individual engineers.
- Facilitation of reuse of stress-engineering knowledge.
- Support for improving the quality of designs through support for analyzing more variants (trade-offs) within the same turnaround time.

The SAWA Concept

In reaction to these challenges, the stress department needs to capitalize on the stress analysis knowledge available, by promoting re-use and by automating non-creative (data manipulating) process steps. SFA is developing a methodology called Structural Analysis Workflow Automation (SAWA) to achieve this goal.

The point of departure for SAWA is the generic stress analysis workflow derived from the basic stress analysis steps; see Figure 2. This generic workflow is the blueprint for all stress analysis activities. As described in the challenge, different customers, projects, and products may require different analysis methodologies and tools. As a result in practice, an analysis-case specific instance of the generic workflow must be defined; this usually requires extra effort, time and costs. SAWA is aimed to support the definition and the subsequent application of specific stress analysis processes. This section describes the SAWA key concepts – the knowledge base, workflows, and tool encapsulation and chaining – that contribute to the targets.

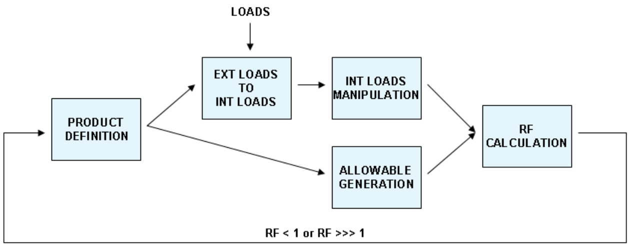

Figure 2. Generic stress analysis workflow for executing the basic stress analysis process as depicted in Figure 1.

The key constituent of SAWA is knowledge about stress analysis and its application. The knowledge comprises the stress analysis principles and expertise, which may be translated into methodologies and skill tools that support application of the methodologies. The knowledge is either already present or is gained by the engineers on the job. It may be capitalized by efficient reuse of it in subsequent analysis cases, whenever and wherever possible. Stress engineering knowledge is managed by practical application of Knowledge Management (KM; Ref. [3]) and Knowledge Based Engineering (KBE) technologies.

The knowledge is captured and "modularized", which means that the knowledge is translated and organized into "knowledge modules". These modules are reusable pieces of knowledge written down and made available explicitly in a form suitable for practical use in stress analysis. Examples of such modules are methodology descriptions, documented procedures and skill tools. The knowledge modules are managed in a knowledge library, called Fokker Structural Analysis Methods (FSAM).

The knowledge modules may be combined and chained into workflows. A workflow enables precise definition of a detailed stress analysis process as an instance of the generic stress analysis workflow in terms of a well-defined combination of knowledge modules and other workflows. The workflows may form a basis for automated application of the processes, and hence may enable engineers to execute stress analysis processes automatically and repeatedly. Automated and repeated execution of a workflow significantly contributes to reduction of analysis time in case the design specifications change. Notwithstanding any automation, an engineer always remains responsible for the analysis results. To achieve this, transparency of any automated analysis process is required to enable the engineer to view all basic analysis steps and (intermediate) results, being able to check results by hand.

SAWA distinguishes three levels of automation of stress engineering activities. *Level 1* is the automation of analysis activities by a single individual engineer. An engineer manually translates a specific analysis into a workflow, for personal use. Automated use of the workflow enables the engineer to perform similar tasks efficiently. The engineer is responsible for checking the consistency of the analysis result data, independently from any automation. *Level 2* is the automation of analysis activities at project level. Workflows may be created for use by the project team, for use only in the specific project during the project's life time. The project as a whole – instead of each individual engineer – is responsible for maintaining the flow and for checking the consistency of the analysis result data independently from any automation. *Level 3* is the automation of analysis flows for the whole company. At this level, an analysis flow is proclaimed a methodology, of which the results may be trusted without explicit checking by the user. SAWA promotes the establishment of methodologies along this lifecycle. A good practice at level 1 ideally promotes to the project level (level 2), and eventually evolves into a methodology at level 3. In this way, the knowledge base remains up to date with state-of-the-art stress engineering knowledge, and hence enables effective deployment of any new expertise.

Reuse of the knowledge available in the form of skill tools is facilitated through the notions of skill-tool encapsulation and skill-tool chaining. Skill-tool encapsulation supports easy application of skill tools by stress engineers. Typical heterogeneous commercial, legacy (also customer specific), and other tools are equipped with so-called wrappers that provide users with a unified and intuitive means to start and operate the tools and to manipulate the input and output data involved. Skill-tool chaining comprises the, possibly hierarchical, composition of chains (workflows) of encapsulated skill tools. It enables reuse and automated use of analysis workflows comprising skill tools. A chain may additionally include tools for recording actions and for managing (intermediate) data. As such, tool chaining may support the validation and certification of analysis results in that traceability information may be managed automatically, according to well-defined rules.

The concepts of FSAM, workflows, and skill-tool encapsulation and chaining support the lead stress engineer in translating stressing guidelines and any specific requirements into an instance of the generic stress analysis workflow for a specific stress analysis case. This instance can be further detailed by KBE engineers or stress engineers. Finally, the instance is ready for use for performing stress analysis. The combination of the concepts contributes to efficient definition and application of the stress analysis flow; see Figure 3.

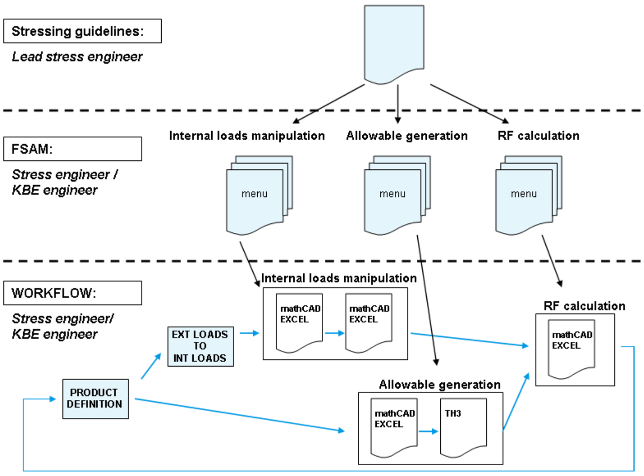

Figure 3. The SAWA concepts enable efficient definition and application of the stress analysis flow.

First steps towards SAWA realisation

SFA is in the process of implementing the SAWA concepts. It has recognized and adopted KM and KBE as the main contributing technologies in the implementation. NLR helps SFA with investigating and introducing new innovative concepts as well as with the technical realisation of SAWA. NLR has experiences with practical KBE solutions that support aerospace engineering processes, as exposed in several international projects (e.g., Refs. [7], [8]).

The SAWA philosophy is very promising, but its implementation will not come by itself. In addition to the technical realisation, the psychological aspects of introducing SAWA in an industrial situation require careful attention. The introduction will certainly yield some overhead initially, since it affects the mode of working of individual engineers. Engineers use their years or even decades of experience in carrying out their analysis activities, involving data manipulation and skill-tool operation. They usually deal with any inconveniences individually through use of handy tools, scripts and person-specific tricks. In such settings, SAWA may be perceived as a "big brother" who dictates how to do your work, who looks over your shoulder while you do your work, and who seems to overwhelm you with administrative work. Due to the perceptional in addition to the technical aspects, introduction of SAWA in the industrial situation is a challenge in itself. Consequently, SFA wants to gradually implement and embed SAWA in its industrial situation. A roadmap has been set up to introduce SAWA in projects step by step, and on the job, with minimum overhead for the engineers, the projects, and the organization.

The perceptional aspects of introduction of SAWA in an industrial situation are addressed in the use case in the subsequent section. This section describes the first main technical steps from the roadmap towards realisation of SAWA that are already in progress and that provide the basis for the use case described in the next section: the implementation of skill-tool encapsulation and skill-tool chaining.

Skill-tool encapsulation

Stress analysis involves the application of methods. In addition to public methods and customer-provided methods, SFA has its own collection of validated methods to analyze the strength and life of designed advanced aircraft structures. These legacy methods represent a large part of SFA's knowledge on stress analysis gained during the past decades. Until recently, the methods were certified by the Netherlands Transport and Water Management Inspectorate (IVW). Application of the methods is supported by means of software skill tools. A typical stress analysis requires the operation of several different and heterogeneous skill tools according to some recipe. The tools vary with respect to input and output data formats, required computer platform (e.g., Windows or Linux), way of starting (e.g., clicking an icon or typing a command on a command line interpreter, and tool options), and mode of operation (varying from batch mode to highly interactive, either with a command-line oriented or graphical user interface). In addition, the data involved needs to be manipulated by the stress engineer explicitly. As a result, application of the skill tools requires considerable effort from the stress engineers due to manual, non-value adding operation of the tool and manipulation of the data involved.

Efficient usage of skill tools was recognized as the first important area for improvement along the lines of SAWA. The first practical challenge was to facilitate the application of the SFA's legacy "allowable generation" tools (cf. Figure 1) by engineers in a way that engineers can focus on the stress analysis instead of struggling with skill-tool operation. The response to this challenge consisted of a framework that supports unified operation of the skill tools. The framework hides the heterogeneity of the tools. It enables engineers to use the skill tools in a uniform way, without, for example, having to deal with a variety of sometimes tool-specific input and output formats and the different modes and ways of starting and operation.

The framework is based on a uniform data format for representing the input and output engineering data of the tools. The format supports data exchange among tools and unified data management and manipulation. In addition, it supports the use of the framework's single, uniform and end-user (i.e., engineer) oriented graphical user interface (GUI) for preparing the inputs and for browsing the outputs of the variety of skill tools integrated in the framework.

Incorporation (or integration) of a skill tool in the framework is established by encapsulation instead of modification of the skill tool's code. Modifying an existing tool is either impossible or highly undesirable. It usually requires source code to be changed and recompiled or alternate run-time libraries to be linked with the tool.

Modification of commercial and customer-supplied tools is often either impossible or too costly, in case the supplier of the tools wishes to cooperate at all. Modification of the legacy skill tools is highly undesirable. The tools as available have been validated and certified as is, and any code changes would require new validation and certification, which is costly. Encapsulation is accomplished by wrapping an existing tool "as is" with software modules that bridge the gap between the unified use and the tool; see Figure 4. The wrapper includes input and output data converters, and handles the screen inputs and outputs on behalf of the user. The uniform GUI enables the engineer to operate the tool in an intuitive, uniform and tool-independent way. It applies knowledge about the legacy tools to provide the engineer with support in preparing the input data, executing the skill tool, and browsing the output data.

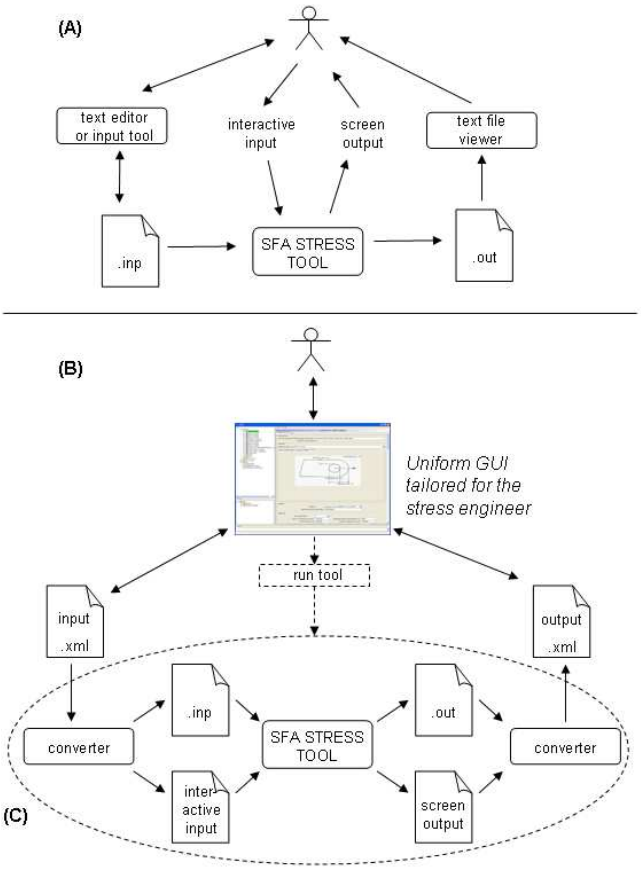

Figure 4. Comparison of skill-tool operation by the stress engineer in the traditional way of working without a framework (A) and in the innovative way of working with the framework (B). The oval (C) indicates the encapsulated tool.

Despite the wrapping, the framework allows for inspection and preservation of the actual ("original") input and output files of the legacy skill tool. This openness enables the engineer to check the actual data being used for analysis. As such, it may contribute to enlargement of the engineer's confidence in the tool encapsulating facilities, and hence to acceptation. The openness is also required for certification purposes, which are based on the certified legacy skill tools instead of the encapsulated tools.

The framework is currently being implemented. Experiences with preliminary versions are positive and seem very promising. SFA's own GUI-less legacy stress-analysis skill tools are being encapsulated. The framework will accommodate commercial and customer-provided skill tools in the foreseeable future.

Skill-tool chaining

Skill-tool encapsulation facilitates application of stand-alone skill tools, and as such is an important building stone for optimizing stress analysis. However, stress analysis typically involves the execution of combinations of skill tools according to well-defined analysis flows. As a result, skill tools are usually used in chains. Skill-tool chaining is recognized as the next practical step towards realization of SAWA.

Skill-tool chaining facilitates definition and automated execution of analysis flows that comprise skill tools and other skill-tool chains, data-conversion and data-manipulation tools. In combination with functionality for loops and iteration over parameter values, skill-tool chaining also facilitates parameter variation studies and optimization techniques. In addition, it supports validation and certification of analysis results. Traceability of information can be managed automatically, according to well-defined rules as specified as part of the methodologies. Finally, tool chaining practically contributes to design-time reduction if the design specifications change: stress analysis flows may be rerun automatically with modified input values, possibly due to changes in customer requirements.

Basis for the implementation of tool chains is an NLR tool-chain management middleware utility. This middleware supports interactive integration of tools, interactive definition of tool chains, and interactive as well as batch-mode, manual and automated usage of tools and tool chains (Refs. [5], [6]); see Figure 5. The middleware caters for uniform use of heterogeneous commercial, customer-provided, and in-house developed engineering tools. It facilitates easy integration of the tools, including any encapsulated tools as described in the previous section. Tool integration is accomplished using a wrapping technique, which takes care of unified operation of the tool with respect to start-up, input and output file handling. The legacy tool's GUI (e.g., the uniform GUI of an encapsulated tool), if any, is left intact.

An integrated tool may be used stand alone. In addition, it may be included in a tool chain. A tool chain defines a possibly hierarchically organized graph of tools, other (child) tool chains, and data boxes for the exchange of data among its constituents, representing a scenario of tools and manipulation of the data involved. In addition, the manual or automated (e.g., as soon as the inputs are available or change) execution of tools and child tool chains may be controlled explicitly. The notions of tools and tool chains enable preservation and reuse of the knowledge on skill-tool usage. An expert, usually a lead stress or KBE engineer, defines a chain for an analysis process. The chain may next be easily detailed and used – either stand-alone or embedded in a larger chain – by other engineers.

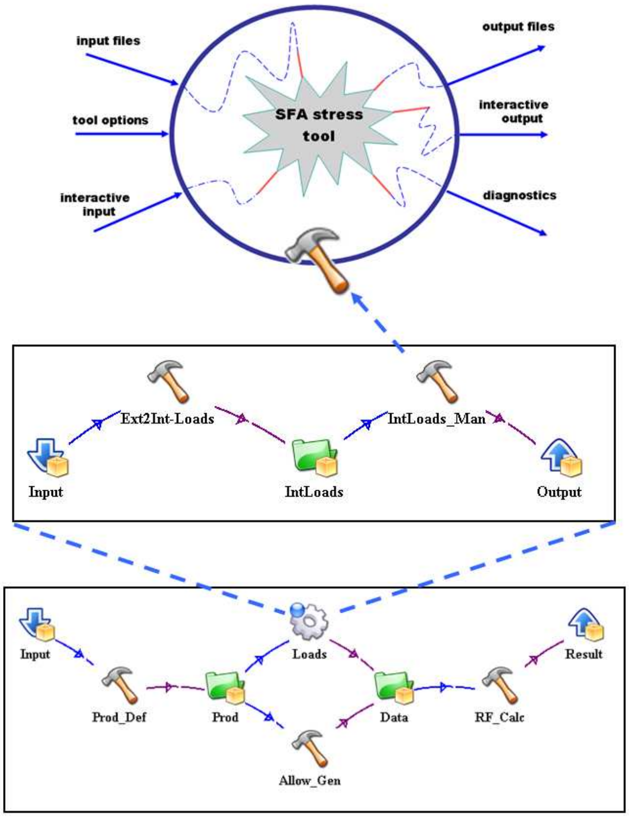

Figure 5. Graphics enabled skill-tool wrapping and chaining. Legacy skill tools are wrapped into a uniform tool object. Tool objects may be chained together with folder objects for data storage. Hierarchical skill-tool chains may be composed to deal with complexity.

The middleware supports local as well as secure remote web-based access to tools and tool chains, both interactively as well as in embedded mode. Interactive access is provided through a general-purpose user interface or a specialized user interface. The middleware provides a general-purpose graphical user interface (GUI) for tool and tool-chain manipulation, providing the user with a point-and-click and drag-and-drop interface. The specialized user interface is a user interface that is tailored for a special group of end users, such as stress engineers. Embedded access enables other applications, such as an engineer's own desk-top applications, to use tools and tool chains "under the hood". Embedded access may be combined with web technology to realize secure remote web-based access. In this way, SFA's supply chain and engineers located at customers may apply tools and tool chains, while preserving the intellectual property of the knowledge represented by the tools and tool chains.

SAWA uses the tool-chaining middleware's general GUI at automation levels 1 and 2 to cater for composition and use of tool chains. SAWA uses the middleware's embedded mode to accomplish level-3 use of tool chains. In this latter case, the GUI is provided in terms of the uniform GUI as depicted in situation (B) in Figure 4, with the oval (C) depicted in Figure 4 replaced by a secure remote call to the embedded workflow managed by the tool-chaining middleware.

Fokker Structural Analysis Methods

The knowledge on how to perform a specific analysis is stored in the Fokker Structural Analysis Methods (FSAM) knowledge base. The philosophy of creating flows of skill tools for process automation is reflected in FSAM. The lowest FSAM level is the tool or module level, describing the methodology captured in a specific tool. The workflow level describes the order of execution of the modules, and defines input and output relations. A workflow is at the level of the generic SAWA steps, see figure 2. The highest concept level is the application, which defines the generic steps that are needed for the analysis of a specific structural entity for different failure modes.

The creation of a workflow level is needed to show the relation to the generic stress process description, whereas the module level relates to the actual tool that is used to perform the analysis. Splitting the high-level process steps into smaller modules promotes the reuse of tools, since similar steps are performed in the large amount of analyses performed during the structural analysis process.

FSAM is essential for the documentation of the stressing methodology, by creating multi-level process diagrams and describing the process knowledge for each process step. FSAM is also used for making sure that the correct relations and execution order of the modules is established in the software. Finally, FSAM makes reuse of modules possible by keeping track of module usage in different applications.

Embedding SAWA in the organization: A use case

A use case of the SAWA concept is discussed to assess whether the challenges are met. The development of applications for the analysis of the joints in a thermoplastic rudder will be presented; see Figure 6. Thermoplastics are polymers that melt at elevated temperatures and consolidate at cooling. This property is used for joining thermoplastic parts, and it is called "welding" at SFA. Besides welding, also fastening is used to join thermoplastic parts. The analysis of a joint entails multiple failure modes. For the analysis of the joints in an elevator, three different applications have been developed; for welded joints, for short-fastened joints (≤4 consecutive fasteners) and for long-fastened joints (>4 consecutive fasteners).

As described in the previous section, SFA developed these applications in the philosophy of level-2 automation. This means that the output created by the applications cannot a priori be assumed to be flawless. A check needs to be performed, which is done using a hand calculation. Such a hand calculation describes at module level the manner in which to evaluate correct execution of the module. Hence, there is a father-child relation between FSAM and the hand calculation document.

Concluding, before being able to create the first structural analysis report, the FSAM and hand calculation have to be developed and approved, and the application has to be programmed.

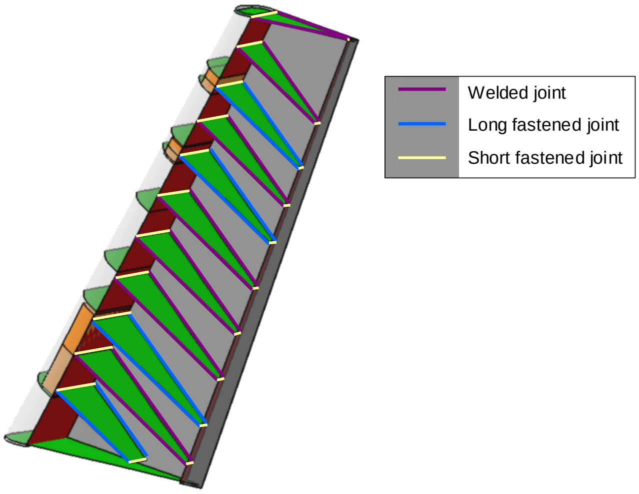

Figure 6. General structural layout of a rudder.

Application development process

For the development of the above-described deliverables, a team of a lead stress engineer, a stress engineer, and a KBE engineer has been assembled. The lead stress engineer, as indicated in figure 3, is responsible for defining the stressing guidelines. Using these guidelines, the stress and KBE engineer together developed a step-by-step process description, which serves as the basis for the FSAM and hand calculation. The role of the stress engineer in this process is to make sure that the correct analysis methodology is used, which is validated by the lead stress engineer; the KBE engineer is responsible for defining the generic process steps. The more generic a process step is, the higher the change for reuse of modules. Having defined the individual steps, the stress engineer starts developing the actual software tools; the KBE engineer is responsible for the correct order of execution, and for an explicit and formal description of the methodology (in FSAM). Finally, the stress engineer develops the hand calculation for checking the data generated by the application.

This well structured way of working proved to be quite a deviation from the normal structural analysis process. In the conventional process, the stress engineer would use spreadsheets, combined with low-tech programming tools and manual processes, to perform various data manipulations. The checking of these spreadsheets poses a formidable challenge to the lead stress engineer, since each cell in the worksheet should be checked for compliance with the stressing guidelines. However, these stressing guidelines present a high-level process description, resulting in a continuous supervision of the individual stress engineers creating the spreadsheets.

Initiating the development process

Although the benefits were obvious for the KBE office, the implementation proved to be not as straightforward as anticipated. A focus on the success factors for this particular change process proved imperative.

Four main groups of success factors have been identified: MUST, HAVE, CAN, and WANT (Refs. [3], [4]). The MUST factors are external motivations like managers, co-workers, and social networks. Time, money, resources and support are examples of the HAVE factors. The CAN factors are for instance competences, skills needed, tools and the ability to use them. Finally the WANT factors are intrinsic motivations such as ambition, attitude, perceived advantages and disadvantages.

A strong focus has been put on the development of working methods, software encapsulation and execution techniques in the development of SAWA: the CAN factors. Furthermore, using the challenges faced by the engineering department, an attempt had been made to create a sense of urgency amongst both managers and engineers. The managers provide channels to enforce a new way of working (MUST). A sense of urgency amongst engineers can help to create intrinsic motivation (WANT).

During an identification phase of possible areas of high return-on-investment (ROI) in the stress process automation, the analysis of joints had been identified. A high ROI was determined by the enormous amount of fastened and welded joints, and given the fact that the same analysis will have to be performed multiple times because of changing inputs.

In a subsequent session, SAWA and the application development process have been presented. A first reaction of the lead stress engineers was that SAWA would take them more time and effort to do the same jobs. Why would they invest, and why would others benefit from this investment? Although they acknowledged the possible benefits in the long run, they needed time, resources and budget to justify the development. Time was limited because anticipated benefits from SAWA had already been incorporated in the project planning. Resources and budget were made available, and finally the decision was made to start the development of the applications.

Application development

During several sessions, the analysis methodology was presented by the lead stress engineer to the stress and KBE engineer. However, given the limited time available, the methodology had not been worked out to a sufficient level of detail to correctly start the development process. Again due to time pressure, the development process did start, in a somewhat changed order of deliverable generation than described above. The hand calculation, modules and FSAM were created simultaneously. This required close communication between stress engineer and KBE engineer, and the continuous supervision of the lead stress engineer. Because of this simultaneous development, no clear overview of the details of the stressing methodology was available. Hence, the lead stress engineer could only give corrections to the methodology at a late stage, resulting in late changes to all three deliverables.

Nevertheless, because of the modular approach, modules and accompanying FSAM documents could already be reused in the development of the joint application. This accelerated the development process, and confirmed the a priori assumption that SAWA would result in reuse of both knowledge and tools.

Some remarks of a stress engineer involved in KBE application development:

- A tradeoff is made between the generic character of application vs. development time.
- Checking/adjusting of KBE application can be difficult (programming experience of developer/checker).
- Development of application is mainly programming (programming experience of stress engineer is required).

Thus, besides time needed to do the initial investment (HAVE), also programming skills (CAN) are important.

Application deployment

One of the objectives of the SAWA initiative is to increase the span of control of the lead stress engineer. The conventional process requires the lead stress engineer to check every data manipulation step for compliance with the stressing guidelines. The SAWA methodology requires the lead stress engineer to evaluate whether the FSAM modules are according to the stressing guidelines. The stress engineer uses the hand calculation to check the actual data.

Furthermore, reuse of knowledge is promoted, because of the possibility to reuse FSAM modules, software modules and hand calculations. If this reuse is to result in development time reduction, it is essential that lead stress engineers put confidence in the work of other lead stress engineers. Re-evaluating FSAM and hand calculations could cancel out the possible lead-time reduction.

Another performance indicator is the generic character of a module. The more generic a module is, the more likely the module concepts (FSAM, software and hand calculation) can be reused. It is up to the KBE engineer to monitor the generic character of the modules, since he has the best overview of formalized knowledge (FSAM) and software development.

Figure 7 qualitatively shows the possible lead-time reduction of a SAWA enhanced design process. The initial calculation takes more time, thus investment in time and resources is needed. However, the inevitable iterations due to input changes take less time. Furthermore, errors were found in the conventional calculation at a later stage, resulting in an additional iteration. The calculations had to be redone and the stress reports had to be generated for a second time. The figure also shows in the upper right corner reuse of the applications for a different movable. Since the initial investment had been done for the SAWA enhanced process, an even more significant lead-time reduction could be achieved for the project. It is expected that in the near future this trend in lead-time reduction will persist.

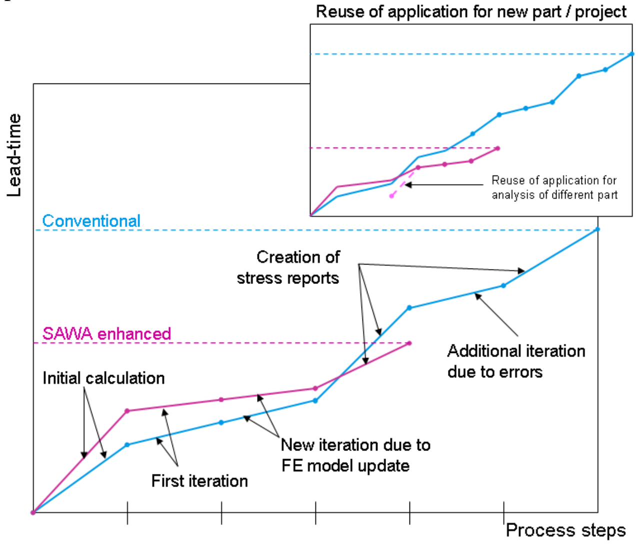

Figure 7. Time and design cycle comparison between the traditional and the KBE-enabled joint analysis processes. The figures depict the expectations from the engineers based on current experiences. The SAWA enhanced process takes fewer steps because the initial calculation step, in which the designed calculation flows are verified using hand calculations, minimizes errors in the subsequent steps. Notice the large reduction in lead time.

Besides the lead-time reduction, also the perception of the user is important. Some remarks of a stress engineer involved in KBE application deployment:

- Results can be obtained easily and fast for small changes in input (e.g. updated load data).
- Reuse of existing applications in different projects (e.g. joint analysis tool).
- Easy to use because of centralized documentation system (FSAM).
- Because of modular approach, errors are located relatively easy.
- It is essential that all three deliverables are present. Otherwise erroneous results will be obtained.
- Check on input is needed, since most errors originate at incorrect input.

Conclusions

The SAWA methodology of application development provides a very flexible format, which is needed in the more creative stages of the design process. This flexibility is provided by the hierarchic creation of deliverable, where stressing guidelines provide the starting point of further development. A lead stress engineer is not limited by software requirements when designing the solution process. Next, flexibility is provided by the modular approach, giving the opportunity to easily incorporate changes in the stressing guidelines.

It is important to acknowledge that implementing a process improvement such as SAWA incorporates a large change from the conventional process. All the success factors should be emphasized. Indeed, in the use case it is made clear that not only the CAN factors can result in a successful deployment. Also an intrinsic motivation of the engineers, developing and using the applications, is needed. Furthermore, time and budget to make the initial investment should be available.

A significant lead-time reduction can be achieved, taking into account the iterative character of aircraft design. Furthermore, the same toolset proved to be useful for the analysis of other parts and other projects, providing time saving without additional investment.

The process improvement achieved by SAWA allows a supplier of advanced structural components to major aircraft integrators to actively be competitive. The significant lead-time reduction enables the supplier to apply an analysis of a design in less man hours, to apply a more thorough analysis (thereby considering more cases) of the same design for the same man hours, or to apply an analysis of a more complex design also for the same man hours. In the first case, the same quality products can be delivered in shorter time and at less cost. In the latter two cases, more advanced and complex quality products can be delivered for the same price and within the same time frame. In practice, the supplier will choose for a mixture of the cases, depending on the integrator's requirements and the market situation. In addition, SAWA allows the supplier to be more resilient – and hence more attractive for an integrator – with respect to design iterations resulting from changes in the specifications.

As described in this paper, the first steps towards practical application of SAWA have been taken and already positive experiences have been gained. A next important step is to smoothly introduce SAWA in the industrial environment. The technical aspects (i.e., CAN factors) to be taken are clear: productisation and broad application of the SAWA notions of FSAM, tool encapsulation and chaining, and tool-chain automation. The challenge is the true acceptation by the engineer: the WANT factor. Another important step is to exploit the possibilities of secure remote access to tools and tool chains. Third parties such as the supply chain, partners, and subsidiaries are able to perform analyses using SFA's methodologies and tools, while preserving the intellectual property of these. Yet another important step is to put integrated and automated data and configuration management into practice, to support results traceability, certification, production, and maintenance. The road to full application of SAWA will certainly be a bumpy one, but the early experiences are very promising.

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References

[1] S. Cooper, I.S. Fan, G. Li, "Achieving Competitive Advantage through Knowledge-Based Engineering. A Best Practice Guide", Department of Trade and Industry, Cranfield University, Cranfield, UK, 2000.

[2] M.J.L. van Tooren, G. La Rocca, A.H. van der Laan, J.P.T.J. Berends, C. Cerulli, J.E. Schut, M. Nawijn, H.A. Baluch, "Knowledge Based Engineering supported design", a collection of selected KBE publications, Faculty of Aerospace Engineering, Delft University of Technology, the Netherlands, 2006.

[3] Rob van der Spek, Mike Kelleher, "Knowledge management: reducing the costs of ignorance". http://www.dnv.com/services/consulting/knowledge_management/Publications/, 2005. Last visited September 2008.

[4] Richard McDermott, "Knowing in Community: Ten Critical Success Factors in Building Communities of Practice", IHRIM Journal, Vol. IV, No. 1, Match 2000.

[5] E.H. Baalbergen and H. van der Ven, "SPINEware - a framework for user-oriented and tailorable metacomputers", Future Generation Computer Systems 15, 1999, p. 549-558. Also NLR Technical Publication NLR-TP-1998-463.

[6] T. Kanakis, E.H. Baalbergen, H. van der Ven, "Integrated Technology for Collaborative Engineering in Aerospace", European Concurrent Engineering Conference (ECEC), 11-13 April 2005, Toulouse, France. Also NLR Technical Publication NLR-TP-2005-735.

[7] W.F. Lammen, E.H. Baalbergen, M.H. van Houten, "Knowledge-Based Engineering for Concurrent Design Applications", Concurrent Engineering for Space Applications Workshop, ESTEC Noordwijk, the Netherlands, 19-20 October 2006. Also NLR Technical Publication NLR-TP-2007-677.

[8] Ernst Kesseler, Paul Arendsen, Rien van Houten, Roland Parchem, Bernd Meissner, Marc Nagel, Johannes Barner, Holger Wenzel, "Empowering Engine Engineers. Advancing the state of the art in collaborative multi-national multidisciplinary engine design", 1st European Air and Space Conference, Berlin, Germany, 10-13 September 2007. Also NLR Technical Publication NLR-TP-2007-902.