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The Engineering Service Bureau-

Empowering SMEs to Improve Collaboratively Developed Products

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ABSTRACT

Although the development of major engineering products currently depends on small manufacturing enterprises (SMEs) for over 50% of the design/manufacturing effort, SMEs are typically unable to afford sophisticated analysis, such as FEA. Since often only the SME has sufficiently detailed product and process knowledge to carry out meaningful analysis, the engineering knowledge of the entire development team is diminished. The Team InteGrated Electronic Response (TIGER) Project addressed this issue, developing an Engineering Service Bureau (ESB) concept as a means of empowering SMEs with advanced analysis capabilities. An ESB provides a fee-for-service analysis service, ranging from consulting to 'self-service analysis', where engineers at the SME interact with pre-developed analysis modules directly. This highly automated plug-and-play self-service analysis is enabled by usage of STEP rich product models and design-analysis integration techniques. Example services an ESB might provide and guidelines for establishing such a service are also discussed.

ABBREVIATIONS

AP210 - ISO STEP standard for PWA/PWB descriptions
PWA - Printed Wiring Assembly (circuit board and components)
PWB - Printed Wiring Board (circuit board only)
SME - Small-to-Medium-sized Enterprise (supplier)
TIGER - Team InteGrated Electronic Response
ESB – Engineering Service Bureau
ECRC – Electronic Commerce Resource Center
DARPA – Defense Advanced Research Projects Agency

1. INTRODUCTION

Complex engineering products such as automobiles, aircraft, computer systems, and energy systems are currently designed and manufactured by a web of interrelated companies. Typically one corporation, the major product developer, is responsible for the overall design of the product. We refer to this corporation as the Prime. The Prime will often subcontract specific portions to smaller corporations, which we term the First Tier Suppliers. The First Tier Suppliers, in turn, obtain their components from Small-to-Medium-sized Enterprises (SMEs), who typically specialize in manufacturing products in a narrow market niche. This structure results in over 50% of the design/manufacturing effort being carried out by SMEs [Ramesh et al., 1995]. However, because of the separation between the Prime, who controls the design specifications, and the SMEs, who have the domain-specific expertise, many delays are introduced into the product development cycle. In addition, the SMEs are not able to fully leverage their process and product expertise because they cannot perform sophisticated 'what-if' analyses to study the product-wide effects of cost saving measures or other product enhancements.

A recent project, TIGER- Team Integrated Electronic Response, was sponsored by the Department of Defense and funded through the National ECRC Program to improve the process by which products are developed in this multi-tiered business environment. TIGER focused on reducing time-to-market and design revisions by bringing the various companies together to form a collaborative engineering team. One facet of this work was establishing a technical infrastructure that enables small enterprises to effectively participate in the team's collaborative review and determination of product technical specifications as the design evolved.

The Concurrent Engineering approach mandates considering requirements, design and analysis, plan to manufacture, production and procurement, product support, and disposal activities early in a product's development cycle. SMEs can contribute the expert manufacturing knowledge and detailed product information needed to perform analysis with high quality models and sophisticated techniques such as FEA.

Unfortunately, there are a number of barriers that make it difficult in practice for the SME to carry out this level of analysis:

- Access to analysis information. It is difficult for the SME to either (a) find proven analysis models in ready-to-use form, or (b) develop the models internally and validate them experimentally.
- Cost. A considerable expense is involved in both infrastructure investments (hardware and software), and intellectual investments (training and model development).
- Ease of use. The general nature of most CAE analysis tools means that they have complex interfaces that are difficult for the non-expert to use. In addition, they cannot exploit domain-specific structure in the problem being analyzed, so product descriptions must be built up from scratch.

The SME’s low volume analysis requirements may not justify the resource expenditures required to overcome these barriers and develop in-house analysis capabilities. Since often only the SME has sufficiently detailed product and process knowledge to carry out meaningful analysis, it is difficult for other members of the collaborative team (such as the Prime) to fulfill the analysis function. Therefore, a lack of analysis at the SME level diminishes the engineering knowledge of the entire product development team.

The TIGER project team proposed and developed an Engineering Service Bureau (ESB) concept as a means of empowering SMEs with advanced analysis capabilities. A Service Bureau provides a fee-for-service analysis service, ranging from ‘self service’, where engineers at the SME interact with pre-developed analysis modules directly, to ‘full service’, where ESB consultants carry out all aspects of the analysis for the SME.

The Engineering Service Bureau concept potentially offers SMEs several benefits. Because the ESB specializes in analysis services, the ESB can guarantee much greater utilization of investments in infrastructure and intellectual property than would be possible for a SME, lowering the per-use cost of analysis. The decreased cost of sophisticated analysis enables the SME to perform process simulation tasks to improve manufacturing yields, analyze product performance to judge design alternatives, and other analysis-driven optimizations.

Other possible drivers for analysis outsourcing are one or more of the following. 1) The SME is unable to be price competitive in the market when analyzing their own products and processes. 2) The SME wants to concentrate on new product technologies such as Flip Chip Attach or Multi-Chip Modules, and therefore has greater analysis needs than when producing its mature technology designs. 3) The SME cannot provide enough in-house analysis to meet current demand, but the demand may be only a temporary peak, and so the capital/personnel commitments necessary for analysis ‘production’ expansion are risky. 4) The SME has little electronic design and manufacturing analysis experience (for instance, SMEs new to the field of electronic assembly).

Section 2 below portrays how the Engineering Service Bureau paradigm fits into a distributed, multi-company collaborative engineering environment by describing in general terms the use of the demonstration ESB U-Engineer in the TIGER example scenario. Section 3 gives some examples of what the value-added services of an ESB might be, while Section 4 provides preliminary technical requirements for establishing an ESB. Section 5 provides a concrete, step-by-step ESB usage example from TIGER to illustrate the concepts discussed in the previous sections, while Section 6 presents an overview of the paper.

2. TIGER PROJECT BACKGROUND

The concept of the ESB developed during work performed by Georgia Tech on the DARPA/ECRC-funded TIGER project [TIGER, 1997]. TIGER focused on three organizations representing the three levels of a typical large-scale product development program. The Boeing Defense & Space Group, headquartered in Seattle, Washington, represented the Prime contractor. The Defense & Space Group designs, produces and maintains avionics and other aviation-related electronics. Examples include radio communication equipment, audio equipment, and attendant and navigation panels. It also furnishes secondary flight controls and specialty avionics products and services such as interface electronics, controllers, build-to-print items and associated test and support equipment unique to Boeing airplanes. [Boeing, 1997]

The electronics designed by the Defense & Space Group are primarily produced at the company's commercial electronics manufacturing facility in Irving, Texas. This wholly owned Boeing subsidiary represented the First Tier Supplier in TIGER.

Boeing-Irving in turn subcontracts out to a vast array of specialty fabrication and component suppliers. Holaday Circuits, Inc. of Minnetonka, Minnesota, a Printed Wiring Board (PWB) supplier, represented a typical SME.

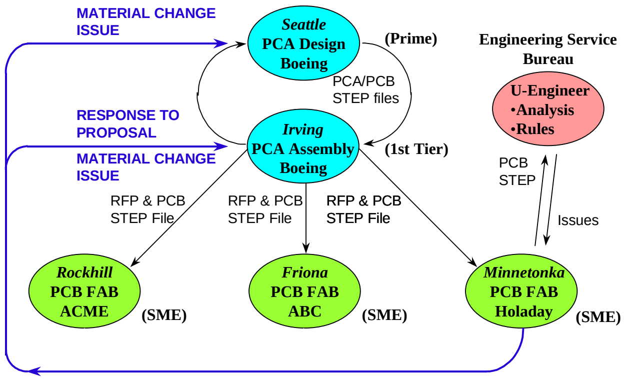

Figure 2-1: TIGER Collaborative Development

The TIGER scenario involves the development of a Printed Wiring Assembly/Board (PWA/B) design through interactions with the Prime (Boeing Defense & Space), the Assembly Factory (Boeing Irving), and Holaday Circuits. As illustrated in Figure 2-1, after some initial iteration with the Prime, the First Tier Supplier offers the PWB fabrication work to several SMEs. One of the SMEs, Holaday Circuits, turns to U-Engineer, a demonstration Engineering Service Bureau at Georgia Tech, for assistance in running computer-aided analyses of the bare PWB. These analyses suggest that a lower in cost material than the initially specified material will meet the product requirements, enabling Holaday to make a cost-savings recommendation to the product development team.

TIGER demonstrated advanced prime-supplier collaboration through standards including STEP and X12. In particular, it emphasized the need for SME analysis in order to improve product quality and cost. However, TIGER has also highlighted the formidable barriers against suppliers performing such analyses, including analysis model development and awareness, CAE tool costs, and ease-of-use. We believe self-service, Internet-based Engineering Service Bureaus are a key means to help resource-limited SMEs overcome these barriers and become an effective part of the product team.

3. EXAMPLE ESB SERVICES

ESBs may provide a wide array of services, ranging from AI-based heuristic evaluations such as process specific design checks or design-for-manufacturability (DFM), to discipline-specific numeric computations, such as thermo-mechanical analysis. Rather than having one ESB offer all these services, we envision multiple ESBs, each operating as a Center of expertise, with a healthy competition between bureaus. While there will be several differentiating factors between centers (including user assistance and documentation, ease of use of the tools, etc.) ultimately their service will only be as good as the analysis modules they provide.

One of the services an analysis-focused ESB should provide is a catalog of diverse analysis models with differing levels of complexity for the product domain of interest. These might include: 1) models "widely accepted" in the industry (i.e. Electronic Packaging models documented by the Institute for Interconnecting and Packaging Electronic Circuits [IPC-D-279]) 2) models which have been published in respected journals or other literature 3) internally developed, proprietary models which are based on experimental data. Normally, the higher complexity models such as FEM produce higher accuracy results but are more expensive to run. We envision the high accuracy models being used as a verification of designs after iterative improvement using lower cost, simpler analysis modules. (For example, see the ESB usage example in Section 5.)

It is important to realize that many of the ESB clients will be only occasional users, connecting to study the unusual or cutting edge product configurations they are asked to manufacture. An important feature of the provided services therefore is that the ESB needs to wrap solution tools in such a way as to shield the clients from the gory details of the tools. For the sake of users with a greater understanding of the tools involved, it is probably still useful to make available suitable intermediate analysis results (screens showing analysis variables of interest, output files from tools such as ANSYS, graphical representations of analysis results, etc.). However, the mapping from the product domain (PWB attributes such as length, width, and height) to the analysis domain (mesh size, density, and element type in the case of FEA) must be handled automatically. Similarly, the reverse mapping, where for example the dimensionless nodal displacement of element 843 needs to be converted back into a PWB board warpage measurement, must also be handled transparently. In addition to wrapping the inputs and outputs of analysis tools, the ESB must also provide a means (hopefully a GUI) to enable SME clients to manipulate the product description in some fashion as they "do design".

There is a wide arena of information needed to support analysis, and another value-added service of the ESB is to provide this data. In the structural and thermal analysis of electronic packaging, this requires catalogs of mechanical and thermal properties. Again, varying levels of complexity are needed, from constant, elastic, temperature-independent properties, to nonlinear, strain and time dependent, temperature dependent properties. In general, "typical values" for many of the analysis parameters of interest are useful. For example, a design engineer performing a quick verification of how a particular design will fare in the manufacturing environment will need 'typical' values for various stages of the manufacturing process. A manufacturing engineer making process design decisions concerning how to manufacture a specific part will probably want to use company- or factory-specific values for these same parameters however. Thus, all properties that the ESB provides must have the provision of being over-ridden by user input, and where possible should be capable of being extracted from standard files, to avoid error-prone manual re-entry.

In addition to delivering these capabilities to SMEs on a self-service basis for highly automated routine analyses, a commercial ESB should also offer consultation-based full-service analyses for challenging new problems. Potentially, these new analyses eventually become repackaged for self-serve analysis as the industry as a whole evolves. For example, a custom analysis of an ambitious new application using Flip Chips could eventually become a routine analysis as this technology becomes more of a standard packaging option. This potential inter-relation between custom consulting work and self-serve analysis means that commercial ESB operations will probably most successfully evolve from existing engineering consulting businesses over time. The section below details some of the infrastructure that has to be developed to allow this to happen.

4. GUIDELINES FOR ESTABLISHING AN ESB

4.1. Connectivity

TIGER project experience indicates that the Engineering Service Bureau should be connected to the Internet for ease of electronic data transfer and access to the graphical interfaces controlling the analysis tools. This is of substantial benefit to the SME, since by acquiring the technology to access a single service (the Internet) they gain access to a worldwide marketplace of competing Engineering Service Bureaus. This is in contrast to other approaches which champion separate networks for each service, such as the Value-Added Networks (VANs) espoused by some Electronic Data Interchange (EDI) software vendors, or the proprietary networks for video conferencing. While these approaches have merit for highly capitalized companies, SMEs must carefully examine the value of each dollar spent. Internet access is also attractive to cost-conscious companies because it provides many other benefits to the SME as well, and is increasingly being viewed as a standard method for customers to get in contact with a company.

The Internet is a useful marketing and distribution medium for a wide variety of businesses. It provides an inexpensive and ubiquitous platform for conducting commerce, enabling both business-to-business and consumer exchange of goods, services, and information. These exchanges between an SME and an ESB or several ESBs are essentially the formation of a 'virtual enterprise', which allows the SME to reduce costs, extend their reach, and develop a competitive edge.

4.2. Standards Driven

To minimize the need for specialist intervention and to provide rapid response, high accuracy, and lower cost analysis, the ESB analysis modules should be capable of reading necessary information from neutral product and process files (e.g. STEP-standard files). The maxim 'Garbage In, Garbage Out' is especially valid for computer aided analysis tools. Building accurate analysis models takes time, however, and in the past was typically manually performed for each product to be analyzed. This raises both the response time and the ultimate cost of the analysis, preventing the early and frequent use of analysis through the product development cycle. To overcome this obstacle, a major thrust of the TIGER-developed technical infrastructure is the ability to intelligently "routinize" analysis [Peak, et. al. 1996]. This process parameterizes analysis to the extent that data read from neutral product and process files (ISO 10303 STEP files), combined with Artificial Intelligence (AI) techniques, can provide highly detailed analysis modules. The design-analysis integration (DAI) techniques underlying this methodology are covered in [Peak et. al., 1995], [Tamburini et. al., 1996], [Tamburini et. al., 1997] and [Zhou et. al., 1997]. From an infrastructure point of view, this approach means that the ESB must be able to accept and analyze product and process files which can be large (e.g. 25 megabytes for some STEP files) from an Internet point-of-presence.

The TIGER Demonstration ESB project applied these techniques to drive self-serve thermo-mechanical PWB analyses from STEP AP210 data files exported from Mentor Graphics ECAD tools. [Peak et. al., 1997]

Increasing pressure to bring products to market faster means that the traditional bottleneck in the contract consulting/analysis business- the transfer of product information from the designers to the analysis provider- is fast becoming the areas where 'Standards savvy' ESB companies can differentiate themselves from the global consultancy pack.

4.3. Security

SMEs must have confidence in the ESBs they deal with in order to enter a partnership of trust with them. In some cases, the Prime contractor will mandate a certain level of security. Even in the absence of external decrees, once a SME has agreed to upload their product and process information to run analysis tools at an ESB, that information needs to be secured from unauthorized access. Furthermore, in the "virtual" environment of the Internet, the ESB must establish its identity and credibility to protect itself and its customers from impostors.

These objectives are readily achievable with current technologies, such as Secure Sockets Layer transmissions and Digital IDs. [Verisign, 1997]

A Digital ID provides an electronic means of verifying that the individual or organization is who they claim to be. The Server Digital ID, for example, provides third-party evidence of an Internet Web server's authenticity, establishing that the server is operated by an organization with the right to use the name associated with the server's Digital ID. Web browsers generally perform server authentication automatically. The user is only notified if authentication fails due to an expired certificate, mismatched URL, or other problem.

The Secure Sockets Layer (SSL) is a technology developed by Netscape and adopted by many vendors producing web-related software. It negotiates and employs three fundamental security services:

1) *Mutual Authentication*. SSL 3.0 allows the identities of both the server and client to be authenticated through exchange and verification of their Digital IDs.
2) *Message Privacy*. All traffic between an SSL server and SSL client is encrypted using a unique session key. The server's key-pair is used to encrypt the session key itself when it is passed to the client.
3) *Message Integrity*. SSL also protects the contents of messages exchanged between client and server from being altered enroute.

By taking security measures such as these, an ESB protects SME data property during transmission. Other security issues such as secure data storage are discussed in [DoD 5200.28-STD].

4.4. Account Management

Each ESB needs to make several decisions regarding the user accounts. First, they must decide if accounts are to be managed at the group (e.g. company) level or the individual level. The typical tradeoff here is less ESB administrative overhead with fewer, company-level accounts versus any client concern over the lack of compartmentalization of data between different users of the company account. Second, the ESB must decide if data is persistent between sequential accesses to an ESB. Persistent objects in a CAE environment would then dictate each customer (or aggregate customer such as a corporate account) has his or her own instantiation of the environment. This is potentially costly for the ESB because additional capacity must be purchased as the number of clients increases. Non-persistent data is cheaper for the ESB, but potentially could be more inconvenient for the clients. Many small enterprises obtain their Internet access via relatively slow dial up links, and pay for connect time hourly. Since STEP files in the electronic domain may range in size from 5 to 25 megabytes or more in size, data uploads can be moderately expensive and time-consuming. This may be less of a factor depending on the rapidity of iterations in the design environment, however. If each time the ESB is accessed, a new design or designs are analyzed, the advantages of keeping the last upload in the SME account are much reduced.

4.5. ESB Computing Infrastructure Requirements

Several servers are required to build a robust, large scale ESB. For example, a high volume analysis bureau might include a Web server, an E-commerce server, analysis module server(s), and possibly a materials database server. Smaller ESBs may combine these functions on to fewer servers.

Because the interaction between the ESB and its clients is essentially an interactive, design-oriented one (with a large number of files and graphics being exchanged) the ESB will have to have a high speed connection to the Internet, preferably a T-1 connection (bandwidth up to 1.5 Mbps) or greater.

Table 1 below is a rough indication of the computing infrastructure (1997 figures) necessary to set up and run a basic commercial ESB (low volume, single server).

Table 1: Computing Infrastructure for a Basic ESB

Item	Description	Approx. Cost
Computing Hardware	Workstation, OS, and Router • 256 MB of memory • 50 GB hard drive space	$35,000
Internet Connection	T-1 Connection (1.5 Mbps)	$18,000/year
Internet Software	Netscape Enterprise 3.x WWW Server or similar • HTML 3.0 and up • SSL encryption	$5,000
Electronic Commerce Software	Accept on-line electronic payments	$1,000
Analysis Integration Tools	Dependent upon client needs	$10,000
Solution tools (e.g. ANSYS, *Mathematica*)	Dependent upon client needs	$20,000/year

A full business case which includes personnel and other costs was beyond the scope of TIGER but will be useful for potential ESB providers. The self-service aspects of the ESB paradigm have a strong potential and could be a natural outgrowth of existing engineering consulting businesses.

4.6. Customer Computing Requirements

Ideally, analysis services need to be accessible from any computer, running any OS, connecting from anywhere. Currently, the closest software platform approaching this ideal state is the Internet browser. So-called 'Thin Clients' [Korzeniowski, 1996] can run on virtually any hardware and provide the interactivity and graphical displays required for effective analysis. In TIGER the SME accessed the U-Engineer ESB from his PC via a web browser and an X Windows emulator. We envision future versions of this toolkit dispensing with this need by utilizing all HTML, JavaScript, and Java-based interfaces.

The TIGER project showed that a 28.8 kbps dial-up Internet connection is workable for utilizing the Graphical User Interfaces (GUIs) to manipulate the product and process information and display the analysis results. With emerging technology such as 56 kbps modems, remote tool use will become comparable to local use, since response times will be dominated by calculations running on the ESB analysis servers. Hence we argue that the level of computing technology currently utilized at SMEs for business purposes will be perfectly adequate for accessing ESB-type services.

4.7. Customer Training Requirements

One of the most important principles for the beginning ESB to understand is that proper education is a fundamental part of analysis. By making analysis easier to use, there is a real danger that the ESB will also make analysis easier to misuse! This danger can only be mitigated by appropriate education of the ESB's customers. This training may take many forms. Appropriate on-line documentation, whether in the form of web pages or context sensitive help, must be provided. A Frequently Asked Questions (FAQ) document should also be available, since it can be invaluable in guiding a new user through complexity of interacting with analysis modules while illustrating their boundaries and limitations. Finally, ESBs specializing in particular problem areas, such as PWB warpage, may give short training courses or seminars on how to correctly apply the analysis modules they make available.

It is possible, however, that some ESB users may have only a trade school education. To help ensure valid analysis results, some form of knowledge capture and subsequent execution is required, documenting that this analysis module works for these products under these conditions. Although we recognize the need for such automated results and analysis assumptions checking, unfortunately the realization of this capability is still largely a research issue.

Until automated analysis toolkits such as *DaiTools-PWB* [Peak et. al, 1997] have animated context-sensitive assistants similar to those found in Microsoft's Office 97 business software suite, good documentation and good interface design are the minimum requirements for safe, reasonable automated analysis.

5. ESB USAGE EXAMPLE

The TIGER project used PWB warpage as an analysis case study in the Demonstration ESB U-Engineer, since warpage affects many other process problems (chip/component surface cracking, solder joint failure, edge deformation, poor connectivity, and misregistration) [EPS, 1997]. Specifically, a PWB assembly process (lamination) created thermally induced warpage which had to remain below a Prime-specified limit.

The TIGER demonstration involved fabrication engineers from a SME, Holaday Circuits, receiving a STEP file describing the PWB after an electronic bidding process formalized them as members of the collaborative engineering team. Since the STEP file contains PWB design details in a neutral form, SME fabrication engineers can use it to drive internal tools such as layup design and fabrication panel layout. In the TIGER case, they choose to perform the layup design at U-Engineer rather than internally. The sequence of steps was as follows:

1. The Holaday Circuits fabrication engineer, starting from his company's Intranet, selects a page listing preferred suppliers. U-Engineer is listed as a preferred supplier of analysis services, specializing in self-serve analysis of warpage and plated-through-hole issues in PWBs. He connects to the U-Engineer web site on the Internet through a 28.8 kbps dial-up line. He then browses the U-Engineer web-based analysis documentation, reading what analyses are available, how to enter data into the analysis modules, and how the results may be safely interpreted.
2. Utilizing the company account for Holaday Circuits, the fabrication engineer logs in and establishes a SSL-secured connection through the Internet to U-Engineer. By clicking on the key in the lower left hand corner of his Netscape Navigator he views the site's security information, including the number of

bits in the encryption algorithm and the site's Digital ID.

3. Satisfied that his data is safe from eavesdropping and is being sent to the real U-Engineer, he uploads the AP210 STEP file describing the PWB via an HTML form.
4. The fabrication engineer then launches the TIGER toolkit from the upload results web page. Emulator software running locally on his PC allows him to interact with X-Windows interfaces to the TIGER Mechanical Analysis Tools, *DaiTools-PWB*.
5. GUI-based tools allow him to parse in the specifications for the layup from the uploaded AP210 STEP file, and then interactively design the details of the layup to meet those specifications. The specific combination of various laminates, prepregs, and copper foils selected to physically realize the requirements specified by the Prime designers affects the PWB thermomechanical behavior, so some iteration may be necessary to design a suitable layup. (Figure 5-1 overleaf).
6. The fabrication engineer in the TIGER scenario chose to evaluate PWB warpage. DaiTools-PWB presents a GUI tailored to analyzing this warpage, (Figure 5-2 overleaf) presenting a catalog of three analysis modules, the ability to select various products to 'plug' into the analysis module, and input fields to specify the boundary conditions of the analysis. In this case, the boundary conditions arise from the lamination process of PWB manufacture. Since the fabrication engineer has read the on-line documentation for this analysis module, he understands that the 'analysis entity' being requested is the maximum temperature of the lamination process.
7. The fabrication engineer initially chooses a formula-based *Thermal Bending Model* from the catalog of PWB warpage modules for a quick comparison of several designs. Once he has determined a particular layup looks promising, offering good performance at a lower cost, he decides to confirm the estimated warpage with a more accurate analysis module. He selects the FEA-based *Plain Strain Warpage Model* (Figure 5-2), leaving the product and boundary conditions unchanged, and re-runs the analysis. After the analysis has run, the results are parsed out of the FEA output files, and translated into product-specific terms.
8. A preliminary error checking routine compares the analysis results to Prime specifications for warpage and notifies the fabrication engineer of the margin of safety of the particular design. Since the margin is comfortable, the fabrication engineer feels confident this design permutation can be proposed to the collaborative product development team. The Engineering Service Bureau has enabled unique supplier expertise and product based automated analysis to lower the cost of the product.

6. SUMMARY

We have introduced the Engineering Service Bureau (ESB) concept as a multifaceted means of empowering SMEs with advanced analysis capabilities. An ESB provides catalogs of highly automated plug and play analysis modules and necessary supporting information such as material properties. By wrapping the tools that carry out the analysis in interactive product-specific Graphical User Interfaces (GUIs), ESBs remove the need for the end user to know how to operate complex analysis software. The use of rich product models contained in neutral standard files such as STEP ISO-10303 files reduces tedious manual data entry and enables analysis automation to a greater extent than is currently practiced. By employing such design-analysis integration techniques and specializing in the volume utilization of expensive analysis tools and associated intellectual investments, ESBs are able to lower the cost of sophisticated analysis and substantially expand the roster of potential users. For SMEs, accurate analysis capabilities provide an important value-added service that can improve manufacturing yields and product costs, providing a competitive advantage. Primes and their customers gain by having potential problems caught earlier in the product realization process, resulting in higher quality products.

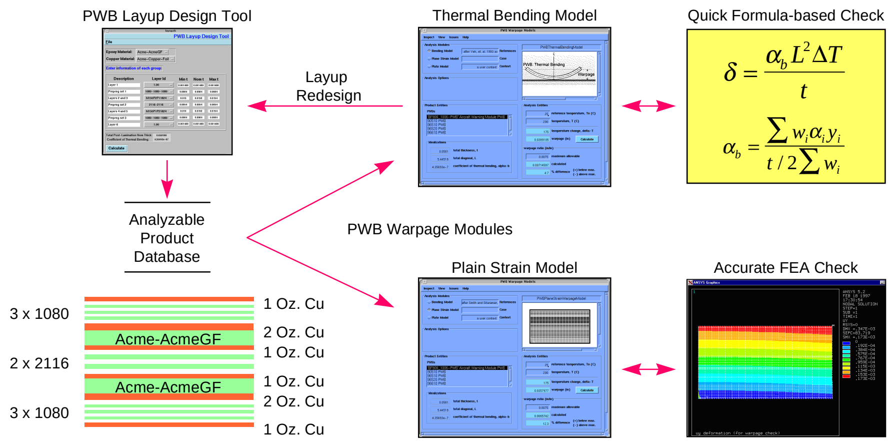

Figure 5-1: PWB Warpage Modules for Iterative, Multi-Fidelity Design Analysis

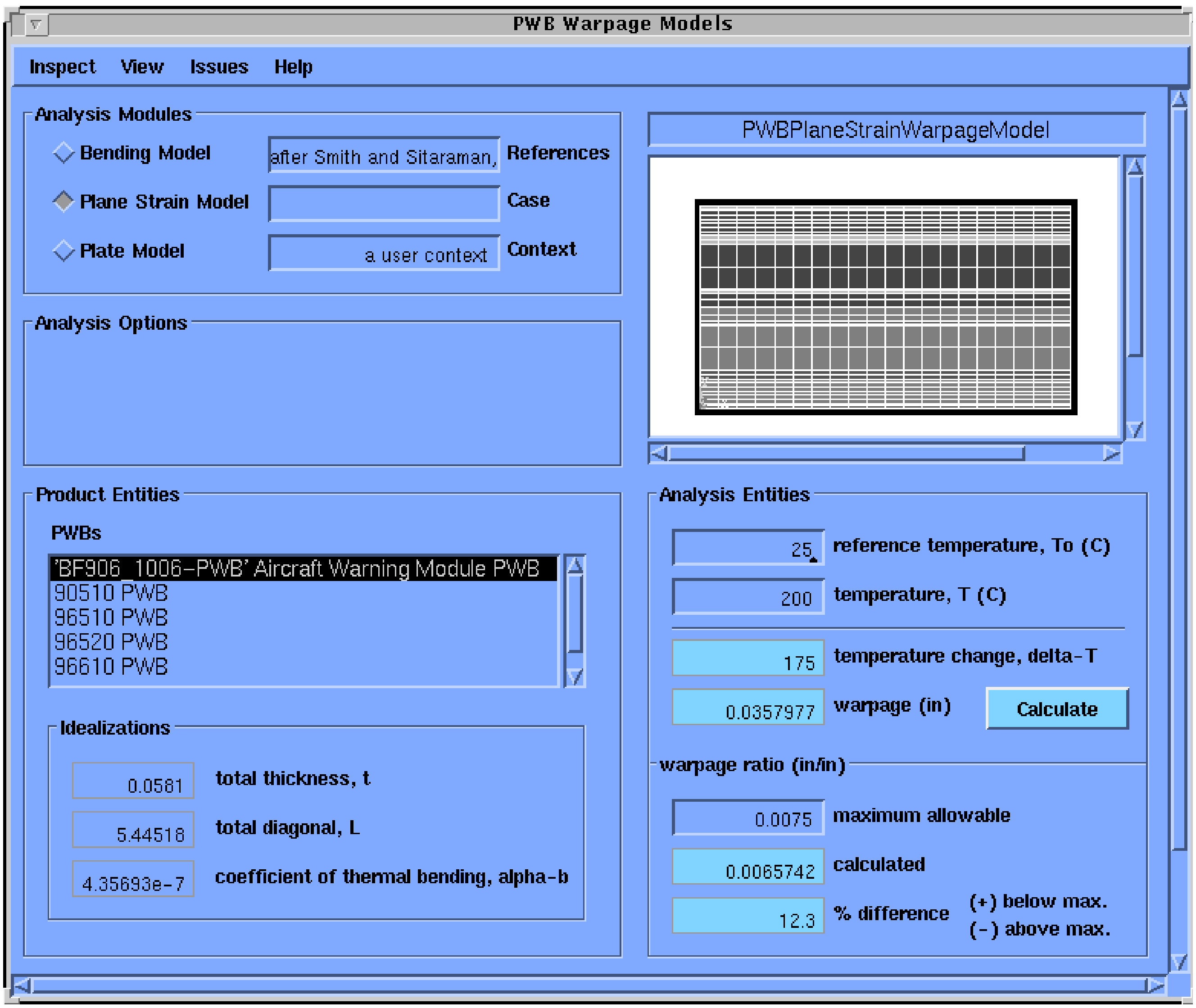

Figure 5-2: Usage of *Plain Strain Warpage Model* in a PWB Warpage Catalog

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