Towards the Routinization of Engineering Analysis to Support Product Design†

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ABSTRACT

While it is generally agreed designers would like to benefit more from analysis, methodologies are lacking for identifying appropriate analysis models and transforming them into readily usable tools. This paper identifies designer needs regarding analysis of physical behavior, and introduces the term "routinization" to describe the process of creating automated analysis modules that can be regularly used in product design.

A routinization process is presented with electronic packaging examples. Based on the multi-representation architecture design-analysis integration strategy, this process creates catalogs of product model-based analysis models (PBAMs) - analysis modules that associate design data with analysis models to obtain results in a highly automated manner.

Routinization is illustrated using a PBAM for printed wiring board warpage analysis from the TIGER project. Other electronic packaging applications such as solder joint fatigue are highlighted. Design inputs come from STEP product models and solution methods range from encoded formulae to multi-vendor finite element analysis. Observations are given, including how routinization is a knowledge capture technique that aids both engineering analysts and product designers. While it transforms the research of the analyst into tools for the designer, it serves as a catalyst that reveals new problems for the analyst to tackle.

KEYWORDS

computer aided design (CAD), computer aided engineering (CAE), constraint schematic, design-analysis integration (DAI), multi-representation architecture (MRA), routinization

NOMENCLATURE

ABB	analysis building block
APM	analyzable product model
DAI	design-analysis integration
MRA	multi-representation architecture
PBAM	product model-based analysis model
PWB	printed wiring board
PWA	printed wiring assembly (a PWB populated with components)
SMM	solution method model
Ψ	ABB-SMM transformation
Γ	idealization relation between design and analysis attributes
Φ	APM-ABB associativity linkage indicating usage of one or more Γ_i

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1 ROUTINE ANALYSIS IN DESIGN [1]

Due to a variety of pressures, product designers typically do not perform as much engineering analysis as they would like [2]. This section identifies some of these analysis needs and introduces a process to fulfil them in light of previous design-analysis integration (DAI) work.

During a typical product design process (Fig. 1 [3]), a variety of checks would ideally be performed to ensure performance, reliability, and manufacturability [4, 5, 6, 7, 8, 9]. For products like printed wiring assemblies (PWAs) that are based on relatively mature technologies, the same types of analyses typically need to be run on a regular basis (for each new product instance, and at several stages during the design process). When asked about such analysis problems, designers typically express the following needs:

- Tools that are easy to use and that automate tasks as much as possible.
- Predefined catalogs of common analysis models, along with usage guidelines.
- Product-specific terminology for model interaction (e.g., product-specific variable names).
- Design tools linkages with selective bidirectional associativity.
- Ability to utilize commercial analysis tools without becoming a tool expert.
- Insulation from analysis model details (e.g., node numbers), but access if needed.

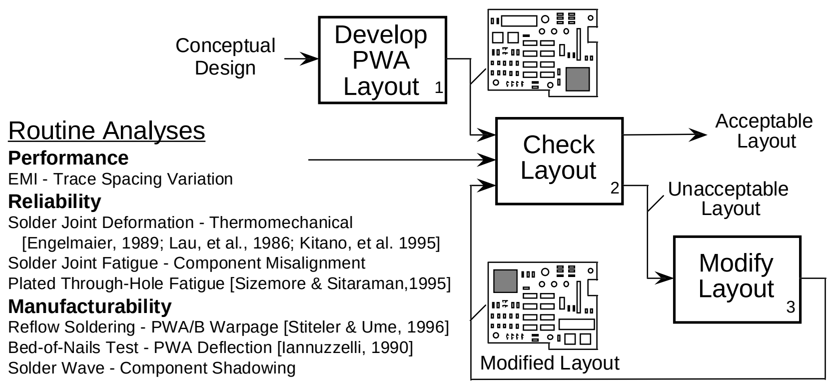


Fig. 1 Routine Analysis in the PWA Design Process

To address such needs, we have coined the term **routine analysis model** to describe an established analysis model that is regularly used to support product design [10]. Fig. 2 illustrates an overall routine analysis methodology [11] which includes two distinct phases: **routinization** (the creation of **analysis module** templates) and **routine analysis** (the usage of analysis module instances). This paper focuses on the first phase, routinization: the process of transforming routine analysis models in paper-based forms (e.g., physical behavior research and design handbooks (Fig. 1)) into catalogs of computational analysis modules. This process involves developing information models based on the **multi-representation architecture** (MRA) design-analysis integration strategy [11]. The second phase, routine analysis, is defined as the process of employing a routine analysis model. During this phase designers interact with analysis module instances that are composed of MRA entities. These entities integrate commercial design and analysis tools in a flexible, modular manner as highlighted in the next section.

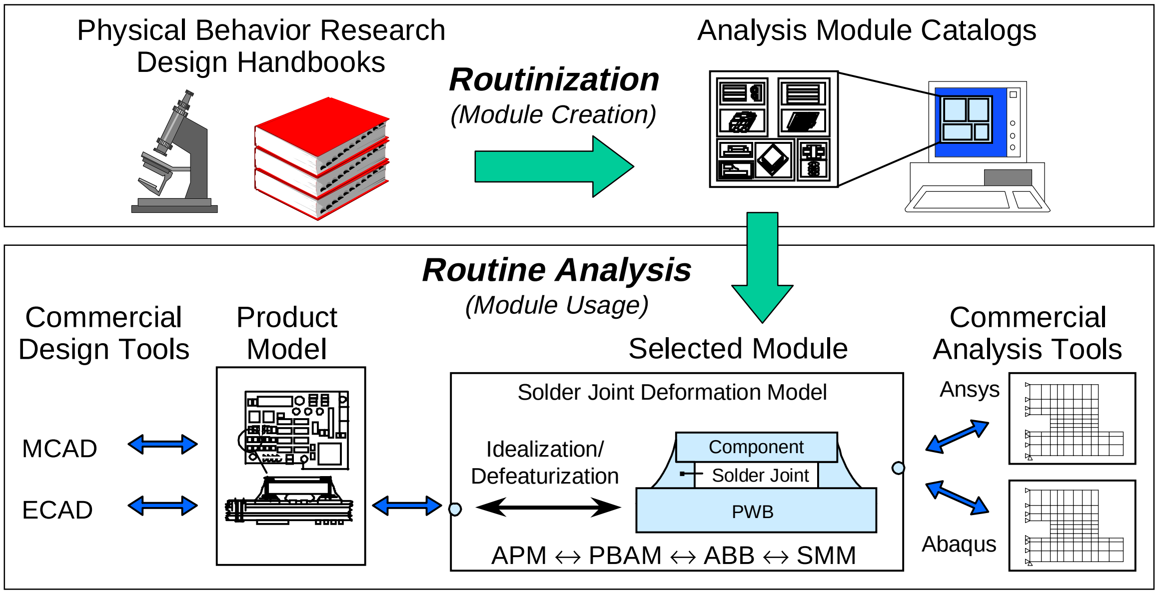


Fig. 2 MRA Routine Analysis Methodology

It should be noted that the terminology used here is not to diminish the role of engineering analysts or imply that all types of design analysis can be made routine. Instead, routine analysis emphasizes *using* established models that experienced analysts have already developed and proven in. Other classes of analysis (termed **adaptive analysis** and **original analysis**) focus on *developing* new types of analysis models and typically require analyst involvement even in the usage stage. This distinction allows us to focus on problems that are prime candidates for automation and leverage the repetitive nature of some design analysis processes.

2 DESIGN-ANALYSIS INTEGRATION BACKGROUND [10, 11]

Linking design and analysis models is fundamentally different than typical data integration tasks in that it requires **heterogeneous transformations -** transforming one or more types of information (e.g., design

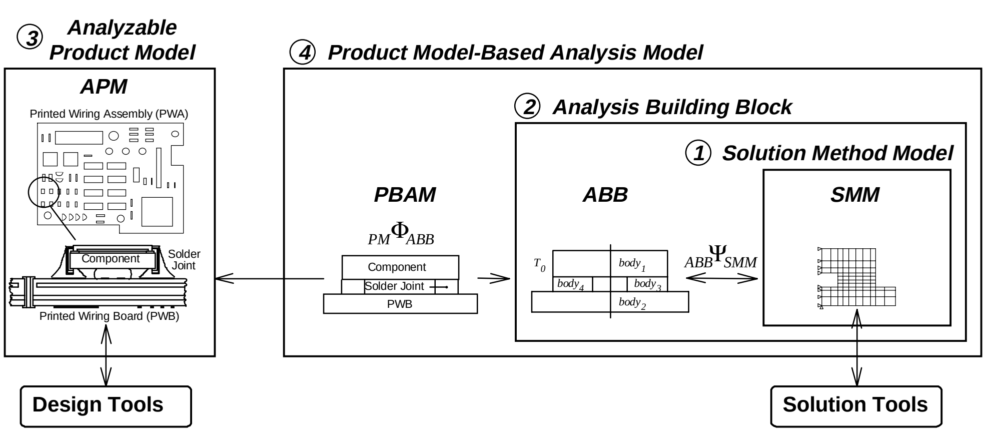
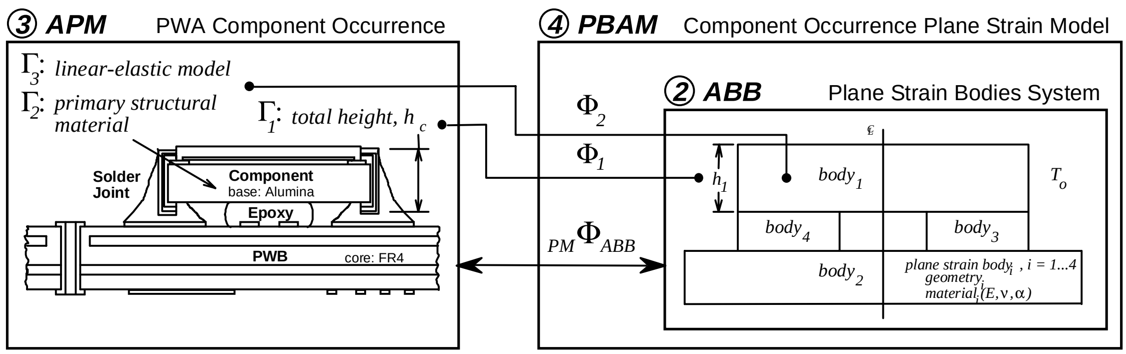


Fig. 3 The Multi-Representation Architecture for Design-Analysis Integration

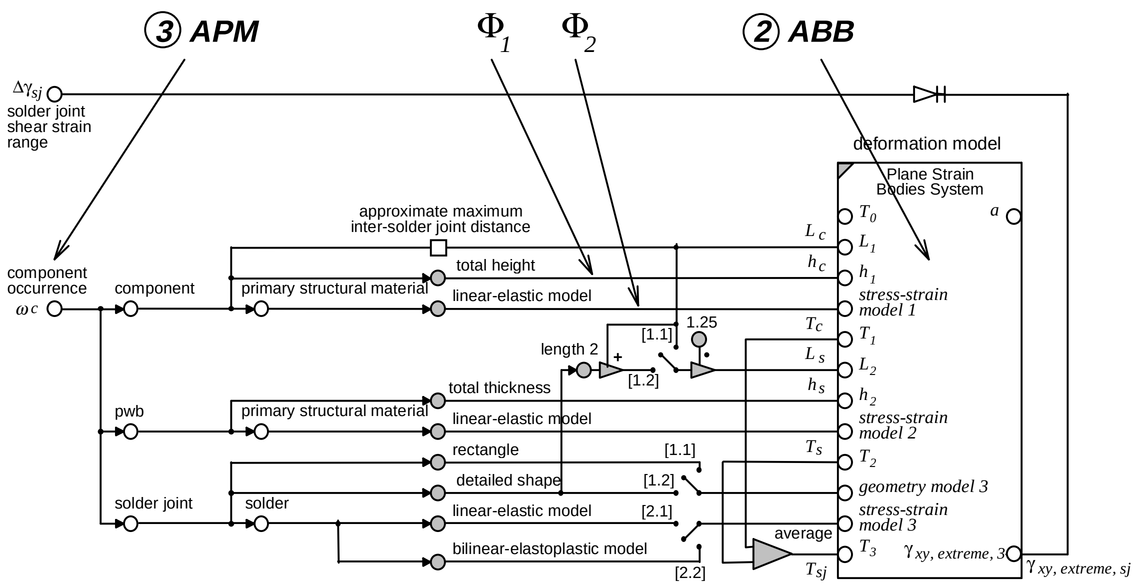
geometry and materials) into a *different type* of information (e.g., a finite element model). The integration challenge is further complicated in that a given type of product can have numerous types of analysis models that vary in discipline, resolution, application, and fidelity. This diversity makes the gap between design and analysis too large for a single integration bridge. Hence, the MRA was developed with intermediate representations as stepping stones to achieve flexible, modular design-analysis integration (Fig. 3).

2.1 The Multi-Representation Architecture

In the MRA, **solution method models** (SMMs) are object-oriented wrappers around solution tools that utilize an agent-based framework to obtain analysis results in a highly automated manner. **Analysis building blocks** (ABBs) represent engineering analysis concepts with high semantic content. ABBs generate SMMs based on solution technique-specific considerations such as symmetry and mesh density. **Analyzable product models** (APMs) represent design-oriented details, providing a common stepping stone to design tools, while also supporting idealizations needed by analysis models [12]. Finally, **product model-based analysis models** (PBAMs) explicitly represent the associativity between analysis models and design models (i.e., between ABBs and APMs). Object and constraint graph techniques are combined in a new graphical notation termed **constraint schematics** (Fig. 4b), providing modularity, multidirectionality, and rich semantics.



a. Informal Pictorial View



b. Information Model View: PBAM Constraint Schematic

Fig. 4 Design-Analysis Associativity in a Solder Joint Analysis Model

2.2 Design-Analysis Associativity Example

Fig. 4 illustrates these concepts via a solder joint analysis example [11]. Due to the coefficient of thermal expansion mismatch between the printing wiring board (PWB) and component, the solder joint deforms under thermal loads. The overall goal of this analysis model is to compute the resulting strain in order to estimate solder joint fatigue life. The left side of Fig. 4a shows design-related details of APM entities: the cross-section of a component, a PWB, solder joints, and epoxy. The assembly of these entities is another APM entity, a PWA component occurrence, ω_c. On the right, the ABB is a generic analysis system, *Plane Strain Bodies System*, that can also be used in analyses for other types of products.

The PBAM, *Component Occurrence Plane Strain Model*, contains associativity linkages, Φ_i, which indicate how the APM design entities are idealized as homogeneous plane strain bodies in the ABB. For example, linkage Φ_1 explicitly specifies that the height of ABB $body_1$, h_1, equals the total height of the component, h_c (a geometric idealization, Γ_1, of the detailed APM component entity). Linkage Φ_2 similarly specifies the material model for $body_1$. While Fig. 4a shows this design-analysis associativity informally, Fig. 4b is the PBAM constraint schematic - a structured information model that specifies all associativity linkages. Underlying lexical forms of such product-specific analysis models are also possible as shown later (Fig. 9).

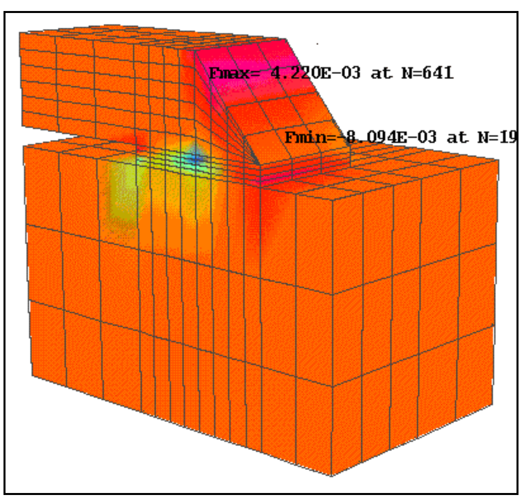
2.3 Design-Analysis Integration Toolkit

DaiTools is a prototype design-analysis integration (DAI) toolkit that is one implementation of the above MRA concepts [13]. It is largely independent of product domain and has the following capabilities:

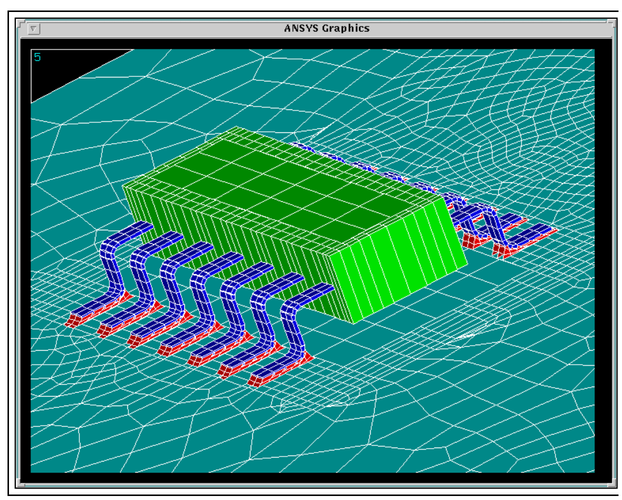
- Abstract superclasses for each MRA representation: APM, PBAM, ABB, SMM.
- The **analyzable product model** (APM) technique for STEP-based design tool links [12].
- A representative set of ABBs.
- Explicit constraints implemented around the SkyBlue constraint solver [14].
- SMMs for ANSYS and CADAS finite element analysis (FEA) tools [15, 16] along with related highly automated agents.

2.4 Example Applications

Product-specific applications can be built on the generic MRA foundation in *DaiTools*. In a nutshell product-specific PBAMs and product model entities (APMs) are added as subclasses [11]. Thus, the



a. Solder Joint Shear Strain



b. PWA Finite Element Mesh

Fig. 5 Highly Automated Integrated Analysis

analysis modules created by the routinization process described in this paper are actually PBAMs within the MRA. Applications addressed to date [11, 17, 18] have been largely in the electronic packaging domain and include solder joint deformation (Fig. 5a), PWB warpage (Figs. 8-12), and plated-through hole deformation. Cimtalay *et al.* [19] have demonstrated initial usage of PBAMs in a modular optimization technique. A related technique [20, 21] intelligently leverages product model knowledge to mesh and combine building blocks into complex finite element models - models that are impractical with brute force automeshing (Fig. 5b). Overall we believe the MRA and this meshing technique begin to fundamentally address the CAD-CAE integration issues identified above.

3 MRA ROUTINIZATION PROCESS

Fig. 6 highlights the major steps in the MRA routinization process (the process of creating routine analysis modules) and identifies the primary roles of people involved at each step. The **Designer** and **Analyst** first decide which routine analyses are needed. The Analyst then works with the Integrator to develop PBAMs and related entities to represent the identified models. After implementation, the end result is one or more analysis modules ready for Designer usage. Depending on the size of the effort, the roles in this process may all be performed by a single person, or each role may itself involve several people.

The remainder of this section discusses each step in more detail with examples from a previous solder joint fatigue case study [10, 17] and a simple PWB warpage model. Based on experience from these case studies, a comprehensive set of guidelines with detailed examples is planned.

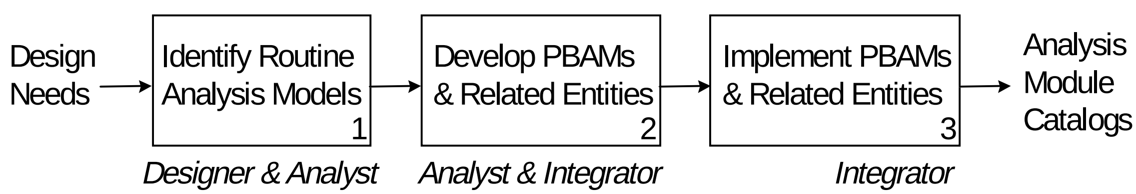


Fig. 6 MRA Routinization Process

Step 1: Identify Routine Analysis Models

To start the routinization process, the Designer and Analyst first identify which routine analysis models are to be transformed into automated analysis modules. These two people should be familiar with the types of products and analysis models being considered.

If it is indeed a *routine* analysis model (one that is truly used regularly), a description of the analysis model will typically already exist in some form. If design needs call for a new type of analysis model, the Analyst can look to a variety of resources as starting points (Table 1). Alternately, the Analyst may go through an adaptive or original analysis process to develop and validate the needed analysis model. Some combination of merging models from existing resources and in-house development is often required. The output of Step 1 is an informal analysis model description containing the following:

Model Purpose - A brief statement about the model and what design needs it fulfills. It should indicate

Table 1 Starting Points for Routine Analysis Models

• Journals	• Corporate technical memos
• Conference proceedings	• Unpublished notes
• Handbooks	• CAE tool input files
• Textbooks	• Computer programs

what design stages best benefit from the model, (typically based on model accuracy versus computational cost).

Major Analysis Steps and Variations - A high-level, top-down view of the major analysis steps in the form of a tree/network diagram (Fig. 7) or an $IDEF_0$ process model. Variations such as directionality loading conditions and product configurations should be identified.

Analyst Sketches - Sketches of analysis models noting types of bodies, loads, and material models in product-specific terms.

Relations and Variables - A list of relations and variables. For models that require solution tools such as finite element analysis (FEA) programs, the list should contain a relation whose variables are the inputs and outputs for that tool.

Model Limitations - Guides for the end user, including model assumptions and acceptable ranges of inputs and outputs.

Model References - Background information about the model, including application to the product type at hand, as well as descriptions of product-independent analysis concepts.

Representative Datasets - Example values for input, intermediate, and output variables for each major variation. These datasets should include related solution tool input and output files (e.g., FEA preprocessor models and results files). If possible, tool files should be parameterized according to their relations and variables identified above.

Given the analysis model description with these contents, someone besides the Analyst should be able to "manually" walk through the analysis steps using the example datasets. Here "manually" means that at a minimum someone can manually provide input to the appropriate tools and manually exchange data among these tools to obtain the example results (e.g., using a calculator, creating and running a finite element analysis model, and exchanging information among such tools). This exercise also helps non-Analysts better understand the model and accelerates the below steps.

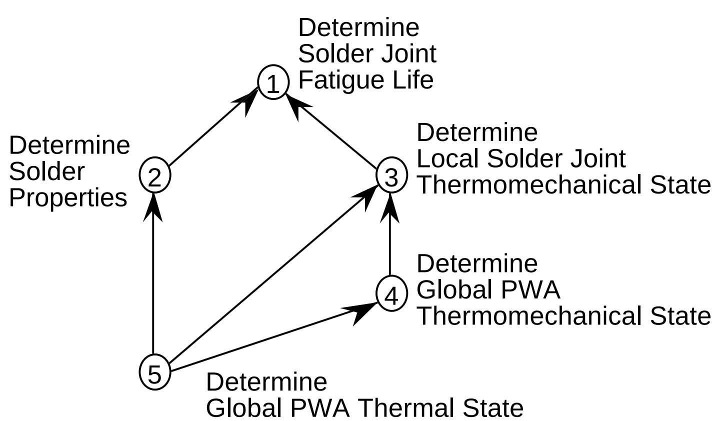


Fig. 7 Major Steps in Solder Joint Fatigue Analysis

Step 2: Develop PBAMs and Related Entities

In this step the **Integrator** (a person familiar with the MRA and associated object and constraint techniques) develops PBAMs and related entities that will represent the analysis models from Step 1. PBAM development means transforming the above informal descriptions into structured information representations.

First the Integrator assigns one or more PBAMs/ABBs to perform each major step or variation identified above (e.g., Fig. 7). These entities may be further broken down into smaller PBAMs/ABBs. Associated APM and SMM entities are likewise identified. Experience has shown that much of the information and relations in analysis descriptions can be logically divided into these four MRA representations. Emphasizing the modular, recursive, object-oriented nature of the MRA, this step roughly corresponds to object-oriented design and analysis in information technology terms.

```
ENTITY thermal_bending_system
    SUBTYPE OF ( thermomechanical_system );

    (* Analysis Variables *)
        length : positive_length_measure;
        thickness : positive_length_measure;
        coefficient_of_thermal_bending : REAL;
        total_deflection : length_measure;
    (* Subsystems *)
        (* none *)
    (* Mapped Variables *)
        (* none *)

    WHERE
    (* Analysis-Analysis Transformations *)
        aat1: total_deflection = (coefficient_of_thermal_bending * length**2 *
            temperature_change) / thickness;
        aat2: temperature_change = temperature - reference_temperature;

    (* Subsystem Conditions *)
        (* none *)

    (* Mappings *)
        (* none *)

END_ENTITY;
```

Fig. 8 An ABB in STEP EXPRESS

Next, each PBAM/ABB that does not already exist from previous work is itself developed. This process ultimately results in populated PBAM/ABB structures - computer-processable knowledge representations of analysis models that combine object and constraint graph techniques [11]. For example Fig. 8 gives the ABB structure of a thermomechanical analysis model in STEP EXPRESS syntax [22, 23, 24], defining variables and relations among those variables. This ABB, *Thermal Bending System,* is a somewhat generalized version of a bimetallic beam model that can be used in potentially many product applications; thus it is expressed in product-independent terms. This ABB contains the relation in Fig. 12 for deflection, as represented by the multidirectional WHERE rule *aat1*. Fig. 9 is the PBAM structure of a basic analysis module, *PWB Thermal Bending Model*, that applies this ABB to PWB warpage by using it as a subsystem. Analysis linkages explicitly represent the associativity between the product model entity, *pwb,* and the analysis model entity, *deformation model*.

To aid the development process, the Integrator typically starts by sketching graphical views of the PBAM/ABB structures that are more human-friendly. Such views include constraint schematics (emphasizing multidirectional relations among variables and subsystems - Fig. 10) and object relationship diagrams in STEP EXPRESS-G form (emphasizing object-oriented relationships such as entity-attribute and superclass-subclass). Similar to Fig. 4b., Fig. 10 shows that the length variable, *L*, used by the analysis model comes from the idealized diagonal length of the PWB (associativity linkage *al1*). This linkage can also be seen in the Fig. 9 lexical form. In the end, each relation and variable identified in Step 1 should be reflected in the developed entities - either directly or spread among several entities per good object-oriented practice.

The Integrator must also perform other roles in this process (or interact with other people who do):

Product Modeler - Works with the Designer to identify the root sources of the design data used in the analysis models. Extends linkages between these design tools and the APM that drives the analyses, including supplying missing data and idealizations [12, 22]. For example the *pwb* attribute *coefficient of*

```
ENTITY pwb_thermal_bending_model
    SUBTYPE OF (pwb_warpage_model);

    (* Product Variables *)
        pwb : pwb;
    (* Subsystems *)
        deformation_model : thermal_bending_system;
    (* Analysis Variables *)
        (* none *)
    (*Mapped Variables *)
        length : positive_length_measure;
            thickness : positive_length_measure;
        coefficient_of_thermal_bending : REAL;
        temperature : temperature;
        reference_temperature : temperature;
        temperature_change : temperature;
        warpage : length_measure;

    WHERE
    (* Analysis Linkages *)
        al1 : deformation_model.length = pwb.total_diagonal;
        al2 : deformation_model.thickness = pwb.total_thickness;
        al3 : deformation_model.coefficient_of_thermal_bending =
            pwb.coefficient_of_thermal_bending;
    (* Analysis-Analysis Transformations *)
        (* none *)
    (* Subsystem Conditions *)
        (* none *)
    (* Mappings *)
        mv1 : warpage = deformation_model.total_deflection;
        mv2 : length = deformation_model.length;
        mv3 : thickness = deformation_model.thickness;
        mv4: coefficient_of_thermal_bending =
            deformation_model.coefficient_of_thermal_bending;
        mv6 : reference_temperature = deformation_model.reference_temperature;
        mv7 : temperature = deformation_model.temperature;
        mv8 : temperature_change = deformation_model.temperature_change;

END_ENTITY;
```

Fig. 9 A PWB Warpage PBAM in STEP EXPRESS

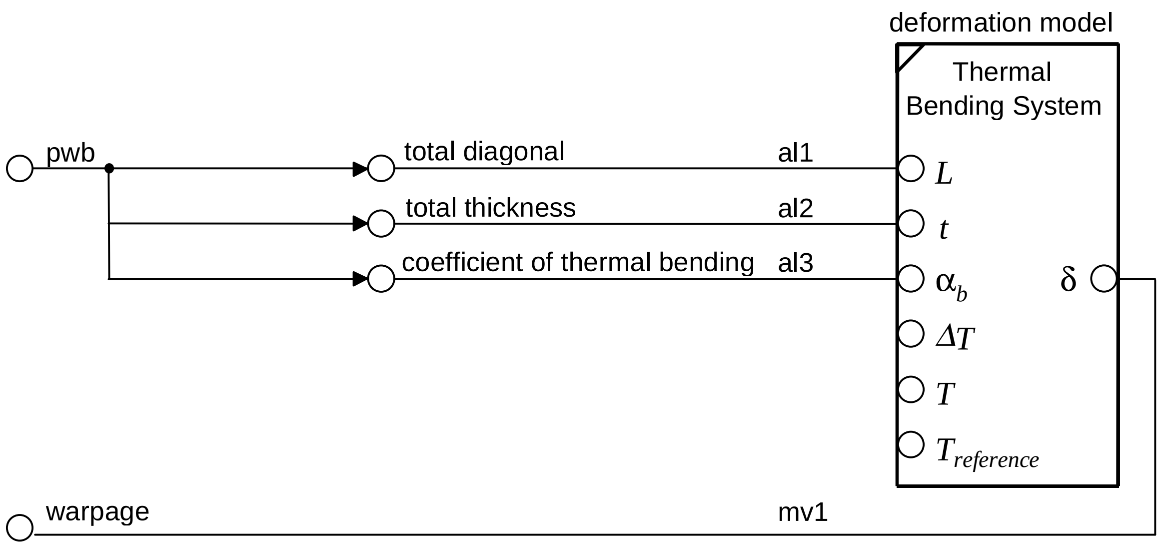


Fig. 10 A PWB Warpage PBAM Constraint Schematic

thermal bending, α_b, in Fig. 10 is an idealized variable contained in the APM (see idealization relation for α_b in Fig. 14). Creates and maintains example datasets.

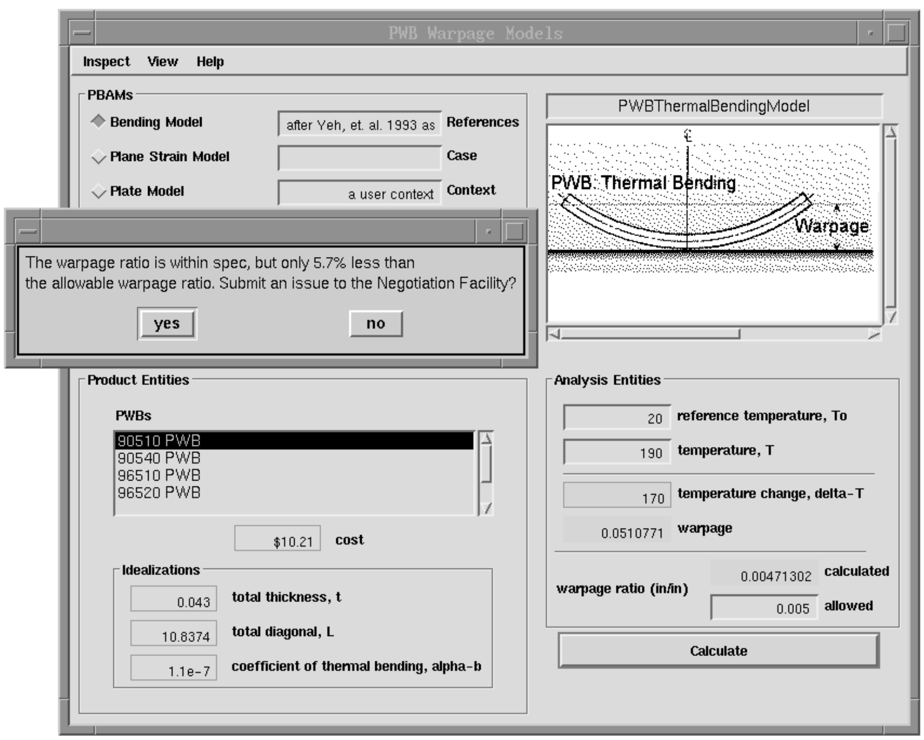
Parts Librarian - Similar to the Product Modeler, but someone who specifically focuses on parts libraries (e.g., electrical components). Maintains links to design tools, and coordinates data keys by which the parent part references the library entities (e.g., part number for PWA-component references). As analysis often requires part details like materials and parameterized 3D geometry not found in electrical CAD systems, the Parts Librarian typically will need to create a semantically richer component library with links to other component libraries.

Materials Librarian - Similar to the Parts Librarian, except for materials. Again, a single richer library may be needed with links to several internal and commercial databases.

Tool Specialist - Someone for each design and analysis tool involved who understands the operation of the tool and the interfaces to it. Helps other people use the tool. Assists Analyst in creating exemplar solution tool inputs. Works with Integrator to wrap the tool for automated use via agents in a framework.

Step 3: Implement PBAMs and Related Entities

Based on the populated structural views developed above, the Integrator next implements new PBAMs and supporting entities in a specific computing environment. The present representative implementation, *DaiTools*, is a product-independent design-analysis integration toolset described above. The examples come from the PWA-specific analysis tool, *DaiTools-PWA/B*, built upon this generic foundation. A prototype STEP AP210-based link with the Mentor Graphics BoardStation PWA layout tool has been developed using the APM technique [12, 22, 25, 26]. This link extracts product information and adds idealizations to support a variety of analyses (Fig. 13).



a. Catalog of PWB Warpage PBAMs

Fig. 11 Analysis Module Catalogs in *DaiTools-PWA/B*

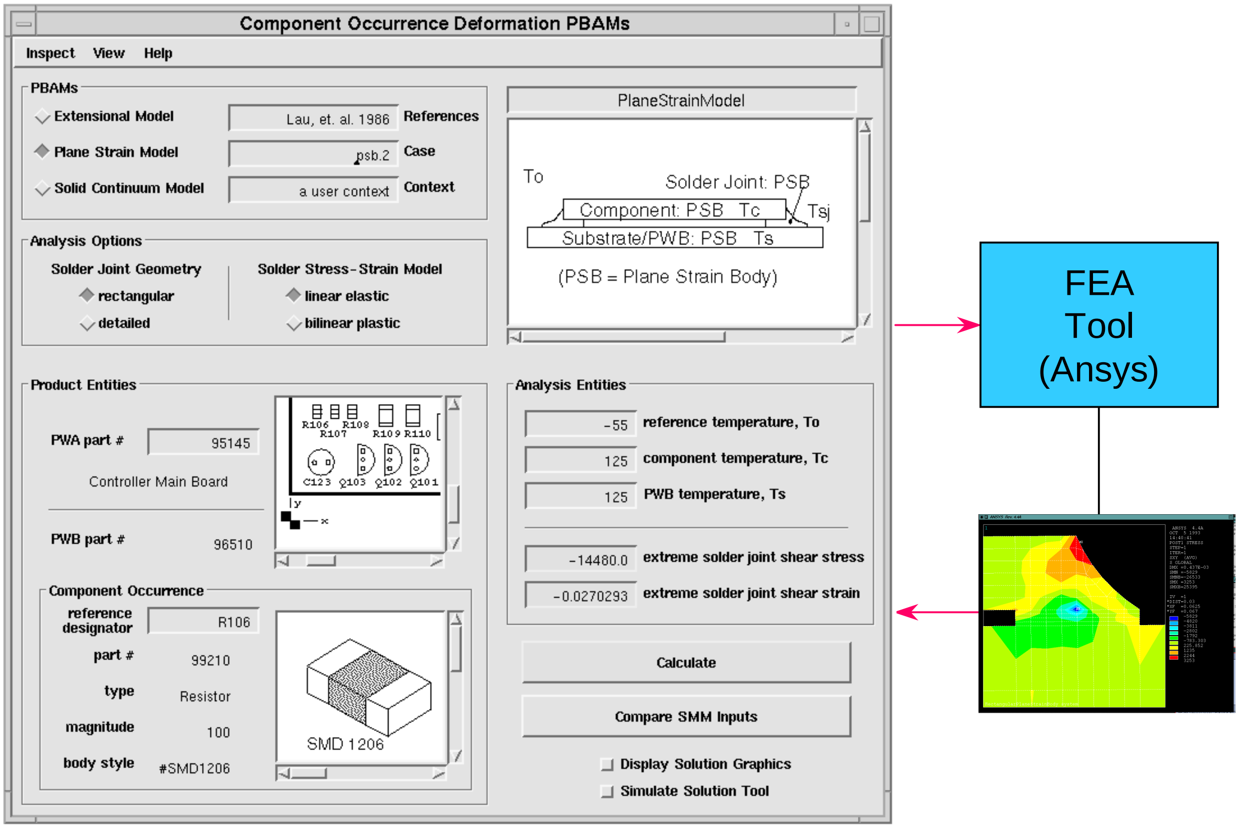


Fig. 11 b. Catalog of Solder Joint Deformation PBAMs

Given the PBAM/ABB structure as a computer-processable specification, PBAM/ABB implementation as object classes is largely automated in *DaiTools*. When a PBAM is used, an instance of the corresponding class is created which contains variables and relations generated as constraints in a constraint graph. PBAM subsystems (other PBAMs or ABBs it uses) are recursively instantiated in the same automated manner.

The Integrator also implements graphical user interfaces for each analysis module catalog (a family of related PBAMs). For example, Fig. 11 shows catalog implementations that include the PWB warpage and solder joint deformation PBAMs discussed above. The Integrator also documents the modules in structured specifications that include textual descriptions, PBAM/ABB structure and graphical views (e.g., constraint schematics), and hyperlinks to related entities and references (Fig. 12). Finally, the implementation and documentation is verified by the Analyst and Designer, using example datasets as reference points.

4 USAGE OF ANALYSIS MODULES

After the analysis modules are verified, the routinization process is complete and the next phase of the MRA methodology is entered: routine analysis, where users regularly apply the PBAMs to check product designs (Fig. 2). While routinization is analogous to *creating* reusable parts libraries, routine analysis is analogous to *using* parts libraries. For example, Fig. 5a shows shear strain results for a particular design that were automatically obtained from the 3D solder joint deformation module (from the Fig. 11b catalog) using the Hitachi Cadas FEA system.

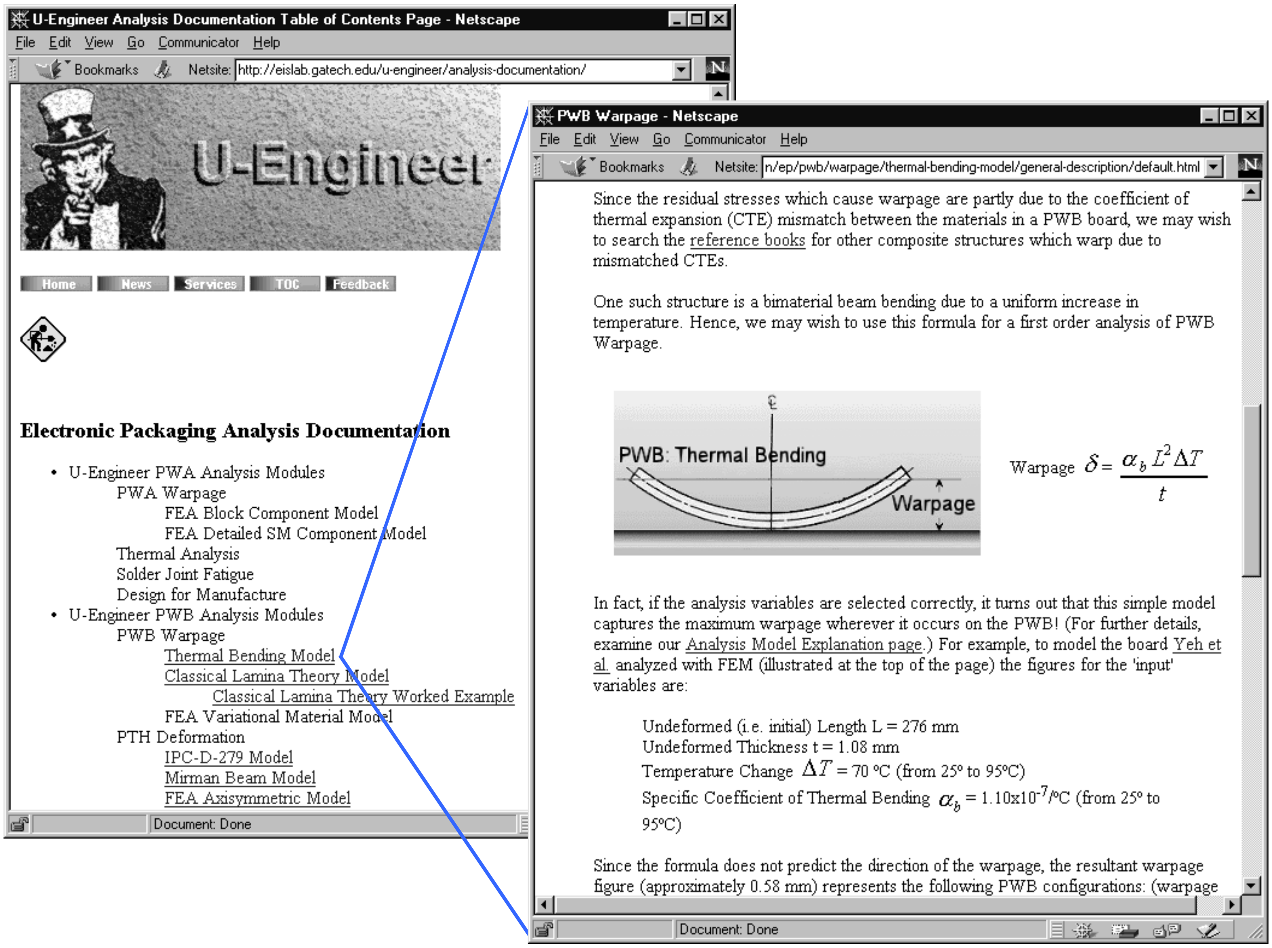


Fig. 12 Web-based Analysis Module Documentation

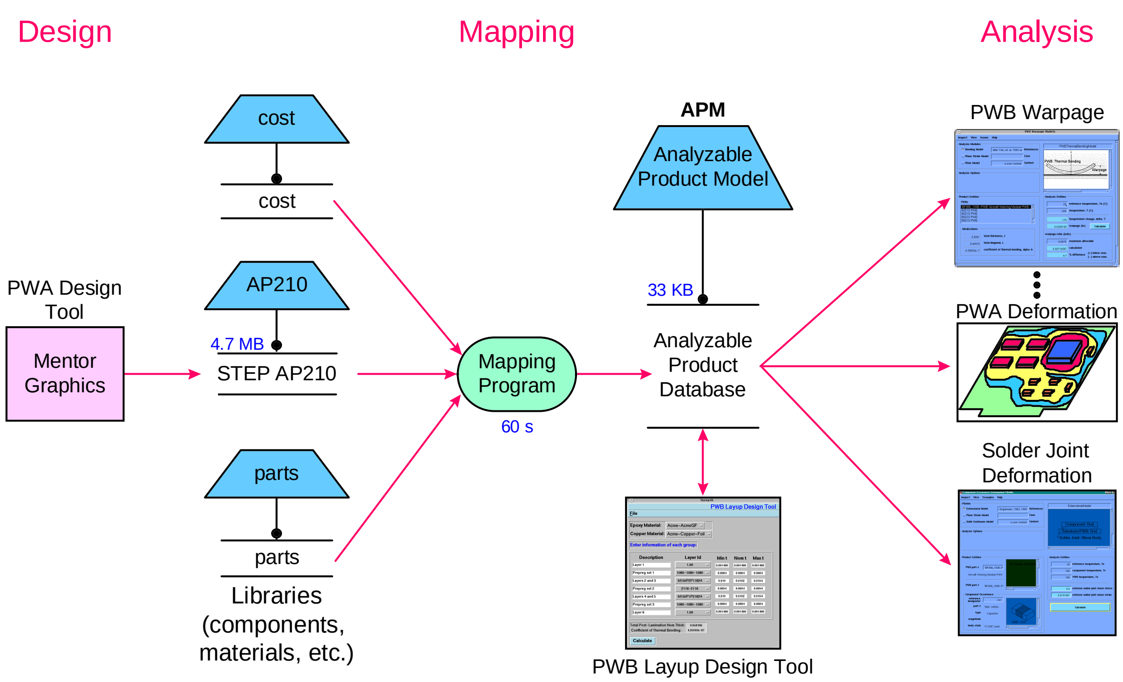


Fig. 13 STEP Product Data-Driven Analysis

5 RECENT APPLICATIONS [18, 25]

5.1 STEP Product Data-Driven Analysis

The MRA routinization process was employed in TIGER - a recent project which focused on advanced engineering collaboration between primes and suppliers. In the TIGER scenario, a Prime releases early printed wiring assembly/board (PWA/B) design information to its suppliers in a standard STEP format (an AP210 file translated from a Mentor Graphics BoardStation file). Suppliers access the TIGER toolset via an Internet-based engineering service bureau to perform a variety of process-specific design checks on this STEP data, including design-for-manufacturability (DFM) and thermomechanical analysis (in *DaiTools - PWA/B*). Based on these checks, suppliers feedback suggested design improvements, making them effective members of the integrated product team (IPT).

The TIGER Team consisted of Boeing and Holaday Circuits as a representative prime and supplier, respectively, as well as Arthur D. Little (ADL), the Atlanta Electronic Commerce Resource Center (AECRC), Georgia Tech, International TechneGroup Inc. (ITI), and SCRA (the program lead). Georgia Tech focused on STEP product data-driven analysis techniques and creating representative thermomechanical analysis capabilities using the MRA routinization process (Fig. 13).

5.2 Premier Demonstration

On Feb. 21, 1997 in Charleston, South Carolina the TIGER Team conducted the premier demonstration of this prime-supplier collaborative engineering scenario. With each IPT member located at separate workstations and PCs, design and business information was exchanged some 20 times during the hour long demo. From his PC, the PWB fabrication engineer uploaded the live, Mentor Graphics-originated AP210 model to U-Engineer (the self-service analysis bureau located in Atlanta). He then performed warpage analysis iterations over the Internet using the PWB warpage catalog in *DaiTools - PWA/B* (Fig. 14). The demonstration included the formula-based warpage module of Figs 8-12, as well as a finite element-based plane strain module which was automatically run in real time via ANSYS. The same scenario has also been performed by Boeing and Holaday team members while located at their facilities in Seattle, Washington; Irving, Texas; and Minnetonka, Minnesota - confirming that TIGER is truly "a STEP towards printed circuit design iterations in about an hour".

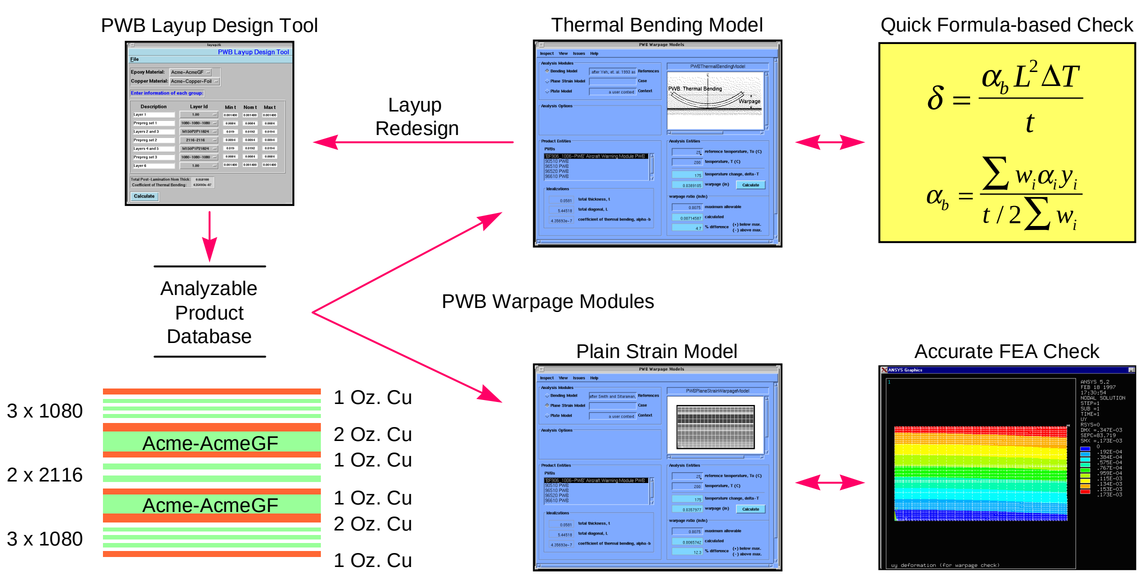


Fig. 14 Multi-Fidelity Design Analysis Using PWB Warpage Modules

5.3 Lessons Learned

TIGER experiences showed the value of rich product models like STEP AP210 for analysis integration. However, the multi-fidelity idealization nature of analysis leads to an insatiable information appetite that no product model, no matter how rich, can continually satisfy. One can almost always think of a higher fidelity analysis that requires more information than a standard format like AP210 supports. Thus, we developed the APM technique [12] as a general STEP-based link to design tools in order to harmonize diverse data, include idealizations, and add such missing data. Overall, experiences in TIGER confirmed the basic tenants of the MRA approach and helped refine the routinization process.

6 DISCUSSION

Observations from these experiences with the routinization process include the following:

Knowledge capture - The MRA methodology to achieve design-analysis integration can be viewed as an expert system technique. (For example, refer to Fig. 6 and replace the term 'Integrator' with 'Knowledge Engineer'.) The MRA can be conceptualized as a domain-specific expert system shell which allows the Integrator to capture knowledge about:

- Input/output characteristics of solution tools (stored in SMM objects).
- Technique-specific considerations, such as symmetry and mesh density for FEA (stored in ABBs).
- Logical groupings of related engineering analysis relations (stored in ABBs).
- Product idealizations which are analysis driven, such as temperature dependent material properties (wrapped in APMs).
- Idealization linkages between given analysis methods and given products. We term such usage of idealizations design-analysis **associativity linkages**, Φ_i, (stored in PBAMs).

In brief, the MRA captures the expertise of the analyst and provides it in a reusable form for the designer. As an object-based formalism for knowledge representation, the MRA inherits the widely recognized benefits of expert system technologies: rationalization, improved quality, and positive effects in corporate organizations [26].

Synergy of specialists - Designers benefit from the routinization process by getting tools that meet many of their needs (Section 1) and help them design better products. Analysts benefit by their work getting more exposure. Without such modules, barriers like computing tool complexity can make regular application of their work unlikely. Hence, analysis modules become a focal point of common ground between Designer and Analyst.

As the modules enable the *Designers* to perform *routine* analysis, Analysts are freed from this task to focus on adaptive and original analyses. As a side benefit, the precise nature of PBAM structures sometimes brings out unforeseen gaps in analysis capabilities, thus revealing new research challenges for the Analyst to tackle.

Catalyst for more analysis - Designers say they would like to have routine analysis tools but often have few answers when asked what specific analyses they perform regularly today. Simply explaining the definition of routine analysis and a process like Fig. 1 can spark curiosity and enthusiasm. As alluded to above, beginning Step 1 often leads to a detour or parallel effort to first develop an analysis model itself before attempting to routinize it. One can begin this adaptive or original analysis process by identifying what questions the Designer wants an analysis module to answer.

Ensuring proper usage - One concern sometimes raised is proper usage of analysis modules, as their high degree of automation can make it easier for someone to misuse them. The ABB and PBAM representations currently do not include explicit checks, for example, on assumptions being violated. Such guidelines can be included in the textual specs, but automated checks are admittedly more desirable.

Usage by non-Designers - The TIGER scenario has reinforced the observation that engineers other than designers can benefit from routine analysis. Manufacturing engineers, with access to real-time process information, could potentially use analysis modules to check how their processes are operating, as well as ensuring producibility of a particular design [18].

Delivery by engineering service bureaus (ESBs) - The TIGER group developed the engineering service bureau concept to empower small companies with advanced analysis capabilities [27]. An ESB like U-Engineer [28] provides Internet-based fee-for-service analysis capabilities, ranging from 'self service', where engineers interact with analysis modules directly (i.e., routine analysis), to 'full service', where ESB consultants carry out analyses (i.e., adaptive analysis or original analysis). An ESB follows the MRA routinization process to create product-specific analysis module catalogs for the self-service mode of operation. Rich product models in standard forms like STEP AP210 enable the plug-and-play nature of these modules and reduce tedious manual data re-entry. As a result of highly automated MRA wrappings, the end user can concentrate on understanding their specific analyses rather than the idiosyncrasies of general purpose CAE tools. By employing the techniques in this paper and specializing in the volume utilization of expensive analysis tools (and associated intellectual investments), ESBs should be able to lower the cost of analysis and expand their audience of potential users.

7 SUMMARY

This paper describes a process called routinization for creating structured computer-based analysis catalogs. The process roles of Designer, Analyst, and Integrator are identified, as well as the context within the multi-representation architecture (MRA) design-analysis integration strategy. Example electronic packaging modules from the TIGER collaborative engineering project demonstrate the routinization process. Resulting analysis modules obtain inputs from product design data (e.g., STEP models) and retrieve solutions from commercial analysis tools. Other benefits include leveraging analysis resources and capturing analysis knowledge in a persistent, computer-processable form. In the end, the MRA routinization process enables the creation of extendible, modular, product-specific analysis tools that support product design in a highly automated plug-and-play manner.

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BIOGRAPHICAL NOTES

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