Integrating Product Design and Analysis Models

An Overview of ProAM:
Product Data-Driven Analysis in a Missile Supply Chain

Russell S. Peak
Senior Researcher & Assistant Director
Engineering Information Systems Lab
eislab.gatech.edu

CALS Technology Center
Georgia Institute of Technology
Extended Abstract

The U. S. Department of Defense Joint Electronic Commerce Program Office (JECPO) has sponsored the ProAM effort with the Army Aviation and Missile Command (AMCOM) as primary stakeholder. Under subcontract to Concurrent Technologies Corp. through the Atlanta Electronic Commerce Resource Center (AECRC), ProAM has focused on improving missile electronics through advanced engineering analysis integration and delivery. This Georgia Tech-led effort has addressed barriers to small & medium-sized enterprise (SME) analysis of product physical behavior with the involvement of Circuit Express Inc. and System Studies and Simulation Inc., two SMEs in the AMCOM supply chain.

This presentation overviews the ProAM project and resulting tools and technologies:

- **U-Engineer.com, a self/full-serve Internet-based engineering service bureau (ESB)** with highly automated analysis modules for printed wiring board (PWB) fabricators and designers. Some modules, including PWB impedance models and the IPC-D-279 plated-through hole fatigue model, are available for usage via web-based thin clients. Accessing U-Engineer.com-based solvers as a thick client, *XaiTools PWA-B* provides other tools for PWB layup design and warpage analysis.

- **General ESB and analysis integration techniques** underlying U-Engineer.com, including:
  - A prototype template to aid establishing other Internet-based ESBs via technologies such as thick and thin client tools, CORBA-wrapped analysis solvers, and Internet security.
  - Product data-driven analysis techniques to enable highly automated plug-and-play usage via emerging product standards like ISO STEP AP210 and IPC GenCAM/GenX. *XaiTools*, the general-purpose analysis integration toolkit underlying *XaiTools PWA-B*, is highlighted with its integration to commercial CAD/CAE tools and applications to other product domains.

U-Engineer.com utilization by SMEs and Primes is highlighted, including evaluating design/process alternatives, and increasing awareness of potential issues. Experience has shown that ProAM technology excels at delivering automated product-specific analysis to places it has never gone before.

While ProAM has focused on tools for the AMCOM PWB supply chain, these same tools and techniques can benefit other industries. Envisioned applications include development of analysis module catalogs for other domains and establishment of company-specific Internet/Intranet-based engineering service bureaus.
Motivation for Physical Behavior Analysis

Need for Predictive Analysis

- Costly delays
- Serious consequences
- High improvement potential

Representative Product Domain: Electronics

- $300B+ industry; widespread technology
Analysis Motivation for Small-Medium Enterprises (SMEs)

- Typically niche-experts
  - Precise mfg. process knowledge
  - Specialized product design knowledge (ex. PWB laminates)
- SME analysis needs
  - Product improvements (DFM)
  - Mfg. process troubleshooting
  - Mfg. process optimization
- More accurate data → Better analysis
- Bottom line drivers:
  
  Higher Yields, Lower Cost, Better Quality, Fewer Delays
Barriers to SME Analysis

- Lack of awareness
- High costs of traditional analysis capability
  - Secondary: Specialized Software, Training, Hardware
  - Primary: Model Access/Development, Validation, Usage
- Lack of domain-specific integrated tools
ProAM Deliverable Highlights

Applications in U. S. Army AMCOM context

- *U-Engineer.com* pilot commercial ESB
  - Internet-based PWA-B analysis modules & toolkit
  - Usage in AMCOM supply chain

General techniques

- Internet-based engineering service bureau (ESB)
- X-analysis integration (XAI)
  - Product data-driven plug-and-play analysis modules
  - General purpose XAI toolkit, *XaiTools*
Analysis Documentation  Ready-to-Use Analysis Modules

Lower cost, better quality, fewer delays in supply chain
ESB Analysis Module
Catalogs & Documentation

PWB Analysis Services (Bare Board)

PWB Layup Design
- Post-Lamination Thickness
  - \( f(x) \)
  - \( \bigcirc \)
  - \( \bigcirc \)
  - \( \bigcirc \)
  - AP210
- Coefficient of Thermal Bending
  - \( f(x) \)
  - \( \bigcirc \)
  - \( \bigcirc \)
  - \( \bigcirc \)
  - AP210

PWB Warpage Analysis
- Thermal Bending Model
  - 1D
  - \( f(x) \)
  - \( \bigcirc \)
  - \( \bigcirc \)
  - \( \bigcirc \)
  - AP210
- Classical Lamina Theory Model
  - 2D
  - \( f(x) \)
  - \( \bigcirc \)
  - \( \bigcirc \)
  - \( \bigcirc \)
  - AP210
- Plane Strain Model (Material Variation)
  - 2D

PTH Deformation & Fatigue Analysis
- IPC 279 Model (cylinder/Coffin-Manson)
  - 1D
  - \( f(x) \)
  - \( \bigcirc \)
  - \( \bigcirc \)
  - \( \bigcirc \)
  - GenX
- Minim Beam Model
  - 1D
  - \( f(x) \)
  - \( \bigcirc \)
  - \( \bigcirc \)
  - \( \bigcirc \)
  - GenX
- Asymmetric Model
  - 2D
  - \( f(x) \)
  - \( \bigcirc \)
  - \( \bigcirc \)
  - \( \bigcirc \)
  - GenX
- Palgren-Miner Model
  - \( f(x) \)

Since the residual stresses, which cause warpage, are partly due to the coefficient of thermal expansion (CTE) mismatch between the materials in a PWB board, we may wish to search the reference books for other composite structures which warp due to mismatched CTEs.

One such structure is a bimaterial beam bending due to a uniform increase in temperature. Hence, we may wish to use this formula for a first order analysis of PWB Warpage.

\[
\text{Warpage } \delta = \frac{\alpha_0 t^2 \Delta T}{t}
\]

In fact, if the analysis variables are selected correctly, it turns out that this simple model captures the maximum warpage wherever it occurs on the PWB. (For further details, examine our Analysis Model Explanation page.) For example, to model the board Yeh et al. analyzed with FEM (illustrated at the top of the page) the figures for the input variables are:

- Undeformed (i.e. initial) Length \( L = 376 \text{ mm} \)
- Undeformed Thickness \( t = 1.08 \text{ mm} \)
- Temperature Change \( \Delta T = 70 ^\circ \text{C} \) (from 25\(^\circ\) to 95\(^\circ\))
- Specific Coefficient of Thermal Bending \( \alpha_0 = 1.10 \times 10^3 \text{C} \) (from 25\(^\circ\) to 95\(^\circ\))

Since the formula does not predict the direction of the warpage, the resultant warpage figure (approximately 0.59 mm) represents the following PWB configurations (warpage...
Paper-based IPC-D-279

Plated Through Hole Fatigue Analysis

Tedious to Use

PTH/PTV Fatigue Life Estimation

\[
\sigma_{\text{avg}} = \frac{\left(\alpha_E - \alpha_{\text{Cu}}\right) \Delta \tau + S_j \left(\frac{E_{\text{Cu}}}{E_E} - \frac{E_E}{E_{\text{Cu}}噤\right)} A_E E_{\text{Cu}}}{A_E E_{\text{Cu}} + A_{\text{Cu}} E_E}
\]

\[
\Delta \varepsilon_{\text{avg}} = \frac{\left(\alpha_E - \alpha_{\text{Cu}}\right) \Delta \tau \cdot A_E \cdot E_{\text{Cu}} \cdot S_j \cdot A_{\text{Cu}} \cdot \left(\frac{E_{\text{Cu}} - E_E}{E_{\text{Cu}}}ight)}{A_E E_{\text{Cu}} + A_{\text{Cu}} E_E}
\]

\[
N_f^{-0.6} D_f^{0.75} + 0.9 \frac{S_u}{E} \left[\frac{e^{D_f}}{0.36}\right]^{0.1785 \log \frac{10^3}{N_f}} - \Delta \varepsilon = 0
\]

\[
N_f (x\%) = N_f (50\%) \left[\ln\left(1 - 0.01x\right)\right]^{\frac{1}{\beta}} \left(\ln\left(0.5\right)\right)
\]
Web-based

IPC-D-279 PTH Analysis Module

Easy to Use

PTH Analysis Results

Input Variables
- Drilled hole diameter, \( d \): 0.0125 inches
- PWB Board thickness, \( H \): 0.0628 inches
- Barrel average plated thickness, \( h_p \): 0.0012 inches
- Barrel minimum plated thickness, \( t_{m} \): 0.001 inches
- Estimate of Plating Quality, \( K_Q \): 6
- Reduction in local cross sectional area due to plating or drilling defects, \( K_r \): 10%
- Change in temperature, \( \Delta T \): 200°C
- Reference temperature (ambient), \( T_{ref} \): 25°C
- Compression modulus of resin, \( E_r \): 500,000 psi
- Coefficient of Thermal Expansion of resin, \( \alpha_r \) below \( T_g \): 0.000167/°C
- Coefficient of Thermal Expansion of resin, \( \alpha_r \) above \( T_g \): 0.000015/°C
- Glass Transition Temperature, \( T_g \): 317°C
- Tensile modulus of barrel material, \( E_b \): 300,000 psi
- Plastic modulus of barrel material, \( E_p \): 100,000 psi
- Yield Strength of barrel material, \( S_y \): 25,000 psi
- Ultimate Strength of barrel material, \( S_u \): 40,000 psi
- Plastic strain at fracture of barrel material, \( \varepsilon_p \): 0.203
- Coefficient of Thermal Expansion of barrel material, \( \alpha_b \): 0.000017/°C

Analysis Model
- IPC-D-279 Plated Through Hole Model

Results
- Average Stress in the PTH barrel: 30,03176e3 psi
- Maximum Strain in the PTH barrel: 0.121682
- PTH barrel fatigue life: 10,61e3 cycles to 50% failure probability.
Product Data-Driven
IPC-D-279 PTH Analysis Module

Easier to Use

- Local browser:
  + Idealizes design data
  + Inserts into analysis

- Benefits
  + Fewer errors vs. manual idealization & re-entry
  + Automated exhaustive search (100s of PTHs)
  + Data compression (as much as 100x)
  + Increased security

GenCAM/GenX
Neutral Design File

Xparse
JavaScript parsing
Iterative Design & Analysis

PWB Layup Design Tool

1 Oz. Cu
1 Oz. Cu
1 Oz. Cu
2 Oz. Cu
2 Oz. Cu
1 Oz. Cu
Tetra GF
Tetra GF

1D Thermal Bending Model

Quick Formula-based Check

\[ \delta = \frac{\alpha_b L^2 \Delta T}{t} \]

\[ \alpha_b = \frac{w_i \alpha y_i}{t / 2 \ w_i} \]

PWB Warpage Modules

2D Plane Strain Model

Detailed FEA Check

3 x 1080
2 x 2116
3 x 1080
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ProAM Technical Team

Missile supply chain SME
- PWB design & fabrication expertise
- Tool usage & feedback

Missile system end-user
- Supply chain context
- Technical oversight

Electronic commerce resource center
- Mgt., ESB, and computing support

Research & development lab
- Program management
- Technical concepts
- Tool implementation

Circuit Express
AMCOM
S3
Georgia Tech
ECRC

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ProAM Focus
Automated Internet-based Analysis for Supply Chains

ProAM Focus
World Wide End User
AMCOM

Feedback, Products

Response to RFP, Technical Feedback, Products

RFP with Product Data (STEP, GenCAM, …)

Missile Mfg.
Prime 1

Internet-based Engineering Service Bureau
Atlanta
Physical Simulation
U-Engineer.com

Idealized Product Data
Self-Serve Results

Rockhill
PWB Fabricator
SME 1

Friona
PWB Fabricator
SME 2

Tempe
PWB Fabricator
SME n
Example SME Usage

- **Original design:**
  - Six layer board
  - Unsymmetrical layup
  - Severe warpage
  - Analysis predicted thermal distortion

- **Alternate design:**
  - Modeled construction variables
  - Analysis predicted improved distortion

- **New capability aided design improvement**
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Example
ESB Client-Server Architecture

User

Client PC

Thin Client

Web Browser

Thick Client

XaiTools

Engineering Service Bureau

Web Server

cgi (Perl)

html

forms

Solver Server

Finite Element Analysis (FEA) Solver

Ansys

Math Solver

Mathematica

CORBA

Internet

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CORBA

Internet
Internet-based ESB Techniques

- Analysis module template & methodology
- Range of access methods:
  - Remote Tools
    - Login to remote workstation; X-Windows display
  - Thick Clients
    - Locally installed w/ Internet/LAN-based solvers via CORBA
  - Thin Clients
    - Web-based forms & solvers all located at ESB
- General web techniques
- General e-commerce: electronic payment, etc.
ESB Characteristics

- **Self-serve analysis**
  - Pre-developed analysis modules presented in product & process contexts
  - Available via the Internet
  - Optionally standards-driven (STEP, GenCAM ...):
    » Reduce manual data transformation & re-entry
    » Highly automated plug-and-play usage
  - Enabled by X-analysis integration technology

- **Full-serve analysis as needed**

- **Possible business models:**
  - Pay-per-use and/or pay-per-period
  - ESB hosting
  - Costs averaged across customer base
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**X-Analysis Integration Concepts**

### Multi-Representation Architecture (MRA)

1. **Solution Method Model**
   - Analyzable Product Model
   - Context-Based Analysis Model
   - Analysis Building Block
   - Solution Method Model

2. **Analysis Building Block**
   - APM (Printed Wiring Assembly (PWA))
   - CBAM (Component)
   - ABB (Solder Joint)
   - SMM (Printed Wiring Board (PWB))

### Design-Analysis Associativity

1. **Design Model**
   - APM (PWA Component Occurrence)
   - CBAM (Solder Joint Plane Strain Model)

2. **Analysis Model**
   - Plane Strain Bodies System

### Analysis Module Creation Methodology

Physical Behavior Research

- Design-Analysis Associativity Diagram

Routinization (Module Creation)

- Routine Analysis (Module Usage)

Commercial Design Tools
- MCAD
- ECAD

Product Model
- Solder Joint Deformation Model

Analysis Module Catalogs
- Idealization/Defeatuarization
  - Component
  - Solder Joint
  - PWB

Commercial Analysis Tools
- Ansys
- CAE
- Abaqus

Selected Module
- APM ↔ CBAM ↔ ABB ↔ SMM

Constraint Schematic (Information Model)
Multi-Representation Architecture (MRA) Implementation

CAD/E Framework Architecture

Analysis Modules & Building Blocks
Constraint Schematics Implementations

Product-Specific Applications

- Aerospace structural analysis
- PWA-B thermomechanical analysis & design
  *XaiTools PWA-B™*
- Electronic package thermal analysis
  *XaiTools ChipPackage™*
STEP AP 210
PWA/B Design Information

Physical
- Component Placement
- Bare Board Geometry
- Layout items
- Layers non-planar, conductive & non-conductive
- Material product

Geometry
- Geometrically Bounded 2-D Shape
- Wireframe with Topology
- Advanced BREP Solids
- Constructive Solid Geometry

Product Structure/Connectivity
- Functional
- Packaged

Part
- Functionality
- Termination
- Shape 2D, 3D
- Single Level Decomposition
- Material Product
- Characteristics

Configuration Mgmt
- Identification
- Authority
- Effectivity
- Control
- Requirement Traceability
- Analytical Model
- Document References

Requirements
- Design
- Allocation
- Constraints
- Interface

Technology
- Fabrication Design Rules
- Product Design Rules
ProAM Design-Analysis Integration

Electronic Packaging Examples: PWA-B

Design Tools

ECAD Tools
Mentor Graphics, Accel*

PWB Layup Tool
XaiTools PWA-B

Laminates DB

Materials DB

Modular, Reusable Template Libraries

Analysis Modules (CBAMs) of Diverse Mode & Fidelity

Analysis Tools

XaiTools PWA-B

General Math Mathematica

FEA Ansys

Solder Joint Deformation* 1D, 2D, 3D

PWB Warpage 1D, 2D

PTH Deformation & Fatigue** 1D, 2D

* = Item not yet available in toolkit (all others have working examples)  ** = Item available via U-Engineer.com

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Summary

- Internet-based engineering service bureaus (ESBs)
  - Key step for affordable SME analysis
- Product data-driven analysis technology
  - Analysis integration toolkit
- AMCOM missile supply chain applications
  - U-Engineer.com & electronic packaging analysis
- Exemplar usage of electronic data files like STEP
- Applicability to other product industries
- Framework for automated analysis
  - Improved product performance, reliability, and manufacturability
For Further Information …

- EIS Lab web site: http://eislab.gatech.edu/
  - See Publications, DAI/XAI, Suggested Starting Points
- ProAM home page: http://eislab.gatech.edu/projects/proam/
- XaiTools home page: http://eislab.gatech.edu/
- Pilot commercial ESB: http://www.u-engineer.com/
  - Internet-based self-serve analysis
  - Analysis module catalog for electronic packaging
  - Highly automated front-ends to general FEA & math tools

Presenter Biosketch

Russell S. Peak is a Senior Researcher in the Georgia Institute of Technology CALS Technology Center where he is the Assistant Director of the Engineering Information Systems Laboratory. He also is part of the Atlanta Electronic Commerce Resource Center Technology Development Group. Dr. Peak's specialty is engineering design-analysis integration (DAI) with applications including electronic packaging and structural analysis.