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CHARACTERIZING FINE-GRAINED ASSOCIATIVITY GAPS: A PRELIMINARY STUDY OF CAD-CAE MODEL INTEROPERABILITY

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ABSTRACT

This paper describes an initial study towards characterizing model associativity gaps and other engineering interoperability problems. Drawing on over a decade of X-analysis integration (XAI)[1] research and development, it uses the XAI multi-representation architecture (MRA) as a means to decompose the problem and guide identification of potential key metrics.

A few such metrics are highlighted from the aerospace industry. These include number of structural analysis users, number of analysis templates, and identification of computing environment components (e.g., number of CAD and CAE tools used in an example aerospace electronics design environment).

One problem, denoted the fine-grained associativity gap, is highlighted in particular. Today such a gap in the CAD-CAE arena typically requires manual effort to connect an attribute in a design model (CAD) with attributes in one of its analysis models (CAE). This paper estimates that 1 million such gaps exist in the structural analysis of a complex product like an airframe. The labor cost alone to manually maintain such gaps likely runs in the tens of millions of dollars. Other associativity gap costs have yet to be estimated, including over- and under-design, lack of knowledge capture, and inconsistencies.

Narrowing in on fundamental gaps like fine-grained associativity helps both to characterize the cost of today's problems and to identify basic solution needs. Other studies are recommended to explore such facets further.

Keywords*:* fine-grained associativity gap, design-analysis integration, CAD-CAE interoperability, knowledge-based engineering (KBE), multi-representation architecture (MRA), constrained object (COB)

NOMENCLATURE

ABB	analysis building block
API	application programming interface
APM	analyzable product model
CAD	computer-aided design
CAE	computer-aided engineering (physics-based analysis in this context)
CBAM	context-based analysis model
COB	constrained object
CORBA	common object request broker (ORB) architecture
DR&O	design requirements and objectives
FEA	finite element analysis
KBE	knowledge-based engineering
MRA	multi-representation architecture
M&S	modeling and simulation
PDM	product data management
SMM	solution method model
SBD/E	simulation-based design/engineering
SOAP	simple object access protocol
XAI	X-analysis integration [1]

1 Background: Recent XAI Progress

First we overview a framework developed over the past decade to address CAD-CAE interoperability needs. This framework also helps us more precisely identify basic issues and metrics.

The multi-representation architecture (MRA) in Figure 1 is the conceptual foundation of an X-analysis integration (XAI) methodology based on object-oriented patterns that naturally exist in engineering analysis processes [1]. It is particularly

[1] X = design, mfg., sustainment, and other lifecycle phases.

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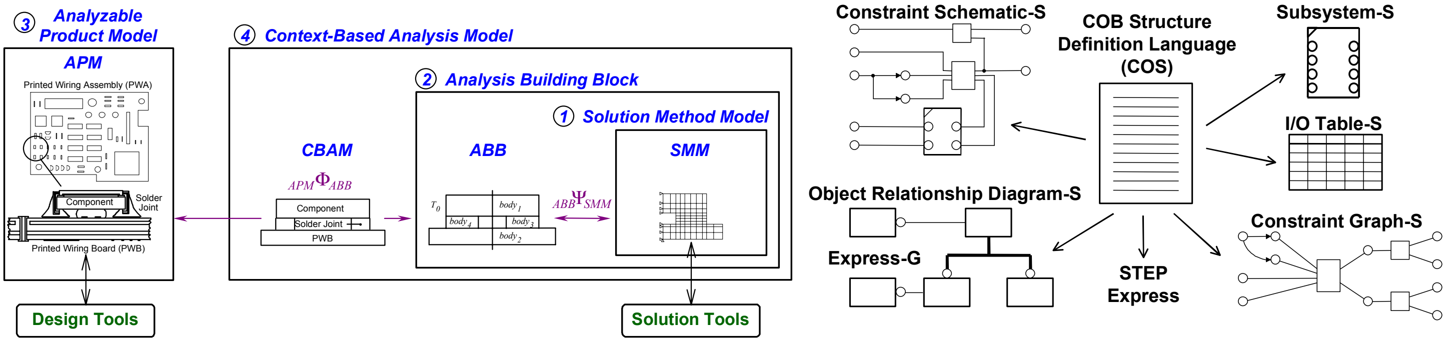


Figure 1 - The multi-representation architecture (MRA) for analysis templates and the constrained object (COB) representation [1].

aimed at design-analysis integration in CAD/CAE environments with high diversity (e.g., diversity of parts, analysis discipline, analysis idealization fidelity, design tools, and analysis tools) and where explicit design-analysis associativity is important (e.g., for automation, knowledge capture, and auditing). In this context, analysis means simulating the physical behavior of a part or system (e.g., determining the stress in a circuit board solder joint).

The constrained object (COB) knowledge representation captures engineering semantics in a modular, reusable manner due to its object-oriented non-causal nature. COBs support the MRA to address the specific needs of engineering analysis integration for simulation-based design & engineering (SBD/E), including virtual prototyping, knowledge-based engineering (KBE), and CAD-CAE interoperability.

Analysis integration applications of COB capabilities include support for design synthesis (sizing) and design verification (analysis), and implementation of MRA concepts as four main object patterns (Figure 1):

- *Analyzable product models (APMs):* Represent knowledge-based design models augmented with analysis-oriented overlays. Include multi-fidelity idealizations (Γ_i) and multi-source design information coordination.

- *Context-based analysis models (CBAMs*): Represent product-specific analysis modules/templates. Capture idealization decisions inside CAD-CAE associativity relations (Φ_j). Connect APMs and ABBs via these relations.

- *Analysis building blocks (ABBs):* Represent product-independent analytical concepts as reusable, modular, solver-independent objects. Generate SMMs for solution purposes.

- *Solution method modules (SMMs):* Represent solution method-specific models. Support white box reuse of existing tools (e.g., FEA tools and in-house codes). Automatic interactions occur through native command lines or APIs, and/or APIs based on standards like CORBA or SOAP.

Today's typical gaps are the fundamental drivers behind the MRA. Given the diversity of CAD and CAE methods and tools, a desire for modularity necessitates having at least the four patterns/representations above. Just as a single type of shock absorber can be used on many different types of cars, a given SMM type (e.g., an Ansys FEA SMM) can be used by many types of ABBs; a given ABB can be used by many CBAMs; and so on.

Industrial applications include airframes (for structural analysis), circuit boards (for design and thermomechanical analysis), and electronic chip packaging (for thermal resistance analysis and thermomechanical analysis). Benefits include decreasing total simulation cycle time by 75% [1] and leveraging the richness of an ISO 10303 product model standard for electronics (see www.ap210.org).

2 Preliminary Characterizations

2.1 Analysis Templates, Users, and Computing Environments

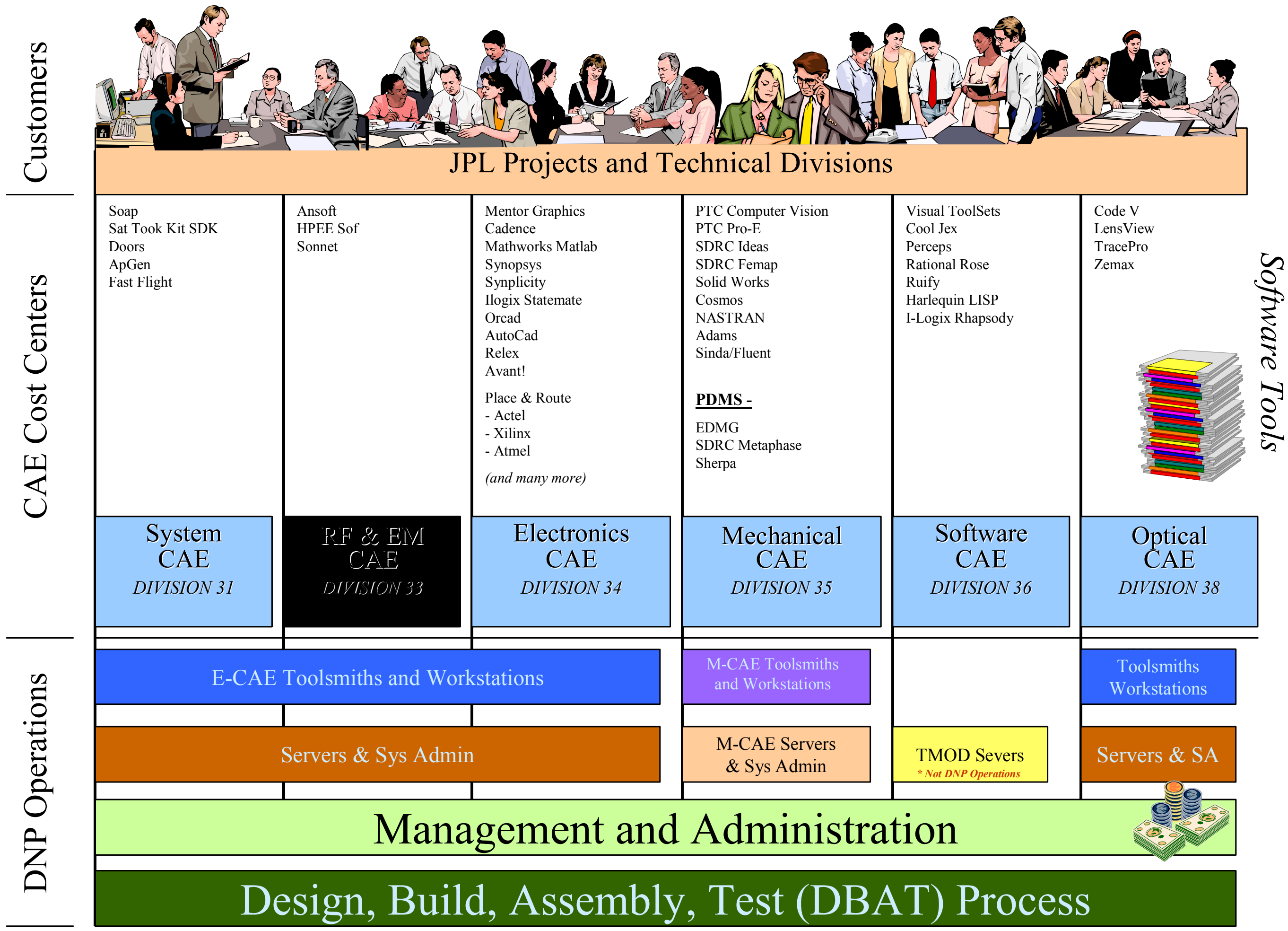
With the above as context, this section identifies several XAI metrics, their position within the MRA, and sample values from two aerospace industry organizations.

A public Request for Information (RFI) document from the Boeing Common Structures Workstation (CSW) effort [2] identifies industrial needs for analysis templates and their context within complex engineering development environments.

The RFI is Boeing-specific and aerospace-oriented, and it focuses on the structural analysis domain. Still, we have found that similar abstracted needs and issues occur in other companies and with other product types and analysis domains.

Documents like this RFI provide useful starting points towards characterizing the magnitude of modeling and simulation (M&S) interoperability problems at a more generic cross-industry level.

Our multi-representation architecture (MRA) for CAD-CAE integration provides a framework and methodology for decomposing such problems into logical units (based on their engineering meaning and the application of object-oriented



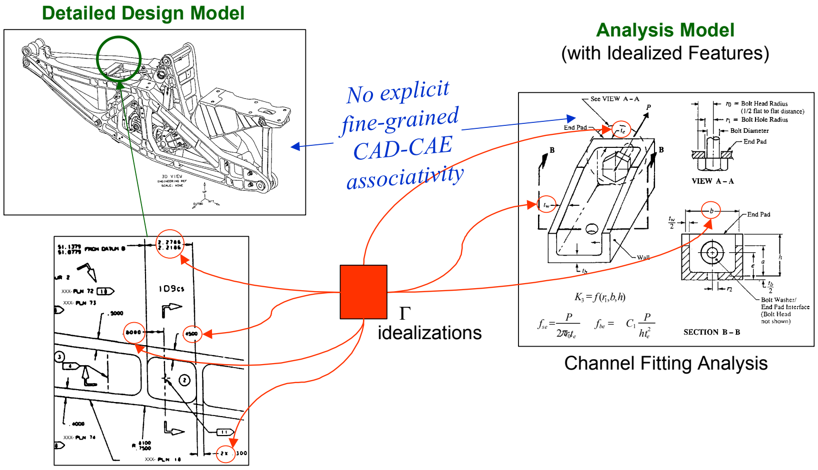
Adapted from “Computer Aided Engineering Tool Service at JPL” - 2001-07-22 - Mike Dickerson -NASA-JPL

Figure 2 - Major engineering tools in the NASA JPL Design Hub [3].

thinking). For example, one can organize and analyze items from the above RFI by identifying which MRA concepts they belong to. As noted in Section 1 above, Reference [1] points to several studies where we have done such “object-izing” in detail for diverse industrial M&S problems.

The above Boeing RFI and information from JPL provide the following statistics either directly or indirectly. Here we have also identified their MRA context as an initial estimate:

1. 110 groupings of generic structural analysis templates, with each grouping usually containing several actual templates and template elements.
   a. *Source:* Counting leaf items in Appendix B “Required Standard Analysis Methods” in [2a]
   b. These templates typically represent general engineering analytical concepts and are termed analysis building blocks (ABBs) within the MRA.
   c. Similar listings exist in structural design manuals from organizations like NASA and the U. S. Air Force.
2. 10,000 product-specific analysis templates.
   a. *Source:* Section 4.5.1 “BCAG Requirements” in [2a]
   b. These probably include some of the above ABB-type generic templates, but typically they are product-specific usages of such ABBs (e.g., see “Figure 1-3 Part-based Analysis Template” in [2a] for a specific structural part). These are called context-based analysis models (CBAMs) or simply “analysis templates” in the MRA.
3. 1,800 users (for structural analysis-oriented capabilities) located “at many sites, world wide”.
   a. *Source:* [2b]
   b. These engineer users typically *create* CBAM-like models that idealize their specific designs and apply generic analysis methods. Their designer counterparts (i.e. CAD users focused on manufacturability and other detailed requirements) typically would like to *use* pre-developed CBAM-like templates.



Categories of Gap Costs

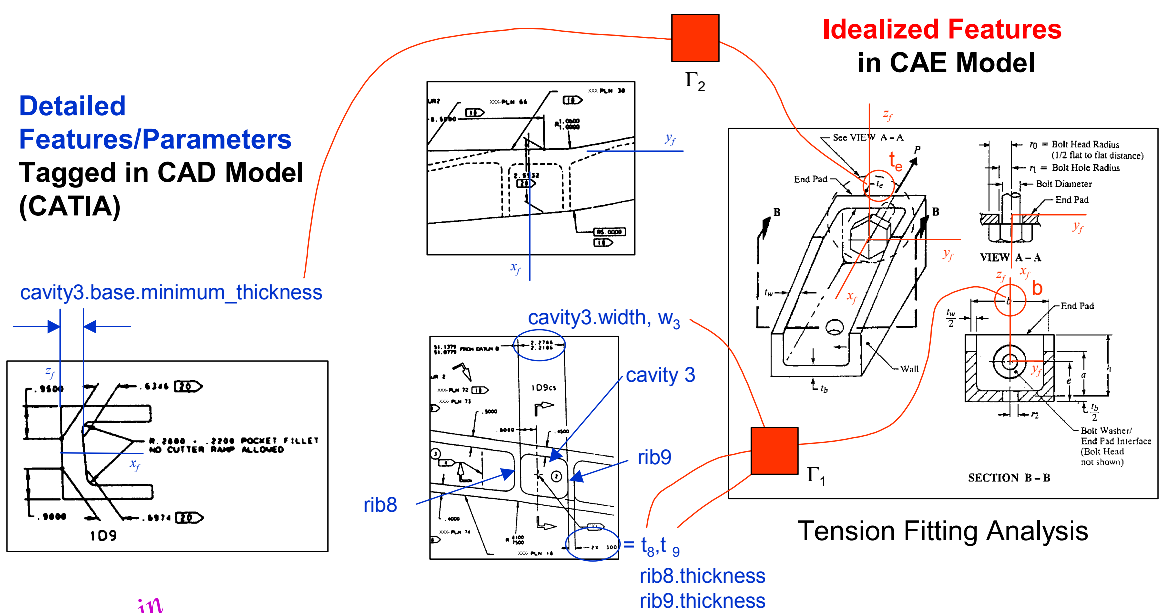
- Associativity time & labor
  - Manual maintenance
  - Little re-use
  - Lost knowledge
- Inconsistencies
- Limited analysis usage
  - Fewer parts analyzed
  - Fewer iterations per part
- "Wrong" values
  - Too conservative:
    Extra part costs and performance inefficiencies
  - Too loose:
    Re-work, failures, law suits

Initial Cost Estimate per Complex Product (only for manual maintenance costs of structural analysis problems)

$$O(10{,}000)\,\text{parts} \times O(10)\,\frac{\text{analyses}}{\text{part}} \times O(10)\,\frac{\text{variables}}{\text{analysis}} = O(1{,}000{,}000)\,\text{gaps}$$

$$O(1{,}000{,}000)\,\text{gaps} \times O(10)\,\frac{\$}{\text{gap}} = \$O(10{,}000{,}000)$$

Figure 3 - Costs of CAD-CAE associativity gaps.



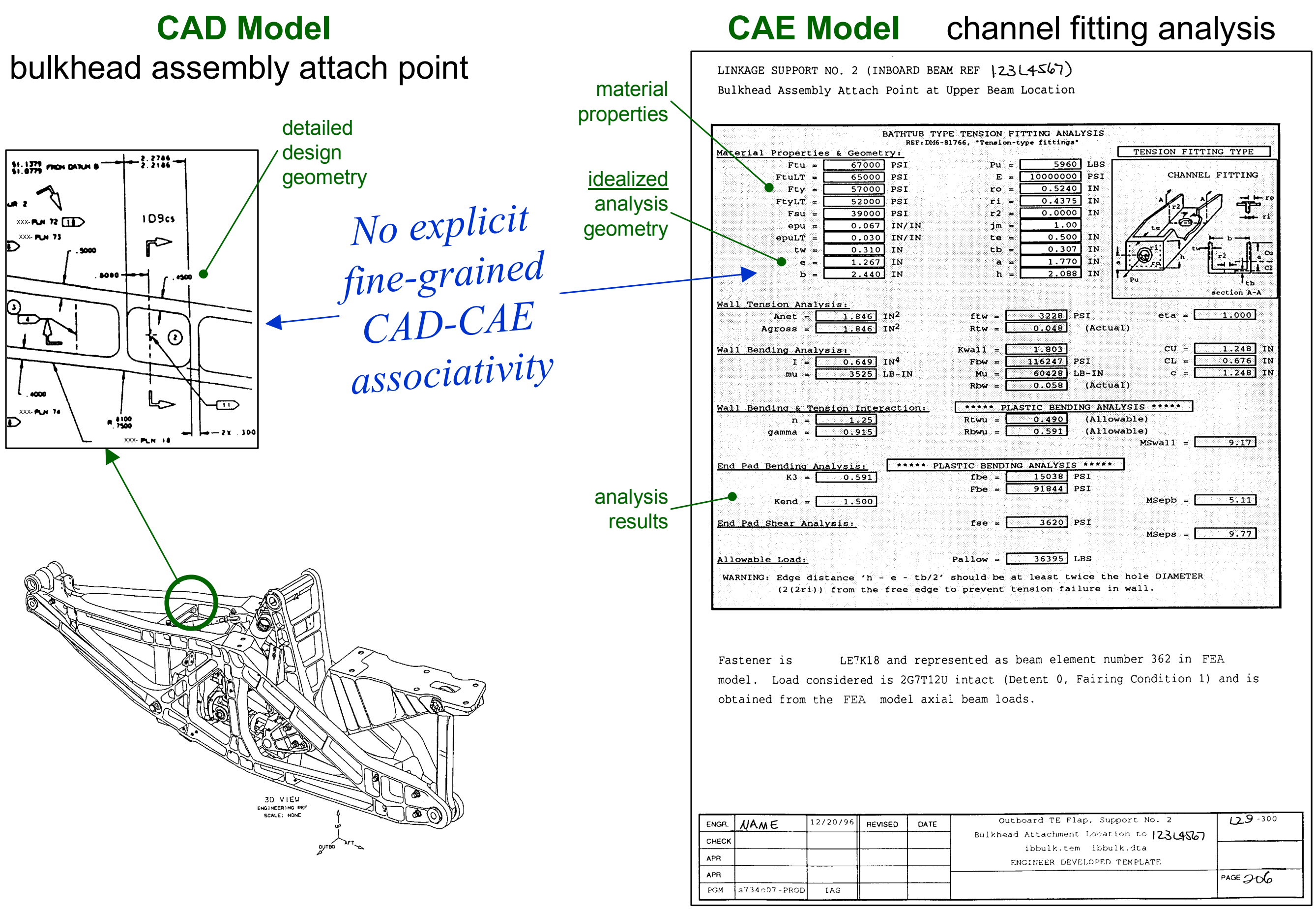
Often missing in today's process

Γ_i - Relations between idealized CAE parameters and detailed CAD parameters

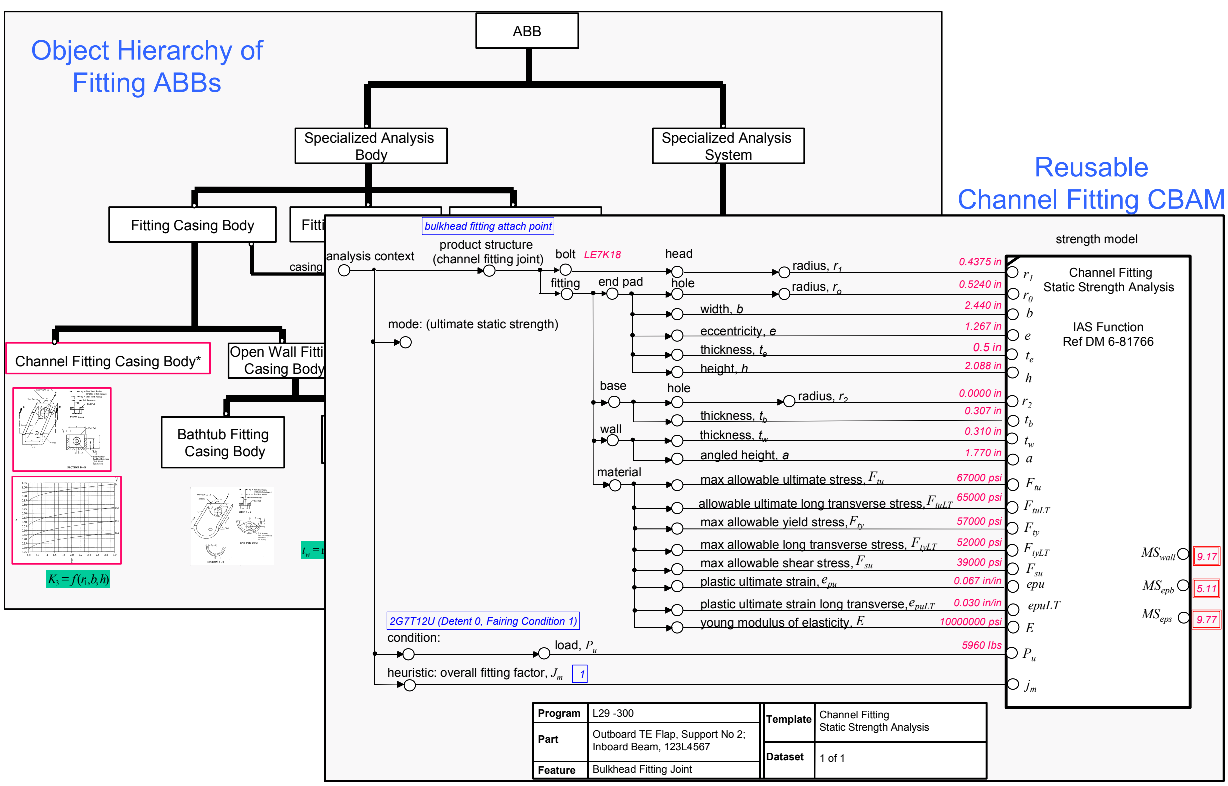
Γ_1 : b = cavity3.inner_width + rib8.thickness/2 + rib9.thickness/2

Γ_2 : t_e = cavity3.base.minimum_thickness

Figure 4 - Examples of fine-grained CAD-CAE associativity relations in an airframe structural analysis [4].

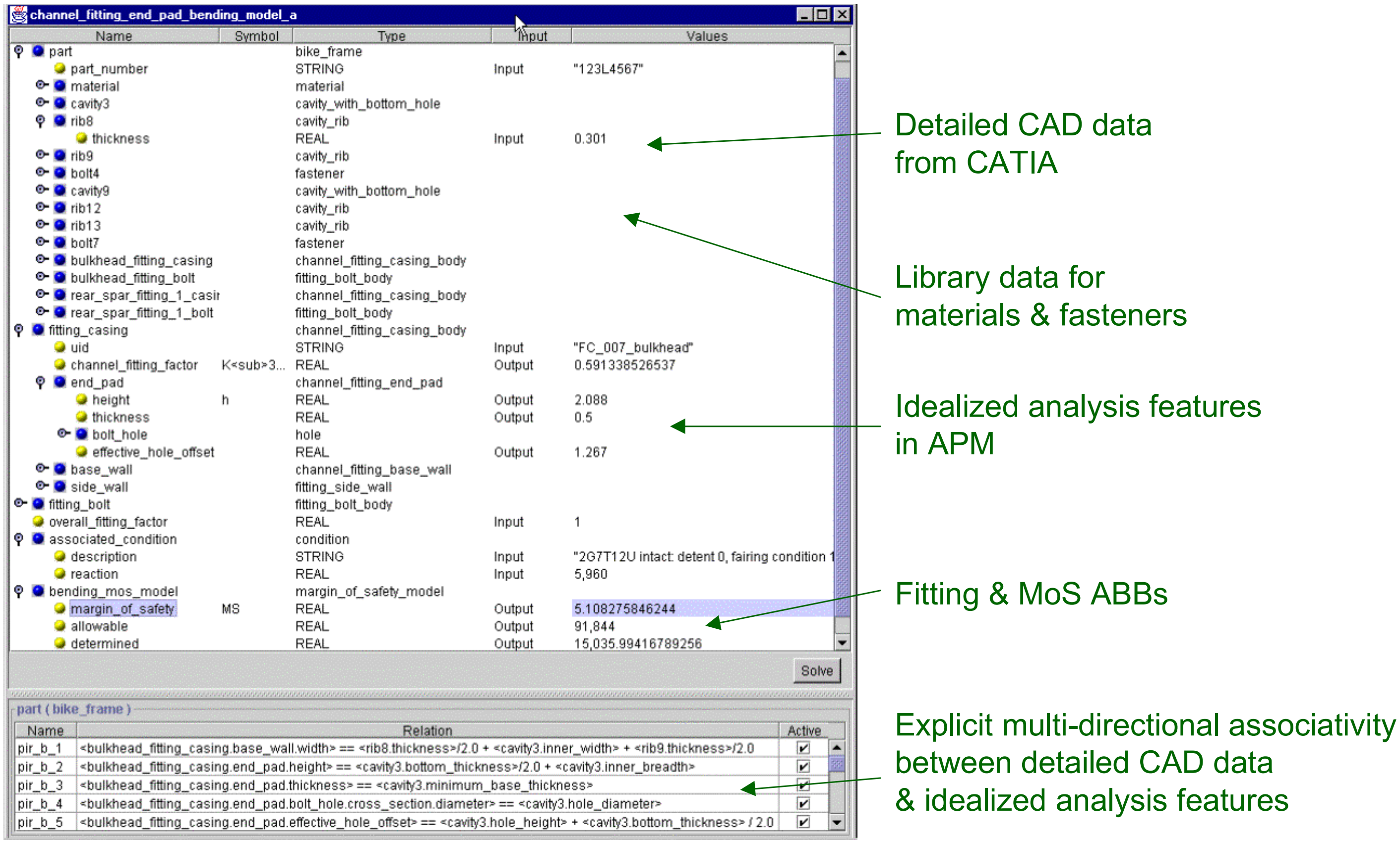


a. Representative current practice.



b. Analysis template representation as COBs.

Figure 5 - Airframe analysis templates for channel fitting analysis (Parts a. and b.).



c. Integrated implementation in MRA-based *XaiTools.*

Figure 5 - Airframe analysis templates for channel fitting analysis (continued: Part c.).

4. Example variety and number of hardware and operating system (OS) platforms, software tools, and related technologies. Figure 2 shows ~45 major engineering tools present at another aerospace organization (the Jet Propulsion Lab, www.jpl.nasa.gov).

a. *Source:* [2b] and Figure 2 adapted from JPL.
b. Development organizations typically maintain detailed listings of the CAD/E software they use (some organizations use O(100) such tools; one can imagine the configuration management and version control issues this causes, as each tool will typically evolve with a new release every 1-2 years).
c. CAD models and parts libraries are related to MRA APMs.
d. CAE models (for engineering analysis like FEA) and associated libraries (e.g., for material behavior, loads, and environments) are related to SMMs in the MRA.
e. The CAD and CAE tools themselves correspond to the items labeled *Design Tools* and *Solution Tools* in the Figure 1 view of the MRA. A CAD tool typically interacts with a major subset [3] of an APM, while a CAE tool usually deals with a complete vendor-specific SMM.

2.2 Identifying CAD-CAE Associativity Gaps

The upper left portion of Figure 3 and Figure 5a exemplify one of the root problems faced in modeling and simulation today: the fine-grained associativity gap [1, 4]. On the left is a detailed design model (a CAD model focusing on shape and assembly) and on the right is one analysis model for one feature in this assembly (a formula-based CAE model for estimating fitting feature strength). This CAE model has 18 idealized parameters related to shape and material. Each idealized parameter is related to one or more detailed parameter in the CAD model. Figure 4 shows two shape-oriented relations for this example: Γ_1 and Γ_2 that connect with idealized parameters b and t_e. A recent project report [4] overviews the MRA implementation of this example as summarized in Figure 5b-c.

The MRA organizes such idealization relations, Γ_i, inside APMs to maximize their modularity and reusability (e.g., usage by possibly many different types of CBAM analysis templates). When a CBAM uses such a relation to connect a design model (an APM) to a generic analysis model (an ABB system), the usage is termed an **associativity relation** and is denoted by the symbol Φ_j. as seen in Figure 1. The CBAM implementation of the fitting analysis template is given in Figure 5b as a COB constraint schematic. It shows these explicit fine-grained associativity relations graphically as 18 circuit-like connection lines [4]. These lines represent computer-sensible relations that are implemented in a lexical form, which facilitates analysis management and execution (e.g., as shown in the object-oriented spreadsheet-like tool in Figure 5c).

Today associativity between such models is typically represented in a computer-sensible form only at the macro

Table 1 - Attributes used in the associativity cost estimate in Figure 3.

Attribute	Explanation for order of magnitude values used
Number of "analysis-significant" parts per complex product.	10,000 is a rough estimate. The Boeing 777 has some 3 million total parts [5], hence this number is less than 1% of the total parts in that case. Here "analysis-significant" indicates a part that needs some type of physics-based analysis to ensure that it meets specified requirements (not all parts have such needs, e.g., if they do not experience significant loading).
Number of analysis templates per part.	10 is an estimate based on experience with a variety of such templates. These templates are typically categorized as CBAMs per the MRA.
Number of variables (each with a related associativity relation) per analysis template.	10 is again an estimate based on experience with templates like that in Figure 4. Such variables are typically idealized values related to shape and material. Each one is usually involved in one or more distinct associativity relations within a given CBAM. Each variable represents an associativity gap in that a user must transfer the value from a design model or other source and place it into the analysis template. To maintain consistency, they must do this each time the original source changes.
Cost per associativity gap	$10 is a (conservative?) estimate assuming that each variable takes on average a few minutes to find and manually transfer into the analysis model of interest. Some such transfers are simple equality relations, whereas others involve computing an analysis model attribute from one or more design model attributes (as for parameters b and t_e in Figure 4). This estimate does not consider multiple transfers or reverse transfers (from CAE to CAD).

level, if at all. For example, a product lifecycle management (PLM) system might tell you "part P1 has analysis models A1 and A2" (macro-level associativity relations), but it usually contains nothing about detailed relations that exist between attributes inside P1 and A1 (e.g., like Γ_1 and Γ_2 in Figure 4).

These root-level relations are where CAD-CAE interoperability actually occurs. An **associativity gap** is defined as the case where an individual associativity relation[2] is not captured in a computer-sensible form. For example every time a person manually copies a value from model M1 and re-enters it into another model M2, an associativity gap[3] is being encountered. In the case of the relation Γ_2 in Figure 4, a person must manually obtain the cavity 3 minimum base thickness CAD value and assign it to end pad thickness, t_e, in the CAE model. Due to such gaps, engineers must repeatedly expend manual effort enforcing and maintaining the corresponding computer-insensible associativity relations.

2.3 Costs of CAD-CAE Associativity Gaps

Having identified the fine-grained associativity gap, one can begin to estimate related costs. First the categories[4] of problems this gap causes are identified in the upper right portion of Figure 3. Next, we focus on one such problem in the calculation in this figure: the manual labor cost to maintain associativity between CAD models and structural CAE models in a single complex system like a commercial airframe.

Table 1 explains each of the attributes employed in this order of magnitude calculation. The end result estimates that O(1 million) associativity gaps exist in such systems.

2.4 Discussion

Note that this simple cost model deals only with one category of associativity gap costs. Consideration of other cost categories and data sources will help better estimate the true total costs of the CAD-CAE interoperability problem. For example, statistics for part type and part occurrence-specific analysis would help determine a more accurate estimate for the number of "analysis-significant" parts. Also some organizations have developed in-house codes to automate associativity for some analysis templates. Thus, more detailed cost estimates should consider these cases and the costs necessary to develop such aids.

CAD systems are making progress in capturing parametric relations (e.g., in CATIA v5). However, challenges remain in terms of knowledge modularity, reusability, and accessibility (e.g., the relations are often buried inside compiled code or proprietary vendor formats), not to mention directionality, fidelity, control, and multi-disciplinary associativity. Facilities for efficiently defining and managing template-level associativity relations are a significant meta-issue (beyond simply managing the specific values the relations produce for a given design-analysis instance).

[2] This definition holds for any models M1 and M2 (not just between CAD and CAE models). The term "fine-grained" informally denotes micro-level associativity, meaning that the relations are among root level attributes like real-valued attributes (as opposed to the macro-level PLM associativity discussed above).

A more general "relation gap" could be defined to cover the similar case where the computer-insensible relation is between attributes within the same model (e.g., if the relation $A = ½bh$ is missing inside a triangle object).

[3] If the exact same value from M1 is entered into M2, then the corresponding associativity relation is an equality relation. If some computation is performed before the value is entered into M2, then the associativity relation could be any arbitrarily complex relation. This simplicity of the former case makes it easy to overlook the existence of such relations.

[4] A detailed description of each category is beyond the scope of this paper.

3 Summary

This paper presents a preliminary study towards more precisely characterizing X-analysis integration (XAI) issues like CAD-CAE interoperability. It identifies several engineering information metrics and example values from the aerospace industry: number of structural analysis users, number of analysis templates, number of computing environment components (e.g., number of CAD and CAE tools used in an example aerospace electronics design environment), and number of CAD-CAE associativity relations.

We use a combined top-down and bottom-up approach in this study. The multi-representation architecture (MRA) guides top-down problem decomposition. It also identifies several abstraction patterns that exist in diverse CAD and CAE environments. From this conceptual framework we can narrow in and define metrics for each type of pattern.

The bottom-up facet involves recognizing basic issues that occur within several patterns at the root level. In this paper we describe fine-grained associativity as one basic issue: how to connect attributes within and between diverse models. An example analysis template is given containing 18 CAD-CAE associativity relations. Each relation represents an associativity gap in typical practice today where a person must manually enforce such relations (i.e., transform data from one model into another model). From experience with such examples we provide an estimate that some 1 million gaps exist in the structural analysis of a complex product like an airframe. The gap-related costs likely run into the tens of millions of dollars.

Thus we identify supporting fine-grained associativity as a fundamental need. This bottom-level capability, from which higher-level capabilities are built, is analogous to the transistor and other circuit elements in electronics. The transistor's seemingly simplistic ability to provide 1's and 0's is the foundation for digital logic on which the information age has been built. Top-down architectures like the MRA have similar electronics analogies.

Constrained object (COB) technology is one step towards enabling generalized fine-grained associativity. It has basic information processing elements analogous to electronic elements like the transistor. Constraint schematics, analogous to electrical schematics, combine COB elements to form higher level objects like analysis templates. These templates are in fact instances of MRA patterns; hence, bottom-up associativity capabilities are joined to top-down M&S integration concepts.

The above cost estimate helps one think about the problem in more precise terms. We recommend further studies to refine cost estimates and target fundamental issues and solutions. For example, the Engineering Framework Interest Group [6] is addressing other basic gaps with similar potential impact (i.e., the content coverage gap and the content semantic gap [3]). Similar examples from other domains are available to characterize broader interoperability problems and guide solution approaches like the MRA and COBs [1]. We envision that this type of study may ultimately link with macro-level economic studies such as [7].

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Available here:
http://eislab.gatech.edu/projects/boeing-psi/2000-06-csw-rfi/
Includes:
[2a] Attachment A - "Common Structures Workstation - Design Requirements and Objectives"
[2b] Attachment B - "Boeing Computing Infrastructure"

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[6] For further information, see resources including the following:

- Recent project work:
  http://eislab.gatech.edu/projects/
- Engineering Framework Interest Group (EFWIG):
  http://eislab.gatech.edu/efwig/

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