ABSTRACT

Design and analysis are two key aspects of the product development process, which is iterative by nature and requires knowledge from several different domains. For example, designers devise product specifications based on required functions, whereas, analysis experts analyze the behavior of the resulting product using various models to verify that the design meets required functions. Should analysis results indicate unacceptable behavior, the design is sent back to designers for modification, resulting in an often costly, iterative loop between design and analysis that repeats itself throughout the product development process. Significant cost and time savings can be achieved by reducing this iteration between designers and analysts. In this paper, we present a knowledge-based framework for integrating design and analysis activities, aimed at reducing the associated iterations. Specific research issues presented in this paper include developing a knowledge-based repository of analysis models and a means for extracting appropriate models from the repository. The concept of a design model hyperspace is proposed for storing analysis models in a hierarchical fashion. The associations between design and analysis models are captured using flexible associativities between them. The knowledge-based framework is presented in the context of multifunctional design of Linear Cellular Alloys (LCAs).

NOMENCLATURE

Analysis – verification of product behavior using mathematical simulation tools.

Analysis Model – a model is often an idealized representation of the design model used in analysis.

Analysis Template – an established analysis model that is repeatedly used for a specific type of product. Variables and parameters and the relations between design parameters and analysis model parameters are fairly well known.

Behavior - represents how the artifact implements its function.

Design Model – the specification of the artifact as it should be manufactured. The design model is an idealized version of the “real” or “physical” part.

Form - represents physical characteristics and includes aspects such as geometry and material properties.

Function - represents the artifact’s intended behavior. An artifact satisfies engineering requirements through its function.

Idealization - to construct an abstracted model of the real system that will admit some form of mathematical analysis. Most frequently, idealization refers specifically to the transformations that are applied to the design representation.

Fidelity - used to convey the notion of different levels of detail of the models. Higher fidelity models capture more detail than lower fidelity models.

1. FRAME OF REFERENCE: INTEGRATION OF DESIGN AND ANALYSIS

The increased complexity in modern engineered products has forced a change in the way in which products are designed and developed. Engineering design is increasingly becoming a collaborative set of tasks among multidisciplinary, distributed design teams [1]. While the advantages of multidisciplinary, distributed design include increased quality and decreased development time, disadvantages arise in the communication of knowledge and expertise across domains by specialists. These problems are not only present across various design domains, such as electrical and mechanical design, but also between design and analysis activities throughout the entirety of the product development process (PDP).

PDPs are iterative by nature and require consideration of knowledge and expertise from several different domains. Designers, for example, devise product specifications based on required functions. Similarly, analysts simulate the behavior of the resulting product specifications. In a generic PDP, designs emanating from the creative minds of design engineers are usually sent to analysts for validation. Analysis models are thus created based on design specifications and an appropriate set of idealizations. Idealizations are introduced in order make the analysis process tractable by decreasing the complexity and hence the time required to complete required analyses. Such idealizations include geometric simplifications, idealizations of material properties, phenomenological concerns, and boundary/loading conditions to name a few [2].

Should analytic results indicate unacceptable behavior, the design is sent back to the designer for modification, resulting in an often costly, iterative loop between design and analysis
that repeats itself throughout the product realization cycle. Depending on the changes required, such iterations may result in a partial or a complete redesign of the product.

While advances in computing performance and numerical simulation techniques have decreased the overall computational cost of analysis, inefficiencies in the design-analysis cycle are due in a large part to the knowledge-intensive task of creating the appropriate idealized analysis model. Fenves, et al. [3] state that the organization of design teams and the fusion of expert knowledge amongst designers and analysts is frequently lacking. The detailed product specifications captured in product modeling tools must often be recreated by analysts for simplified analysis models [4]. The fundamental research issue thus consists in reducing design-analysis iterations using knowledge based idealizations.

The challenges in integrating design and analysis in modern product development are twofold. On one hand, the disparity in heterogeneous software applications and reliance on proprietary data formats limits sharing product knowledge across tools and organizations. On the other hand, the product representations pertaining to the design and analysis domains are often focused on different product characteristics. In this paper, the authors address the second issue, specifically focusing on the manner by which different representations of the same physical product can be shared between designers and analysts. Finn [2] captures the underlying challenge in design-analysis integration as follows:

"It is usually neither feasible nor desirable to analyze all aspects of a physical system. This is because most problems contain complexities that render numerical simulation difficult and redundancies that are unnecessary to analyze. Thus, in practice, certain complexities can be simplified, thereby facilitating more efficient computation, whereas redundancies can be ignored with loss to the integrity of the physical system. The essence of physical modeling is the ability to effect simplifications and remove redundancies without affecting the integrity of the problem or solution. Thus, in a physical modeling task, the major challenges to the engineer are, identifying the various complexities and redundancies in a physical system, applying the appropriate modeling strategies and techniques to simplify or reduce these features."

Even if a final design is rich in detail, it is sometimes beneficial to use simplified models for analysis because slight increase in detail may result in drastic increase in computational intensity. It is clear that there is a tradeoff between analysis time and accuracy. The question becomes how to effectively choose the right level of complexity for obtaining required information. This choice is often determined by the current state of a product in its progression along its design timeline. In the initial stages of the design process, simple models can be used to provide reasonably good insight into product behavior and designers can base their decisions on low fidelity models. As the design matures and its description becomes both increasingly complex and semantically rich, more realistic and accurate design and analysis models are required for behavioral predictions. Unfortunately, highly detailed models, even at this stage in the design process are often difficult to analyze and require significant time to complete. Consequently, simplified models continue to play a role and are relied upon for gaining insights into the latter stages of product design when time and efficiency are of the essence. Thus, there is a definite need for (1) enabling the knowledge-based selection of models capturing the appropriate level of idealizations throughout the design process and (2) leveraging previously developed analysis models as appropriate.

The issue of creating and capturing reusable design knowledge in engineering design has been addressed by many researchers from various perspectives. Research efforts span the areas of design and behavioral model repositories [1, 5-10], analysis templates [11-15], and product lifecycle management [16], consistently promoting knowledge and information capture and reuse over the life of the product. While these efforts focus on the overarching scope of knowledge capture and reuse in product development, they offer an excellent basis on which to address the specific problem of knowledge reuse in engineering analysis.

An issue inherent in developing a knowledge base for design-analysis idealizations is that idealizations are developed for use in a specific context, thereby limiting reusability. Analysis templates [15], for example, enable close associativity between design and analysis models to be captured. However, they capture associativity in merely a static manner, namely for a specific product and context. Thus, while analysis templates provide the advantage of reducing cycle time, they lack the flexibility and openness required for designing variant products in which parameter values and product features may change. The question that arises is: How can the underlying mapping between analysis and design models be created and captured in a more flexible, extensible, and open manner?

To summarize, the overarching research issue consists in reducing design-analysis iterations and increasing PDP efficiency through the use of knowledge integration. Consequently, (1) the level of idealization and (2) the fidelity must be quantified and captured with regard to design and analysis models. The required metrics can then be used to determine their appropriateness throughout the design process and create a flexible, extensible, and open mapping between the design and analysis models. In this paper, we outline a strategy for answering these research issues. We begin by pointing out some of the underlying nuances in this effort through the use of a motivating example – the design and analysis of a family of emerging complex material structural systems called Linear Cellular Alloys (LCAs).

2. MOTIVATING EXAMPLE: DESIGN OF LINEAR CELLULAR ALLOYS

For demonstrating the requirements of a knowledge-based design analysis integration framework, we present an example
scenario related to the design of Linear Cellular Alloys (LCAs). Linear Cellular Alloys are metallic cellular materials with a constant cross section, fabricated through a process developed by the Lightweight Structures Group at Georgia Tech. The process combines extrusion of ceramic slurry, composed of metal oxides and water through a die, allowing for the achievement of quasi-arbitrary two-dimensional cellular topologies. Extrusion of the ceramic is followed by exposure to thermal and chemical treatments that cure the composites. The inherent advantage in producing materials using this process is the ability to tailor properties of the resulting structure such as the effective moduli of elasticity and conductivity by altering the cell topologies.

**Figure 1.** The shape of Linear Cellular Alloys [17].

LCAs are cellular materials with extended prismatic cells (see Figure 1). Structures may be composed of either periodically repeating unit cells or functionally-graded, non-uniform cells of various topologies. LCAs can be manufactured with arbitrary cross-sections (see Figure 2 for representative examples). LCA wall thicknesses are generally in the range of a few hundred microns.

**Figure 2.** Examples cross-section of LCAs [17].

**Figure 3.** A conceptual illustration of an LCA as a structural heat transfer device for an electronic cooling application.

LCAs are suitable for multi-functional applications that involve not only structural but also thermal considerations (see Figure 3). One of the main advantages of using LCAs is that desired material properties can be obtained by design. Potential applications of LCAs include heat sinks for microprocessors and combustor liners for aircraft turbines, among others.

### 2.1. LCA Design Specifications and Considerations

The models used for LCA design include information about form, function, and behavior, the definitions of which, used in this paper, are taken from [18]:

- **Form** - represents physical characteristics and includes aspects such as geometry and material properties.
- **Function** - represents the artifact’s intended behavior. An artifact satisfies engineering requirements through its function.
- **Behavior** - represents how the artifact implements its function.

Analysis models, used in LCA design, map form to behavior in order to evaluate the satisfaction of functional requirements. Relevant considerations for the design of LCAs, relating to form, function, and behavior are discussed next.

#### Form Characteristics

- **Unit cell topology**: This includes the shape of each unit cell, which can be triangular, rectangular, hexagonal etc. (see Figure 2)
- **Arrangement of cells**: These repeating cells can be arranged in a number of different configurations, captured in the form.
- **Unit cell dimensions** (and possible ranges): The dimensions of each cell can vary, resulting in graded structures. In the product model, we thus need to represent each dimension separately.
- **Geometric Constraints**: Limits on overall dimensions like length, width, rib dimensions, and aspect ratio must be specified.
- **Dimensional uncertainty**: Dimensions are not exact due to variations in the manufacturing process. This uncertainty must be represented in the model.
- **Bulk material properties**: Constituent solid material must be represented in terms of properties such as thermal conductivity, porosity, Poisson’s ratio, density, etc.

#### Function and Behavior Characteristics

- **Thermal requirements**: Amount of heat to be transferred from the surface per unit time or maintaining a certain temperature at a given point.
- **Structural requirements**: The strength of the LCA is predominantly a function of the form. This strength is quantified in terms of the effective elastic stiffness, buckling
Manufacturing requirements: The manufacturing process greatly influences the design considerations of LCAs. There is a limit to the accuracy that the manufacturing process can achieve. For example, porosity plays a role in the behavior of the material and needs to be taken into account during the design process. Other factors related to manufacturing process include defects in cell walls and joints as well as tolerances.

Pressure drop: Generally, fluid is forced through the channels of the LCA to achieve convective cooling. In the case of a CPU heat sink, forced convection is achieved through the use of a fan, the capacity of which is limited by the pressure drop. Similar considerations apply to combustor liners.

Other behavioral information: The design models must capture behavioral information that includes boundary conditions, structural responses (for e.g., stresses, strains, etc.) and thermal responses (for e.g., heat transfer, temperature at notes, etc.). Information regarding uncertainties in behavior evaluation is also important.

LCA product specifications are determined through a well-defined development process. Designers systematically determine the product form specifications through a development process that relies heavily on design-analysis. Engineering designers and analysts work collaboratively to specify the LCA form based on expected requirements and simulate the behavior of the LCA in an iterative manner toward the final design specification. An overview of the LCA development process is presented in the following section in order to more clearly illustrate this point.

2.2. Process for Designing LCAs

The LCA development process is shown in Figure 4. The process consists of six steps starting with gathering customer requirement and formulating the desired behavioral aspects of the LCA and culminating with optimization of the LCA form.

1. Capture customer requirements and determine behavior - customer requirements are captured and formalized into engineering specifications. Based on these requirements, functional and performance characteristics are expressed in terms of LCA behavior.

2. Specify the LCA Design form – the LCA design form is embodied based on expected requirement and designer’s knowledge and experience using CAD tools.

3. Numerical Simulation – numerical simulations are performed to determine the simulated behavior of the LCA. Numerical simulation consists of two primary steps (1) simulation model generation and (2) mathematical modeling. Thermal and structural simulation models are developed from design models and a set of idealizations. Mathematical modeling, then maps the simulation model into the appropriate mathematical formulation. In LCA simulation, mathematical modeling is the finite element method of computational fluid dynamics.

4. Evaluate Simulated Behavior – the simulated behavior of the LCA is compared against the desired behavior (function). If the two do not match, appropriate changes are made to the form parameters to obtain the desired performance.

5. Optimization Decision and Optimize LCA Design - optimization techniques are employed in the form of the compromise Decision Support Problem (cDSP) technique [17] to determine the final geometry of the LCA to best meet behavioral performance requirements.

Figure 4. The process for designing LCAs.

To enable the LCA development process to be completed efficiently and effectively, the following is needed:

- LCA design models must be formalized and include relevant design information, such as function and form
- LCA analysis idealizations must be encapsulated and characterized to promote efficient reuse for generating analysis models used in numerical simulation
- The resulting simplified LCA analysis models must be archived to enable knowledge-based retrieval to reduce the design-analysis cycle time

The overarching goal in the LCA development process is the specification of the LCA form such that it can be
manufactured. In contrast, the goal of analysis is to simulate the behavior of what is actually built. As a result, engineering designers often idealize the design form to enable simulation. In the following section, we identify several idealizations commonly employed by engineering analysts when creating simplified LCA analysis models.

2.3. Idealization in LCA Design and Analysis

Ultimately, analysis models are generated based on the design form and an appropriate set of idealizations. The LCA idealizations are roughly decomposed into Form Idealization and Behavior/Functional Idealization. Form idealizations are used by designers to create a simulation model that operates on the form of the LCA model, including geometry, material and topology considerations. Behavior/Function idealizations operate on boundary and loading conditions and underlying behavioral models. Examples are provided in Table 1 and Table 2, respectively.

Table 1. Representative set of form idealizations used in creating LCA simulation models.

<table>
<thead>
<tr>
<th>Form Idealization</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Diagram" /></td>
<td>Truss members in the LCA structure may be imperfectly connected or breaks or fractures may be present in the structure</td>
</tr>
<tr>
<td><img src="image2.png" alt="Diagram" /></td>
<td>Voids in the material continuum may be present due to manufacturing</td>
</tr>
<tr>
<td><img src="image3.png" alt="Diagram" /></td>
<td>Manufacturing variability may result in wall thickness variations and dimensional variations of cell in the LCA</td>
</tr>
<tr>
<td><img src="image4.png" alt="Diagram" /></td>
<td>Sides of overall LCA and cells within LCA are not parallel</td>
</tr>
<tr>
<td><img src="image5.png" alt="Diagram" /></td>
<td>LCA form is warped due to manufacturing – internal stresses or imperfect heat transfer may result because of shape</td>
</tr>
<tr>
<td><img src="image6.png" alt="Diagram" /></td>
<td>Inhomogeneous material properties and variations in density, thermal conductivity, strength of the LCA due to manufacturing may affect behavior</td>
</tr>
</tbody>
</table>

Table 2. Representative set of behavioral and functional idealization used in creating LCA simulation models.

<table>
<thead>
<tr>
<th>Behavior/Function Idealization</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image7.png" alt="Diagram" /></td>
<td>Uniform heat flow from the entire chip package into the LCA is assumed</td>
</tr>
<tr>
<td><img src="image8.png" alt="Diagram" /></td>
<td>Uniform heat flow from die in the chip package into the LCA is assumed</td>
</tr>
<tr>
<td><img src="image9.png" alt="Diagram" /></td>
<td>Non-uniform heat flow from the entire chip package into the LCA is assumed</td>
</tr>
<tr>
<td><img src="image10.png" alt="Diagram" /></td>
<td>No contact resistance between microprocessor and LCA</td>
</tr>
<tr>
<td><img src="image11.png" alt="Diagram" /></td>
<td>Contact resistance considered between microprocessor and LCA</td>
</tr>
<tr>
<td><img src="image12.png" alt="Diagram" /></td>
<td>Perfect insulation is considered on three sides of LCA.</td>
</tr>
<tr>
<td><img src="image13.png" alt="Diagram" /></td>
<td>Uniform flow and no pressure loss of fluid through cells</td>
</tr>
<tr>
<td><img src="image14.png" alt="Diagram" /></td>
<td>Internal stresses in LCA structure may effect overall structural performance</td>
</tr>
</tbody>
</table>

The idealizations included in Tables 1 and 2 represent common idealization used in the design of LCAs. The list, however, by no means comprehensive. These idealizations represent a set of operations that engineering designers can use to develop analysis models of varying fidelities. For example, an analyst may determine that fractures in the LCA structure will complicate and increase the simulation time, but the
increase in accuracy of the result may provide insight to make key design decisions. Essentially, thus, engineering analysts construct an analysis model based on a design model and a set of appropriate idealizations.

2.4. Discussion

Simplified models do not provide the high level of accuracy that detailed models may provide, but make it possible to complete analysis in a timely and efficient manner. Even if detailed design models are available at the end of a design process, it is sometimes beneficial to use simplified models since even adding small details may increase model complexity drastically. Although higher model complexity generally increases the accuracy it also implies significantly higher computational cost. Hence, there is a tradeoff between analysis time and analysis accuracy. In this paper, we present a method for selecting appropriate sets of idealizations depending on the phase in the design process. This method helps in reducing individual design-analysis iteration time.

3. A REVIEW OF EXISTING LITERATURE ON DESIGN-ANALYSIS INTEGRATION

As previously stated, problems associated with design analysis integration are (1) the disparity and interoperability in design and analysis tools and (2) context-dependent idealizations and simplifications between engineering design and analysis models [3]. Several approaches for addressing these design and analysis problems include standards-based product representations [19-22], automatic mesh generation and shape modification [23-27], attribution and feature recognition of product models [4, 28, 29], and model idealization and simplification to name a few [2, 30-35]. While there has been more than a decade of research effort and technology development, there are still many opportunistic areas for advancement.

Standards-based product representation development efforts, such as eXtensible Markup Language (XML) and ISO10303-STEP, have enabled product models to be shared amongst heterogeneous software applications in engineering design and analysis through the development of common product models [19-22, 36]. For example, STEP AP209 addresses interoperability of product models between CAD and FEA applications, thus enabling closer integration of design models and analysis models. AP209 addresses interoperability issues between diverse software tools. However, idealizations between design and analysis representations are not supported. Standards-based product models enable designers to share LCA design form between design and analysis software applications easily – when the form is not simplified. However, they do not support knowledge-based idealizations between design form and simplified analysis form (see Figure 4, Step 2 and Step 3).

There has been a substantial research effort in design-analysis integration based in artificial intelligence (AI) techniques for generating simplified analysis models. Finn, et al. [34, 35, 37] asserts that while advances in numerical simulation have become an invaluable asset in engineering analysis, the task of creating appropriate simplified physical models of the product remains a key problem. Finn uses artificial intelligence (AI) techniques, such as rule-based systems and model-based reasoning, to capture idealizations and simplifications employed in creating physical models. These idealizations and simplification are often based on first principles, approximations, and heuristics.

Similarly, Armstrong, et al. [26, 27] present the idea of a priori knowledge and a posteriori analysis of the simulation results to make the appropriate idealizations. Operations, such as medial-axis transform, dimensional reduction, and feature removal are used to create analysis model. An AI-based framework is developed to support the automatic creation of analysis models using idealizations.

Finally, Shephard, et al. [30-32] propose a method and software framework for automating the idealization process in developing simulation models. The proposed method is based on “goals and strategies” using a series of knowledge-based systems and analysis applications to generate a idealized analysis models.

The AI-based methods and frameworks in [26, 27, 30-32, 34, 35, 37] address the nature of creating simplified analyzable models of physical systems that are both computationally accurate and efficient. AI techniques, such as model-based, rule-based, and case-based systems, help to address a fundamental research question in [17]: how can downstream manufacturing knowledge be incorporated into LCA design? AI-based technologies provide a viable solution for capturing and reusing manufacturing process knowledge, thus facilitating the interactive creation of simplified analysis models.

However, the aforementioned AI techniques suffer from the following limitations: (1) systems work best in well-structured domains, thus the knowledge is brittle and (2) the systems do not usually scale well, a small increase in problem scope results in the need to capture additional knowledge.

A departure from traditional AI techniques for representing simplifications in engineering design is the development of routine analysis templates. Peak, et al. [11, 12, 14, 15, 38, 39] present the Multi-Representation Architecture (MRA) as a technique for creating analysis templates. These templates facilitate capturing design-analysis asociativities as “hard-wired” relationships between design and analysis model parameters. Design templates are reusable in a particular context, but reusability is limited to variations on design parameters. The MRA provides the capability to capture several aspects in design-analysis integration including (1) the automation of routine analyses, (2) the representation of design and analysis associativity and of the relationships among the models, and (3) the support of various analysis models throughout the life cycle of the product.

Analysis templates enable engineering designers to capture knowledge in established form for variant design. Templates enable quick and efficient analysis integration when product
variants are limited to parametric changes in design specifications. However, design templates cannot be effectively reused when there is a change in the product description. In LCA design, several design templates must be developed to capture the diverse manufacturing variations in simulation models.

Discussion on Existing Literature

The primary goal of design-analysis integration research is to facilitate efficient and effective analysis throughout the product development process. Several research efforts that span over the last 10 years have addressed some part of design analysis integration. While researchers have made significant contributions towards reducing the gaps between engineering design and analysis, there are still opportunistic developments. The MRA provides the advantage of capturing routine analysis in the form of reusable templates. These templates reduce the overall cost and time of analysis that is completed repeatedly, but require analysis expertise when using the templates outside of a specific domain. Similarly, knowledge-based frameworks and methods that are predicated on the existence of complete knowledge capture for a domain are limited to a well-defined scope and tend not to scale well. Capturing idealization in this manner will enable well-defined simulation models to be generated more easily, but may break down when simulation context of domain changes slightly.

Synergistic efforts in the areas of AI techniques, predefined analysis templates, and standard-based representation must be leveraged to reduce the integration problems associated with engineering design and simulation models. In developing simplified LCA simulation models a combination of reusable manufacturing idealization knowledge and analysis templates must be employed for the following reasons:

- The manufacturing idealizations (in Table 1 and Table 2) cannot be captured and characterized in a knowledge-base as individual relations. Behavioral results are often based on models composed of a set of idealizations. The overall accuracy and computation time are determined by the model as a whole and cannot be qualitatively determined for each idealization separately.
- The diverse and variant nature of LCA design and the various manufacturing idealizations result in a large number of design templates for simulating the design space.

We are thus interested in reducing 1) the number of design-analysis iterations and 2) the time required for a single iteration. This leads to the following research questions, addressed in Section 4:

- How can analysis expertise be captured to support idealizations and simplifications of engineering product models?

4. A STRATEGY FOR INTEGRATING DESIGN AND ANALYSIS THROUGH KNOWLEDGE BASED IDEALIZATIONS

Considering the numerous challenges associated with integrating design and analysis activities, we propose a knowledge-based approach to decrease the overall product development cycle time. Specifically, we present the conceptualization and initial development of a knowledge-based framework for capturing analysis knowledge and expertise to reduce overall product realization time. The overarching goal is to enable the modular reuse of analysis idealizations, thus reducing the knowledge gap between engineering design and analysis activities. Design-analysis integration is supported by synthesizing domain expertise as follows:

- Capturing knowledge about analysis models, in a robust fashion that stands in contrast to the brittle nature of expert systems. Idealizations are defined at various levels of abstraction, thereby providing greater reusability. This provides increased context about the analysis models that are used to support design decisions.
- Capturing and formally characterizing idealizations in progressing from design to analysis; thereby increasing the knowledge gained throughout product development. To enable analysis reuse, idealizations are captured using storable building blocks.
- Capturing the domain specificity of idealizations which is important for determining the scope of applicability. Much the same is true for capturing analysis context.
- Selecting appropriate sets of idealizations depending on the current phase in the design process.

These four tasks can be broadly divided between two main research thrusts, namely capturing knowledge and retrieving it, described in Sections 4.1 and 4.2, respectively.

4.1. Developing a Knowledge-Based Repository of Analysis Models

4.1.1. Capturing Knowledge Characterizing Analysis Models

The first step towards creating a knowledge-base for analysis models is capturing all the relevant knowledge that can affect the applicability of a model. Such factors include context, scope, simplifying assumptions, domain, results, information requirements (inputs) and contributions (outputs), accuracy, level of detail, fidelity, complexity, and scalability of a given model.
4.1.2. Structuring Knowledge by Mapping Design Models to the Appropriate Analysis Models using a Hyperspace: A Conceptual Architecture for an Analysis Model Repository

The conceptual architecture of an analysis model repository can be viewed as an n-dimensional hyperspace, with each dimension pertaining to a different type of idealization performed while designing artifacts. In Figure 5, we illustrate a three-dimensional analysis model hyperspace where the three dimensions are geometric idealization, behavioral idealization, and boundary condition idealization. Each point in this hyperspace represents a different analysis model. As we proceed in the positive direction along each axis, models become more and more simplified. For example, Model B constitutes a simplification of Model A with regard to artifact geometry. All other characteristics of the model like boundary conditions and behavioral model remain the same. This is apparent from Figure 1, since there is only a change in the geometry dimension. Similarly, Model D makes use of idealized boundary conditions when compared to model B.

![Figure 5. The Analysis Model Hyperspace.](image)

In general, there are no restrictions on the number of dimensions considered in the analysis model hyperspace. Dimensions must have noticeable impacts on the analysis results. It is evident that the n-dimensional hyperspace offers a convenient way to isolate and organize idealization effects. Directions in the model space may further be viewed as subspaces. For example, the boundary conditions may be subdivided into loads and supports. The loading may further be split into structural loading, thermal loading, etc. Hence, the analysis model hyperspace is inherently based on a hierarchical structure that can be captured using a tree-like construct as commonly employed in the design of repositories. The approach suggested here relies on the use of a “destruction tree” for systematically capture simplifications in analysis models. This “destruction tree” is akin to the construction tree in constructive solid geometric modeling, where detailed models are created from basic geometric shapes and Boolean operations. Hayes and Regli [40] present the model process history as a similar extension to the traditional construction tree to address how the design changes throughout product development. The idealizations in the “destruction tree” are captured in a knowledge base for reuse in different design scenarios. Additionally, capturing idealization knowledge facilitates the selection and creation of

![Figure 6. LCA analysis models hyperspace.](image)

An example of the analysis model hyperspace for LCAs using the idealizations from Table 1 and Table 2 is depicted in

<table>
<thead>
<tr>
<th>Table 3. Description of LCA analysis models in hyperspace.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Model A:</strong></td>
</tr>
<tr>
<td>- Void and fractures are considered in the LCA geometry</td>
</tr>
<tr>
<td>- Radiation heat transfer from the LCA to the environment</td>
</tr>
<tr>
<td>- Non uniform heat from the microprocessor</td>
</tr>
<tr>
<td>- Contact resistance between the heat source and the LCA</td>
</tr>
<tr>
<td><strong>Model B:</strong></td>
</tr>
<tr>
<td>- The simulation geometry is identical to the design</td>
</tr>
<tr>
<td>geometry</td>
</tr>
<tr>
<td>- Radiation heat transfer from the LCA to the environment</td>
</tr>
<tr>
<td>- Non-uniform heat from the microprocessor</td>
</tr>
<tr>
<td>- Contact resistance between the heat source and the LCA</td>
</tr>
<tr>
<td><strong>Model C:</strong></td>
</tr>
<tr>
<td>- Void and fractures are considered in the LCA geometry,</td>
</tr>
<tr>
<td>- Radiation heat transfer from the LCA to the environment</td>
</tr>
<tr>
<td>- Perfectly insulated on three-sides</td>
</tr>
<tr>
<td>- Uniform heat from the microprocessor</td>
</tr>
<tr>
<td>- Contact resistance between the heat source and the LCA is not considered</td>
</tr>
<tr>
<td><strong>Model D:</strong></td>
</tr>
<tr>
<td>- The simulation geometry is identical to the design</td>
</tr>
<tr>
<td>geometry</td>
</tr>
<tr>
<td>- Perfectly insulated on three-sides</td>
</tr>
<tr>
<td>- Uniform heat from the microprocessor</td>
</tr>
<tr>
<td>- Contact resistance between the heat source and the LCA is not considered</td>
</tr>
</tbody>
</table>

Figure 6. The hyperspace is presented in two dimensions: Geometric Idealizations and Boundary Condition Idealizations.
the most appropriate analysis models. Associativities between design and analysis models along with the impact of idealization on the predicted behavior are also captured. The hierarchical relationships between simulation models (SM) and a design model (DM) are illustrated in Figure 7. The design model is related to simulation models of varying complexity through a set of idealizations ($\Gamma$). As depicted in Figure 7, the idealization level of the simulation models are inversely related to the idealization set.

Figure 7. Hierarchical decomposition and idealization relationships between analysis models.

It is important to realize that the hierarchical structure of the analysis model repository can further be taken advantage of in evaluating the effect of different idealizations on the analysis results and computation time required. Generally, idealization of a model leads to increased error and reduced analysis time. A tradeoff between analysis time and accuracy can be obtained by selecting an appropriate model from the analysis model hyperspace. If prior knowledge about the analysis models and associated error is captured in the knowledge repository, the designers can appropriately select a model by moving accordingly throughout the analysis space illustrated in Figure 5.

4.1.3. Implementing Flexible, Hierarchical Design-Analysis Templates

An important prerequisite for effectively using the analysis model hyperspace discussed in Section 4.1.2 is the ability to integrate the design model with various fidelities of analysis models. The fundamental constructs for doing so are flexible, hierarchical idealization templates that model the associativity between these two kinds of models. We thus propose a hierarchical, object oriented model for idealization templates. This is in contrast to the static mapping templates generally used for this purpose.

4.2. Knowledge-Based Retrieval of Analysis Models

4.2.1. Moving Along the Analysis Model Hyperspace

The analysis model hyperspace can be viewed as a design space and the response is a combination of accuracy and cost. The key assumption here is that the knowledge base contains information about all the models and their impact on accuracy, time, cost, etc. Assuming such information is readily available from the knowledge base, the destruction tree can be used to map out a strategy for attaining improvements with regard to any of the dimensions considered in the model hyperspace.

Progression along a design timeline may be illustrated via movement throughout the analysis model hyperspace. This is due to the fact that the appropriateness of a model is greatly dependent upon the current stage in the design process, information requirements, and a designer’s knowledge. In the early stages of the design process, model accuracy is usually not of great concern. In fact, the detailed models are not even available. Consequently, designers must rely on simplified models for quick exploration and evaluation of artifact behavior. Towards the latter stages of a design, however, more detailed models are available and can be used to evaluate product performance. The strategy for moving along the analysis hyperspace is determined by careful consideration of tradeoffs between metrics.

4.2.2. Metrics for Assessing Model Applicability in a Given Scenario

In order to select the model most appropriate for obtaining the desired behavioral information about the design, there is a need for characterizing the models with regard to a set of quantifiable metrics. Some of these metrics are: computational time required for execution of the model, accuracy in results of analysis, value of information obtained with respect to designer requirements, relevance of the model to the analysis situation in terms of the context and application domain, uncertainty associated with the underlying behavioral model, validity of the assumptions made in constructing the model, the level of detail captured in the model, the level of abstraction that is of interest to the designer, complexity of operations in terms of executing the model, adaptability of the model to different situations, modularity of the model with regard to interfacing with other models, and robustness of the model. Multiple metrics can be of interest to designers while selecting a model. Relying on the right set of metrics in choosing among available analysis models will force a designer to remain conscious of opportunity costs and carefully consider the tradeoffs involved. This approach will help reducing the design-analysis iterations and promises a closer integration between the two domains.

5. CLOSURE AND FUTURE WORK

In this paper, we highlight the need for integration of design and analysis activities. In order to address this need, we propose a knowledge-based framework for integration of
design and analysis activities. This framework has the potential to reduce design-analysis iterations significantly. Specific research issues associated with developing a knowledge-base and extracting appropriate analysis models are discussed. The knowledge-base proposed in this paper is based on a conceptual analysis model hyperspace which can be used to model different fidelities of analysis models in a hierarchical fashion. Metrics that can be used to select models from the hyperspace are also given. The enhanced integration between design and analysis models is achieved through flexible object-oriented idealization associations. These templates form a critical part of the design-analysis knowledge base.

Future work includes (1) instantiating analysis model hyperspaces using object-oriented information modeling standards like STEP Express, (2) developing object-oriented models for a hierarchy of idealizations, and (3) using multi-objective selection methods for selecting the right model from a model hyperspace.

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