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Application Table: A Bridge Connecting the Designing “With-The-Material” and “The-Material” Paradigms

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December 2022

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Abstract

Over the last few decades, advances in high-performance computing, new material characterization methods, and, more recently, an emphasis on integrated computational materials engineering (ICME) have been a catalyst for multiscale modeling and simulation-based design of materials and structures in the aerospace industry. In 2016 NASA sponsored a 2040 Vision study (which appeared in 2018) to define the potential 25-year future state required for integrated multiscale modeling of materials and systems (e.g., load-bearing structures) to accelerate the pace and reduce the expense of innovation in future aerospace and aeronautical systems. The study envisions a cyber-physical-social ecosystem comprised of experimentally verified and validated (V&V) computational models, tools, and techniques, along with the associated digital tapestry, that impacts the entire supply chain to enable cost-effective, rapid, and revolutionary design of "fit-for-purpose" materials, components, and systems.

Consequently, the development of a robust information management system that incorporates (across the full life cycle) both experimental (real data) and virtual data resulting from the application of various simulation tools (at single or multiple length scales), therefore enabling the virtual design and optimization of materials throughout their processing – internal structure – property – performance envelope, has become critical. This need is also fueled by the demands for higher efficiency in material testing; consistency, quality, and traceability of data; product design; engineering analysis; as well as control of access to proprietary or sensitive information. This is particularly true when attempting to merge ICME practices with recent additive manufacturing technology which will enable production of the resulting 2040 Vision material and structural designs. At NASA Glenn Research Center we are exploring the future of material science through the use of novel characterization methodologies, high performance computing, and recently an emphasis on integrated computational materials engineering (ICME). Herein, recent efforts to incorporate an Application Table within NASA Glenn Research Center's ICME Granta MI database is presented. The goal is to provide a place where material and structural application information/requirements can be linked so as to marry the "design the-material" and the "design-with-material" paradigms and thereby enable application-driven design and optimization of materials and structures by providing a central location that links material processing at various length scales to the application's performance requirements. This paper discusses the specifics of this Application Table as well as best practices and key principles for the development of a robust materials information management system to enable the 2040 Vision integrated materials and structures ecosystem. Furthermore, it presents the intended role of the Application Table in the future of ICME design of "fit-for-purpose" materials, showing the need for a well-established framework that can successfully bridge the gap between the design "the material" and design "with-the-material" paradigms.

1.0 Introduction

With the increased emphasis on reducing the cost and time to market of new materials, ICME (Integrated Computational Materials Engineering) has become a fast-growing discipline within materials science and engineering. The vision of ICME is compelling in many respects, not only for the value added in reducing time-to-market for new products with advanced, tailored materials, but also for enhanced efficiency and performance in these materials. Although the challenges and barriers (both technical and cultural) are formidable substantial cost, schedule, and technical benefits can result from broad development, implementation, and validation of ICME principles (Ref. 1). ICME is an integrated approach to the design of products, and the materials that comprise them, by linking material models at multiple time and length scales. A key ingredient is the linkage with manufacturing processes, which produce internal material structures, and in turn influence material properties and allowables, enabling tailoring (engineering) to specific industrial applications. Figure 1 illustrates the interconnection of these scales and their cause/effect relationships, e.g., processing conditions produce a particular microstructure from which properties are obtained, which then dictate a specific structural performance (Refs. 2 and 3). Note that the evolution of elliptical line types (i.e., dotted to dashed to solid line) are purposely included to imply an increasing level of maturity/understanding of modeling at each level of scale (both temporal and geometric). Furthermore, the figure illustrates the difference between two non-mutually exclusive viewpoints; that is designing "with-the-material" (structural analyst viewpoint) versus designing "the-material" (a materials scientist viewpoint). It is also apparent that the fundamental linkage between these two viewpoints is ultimately the associated constitutive model(s) for a particular material. One cannot overestimate the importance of understanding the input and output at each scale to determine meaningful properties that are ultimately required by a structural analyst. Equally important is the fact that the associated model parameters – model response/performance must be ultimately experimentally validated and certified.

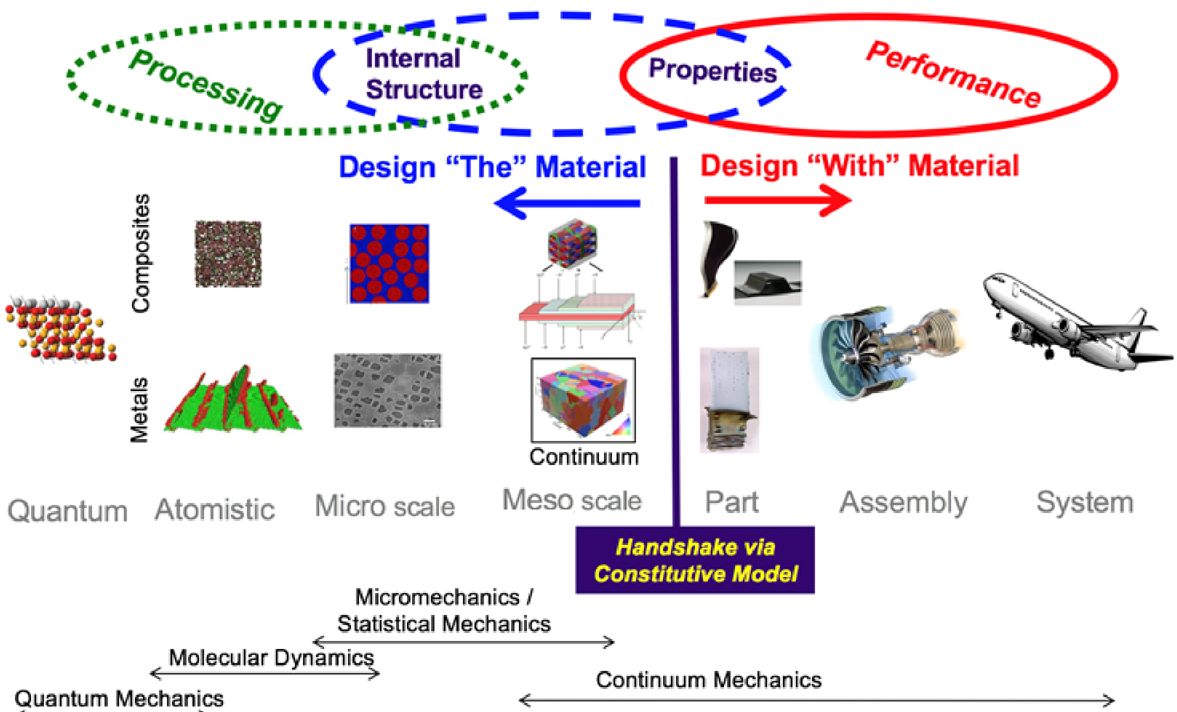

Figure 1.—Description of associated length scale dependence and modeling methods in the context of ICME.

Software to manage the digital footprint related to the “design with-the-material” (structural viewpoint) has evolved and matured significantly over the last two to three decades; particularly with the advent of PLM (Product Lifecycle Management) and SDM (Simulation Data Management) software for managing and integrating engineering data and processes as well as business and manufacturing processes form cradle to grave. Since this viewpoint primarily only deals with existing materials, typically only minimal information pertinent to material properties and allowables is considered. Similarly, numerous material lifecycle management (MLM) systems, both open and commercial, either exist or are under development to manage the digital footprint for the “design the-material” paradigm and span various length scales, from atomic to macroscale (Ref. 4). These systems provide essential input to material models (whether atomic potentials or material properties for example). However, this material property-centered system almost exclusively focuses on the management of the multifaceted material-oriented information (response curves, point-wise properties, processing/heat treatment pedigree, microstructure, etc.) and ignore critical connections to application/system *performance* requirements, thus making the modification of materials or design of new materials much more problematic (e.g., failure to account for “lurking failure modes”). Furthermore, it is critical to understand that ICME is not just developing processing-microstructure (P-M) relationships or microstructure-property (M-P) relationships independently, but rather it is the integration of these various length scale-specific relationships so that linkage from processing all the way up to *performance* can be made and utilized. This requirement greatly increases the need for data/meta-data and contextual linkage so that knowledge can be both captured and discovered across these two design paradigms.

In prior publications (Refs. 5 to 7) the data schema (see Figure 2), best practices, and informatics requirements to establish a robust, 21st century, information management system for capturing and analyzing *material* information necessary to enable: 1) generalized constitutive modeling and 2) data-mining to establish microstructure/property/failure relationships for monolithic and composite materials, was discussed. The proposed schema/requirements for ICME were demonstrated using a turbine disk Ni-based superalloy, i.e., ME3 material in Arnold et al. (Ref. 5). Furthermore, the requirement of integrating both virtual and experimental data, over the entire material data life cycle and at various length scales, in the same information management system was posited as being essential for ICME becoming a reality and permeating the material and engineering cultures within a given organization. For example, Figure 3 illustrates the interaction between experimental data and virtual data (data resulting from simulation tools) in that some experimental processing data (A) serves as input to a process model which in turn outputs some microstructure feature (W), which is stored in the database. This virtual microstructure data is then combined with measured microstructural data (B) and provided as input to a micromechanics and/or statistical mechanics analysis package, which then generates material property data (X and Y), which again is stored in the database. This property data (X,Y) is then subject to experimental validation, as well as used in some continuum level analysis package (e.g., finite element analysis (FEA)) to assess some performance criteria (e.g., fatigue life, creep rupture, buckling load, etc.) Z; typically stored in some other database. Clearly such an information management infrastructure not only enables the capture, analysis, dissemination, and maintenance of various types of data, but also facilitates the verification and validation of model output, and certification of toolsets at multiple length scales. Also, once all the input/output protocols are established (see Arnold et al. (Refs. 7 and 8)), it can enable the seamless integration of these toolsets with optimization algorithms that will provide the final linkage of processing to performance criteria.

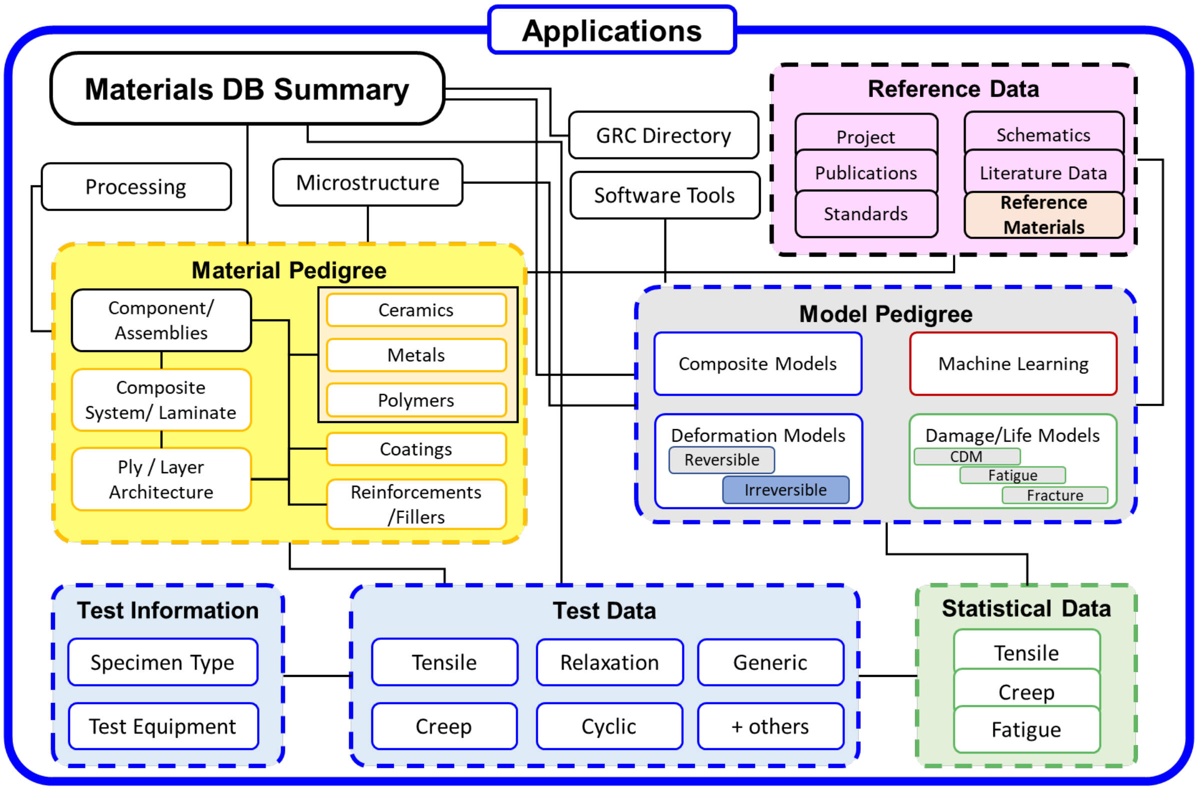

Figure 2.—NASA Glenn's ICME Schema for housing simulation and testing information.

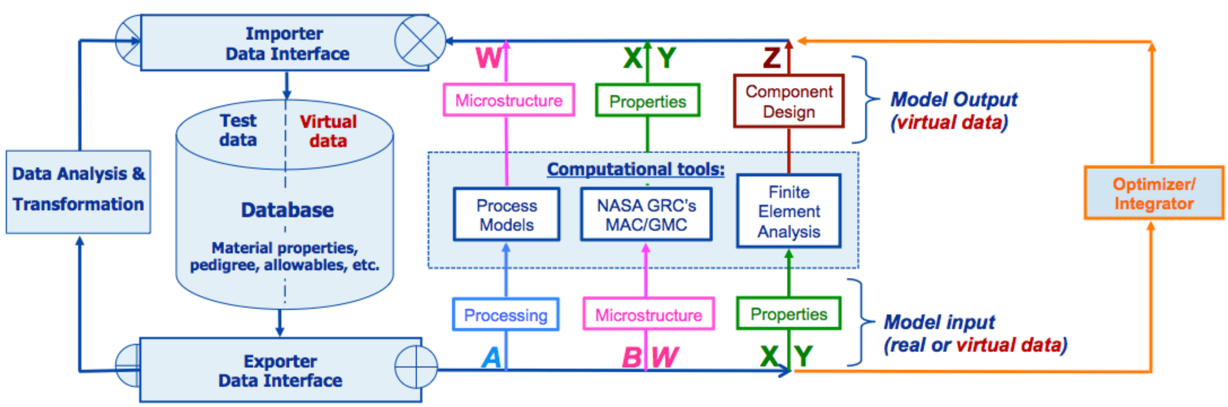

Figure 3.—Multiscale coupling between testing and modeling information enables ICME.

In this paper, attention will be focused on developing a bridge between the "design with-the-material" (structural viewpoint) paradigm (i.e., information stored in traditional PLM systems) and the "design the-material" paradigm (i.e., information stored in MLM systems) along with the associated digital thread (Ref. 9) infrastructure so as to support the NASA 2040 Vision (Ref. 4) and make ICME a reality. Specifically, the Application Table (now taking on a prominent all-encompassing roll and a single connection point to other structural level information management systems, see Figure 2) will be discussed herein. This concept will be demonstrated in the context of the ANSYS Granta MI installation at NASA Glenn for storing not only material-oriented data (both experimental and simulation/virtual), but also application specific requirement/performance information. The information contained within the Application Table will enable/drive the optimization of spatially varying "fit-for-purpose" model-based materials and associated digital footprint (i.e., material digital twin (Refs. 10 and 11) and associated digital thread) throughout a given application. Furthermore, the various application requirements and information for a wide variety of applications, as well as its inherent ability to link to both *material information* and *subcomponent application information*, will be demonstrated. The latter is particularly important when considering maintenance of the digital thread, in which material information must be linked to applications at the part level, and then parts must be linked to their assemblies, resulting in a schema that can effectively link requirements for systems of systems (Figure 4). Consequently, illustrative emphasis will be placed on the requirements (schema and attributes) for the Application Table, rather than on the *data* contained within the systems.

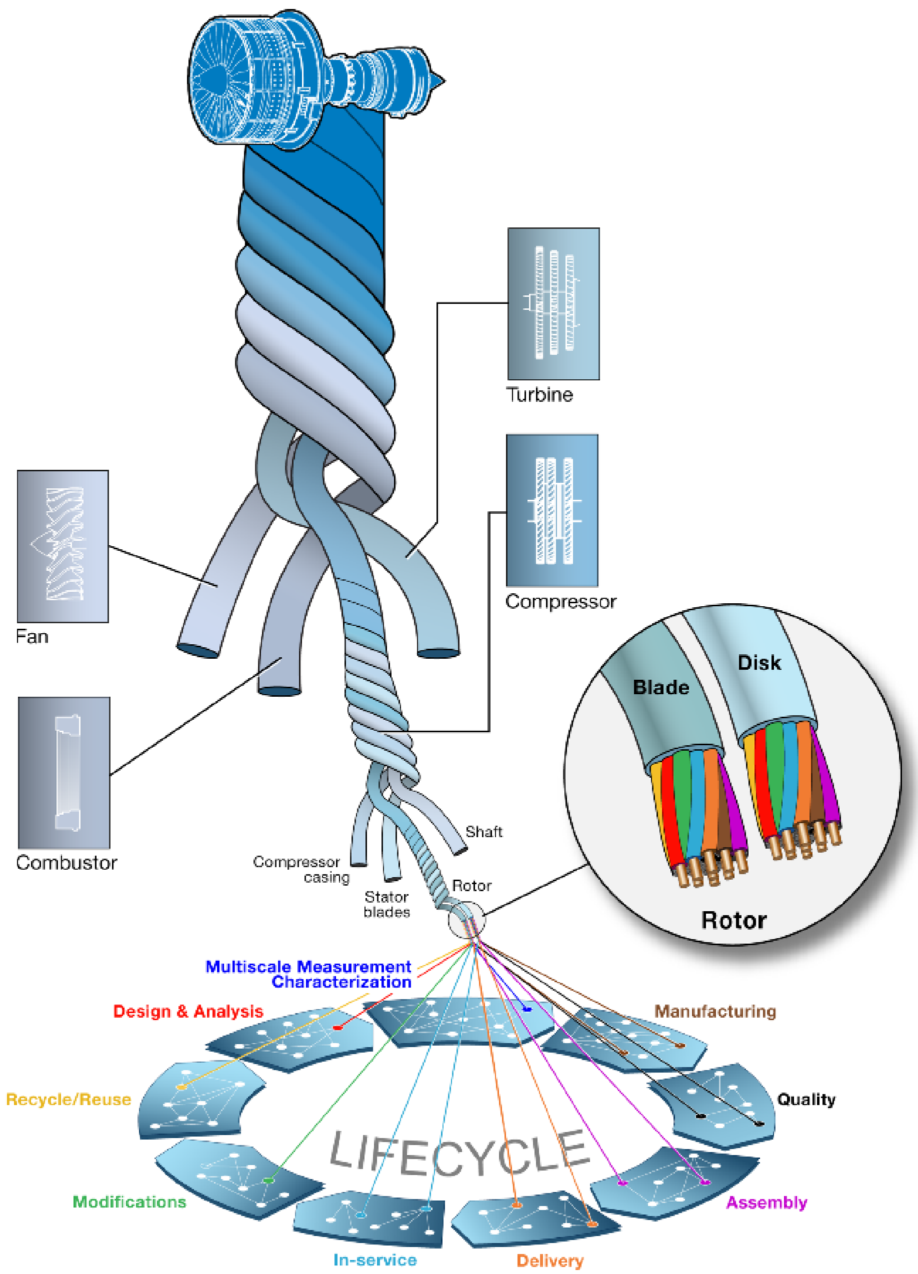

Figure 4.—The Digital Thread for a System of Systems and the Required Lifecycle Information.

2.0 Requirements for Best Practice

Data for design is one very important application for materials information in today's engineering enterprises. There are many others—examples include: materials modification and new materials development, materials selection and purchasing, statistical process control, generation of 'allowable' stress levels for design, regulatory compliance, certification, and quality control and characterization and validation of models (e.g., constitutive, life, processing, etc.). The Material Data Management Consortium (MDMC)[1] has defined the material data *lifecycle* in an engineering organization as:

1. Capturing/consolidating materials data
2. Analyzing materials data
3. Managing and maintaining the information resource
4. Deploying and using materials information.

Clearly, this life cycle can be applied similarly to other types of data associated with constitutive models, software tools in general, documentation/reference data, etc. In general, data is captured and consolidated from external sources, legacy databases, and internal (possibly proprietary) testing programs. Next, data is analyzed and integrated to create/discover useful information pertinent to the various length scales. The third and essential stage of the data lifecycle is the continual maintenance of the whole system (the data and information generated as well as the relationships, or links, between them); with the last but crucial step being the deployment (dissemination) of the right information, to the right people, at the right time and in the right format.

To support the various activities throughout the data lifecycle, it is preferable to have a single, central source, in which all relevant data is captured and consolidated from "birth" to "death" and the (preferably seamless) integration of a variety of software tools. These tools (as depicted in Figure 3) range from i) data importers/exporters; ii) reduction/analysis; iii) visualization; iv) reporting tools; v) process/ microstructure/property/performance models (in the case of ICME); vi) material parameter estimation tools (of both actual and "virtual" materials); vii) statistical and other analyses to reduce the data to a form usable by designers and analysts—for example calculation of 'design allowables'; and viii) to structural analysis codes that utilize a central database. Note that the models and tools listed in (v) through (viii) can operate on a variety of different length scales, thus potentially requiring scale-specific attributes (Ref. 4). If the predicted properties (i.e., virtual data) are stored in the database as well, then it is straightforward to validate such methods and models by direct comparison with actual test data. These tools should enable material and structural engineers to input, manage and utilize information in an efficient, reliable, and user-friendly way (e.g., GUI and APIs). Finally, these tools should also enable enterprise-wide (even world-wide) solution or access. In practice, such information exchanged is complicated by the fact that most organizations must deal with a federated system of data sources (be they dynamic or archived) and tools, thus making the integrity of the digital thread both challenging and critical. Consequently, to assist technologists to be good stewards of scientific and engineering data, guidelines that define what it means to make data Findable, Accessible, Interoperable, and Reusable have been established, i.e., the FAIR principles (Ref. 12).

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[1]A group of aerospace and energy sector organizations (both industrial and governmental) that joined forces to develop best practices and associated software tools to integrate material and structural information technology with the realities of practical product design and advanced research.
https://www.grantadesign.com/industry/collaborations/consortia/mdmc/

2.1 Capture

To maximize the impact on material and structural discipline practitioner and/or researcher, more than just specific predefined (generally accepted) point-wise property values/information needs to be captured from both tests and simulations. In fact, it is essential that a best practice software infrastructure i) has the ability to capture a material's fundamental *multiaxial* response spectrum (under a variety of loading conditions), along with its full pedigree (e.g., chemistry, processing, heat treatment, microstructure, testing information, etc.) for subsequent analysis and modeling; ii) has the ability to capture the application potential of a given material system, be it monolithic, composite, multifunctional, etc.; and iii) enables contextual linkage and association of tacit (or hidden) knowledge (e.g., insight, intuition, skills, experience and other knowledge that has not been formally shared) within a given organization (Ref. 5).

2.2 Analyzing Materials Data

For most organizations a corporate materials database is a dynamic resource—they want to continually add data and analyze that data to generate new or updated information. This requires software that can process, manipulate, and perform calculations based upon the data. For example, materials experts need software to process raw material's test data and analyze it to create approved design data for wider publication. They must update and refine this information and prepare it for use in specialized applications, such as statistical process control or constitutive-life modeling. Whatever the exact nature or source of such software tools, best practice materials information management requires that these tools:

- Be able to be used together so that they combine to offer the range of analyses required by materials scientists and engineers—from single test results, to multiple points, to multiple curves
- Be fully integrated with the information management system, so that data is extracted directly into the analysis tool and results are saved directly back into the correct locations in the database
- Have their results be permanently linked to raw input data and the details of the analyses performed, to maintain full traceability.

2.3 Maintaining Materials Information

Establishing a "gold source" of materials information is not enough; as this source must also be protected, nurtured, and maintained. Several data management features are critical to this process: i) traceability, ii) access control, iii) version control, and iv) data quality control. Perhaps the most important requirement for best practice materials information management is the ability to trace relevant information on the materials beyond their property data. Knowing a "material's pedigree" information can help users understand and correctly apply the materials in component designs and constructions. It also provides important information (processing, microstructure, etc.) and references required for improving the materials properties or developing new materials. Design of the data schema becomes the major issue in ensuring traceability. Note that, to enable both high traceability and high scalability, separating the individual data categories listed above and connecting them with adequate links becomes an essential attribute of any fit-for-purpose information management system. For example, in NASA Glenn's data schema (see Figure 2) the microstructure information is located in a separate table, thus enabling one to go directly to this table and quickly locate typical microstructural images, and then trace backwards through the links to the raw test results. However, for microscopy information associated with changes during (due to either mechanical or thermal loading) or subsequent (failure surface analysis) to testing, this information is typically specimen-specific and thus stored in the specific specimen record. The above comments on data traceability (i.e., the capturing of a model's pedigree) are just as applicable to the material's associated models, parameters, and simulation data; given all types (e.g., process-internal structure, internal structure to property, and property to performance) of models and scales.

2.4 Dissemination of Information

For multiple reasons, e.g., competitive, legal, regulatory, and even, in some applications, national security, it is important to ensure that data is seen only by those authorized to see it. Usability is also a factor—for a massive database, many applications are easier if the user is only exposed to data that is relevant to their application. Further, in today's global economy and international corporate environment, it is commonplace that a database is partially or conditionally shared among different divisions or partners. All this can be achieved through a feature known as access control. While simple in concept, this can be complex to implement in practice, particularly in the context of federated data sources. For maximum flexibility, access control should operate at as low a level as possible in the database, i.e., such that any single item of data (attribute) in the database can be assigned an access control status that determines whether and how it is presented (e.g., based on the user's login information). This feature, specific access control, is essential when desiring to develop an ICME specific database, since typically all process related details (which directly impact microstructure) are export controlled (i.e., EAR (Export Administration Regulation) or ITAR (International Traffic in Arms Regulations)) and thus a coarser-based system (e.g., record, table, or data based level system) would make significant portions, if not all, of the database unavailable to the larger community.

Change management can be a major issue in any evolving (albeit dynamic or archival) database; consequently, a version control system is often a required feature. As it allows the database to store the history of any record, dataset, or item of data, including explanations for any changes made. In addition to adding a further level of traceability to data, it enables control of the process by which updates to the database are made and published. For example, it could be configured such that publishing new data of particular types requires specific approvals. This assures the user that they are seeing the most recent approved data, and also allows changes to be traced and analyzed in previous versions of the data, which may have been used in a design project. In NASA Glenn's current Granta MI configuration, the Data Status access control category (approved or unapproved) is utilized in place of version control, even though Granta MI supports version control.

Data users or producers typically assess data quality. Consequently, when materials property data from different sources are collected into a single database, it is desirable to either manually or automatically assign a "quality score" to the data. This enables users or software applications to determine the degree of confidence they may have in the information as well as its suitability for various applications. Further, when conducting ICME projects wherein multiple software packages/models at varying levels of scale will be used to predict specific outcomes (e.g., material properties) for use by tools at the current or higher scales, the concept of a 'P-basis'[2] or 'P-index' to indicate when a given parameter or "property" is calculated (or predicted—thus the P designation) is particularly important to consider, as is the uncertainty associated with that predication. This way, one can trace the percolation (through various scales) of the various data (be it real or virtual) and its potential impact (e.g., down grading of quality, epistemic uncertainty) on higher scale calculations. Further as more data is captured and assessed the quality index associated with P-basis may or may not change. Such a concept should also facilitate the specification / utilization of needed verification experiments or readiness levels (e.g., Technology,

[2] As distinct from 'A-Basis' and 'B-Basis' properties as used in (for example) the MMPDS handbook to define 'allowable' material strength values at 95% confidence levels.

Manufacturability, Integration). Consequently, when establishing a quality rating, either manually or through an automated system, the quality of a set of data should be viewed as a function of the end use. The concept of a quality index attached to a given model's performance can also be used in a workflow algorithm to initiate a "re-characterization" of the model when its simulation capability (albeit correlative or predictive) exceeds a specified acceptance level. Unfortunately, often "quality" is a subjective thing and therefore can be very difficult for an organization to implement without significant controversy, though quantitative measures can be devised for automation purposes in some cases.

3.0 Overview of Granta MI

Granta MI is a relational database software system offered by ANSYS that allows users to capture, manage, and share material information within an organization (Ref. 13). Data stored in Granta MI is displayed to the viewer through a hierarchical tree structure, with the highest level referred to as a *table*. In a table, all records contain the same list of *attributes*, or pre-defined desired data pertinent to that record, organized into different categories of headings, referred to as the *layout*. Records within a table can be further organized by the user with either *folders* or *generic records*. Folders in Granta MI are analogous to folders in a computer directory tree and can only contain records within. Generic records are a combination of a record and a folder: they contain the same attributes as records within the table that can be populated and can also have child records contained within. An example of a Granta MI tree structure and an associated record or generic record are shown in Figure 5.

Granta MI offers users the ability to link records together for maintenance of traceability. Record links, where one record is directly linked to another record, can be either *static links* or *smart links*. Static links rely on the user to directly link one record to another, whereas smart links automatically link records together through user-defined rules based on the value of specific attributes in each record. Record links in Granta can also be one-way, in which the link is defined only in one record, or two-way, in which reciprocating links are present in both records. For instance, in the example in Figure 6, the user defined Record 2 as being linked to Record 1 as a two-way link, shown in Figure 6(a). Clicking on the link brings the user to Record 2, shown in Figure 6(b). Although not explicitly defined, the reverse direction link is automatically populated in the record, showing that Record 2 is linked to Record 1 as well.

Granta offers a further linking capability for tabular attributes, in which data can be *viewed* from one record in another, rather than simply seeing just the link to the record. Therefore, if the original record is modified, viewed instances of the data in other records is automatically updated without user intervention. When using the *viewed linking* capability, records are linked together by a "Linking Value", or the value of a user-defined attribute that Granta uses to populate the viewed table. For example, in Figure 7, it is desired to view Attributes 1-4 from "Record 1" in "View of Record 1". When populating the tabular attribute in "View of Record 1", the user simply enters the linking value, shown in Figure 7(b). As a result, when viewing the record, the tabular attribute viewing the data from Record 1 is displayed in Figure 7(c). Data from other records can be added to the tabular attribute row-wise by selecting "Add a blank row" in Figure 7(b) and entering the linking value of a different record within that table.

The schema for the Application Table can be applied to any database management system and is not unique to Granta MI. However, Granta MI was chosen as the platform to demonstrate the Application Table, as well as the material data information management system for NASA GRC, due to the various benefits and services offered by the product. The linking capability described above allows users to easily relate records to one another and to display data in one record from another, following the previously outlined best practices for database management. Granta also offers extensive material databases to its users, such as the Material Universe Table, that can save organizations from recharacterizing or searching for relevant material properties when designing new applications. Another key feature Granta MI offers is the ability to write custom Python scripts using the Python SDK to connect to the database. This allows organizations to focus efforts on developing user-specific import and export tools that can easily facilitate the data management process, rather than spending effort on developing the data management system itself. Finally, Granta MI offers connection points, or gateways, to various other engineering programs, such as providing material cards for ANSYS finite element analyses, further facilitating the processes required for the design of fit-for-purpose materials. For these various reasons, the Application Table schema presented herein will be in the context of the Granta MI platform.

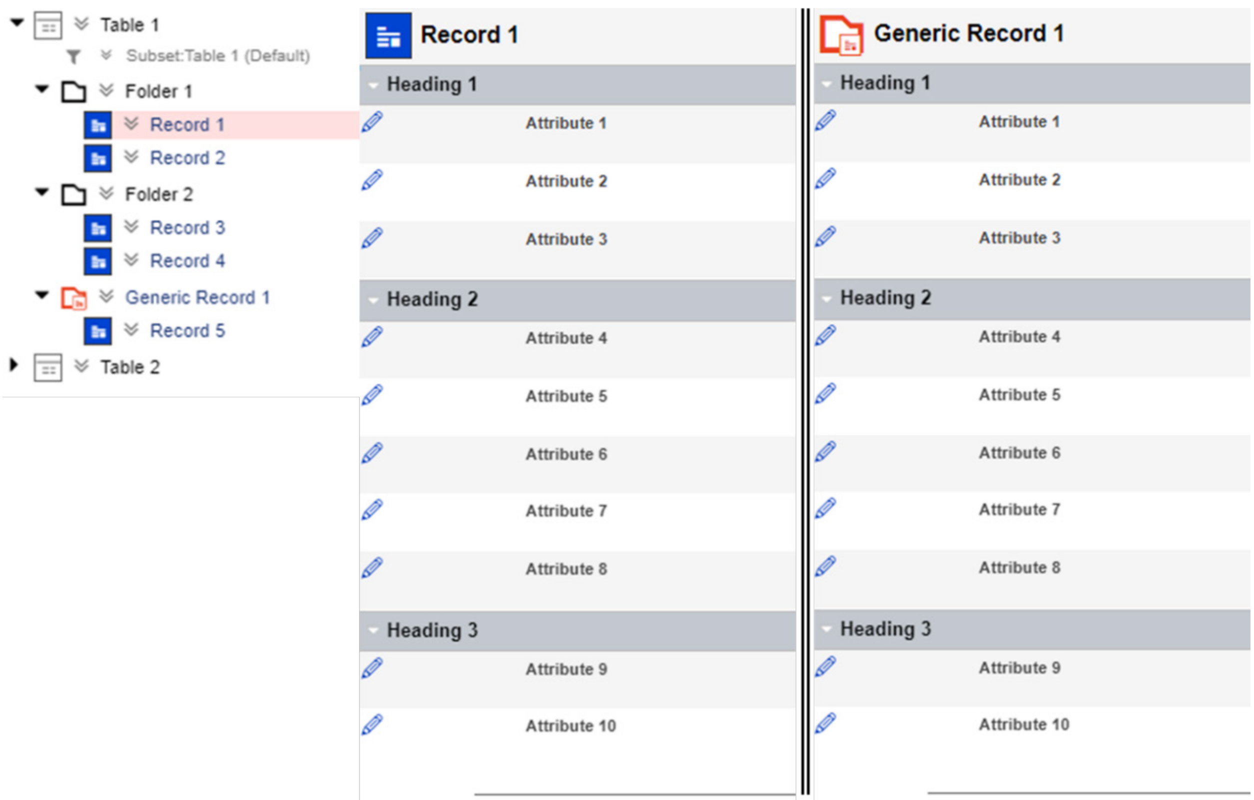


Figure 5.—Granta MI Definitions.

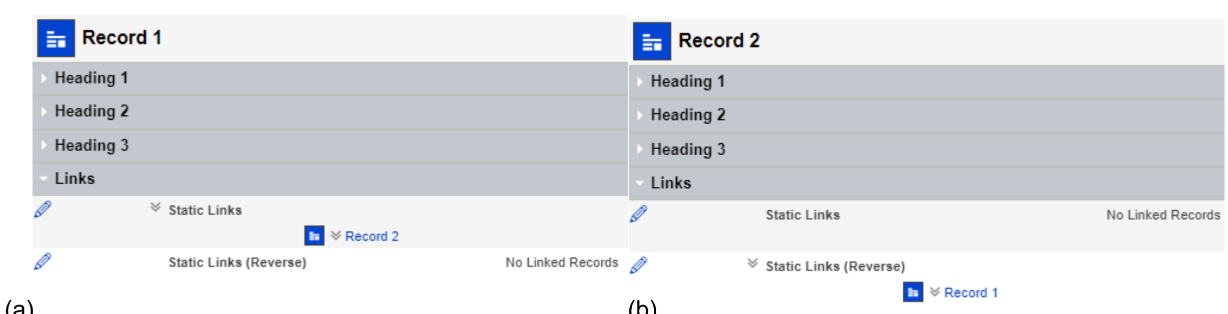
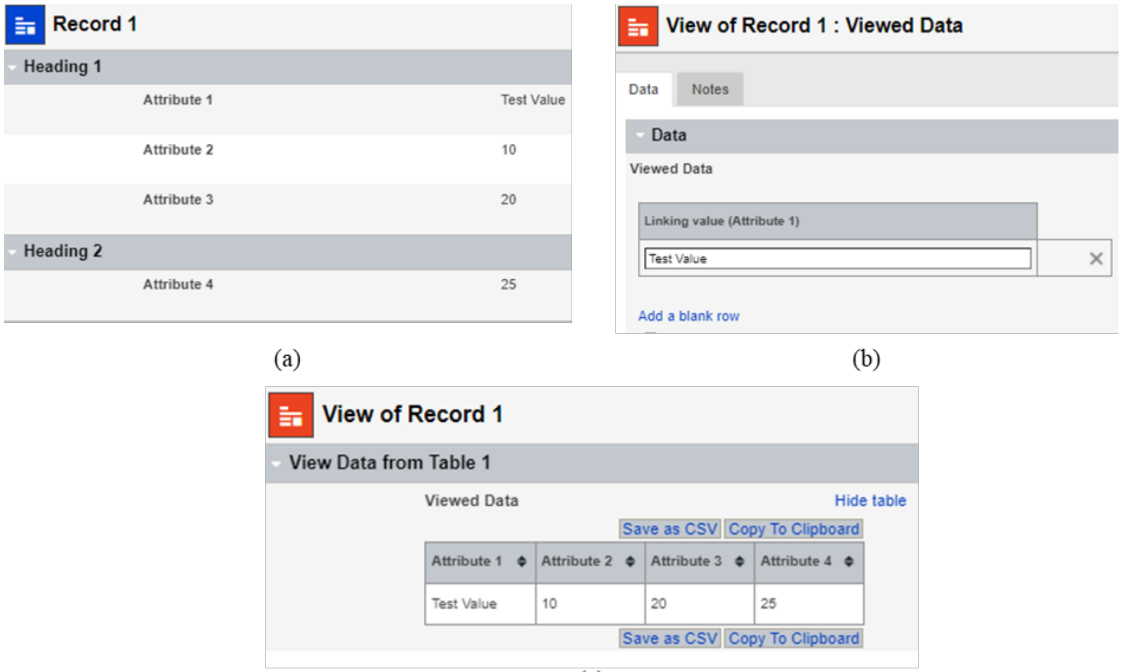


Figure 6.—Linking Directionality in Granta MI.



(a) (b) (c)

Figure 7.—Viewing Linked Data in Granta MI: (a) The record where data is defined, (b) The backend of the record where data is to be viewed, and (c) The front end of the record where data is viewed.

4.0 Application Table Schema

4.1 Overview

The main purpose of the Application Table in Granta MI is to offer a centralized location that bridges or connects the “design the-material” and “design with-the-material” paradigms. Therefore, it is desirable that within the Application Table, data is stored: 1) to aid both in the selection or design of materials for new applications, 2) offering the user a “starting point”, and 3) applications under current development (displaying the specific requirements for that application and the status of those requirements as the material, geometry, and loading evolve). To accomplish this need, data is organized in Granta MI on a per-application basis. At the highest level, applications are defined generally using a generic record, which contains information about typical requirements for similar applications, expected analyses performed, and a list of the approved materials or general subcomponents that are used for that application. Within each generic record are records of applications that are either under development or finalized (e.g., deployed). The requirements, analyses performed, and materials shown in a given record apply to that specific application and are used to drive the design or selection of materials for that given instance. In the example shown in Figure 8, the generic record “Discs” would contain general information about discs (e.g., typical designs, geometry, failure modes, allowable materials, etc.), whereas the records “Disc 1”, “Disc 2”, and “Disc 3” would contain data regarding specific, unique parts currently in design or that have been previously designed and built.

The Application Table is used to capture both the current state and history of an application’s geometry, loading, material information, as well as the information necessary to inform decisions on how to further evolve that application’s design. Consequently, the Application Table becomes a critical member of the part or assembly’s digital thread. To accomplish this in a robust manner relevant to various types of applications, the attributes associated with a given record are separated into nine different categories (or headers in the record layout): General Information, Geometric/Manufacturing

Requirements, Performance Requirements, Analysis Results, Failure Mechanisms/Modes, Material Requirements/Selection, Inspection, Scorecards, and Readiness Levels. A summary of the attributes contained within each header and each attribute type is shown in Figure 9, and a detailed description of the headers, attributes within each header, and the methodology for the current schema will be given in subsequent header-named subsections. Note Figure 9 denotes a significant number (as compared to other Tables in our ICME schema (see Figure 2)) of attributes that are of the Tabular type. This is due to the generality/flexibility that the tabular attribute affords the user, since N number of application specific attributes (or columns) can be defined by the user or database admin. Consequently, in each subsection below these tabular attributes will be describe by example, since each column implicitly represents a specific attribute not explicitly shown in Figure 9. Also, in Figure 9 some attributes are marked with either a "*" or "**" which indicate a nonoptimal specific form (due to the current limitations within Granta) to display the associated data. Section 6.0 describes a feature request made to Granta MI that would significantly improve the ability to display these attributes in a robust manner, and with that feature request those marked attributes would be either changed or removed altogether, respectively.

The Application Table's schema is best demonstrated through an example, showing the ability to define the necessary information to drive the design of parts while simultaneously showing the table's ability to handle systems of systems in a robust manner, as is the case where parts make up subassemblies that in turn make up assemblies. In this paper, the Application Table's schema will be shown by outlining the design, manufacturing, and in-service life of a rotor assembly (Figure 10). Individual records were created for the top-level assembly (rotor), and each part (disc and blade). Assembly records contain a list of parts (with links to the corresponding part records), as well as any analysis performed at the assembly level, failure information, etc. Part records contain the materials used in manufacturing (with links to the material pedigree table) as well as micrograph images of the part, analysis and failure at the part level, and any associated manufacturing information.

It should be noted that the example records shown are merely representative of a real rotor assembly, and that the information populated in the example records does not correspond to any particular assembly. The purpose of the example is not to define a particular rotor system in the database, but to rather demonstrate the capabilities of the Application Table regarding assembly lifecycle management. To fully demonstrate the intended use of the Application Table, the information in the example has been garnered from multiple sources, due to either proprietary data restrictions or a lack of complete available information.

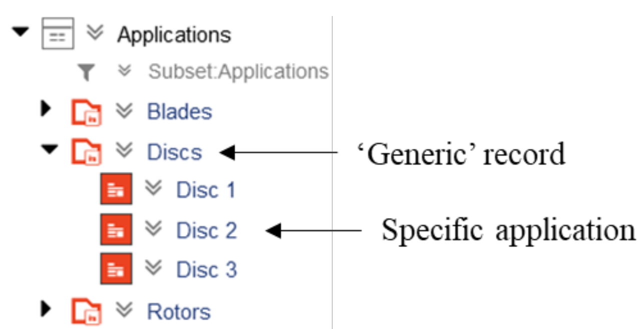


Figure 8.—Example File Tree for the Application Table.

Attribute	Type
General Information	
Application Name	STXT
Application Description	LTXT
Data Ownership	DCT
Data Ownership (Other)	STXT
Distribution Category	DCT
Funding Organization	STXT
Performing Oganization	STXT
Project Name	STXT
Project Code	STXT
Project Notes	LTXT
Point of Contact	TABL
Geometric/Manufacturing Requirements	
Owner Information	TABL
Surface Area	RNG
Volume	RNG
Bounding Box Dimmensions	LTXT
CAD/CAE Link	HYP
Manufacturing Process	DCT
Manufacturing Process (Other)	STXT
Geometric Schematic Time History	TABL
Geometric Description	TABL
Coordinate System Definitions	TABL
Design Points / Points of Inerest*	TABL
Geoemtric Notes	LTXT
Manufacturing Requirements*	TABL
Part Yield	RNG
Surface Treatment	DCT
Manufacturing Notes	LTXT
Microstructure Profile	TABL
Performance Requirements	
Weight	RNG
Life	RNG
Cost	RNG
Risk	DCT
Storage Energy	RNG
Ultimate Strength	RNG
Performance Standards*	TABL
Mechanical Requirements*	TABL
Thermal Requirements*	TABL
Environmental Requirements*	TABL
Other Performance Requirements*	TABL
Performance Notes	LTXT
Form/Fit/Function Notes	LTXT

Attribute	Type
Analyses Performed	
Analyses Performed	TABL
Analyses Performed (Subcomponents)	TABL
Analyses Profiles	TABL
Load Profiles	TABL
Analyses Range Definitions	TABL
Failure Mechanism/Modes	
Failure Mode and Effect Analysis	TABL
Material Selection	
Material Requirements*	TABL
Part List	TABL
Bill of Materials*	TABL
Software Tools Used**	TABL
Selection Criteria	FILE
Property File	FILE
Material Selection Assumptions	LTXT
Inspection	
Inspectability Notes	LTXT
Evaluator	TABL
NDE Method	DCT
NDE Geometry	TABL
Equipment	TABL
Examination	TABL
Calibration	TABL
Testing Parameters	TABL
NDE Images	TABL
NDE Comments	LTXT
NDE Information	FILE
Scorecards	
Requirements Scorecard*	TABL
Risk Scorecard*	TABL
Readiness Levels	
Technology Readiness Level (TRL)	DCT
Manufacturing Readiness Level (MRL)	DCT
Integration Readiness Level (IRL)	DCT
System Readiness Level (SRL)	DCT

* Changed with feature request
** Removed with feature request

DCT	Discrete Text (speificied choices)
FILE	Allows the association of any file type to a given record
HYP	Hyperlink to a web address
IMG	Allows the association of any image format to a given record
LTXT	Long Text Field
PNT	Point Value
RNG	Range Variable
STXT	Short Text Field
TABL	Tabular Attibute

Figure 9.—Application Table Layout.

4.2 General Information

The first layout heading, *General Information*, contains information regarding the name and a description of the application, the owner of the data in the record, the funding organization or project responsible for the creation of the record, and the point of contact for the record. The populated *General Information* attributes for an example record are shown in Figure 11. For the "Point of Contact" attribute, all information is ***viewed*** from the GRC Directory Table (see Figure 2) with the "Name" used as the linking value.

4.3 Geometric/Manufacturing Requirements

The second layout heading, *Geometric/Manufacturing Requirements*, contains all information regarding the physical geometric description of the application. Range attribute types are used for typical geometric attributes that should be applicable to all applications (surface area, volume, etc.). A single value (if desired) can be displayed by setting the maximum and minimum entries of the range to the same value. Greater detail of the geometry can be given in the "Geometric Description" tabular attribute, shown below in Figure 12. The "Geometric Description" contains columns to define: 1) the Component/Zone ID, for multi-material parts or assemblies comprised of different subcomponents, 2) the Assembly ID, 3) schematics for the design (target) and 4) manufactured (actual) geometry, along with long text attribute types for describing any measurements or tolerances associated with each type of schematic. Furthermore, the geometric history of each component (Component/Zone ID) is tracked through additional columns for schematics and measurements/tolerances, named "Change X"[3] and "Change X Measurements/Tolerances", respectively. The user can also define the date of the change and the reason for the geometric change in the "Geometric Schematic Time History" tabular attribute by referencing "Change X" in the "Column Name" column. An example of the dual material disc's designed, manufactured, and changed geometry, as well as how to define the geometric change, is shown in Figure 12. Note that in the figure, the columns marked with the double black line are actually adjacent and a part of the same tabular attribute and were separated only for viewing purposes in this paper. The second heading, shown in Figure 13, allows for the definition of various coordinate systems for the application, including columns for the coordinate system name, schematic, description, and the rotation matrix to the next coordinate system (i.e., the coordinate system in the next row of the tabular attribute).

Also defined in the *Geometric/Manufacturing Requirements* layout heading are the geometric description of any relevant design points/points of interest, or locations of interest for determining specific properties. For many applications, there are often critical areas that could be more likely to fail, experience higher loading, etc., and it can be useful to define these locations and identify any specific requirements for these locations. Conversely, there may be areas within an application where the properties aren't as critical and lower performance is acceptable. When shifting to a "design the material" paradigm, knowing these spatially dependent requirements within a part can be critical to determining the optimal processing and manufacturing that will produce macroscale properties that comply with the application requirements. In the Application Table, these points are identified in the "Design Points / Points of Interest" tabular attribute, shown for the current disc example in Figure 14. The attribute contains columns to give each point an ID for future reference in the record, identify the Component/Zone ID that the point lies in, give a schematic for the points, and identify the location of the point, in either Cartesian or polar coordinates, as well as the coordinate system those values are taken in. In the example only one schematic is given for all eleven points. To prevent the same image from being repeated multiple

[3] Note in Figure 12. X = 1.

times, it is assumed that all design points are defined by the nearest schematic above its row. If a new schematic is needed to define additional design points, that schematic, and all points described by it, should go after the last design point referenced by the preceding schematic.

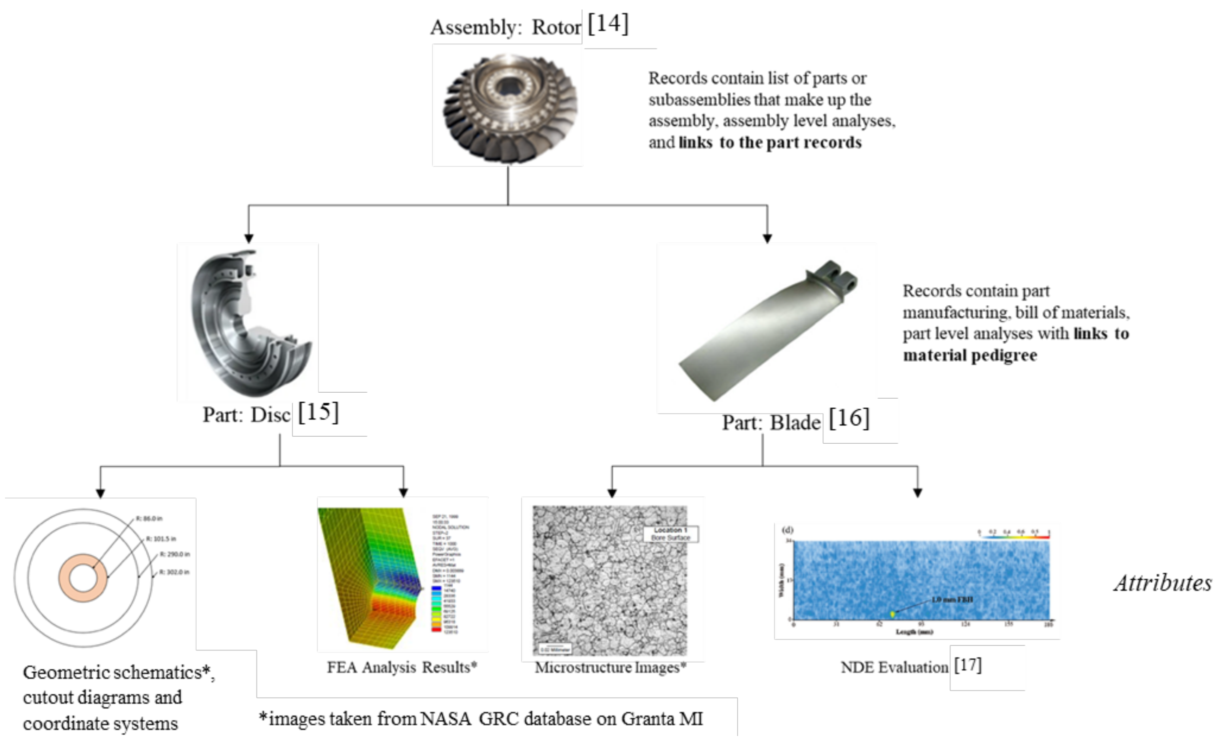


Figure 10.—Example Rotor Assembly (Refs. 14 to 17).

General Information

Application Name	Disc 1
Application Description	

The purpose of this record is to demonstrate the capabilities of the Application Table through an example of an aerospace assembly that can benefi from the ICME approach to material selection/design. This record gives a typical example of the expected fields that could be populated for a disc in a rotor assembly. Note: All material properties, analyses, and other information are for demonstration purposes only and do not apply to any specific developed part/assembly.

Data Ownership	Government/NASA
Data Ownership (Other)	
Distribution Category	Publicly Available
Funding Organization	Aeronautics
Performing Organization	NASA GRC
Project Name	Transformational Tools and Technologies
Project Code	TTT
Project Notes	
Point of Contact	Hide table

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Name	Email	Phone	Office	Mail Stop	Current Employment Status	Additional Information
Brandon Hearley	brandon.l.hearley@nasa.gov		B 49 Rm 210	49-7	Civil Servant	Cell Phone: 518-577-0509
Steven Arnold	steven.m.arnold@nasa.gov			49-7	Civil Servant	Fax: 216-433-8300

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Figure 11.—Example General Information Layout Heading.

Geometric Schematic Time History Hide table

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Column Name	Date of Change	Reason for Change
Change 1	Tuesday, November 1, 2022	Inner Diameter of Zone D1-1 increased to meet tolerance specifica ▸▸

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Geometric Description Hide table

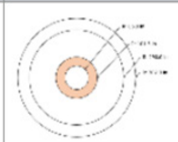
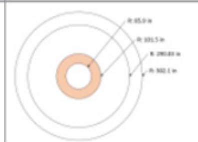
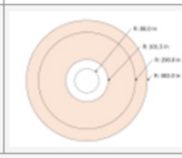
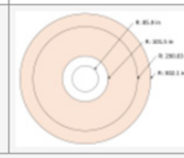
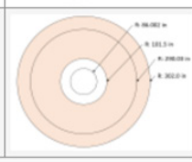
Component / Zone ID	Assembly	Designed Schematic	Designed Measurements/Tolerances	Manufactured Schematic	Manufactured Measurements/Tolerances	Change 1	Change 1 Measurements/Tolerances/Notes
D1-1	D1		Inner Radius = 86.0 in +/- 0.005 in Outer Radius = 101.5 in +/- 0.05 in		Inner Radius = 85.9 in Outer Radius = 101.5 in		Inner Radius = 86.002 in Outer Radius = 101.5 in
D1-2	D1		Inner Radius = 290.0 in +/- 0.05 in Outer Radius = 302.0 in +/- 0.01 in		Inner Radius = 290.03 in Outer Radius = 302.1 in		Inner Radius = 290.03 in Outer Radius = 302.0 in

Figure 12.—Defining the Geometry of the Application.

Coordinate System Definitions Hide table

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Name	Schematic	Description	Rotation Matrix to Next CS
Global		Polar coordinate system	

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Figure 13.—Defining the Coordinate Systems for the Application.

The final key feature of the *Geometric/Manufacturing Requirements* layout heading is the ability to view microstructure images and information associated with the application. In accordance with the existing NASA GRC schema (see Figure 2) all microstructure images are stored in the Microstructure Table, whether they be from specific applications, test specimens, or from the literature. The purpose for this detail is to consolidate all microstructure images into one general location in the database, such that it is easy for an exporting tool to find all relevant images and information to develop a specific physics-based or machine learning model, which will be the ultimate driver in developing fit-for-purpose materials. As a result of this circumstance, microstructure data is ***defined*** in the Microstructure Table and ***viewed*** in the Application Table's Microstructure Profile tabular attribute. The full schema for the Microstructure Table is defined in Reference 7, but suffice it to say that key attributes such as; 1) the Specimen ID, which is used as the linking value when viewing the data (Figure 15(b)), 2) the Cutup Diagram Picture (Figure 15(a)), used to define the locations where micrograph images of the microstructure are taken, and 3) the Microstructure Images tabular attribute (Figure 15(b)), which references and defines the geometric position of the points identified in the Cutup Diagram Picture, displays the microstructure image, and contains various columns for geometric and material properties taken locally at each position. In the Application Table, the data ***defined*** in a Microstructure Table record is ***viewed*** by entering the Specimen ID as the linking value. As a result, the cutup diagram, microstructure images, and local properties can all be viewed in a single row. Granta MI further offers the ability to automatically perform statistical analysis on each of the properties, including calculation of the mean and standard deviation, shown in their own columns. If the microstructure of the application were to change, the time history can be tracked in the current schema by creating a new record in the Microstructure Table, linking that new record to a new row in the Application Table's Microstructure Profile attribute, and additionally defining the "Time History" column in the Application Table. A full example of viewing the microstructure profile in the Application Table is shown in Figure 16.

Design Points / Points of Interest Hide table

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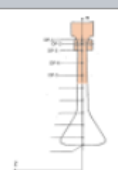
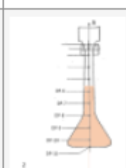
Point ID	Component / Zone ID	Schematic	Coordinate System	X (in)	Y (in)	R (in)	Θ (°)	Z (in)
DP-1	D1-1		Global			86.0	0	0
DP-2	D1-1		Global			102	0	0
DP-3	D1-1		Global			127.0	0	0
DP-4	D1-1		Global			152	0	0
DP-5	D1-1		Global			178	0	0
DP-6	D2-1		Global			203	0	0
DP-7	D2-1		Global			229	0	0
DP-8	D2-1		Global			254.0	0	0
DP-9	D2-1		Global			279	0	0
DP-10	D2-1		Global			293	0	0
DP-11	D2-1		Global			302	0	0

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Figure 14.—The "Design Points / Points of Interest" Tabular Attribute.

Cutup Diagram Picture 1

(a)

Microstructure Images Hide table

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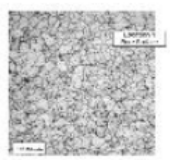
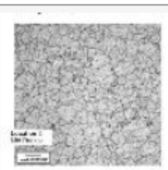
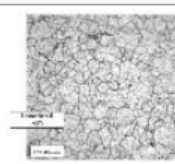
ID	X (in)	Y (in)	Z (in)	Micropgraph	ASTM Grain Size	Modulus (10^6 psi)	Strength (ksi)
1	1	1	0		8.0	29	21.8
4	4	1	0		6.9	28.3	22.5
8	1	4	0		6.5	27.6	22.8

(b)

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Figure 15.—Defining Microstructure Data in the Microstructure Table: (a) The Cutup Diagram and (b) the Microstructure Images Tabular Attribute.

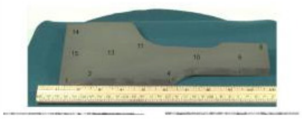
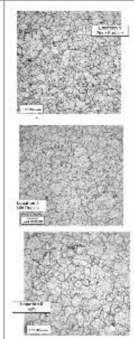
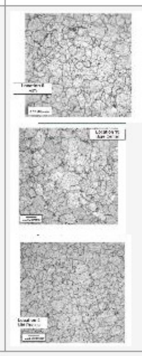
ID	Cutup Diagram Picture 1	Time History	X (in)	Y (in)	Z (in)	Micropgraph	ASTM Grain Size	ASTM Grain Size - Mean	ASTM Grain Size - Std Dev
1 4 8		As-manufactured microstructure.	1 4 1	1 1 4	0 0 0		8.0 6.9 6.5	7.13	0.777
1 4 8		Some damage occured	1 4 1	1 1 4	0 0 0		7.8 6.7 6.3	6.93	0.777

Figure 16.—Viewing Microstructure Data in the Application Table.

Performance Standards Hide table

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Standard	Safety Factor (Standard)	Safety Factor (Program)	Description	Component / Zone ID
Standard 1	1.2	1.4	Example of the Performance Standards tabular attribute. Columns	D1-1

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Figure 17.—Performance Standards Tabular Attribute.

4.4 Performance Requirements

The *Performance Requirements* layout heading contains all information needed to evaluate a new material's candidacy, given the current geometry, for a specific application with regards to the application's performance. The layout heading contains various range attributes for common performance metrics across many applications (i.e., weight, life, cost, strength, etc.), as well as various tabular attributes for more application-specific requirements. The first in the current layout is the Performance Standards tabular attribute, which displays a list of standards the application must comply with (Figure 17). Each row links to a record in the Standards Table (see Figure 2) which then enables one to "view" properties from that record (e.g., Safety Factor), denoted in the column name with "(Standard)". In cases where the Standard is not stringent enough, users can also define their own requirement in columns denoted "(Program)" (i.e., see Safety Factor (Program) in Figure 17 while still linking to the Standard record for any additional information).

The remaining tabular attributes in the *Performance Requirements* heading are used to define more uncommon requirements, categorized into Mechanical, Thermal, Environmental, or Other. Each tabular attribute contains a column for: the requirement name, the Component/Zone ID, the Design Point ID, an associated image, an associated description, a long text attribute type for functional data pairs if the requirement is a curve, target values, designed to values, units associated with the target and designed to values, and a logical attribute type for the presence of an equation. An example of the "Mechanical Requirements" tabular attribute, with some of the unpopulated aforementioned columns hidden, is shown in Figure 18. In the example, the first requirement applies to the application as a whole, and thus the Component/Zone ID (not shown) and Design Point ID columns are left blank. The second requirement (row 2 in Figure 18) is defined for each design point (with each design point having an associated target value). The logical attribute type for equation (both set to No in this example) indicates whether there is an equation in the Description column needed to calculate the target or designed-to value.

4.5 Analysis Results

The fourth layout heading, *Analysis Results*, gives a summary of the analyses performed for the application and the critical results from the analyses that could be used to further drive the design of the material. It should be noted that it is not the intention of the Application Table to replace existing PLM and SDM systems, but rather to summarize the detailed information in those systems necessary to drive material decisions albeit selection or fit-for-purpose design. To accomplish this goal, the *Analysis Results* heading contains various tabular attributes that track the relevant analyses performed and the metrics needed to evaluate the defined performance requirements. The first tabular attribute, "Analyses Performed", provides a list of the different analyses conducted on the application (Figure 19). The attribute contains columns to define the component the analysis was performed on, and ID for the analysis for future reference, a description, a type, the data performed, and the analyst that conducted the analysis.

Mechanical Requirments Hide table

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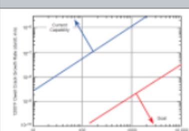
Name	Design Point ID	Image	Description	Target	Units	Equation (Y/N)?
Creep vs. Crack Growth			The part must operate in the defined Hours to 0.2% Creep vs 1200			No
Radial Deflection	DP-1 DP-2 DP-3 DP-4 DP-5 DP-6 DP-7 DP-8 DP-9 DP-10		The maximum allowed radial deflection as a function of position.	0.698 0.746 0.829 0.935 1.093 1.260 1.423 1.589 1.763 1.860	mm	No

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Figure 18.—Example of the Mechanical Requirements Tabular Attribute.

Analyses Performed Hide table

Component / Zone ID	Analysis ID	Analysis Description	Analysis Type	Date Performed	Analyst Name
D1	1	Creep at 1200°F, Hold at 125 ksi for 1000 hrs	Mechanical - Static	Tuesday, October 11, 2022	Brandon Hearley
D1	2	Effective strain during 60 sec dwell	Mechanical - Static	Tuesday, October 11, 2022	Steven Arnold
D1	3	Cooling Rate (°F/min) during Quenching	Thermal	Tuesday, October 11, 2022	Brandon Hearley

Figure 19.—Example of the Analyses Performed Tabular Attribute in the Example Disc 1 Record.

The “Analyses Profiles” tabular attribute gives a summary of the critical results for each of the analyses defined in the “Analyses Performed” tabular attribute. It contains columns for the Analysis ID, Component/Zone ID, Design Point ID, a schematic for the Analyzed Profile, and the Design Point Results, including the individual values, name of the property for that analysis, and units on those values. It also contains generic column names “Range X”, which give the overall range of a certain property/parameter for that analysis. The specific representation that the “Range X” column embodies, and the associated units are defined in the “Analysis Range Definitions” table. An example of the two tabular attributes for the disc example is shown below in Figure 20.

The final tabular attribute under the *Analyses Performed* heading is the “Analyses Performed (Subcomponents)” attribute. It is similar in its column definitions to the Analyses Performed tabular attribute, but differs in that all entries are ***viewed*** from different records in the Application Table. Additionally, this tabular attribute has a column for the Part Record, which provides a direct link to the record of the part or subassembly comprising the specific application (record) in the Application Table. Figure 21 shows an example of the populated tabular attribute for Rotor 1, which is made from parts Disc 1 and Blade 1. When setting the linking value of each row to the respective subcomponent application name, Granta pulls the information from each record and displays it in the table automatically. The purpose of this attribute is to summaries for the user all the analyses that have been performed for an application at the subcomponent level.

Analyses Profiles Hide table

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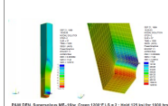
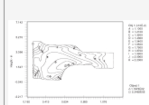
Analysis ID	Component ID	Design Point ID	Analyzed Profile	Design Point Results - Values	Design Point Results - Property	Design Point Results - Units	Requirement Met (Y/N)?	Range 1	Range 2
1	D1-1 D1-1 D2-1 D2-1 D2-1 D2-1 D2-1 D2-1 D2-1 D2-1	DP-1 DP-2 DP-3 DP-4 DP-5 DP-6 DP-7 DP-8 DP-9 DP-10		252.6 287.4 321.1 385.9 387.2 395.5 400.1 402.8 435.1 467.1	Max. Principle Stress	MPa	Yes Yes Yes Yes Yes Yes Yes Yes Yes Yes	220 ≤ x ≤ 500	
2	D1-1 D1-1 D2-1 D2-1 D2-1 D2-1 D2-1 D2-1 D2-1 D2-1	DP-1 DP-2 DP-3 DP-4 DP-5 DP-6 DP-7 DP-8 DP-9 DP-10		2.20 2.09 1.98 1.76 1.54 1.52 1.67 1.84 1.99 2.05	Effective Strain (R-Direction)	%	Yes Yes Yes Yes Yes Yes Yes Yes Yes Yes		1.5 ≤ x ≤ 2.2

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Analysis Range Definitions Hide table

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Column Name	Parameter/Property Name	Units
Range 1	Max Principal Stress	MPa
Range 2	Effective Strain (R-Direction)	%

Figure 20.—Example of the Analyses Profiles and Range Definitions Tabular Attributes in the Example Disc 1 Record.

Analyses Performed (Subcomponents) Hide table

Part Record	Component / Zone ID	Analysis ID	Analysis Description	Analysis Type	Date Performed	Analyst Name
Blade 1	B1	B1-1A	Stress Analysis at operating temperature	Mechanical - Static	Thursday, October 13, 2022	Brandon Hearley
Disc 1	D1	D1-1A	Creep at 1200°F, Hold at 125 ksi for 1000 hrs	Mechanical - Static	Tuesday, October 11, 2022	Brandon Hearley
	D1	D1-2A	Effective strain during 60 sec dwell	Mechanical - Static	Tuesday, October 11, 2022	Steven Arnold
	D1	D1-3A	Cooling Rate (°F/min) during Quenching	Thermal	Tuesday, October 11, 2022	Brandon Hearley

Figure 21.—Example of the Analyses Performed (Subcomponents) Tabular Attribute in the Example Rotor 1 Record.

Failure Mode and Effect Analysis Hide table

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Failure ID	Failure Mode	Failure Mechanism	Probability	Severity	Detection	Risk Level	Failure Report
FID-1	Tension	Creep	Occasional	Catastrophic, completely inoperative, multiple deaths	Certain - will be caught on test	High	Failure Report 1
FID-2	Tension	Fracture	Remote	Catastrophic, completely inoperative, multiple deaths	Certain - will be caught on test	High	Failure Report 1

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Figure 22.—Example of the Failure Mode and Effect Analysis Tabular Attribute.

4.6 Failure Mechanism/Modes

The fifth layout heading, *Failure Mechanism/Modes*, contains only one tabular attribute, “Failure Mode and Effect Analysis”, which is used to identify the associated failure modes and mechanisms expected for a given application, as well as the potential risk and mitigation strategies one can take to avoid such cases (Figure 22). The Failure ID, Failure Mode, and Failure Mechanism columns are short text types, such that the user can specify exact, detailed failure scenarios. The Probability, Severity, Detection, and Risk Level columns are all discrete types, offering the user a list of predefined choices for the column to standardize failure definition across all applications. The final column allows each failure mode to link to a Failure Report record located in the References: Information/Resources Table in the Reference Data collection (see Figure 2).

The use of the tabular attribute for failure information is critical for generalizing the definition of the expected failure modes of an application. In Granta MI, a user can define a tabular attribute with any arbitrary number of rows, meaning that the “Failure Mode and Effect Analysis” attribute can contain any number of expected failure modes for a given application. Although during design of a part or assembly a single failure mode may be expected to dominate, it is important to track all potential failure modes, particularly in the context of “fit-for-purpose” material design. As the material design evolves to meet the various requirements for the application, the “lurking” failure modes can become prominent as well with temperature, loading, and/or time, and thus tracking all failure modes is paramount to determining the eligibility of an optimal candidate material(s).

Material Requirements Hide table

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Name	Component / Zone ID	Design Point ID	Description	Target	Units
Maximum Temperature (Hub)	D1-1		Maximum operating temperature for the material	750	°C
Maximum Temperature (Tip)	D2-1		Maximum operating temperature for the material	1000	°C
Yield Stress		DP-1 DP-2 DP-3 DP-4 DP-5 DP-6 DP-7 DP-8 DP-9 DP-10	Minimum required yield stress for the material at the design point s	187 187 191 195 200 205 208 210 212 214	MPa

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Figure 23.—Example of the Material Requirements Tabular Attribute.

4.7 Material Requirements/Selection

The sixth layout heading, *Material Requirements/Selection*, contains all material information for a given application, including any specific requirements a material used must meet and the actual list of materials in use. Like the tabular attributes in the *Performance Requirements* layout heading, a "Material Requirements" tabular attribute of the same form has been created for requirements specific to the material properties/performance (Figure 23). Requirements can be either defined for a specific component/zone (rows 1 and 2 of Figure 23) or at the defined Design Points/Points of Interest (rows 3 of Figure 23).

When materials are selected for a part record, the "Bill of Materials" tabular attribute is populated (Figure 24). For each identified Component/Zone ID, the user can link to the associated material, whose properties are **defined** in the Reference *Materials* table (see Figure 2), through the material's name to view the material's properties in the "Bill of Materials". The user can also define for each material a component name, the environment of the material for the given application, and any associated notes (Figure 24(a)). The remaining attributes displayed (**viewed**) in the Bill of Materials attribute, are actually **defined** within the *Reference Materials table*; these are the material class, density, manufacturability, cost, accessibility, and material properties, see Figure 24(b). Note, material properties can be either point values or functions of a parameter, such as temperature. Also contained in the *Reference Materials table* are links to the Test Collection and Material Pedigree collection (see Figure 2) which contain cut-up diagrams for any tests performed, test data, and parameters extracted from that data used to determine material properties for the application's analysis. With future updates to the Granta MI software capabilities, the Bill of Materials will contain an additional column with direct links to these records for easier user navigation. Once again, the double black vertical lines, in Figure 24(b), indicate adjacent columns.

Bill of Materials

Component / Zone ID	Component Name	Environment	Notes	Linking value (Material Name)
D1-1	Disc Hub Material	High Temperature		LowTemp Titanium Alloy
D2-1	Disc Tip Material	High Temperature		HiTemp Titanium Alloy

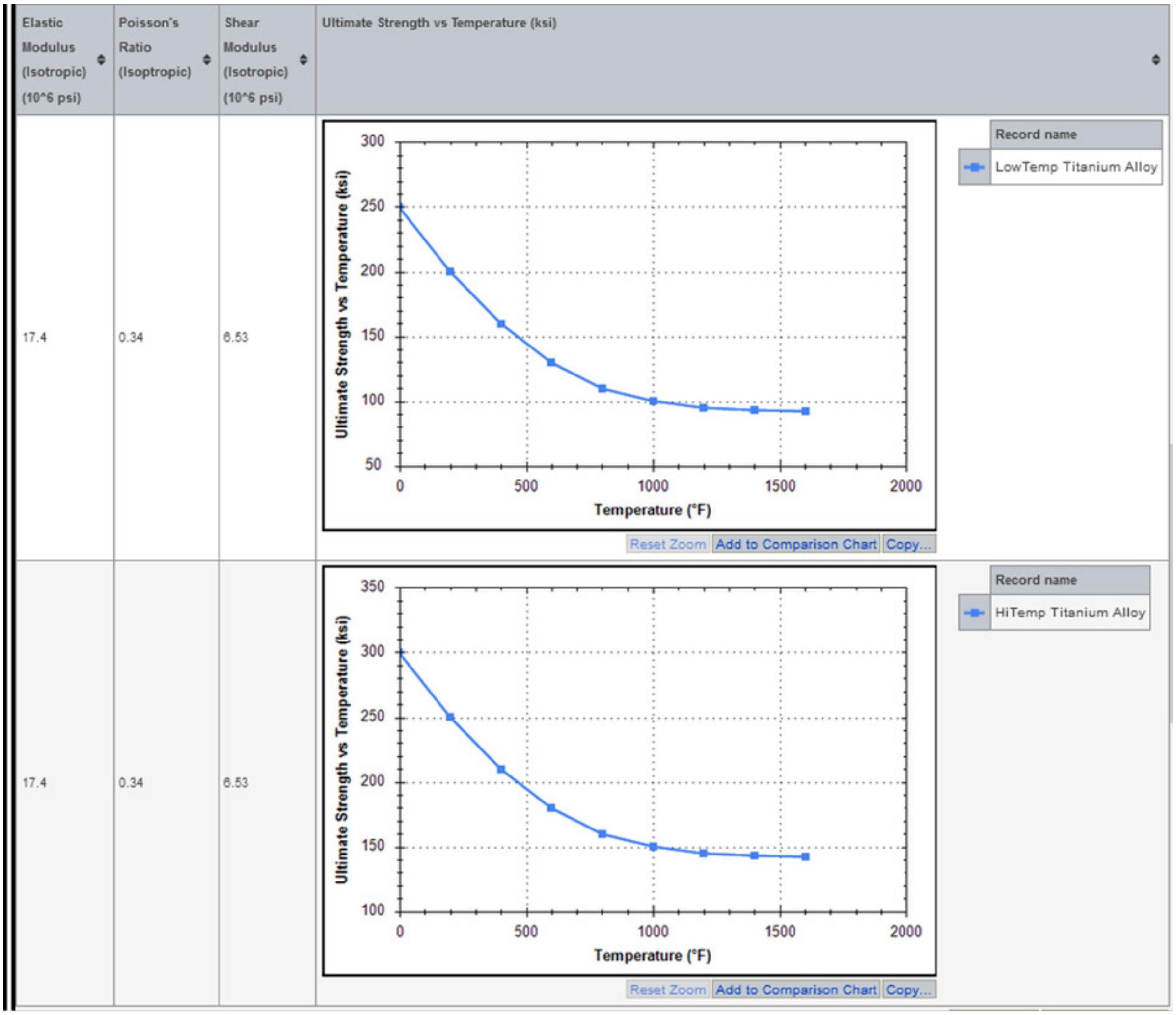
(a)

Bill of Materials Hide table

Component / Zone ID	Component Name	Material	Material Class	Density (lb/ft^3)	Maximum Temperature (°F)	Environment	Hazardous	Machinability	Weldability	Cost ($/g)	Material Accessibility
D1-1	Disc Hub Material	LowTemp Titanium Alloy	Metal	281	2500	High Temperature	No	Yes	Yes	100	Tier I
D2-1	Disc Tip Material	HiTemp Titanium Alloy	Metal	281	2910	High Temperature	No	Yes	Yes	200	Tier I

(b)

Figure 24.—Example of the Bill of Materials Tabular Attribute: (a) Defining the linking value and application specific columns and (b) Material Attributes from the material records listed in the BoM tabular in the Example Disc 1 Record.



(b)

Figure 24.—Concluded.

The “Bill of Materials” is only populated for applications at the part level in which there are no links to other part records in the Application Table. At the assembly level, the “Part List” tabular attribute is populated (Figure 25). When defining the part list, the user enters the “Application Name” of the parts within the assembly, as well as a component ID and the environment and quantity of each part in the given application (Figure 25(a)). When viewing the record for the assembly in the Application Table, the part records are displayed as links, and each row ***views*** the associated part weight, cost, life, and risk.

The *Material Requirements/Selection* heading also contains additional attributes used to maintain the traceability of the material selection/design process and associated properties used during the selection/design (Figure 26). The tabular attribute “Software Tools Used” allows the user to link records in the Software Tools table to each Component/Zone ID used to determine any material properties. The remaining attributes allow the user to upload files providing additional details regarding the selection/design criteria, development of material properties, and assumptions made during the selection/design process. A separate attribute is necessary to define the software tools used for a material’s properties due to the current limitation in Granta MI; that is, that a tabular attribute can only be linked to one table (either the Reference Material Table or Software Tools Table). The proposed feature request in Section 6.0, would allow this information to be stored in the “Bill of Materials” tabular attribute, eliminating the need for the “Software Tools Used” attribute.

Part List

Component ID	Quantity	Environment	Linking value (Application Name)
	1		Disc 1
	16		Blade 1

(a)

Part List Hide table

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Application Name	Quantity	Weight (Each) (lbf)	Cost (Each) ($)	Life (hr)	Risk
Disc 1	1	250 ≤ x ≤ 500	2000	10000	Medium
Blade 1	16	5	1000	10	Low

(b) Save as CSV Copy To Clipboard

Figure 25.—Example of the Part List Tabular Attribute: (a) Defining the linking value and application specific columns and (b) viewing the Part List in the Example Rotor 1 Record.

Software Tools Used Hide table

Save as CSV Copy To Clipboard

Component / Zone ID	Tool Used	Notes
D1-1	GVIPS	
D2-1	GVIPS	

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Selection Criteria

Property File

Material Selection Assumptions

Figure 26.—Example of the Attributes Used for Traceability of the Material Selection Process

4.8 Inspection

The seventh layout heading, *Inspection*, contains information regarding any inspection destructive or non-destructive evaluation (NDE) of the application. For example, in Figure 27. all NDE images, parameters, and associated information has been supplied from Reference 17. The schema allows the user to define the NDE method used and link to the appropriate Standards, like the method described above for the performance standards (Figure 27(a)). The user can also link to any equipment used through the "Equipment" tabular attribute, which links to the Test Equipment table (Figure 27(b)). Additionally, tabular attributes are used to define the examination, calibration, and testing parameters; each of which are generically defined by two columns: category and description. This formulation allows the user to enter all relevant information needed to determine the "success" (proper interpretation of the results) of the NDE without restrictions that may be imposed by the Granta MI software. The final tabular attribute, "NDE Images", allows the user to define images taken during NDE, provide a description of the image, and allow the evaluator to leave their remarks about the image (Figure 27(c)).

NDE Method	Ultrasound
NDE Standards	Hide table

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Standard	Description
EN 12799	Standard for inspection procedure
EN ISO 18279	Standard for acceptance criteria

Save as CSV Copy To Clipboard

Equipment Hide table

Save as CSV Copy To Clipboard

Equipment Component	Equipment	Additional Information
PAUDA	Phased Array C-scan Device (Pased Array C-scan Device)	
Couplant		Water

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(a)

Examination Hide table

Save as CSV Copy To Clipboard

Category	Description
Scanning Method	Immersion
Scanning Coverage	Scanned blade disc section at: 1. 2.5 mm depth and 0.8 mm diameter FBH 2. 2.5 mm depth and 1.2 mm diameter FBH 3. 34 mm depth and 0.8 mm diameter FBH 4. 34 mm depth and 1.2 mm diameter FBH

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Calibration Show tabl

Testing Parameters Hide table

Save as CSV Copy To Clipboard

Category	Description
Near	Type D/mm f/MHz Wave-Type N Coupling Near 1.2 7.5 L 16 Wedge 0.8
Far	Type D/mm f/MHz Wave-Type N Coupling Far 1.2 5, 2.25 T 32 Contact 0.8

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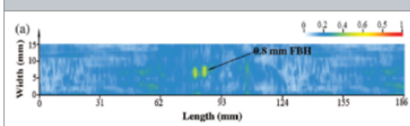
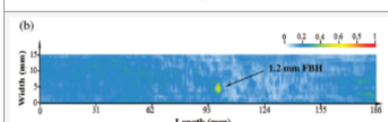
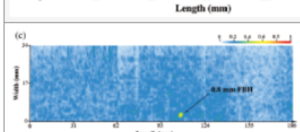
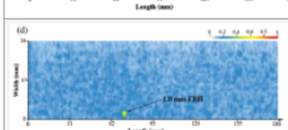
(b)

NDE Images Hide table

Save as CSV Copy To Clipboard

Image	Image Description	Evaluator Remarks
	Phased array c-scan result of 0.8 mm diameter FBH defects at 2.5 mm depth. Near parameters used.	Detection image has higher resolution and less distortion than cor
	Phased array c-scan result of 1.2 mm diameter FBH defects at 2.5 mm depth. Near parameters used.	Detection image has higher resolution and less distortion than cor
	Phased array c-scan result of 0.8 mm diameter FBH defects at 34 mm depth. Far parameters used.	Able to detect defects at 34 mm.
	Phased array c-scan result of 1.2 mm diameter FBH defects at 34 mm depth. Far parameters used.	Able to detect defects at 34 mm.

(c)

Save as CSV Copy To Clipboard

Figure 27.—Example of the Inspection Attributes: (a) NDE Method Definition and Standards, (b) NDE Evaluation Defining Parameters, and (c) NDE Images.

4.9 Scorecards

The eighth layout heading, titled *Scorecards*, contains a summary of the relevant requirements and risk for the application and the status of those requirements and risk given the current materials selected or designed. The purpose of the scorecards is to provide insight on what requirements have not been met and what parts of the application are possibly overdesigned; such that decisions about the material selection or part geometry can be improved. The "Requirements Scorecard" tabular attribute lists each of the requirements defined in the *Performance Requirements*, *Geometric/Manufacturing Requirements*, and *Material Requirements/Selection* layout headings in their own row (Figure 28). Based on their definition in the previous tabular attributes, requirements can either be met for the overall application or at a specified Design Point/Point of interest. Furthermore, requirements may be Boolean (i.e., met or not met) or discrete (i.e., represented by a number). For instance, in the case of safety factor, if the requirement was a minimum safety factor of 1.2 and the current safety factor was 5.0, a Boolean representation of the status of the requirement would be insufficient, since even though the requirement is met, the part is clearly overdesigned at that location and thus could be further optimized. To account for both cases within the current limitations of the Granta MI system, each column type for the Component/Zone and Design Point are kept as short text.

4.10 Readiness Levels

The final layout heading, *Readiness Levels*, is used to assess the current readiness levels of the application, given all the other information in the record but primarily the score card. The user is able to select from a discrete list of readiness maturity indicators: Technology Readiness Level (TRL, see Table A.1) (Ref. 18), Manufacturing Readiness Level (MRL, see Table A.2) (Ref. 19), Integration Readiness Level (IRL, see Table A.3) (Ref. 20), and System Readiness Level (SRL, see Table A.4) (Ref. 21) (Figure 29). Each attribute has an associated hyperlink (shown by the blue text in Figure 29) with a detailed description of the different levels for each attribute (see Appendix A).

Requirements Scorecard Hide table

Requirement Type	Requirement Name	Component / Zone	Design Point 1	Design Point 2	Design Point 3
Mechanical	Creep vs Crack Growth	Met			
Mechanical	Safety Factor		5.0	3.5	1.9
Thermal	Stress vs Temperature	Met			
Material	Maximum Temperature		Not Met	Not Met	Met

Figure 28.—Example of the Requirements Scorecard Tabular Attribute.

Readiness Levels	
Technology Readiness Level (TRL)	TRL 4
Manufacturing Readiness Level (MRL)	MRL 3
Integration Readiness Level (IRL)	IRL 5
System Readiness Level (SRL)	SRL 3

Figure 29.—Example of the Readiness Levels Layout Heading.

5.0 The Application Table's Role in ICME

As demonstrated above, the Application Table contains all relevant requirements for a given application to enable either the material selection or fit-for-purpose design process, and full traceability of the different parameters that influence the material selection/design. By both linking to the relevant tables within the GRC ICME Granta MI database and providing a bridge (connection point) to PLM and SDM systems which utilize the material information to evaluate designs, the Application Table can serve as the "brain" to evaluate given materials for each specific application and potential structural digital twin and associated material digital twins (Ref. 11). In that, if none of the materials available for selection meet the defined requirements, the Application Table can act as the "conductor" of an ICME design of "fit-for-purpose" materials by providing the necessary information to a yet to be developed optimization scheme. However, to enable such a process there must first be a well-established, consistent framework that standardizes the requirements for an application, the means of evaluating those requirements, and the ability to track how the status of the requirements evolve throughout different iterations of the material and geometric design.

Figure 30 outlines such a multiscale ICME design process for "fit-for-purpose" materials. When a designed material's properties are initially defined, information propagates from the lowest applicable scale up to the macroscale, which supplies the material properties (albeit effective for composite materials) needed to run the analyses defined in the PLM or SDM system(s). Using that set of material properties, the geometry of the design can be optimized to meet any specified requirements (i.e., safety factor, maximum deflection, etc.). The resultant analysis and geometry results are then assessed (evaluated) in conjunction with material specific requirements within the Application Table. If requirements are not met or the material is over-designed, a material optimizer would decide how to change the design of the material, and at which scale that change occurs. Information is then propagated back upstream to re-evaluate the new material design with respect to the application performance.

Figure 31 gives a more detailed example of how such an optimization process could be enabled by the Application Table. In the below composite material example, after initialization, the material optimizer decides to change properties at the microscale (Figure 31(a)). To propagate information forward, the Application Table provides the traceability of the location of the microscale properties for the constituent material in the Material Pedigree collection, which then links to the Model Pedigree collections and Software Tools Table to conduct mesoscale analysis. The same process is repeated to further obtain macroscale (effective composite) properties (Figure 31(b)), which can then be passed to the PLM or SDM through the ANSYS Gateway to conduct part-level analysis (Figure 31(c)). The resultant analysis is then passed back from the PLM or SDM to the Application Table to evaluate the defined requirements. If the requirements are not met, the analysis results and requirement margins populated in the Application Table are then sent back to the material optimizer for the next iteration of the material design. In this way the material requirements and performance requirements are mutually updating/interacting so that precious resources are not wasted trying to achieve initially imposed material targets (UTS, Yield, Stiffness, etc.) that are no longer applicable since different (lurking) failure modes are now dominating the optimization process.

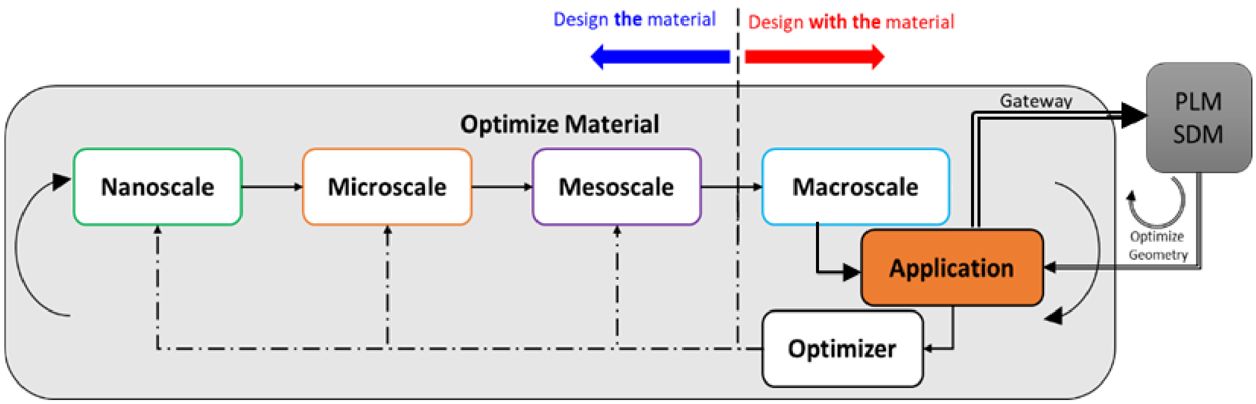


Figure 30.—Generalized Multiscale ICME Design Process of "Fit-for-Purpose' Materials.

It should be noted that the methodology described above is not currently fully implemented, though the backbone of the required relationship between scales has been developed both within the GRC ICME schema and within a Python environment, denoted as the ICME Python framework (grey box in Figure 31). Rather, the example highlights the need for a centralized location that relates material information across the various length scales for a designed material, the requirements needed to evaluate the designed material, and the connection point (bridge) to mature PLM and SDM systems that can facilitate the analysis required to evaluate the listed requirements. With the Application Table schema completed, the developed ICME Python framework can now find the requirements necessary to initiate a design change at a given length scale and automatically propagate information and analyses upstream. The next step involves the development of an optimization scheme (e.g., one for the design of material and another for the application itself) that can connect the ICME Python framework, Application Table, and desired PLM/SDM system (via the ANSYS Gateway applications). However, without a well-developed Application Table schema and the Gateway connections offered by ANSYS, the ICME design process could not be feasibly realized. Therefore, before ICME optimization schemes are developed, an organization must first develop a robust schema that can bridge the gap between the material and structural paradigms. The Application Table is the final link in our ICME schema that provides such a bridge.

6.0 Current Challenges and Proposed Improvements to Granta MI

Although the proposed schema for the Application Table has been shown to be general enough to handle a variety of different applications, and that the Granta MI system has shown to be a reliable database tool for connecting material information across different scales while providing Gateways to the structural paradigm, the limitations imposed by the current Granta MI platform has required the schema to be modified from an idealized version, thus hindering the full capability of the Application Table and violating pre-established database best practices. To mitigate these shortcomings, a new attribute type has been proposed to ANSYS Granta for future development, named here as the "Matrix Attribute Type".

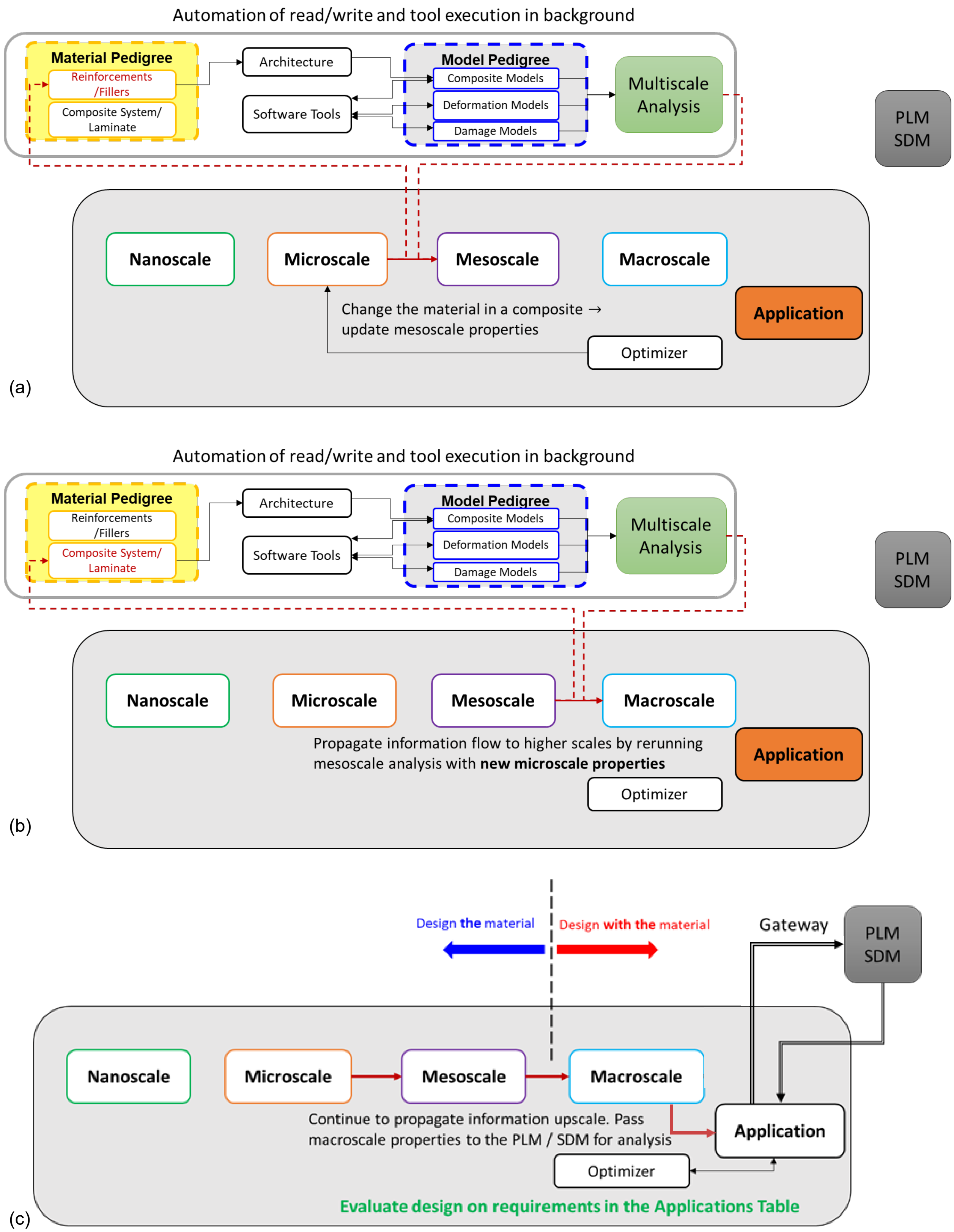


Figure 31.—Example Workflow for ICME Design of “Fit-for-Purpose” Materials.

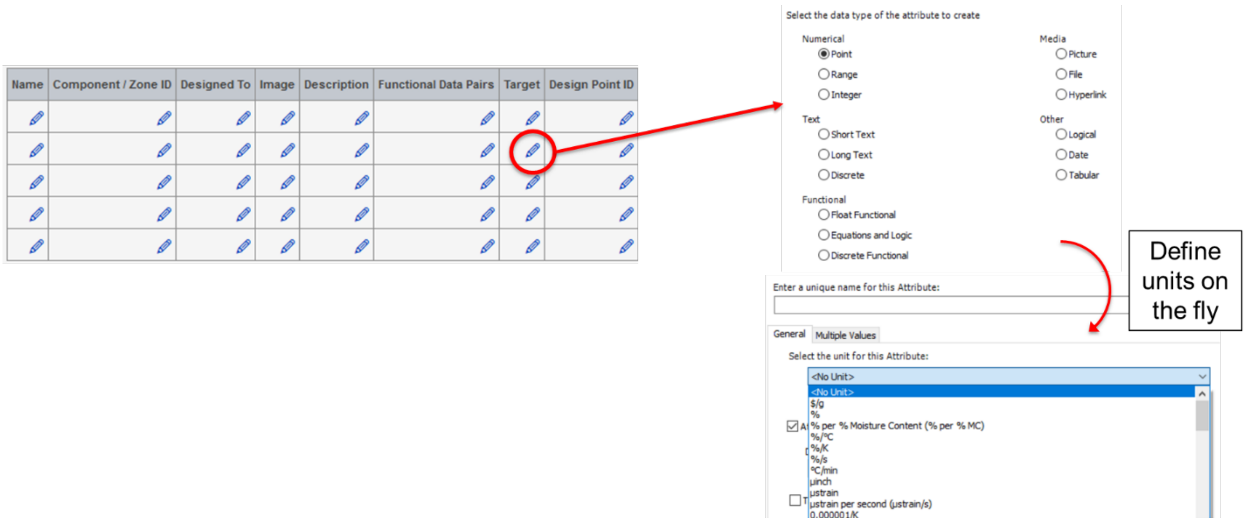


Figure 32.—Proposed Implementation of the Matrix Attribute Type.

Like the tabular attribute, the matrix attribute would be presented to the user as a table with pre-defined columns and an arbitrary number of rows. Unlike the tabular attribute, however, each cell of the matrix attribute would be independent of all other cells, thereby enabling improved efficiency, traceability, and display of the materials, model, and application information presented to the user. Figure 32 shows how the proposed attribute type might be implemented in the ANSYS Granta MI framework. Unlike all other attribute types in Granta MI, in which the type for an attribute is defined beforehand in the schema, the matrix attribute would allow the user to define the attribute type for a given cell, as well as any associated units. Furthermore, because each cell acts independently and is defined when it's in use, each cell can have its own *unique linking value* and link to different tables across the database, further enabling the interconnectedness between the various tables in the information management system required for true ICME design of materials. The remainder of this section highlights the specific attributes and capabilities, within the Application Table schema, that would be improved through the development of the matrix attribute.

The glaring complication in the Attribute Table given the current Granta MI capabilities revolves around the limitation that when viewing data in a tabular attribute, the entire tabular attribute can be linked to only one table in the same database. Therefore, although each row can take on different properties viewed from different records, each of those records must be in the same table, and that table must be in the same database as the Application Table. This setback is most apparent in the "Bill of Materials" attribute, in which material properties are viewed from the Reference Material table. Although organizations may have their own similar Reference Material table in their database, there are also many other material databases available, for example the Material Universe offered by Granta, that contain many relevant materials that material scientists and/or designers may want access to for material selection. Furthermore, organizations may also have material properties that have been found through experimental testing or in-house modeling, particularly in the case of "fit-for-purpose" materials. Currently in Granta MI, there is no capability to view the data from these various tables and databases within a single tabular attribute. As a result, the Reference Material table was created to consolidate all such material information (e.g., material properties and supply chain information) that can be viewed in the Application table. Unlike *viewing* records, however, the Reference Material table records are not dynamically linked to these other tables and databases, but rather are static copies, and thus will not update in the Reference Material table if changes are made in the original records, violating the established database best practices. The introduction of the matrix attribute would remove the need for the Reference Material table and allow direct, dynamic linking to the various material data sources, since each cell could have its own unique linking criteria.

The other major restriction currently imposed by Granta MI's capabilities revolve around how point data is stored in the various tabular attributes for requirements. In MI, typically when an attribute or tabular column is defined, the administrator for the creation of that attribute also defines the default units. Therefore, if a user then wants to view that attribute in a different measurement system (i.e., SI units instead of Imperial), Granta MI automatically calculates the conversion and displays it to the user. Though this works well for the more specific attributes (such as weight, cost, strength, etc.), it is impossible to know ahead of time the units of the application specific requirements in the mechanical, thermal, environmental, etc., requirement tabular attributes since they can take any form. To account for this ambiguity, each "Target" and "Designed To" column for those attributes is defined in Granta as unitless, and an additional column is presented to define what those units are. This approach inherently limits one from utilizing Granta MI built-in capability to update magnitudes based on a change in the unit system, i.e., neither the values in the "Target" or "Designed To" columns nor the value in the "Units" column would update. Though the values would still be accurate with the associated units, this inability to convert is error prone if a user isn't paying close attention. The matrix attribute could alleviate this concern by allowing the user to define the associated units of each individual cell as it's populated. As a result, the cell would have associated units just as any other point attribute type, and conversions could be automatically performed for the user.

7.0 Conclusions

As models become more accurate, their complexity tends to increase, as they rely less and less on simplifying assumptions. This complexity drives the need for more data to be measured, predicted, compared, stored, and tracked. The goals of Vision 2040, which are in alignment with the goals of ICME and the Material Genome Initiative, to link models at multiple scales so as to design and optimize materials, systems, and manufacturing processes in a concurrent manner, drives these same needs and underscores the value of a robust information management system. Often overlooked as a "mere database," a robust information management system should be viewed as a "necessary" or an "enabling" infrastructural aspect to ICME and its associated digital thread and/or digital twin. In this paper, we have taken another step toward achieving such a system by introducing the concept of an Application Table that marries two distinct yet not mutually exclusive viewpoints (i.e., design with-the-material (structural) versus design the-material (material scientist)). A detail description of the attributes and layout of the proposed Application Table was provided with the goal of providing sufficient structural (application) specific information/ requirements to enable not only classic material selection but more importantly revolutionary design and manufacture of fit-for-purpose, spatially-dependent, materials, components, and systems without duplicating the plethora of engineering data management software tools (e.g., CAD, SDM, PDM, PLM) already in existence. Further, the role that the Application Table will play in an ICME design process for "fit-for-purpose" materials was discussed, indicating the need for a centralized location that can define application requirements, link to material information at various scales, provide a bridge to the various structural data management software tools for such a scheme and link to the results of material tests and computational analyses at various length scales. Also discussed were some of the key requirements for best practice in materials informatics, and the current limitations of the Application Table schema with regards to these best practices given the current capabilities of the Granta MI system. Although many hurdles have been overcome with the implementation of both model pedigree tables and the Application table further challenges are to be expected, particularly in the area of ICME information management. Nonetheless, these challenges are likely to be met as materials information management and ICME in general becomes mainstream, particularly in industries like aerospace, defense, and energy, and as more organizations demonstrate a return on their investment in technology and manpower in this area.

Appendix A.—Readiness Levels, Definitions, and Descriptions

TABLE A.1.—TECHNOLOGY READINESS LEVELS

Level	Definition	TRL Description
1	Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties.
2	Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4	Component and/or breadboard validation in laboratory environment.	Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared to the eventual system. Examples include the integration of "ad hoc" hardware in the laboratory.
5	Component and/or breadboard validation in relevant environment.	The Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment.
6	System/subsystem model or prototype demonstration in a relevant environment.	A representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness.
7	System prototype demonstration in an operational environment.	Prototype near, or at, planned operational system. Represents a major step up from TRL 6, requiring the demonstration of an actual system prototype in an operational environment such as an aircraft, vehicle, or space.
8	Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluations of the system in its intended weapon system to determine if it meets design specifications.
9	Actual system has proven through successful mission operations.	The actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. Examples include using the system under operational mission condition

TABLE A.2.—MANUFACTURING READINESS LEVELS

Level	Definition	MRL Description
1	Basic Manufacturing Implications Identified	This is the lowest level of manufacturing readiness. The focus is to address manufacturing shortfalls and opportunities needed to achieve program objectives. Basic research (i.e., funded by budget activity) begins in the form of studies.
2	Manufacturing Concepts Identified	This level is characterized by describing the application of new manufacturing concepts. Applied research translates basic research into solutions for broadly defined military needs. Typically, this level of readiness includes identification, paper studies and analysis of material and process approaches. An understanding of manufacturing feasibility and risk is emerging.
3	Manufacturing Proof of Concept Developed	This level begins the validation of the manufacturing concepts through analytical or laboratory experiments. This level of readiness is typical of technologies in Applied Research and Advanced Development. Materials and/or processes have been characterized for manufacturability and availability, but further evaluation and demonstration is required. Experimental hardware models have been developed in a laboratory environment that may possess limited functionality.
4	Capability to produce the technology in a laboratory environment	This level of readiness acts as an exit criterion for the Materiel Solution Analysis (MSA) Phase approaching a Milestone A decision. Technologies should have matured to at least TRL 4. This level indicates that the technologies are ready for the Technology Development Phase of acquisition. At this point, required investments, such as manufacturing technology development, have been identified. Processes to ensure manufacturability, producibility, and quality are in place and are sufficient to produce technology demonstrators. Manufacturing risks have been identified for building prototypes and mitigation plans are in place. Target cost objectives have been established and manufacturing cost drivers have been identified. Producibility assessments of design concepts have been completed. Key design performance parameters have been identified as well as any special tooling, facilities, material handling and skills required.
5	Capability to produce prototype components in a production relevant environment.	This level of maturity is typical of the mid-point in the Technology Development Phase of acquisition, or in the case of key technologies, near the mid-point of an Advanced Technology Demonstration (ATD) project. Technologies should have matured to at least TRL 5. The industrial base has been assessed to identify potential manufacturing sources. A manufacturing strategy has been refined and integrated with the risk management plan. Identification of enabling/critical technologies and components is complete. Prototype materials, tooling and test equipment, as well as personnel skills have been demonstrated on components in a production relevant environment, but many manufacturing processes and procedures are still in development. Manufacturing technology development efforts have been initiated or are ongoing. Producibility assessments of key technologies and components are ongoing. A cost model has been constructed to assess projected manufacturing cost.

TABLE A.2.—MANUFACTURING READINESS LEVELS

Level	Definition	MRL Description
6	Capability to produce a prototype system or subsystem in a production relevant environment	This MRL is associated with readiness for a Milestone B decision to initiate an acquisition program by entering into the Engineering and Manufacturing Development (EMD) Phase of acquisition. Technologies should have matured to at least TRL 6. It is normally seen as the level of manufacturing readiness that denotes acceptance of a preliminary system design. An initial manufacturing approach has been developed. The majority of manufacturing processes have been defined and characterized, but there are still significant engineering and/or design changes in the system itself. However, preliminary design has been completed and producibility assessments and trade studies of key technologies and components are complete. Prototype manufacturing processes and technologies, materials, tooling and test equipment, as well as personnel skills have been demonstrated on systems and/or subsystems in a 2-4 production relevant environment. Cost, yield and rate analyses have been performed to assess how prototype data compare to target objectives, and the program has in place appropriate risk reduction to achieve cost requirements or establish a new baseline. This analysis should include design trades. Producibility considerations have shaped system development plans. The Industrial Capabilities Assessment (ICA) for Milestone B has been completed. Long-lead and key supply chain elements have been identified.
7	Capability to produce systems, subsystems, or components in a production representative environment	This level of manufacturing readiness is typical for the mid-point of the Engineering and Manufacturing Development (EMD) Phase leading to the Post-CDR Assessment. Technologies should be on a path to achieve TRL 7. System detailed design activity is nearing completion. Material specifications have been approved and materials are available to meet the planned pilot line build schedule. Manufacturing processes and procedures have been demonstrated in a production representative environment. Detailed producibility trade studies are completed and producibility enhancements and risk assessments are underway. The cost model has been updated with detailed designs, rolled up to system level, and tracked against allocated targets. Unit cost reduction efforts have been prioritized and are underway. Yield and rate analyses have been updated with production representative data. The supply chain and supplier quality assurance have been assessed and long-lead procurement plans are in place. Manufacturing plans and quality targets have been developed. Production tooling and test equipment design and development have been initiated.
8	Pilot line capability demonstrated; Ready to begin Low Rate Initial Production	This level is associated with readiness for a Milestone C decision, and entry into Low Rate Initial Production (LRIP). Technologies should have matured to at least TRL 7. Detailed system design is complete and sufficiently stable to enter low rate production. All materials, manpower, tooling, test equipment and facilities are proven on pilot line and are available to meet the planned low rate production schedule. Manufacturing and quality processes and procedures have been proven in a pilot line environment and are under control and ready for low rate production. Known producibility risks pose no significant challenges for low rate production. Cost model and yield and rate analyses have been updated with pilot line results. Supplier qualification testing and first article inspection have been completed. The Industrial Capabilities Assessment for Milestone C has been completed and shows that the supply chain is established to support LRIP.

TABLE A.2.—MANUFACTURING READINESS LEVELS

Level	Definition	MRL Description
9	Low rate production demonstrated; Capability in place to begin Full Rate Production	At this level, the system, component or item has been previously produced, is in production, or has successfully achieved low rate initial production. Technologies should have matured to TRL 9. This level of readiness is normally associated with readiness for entry into Full Rate Production (FRP). All systems engineering/design requirements should have been met such that there are minimal system changes. Major system design features are stable and have been proven in test and evaluation. Materials, parts, manpower, tooling, test equipment and facilities are available to meet planned rate production schedules. Manufacturing process capability in a low rate production environment is at an appropriate quality level to meet design key characteristic tolerances. Production risk monitoring is ongoing. LRIP cost targets have been met and learning curves have been analyzed with actual data. The cost model has been developed for FRP environment and reflects the impact of continuous improvement.
10	Full Rate Production demonstrated and lean production practices in place	This is the highest level of production readiness. Technologies should have matured to TRL 9. This level of manufacturing is normally associated with the Production or Sustainment phases of the acquisition life cycle. Engineering/design changes are few and generally limited to quality and cost improvements. System, components, or items are in full rate production and meet all engineering, performance, quality and reliability requirements. Manufacturing process capability is at the appropriate quality level. All materials, tooling, inspection and test equipment, facilities and manpower are in place and have met full rate production requirements. Rate production unit costs meet goals, and funding is sufficient for production at required rates. Lean practices are well established and continuous process improvements are ongoing.

TABLE A.3.—INTEGRATION READINESS LEVELS

Level	IRL Description
1	An interface between technologies has been identified with sufficient detail to allow characterization of the relationship.
2	There is some level of specificity to characterize the interaction between technologies through their interface.
3	There is compatibility between technologies to orderly and efficiently integrate and interact.
4	There is sufficient detail in the quality and assurance of the integration between technologies.
5	There is sufficient control between technologies necessary to establish, manage, and terminate the integration.
6	The integrating technologies can accept, translate, and structure information for its intended application.
7	The integration of technologies has been verified and validated with sufficient detail to be actionable.

TABLE A.4.—SYSTEM READINESS LEVELS

Level	Definition	SRL Description
1	Concept Refinement	Refine initial concept. Develop system/technology development strategy
2	Technology Development	Reduce technology risks and determine appropriate set of technologies to integrate into a full system.
3	System Development and Demonstration	Develop a system or increment of capability; reduce integration and manufacturing risk; ensure operational supportability; reduce logistics footprint; implement human systems integration; design for producibility; ensure affordability and protection of critical program information; and demonstrate system integration, interoperability, safety, and utility.
4	Production and Development	Achieve operational capability that satisfies mission needs.
5	Operations and Support	Execute a support program that meets operational support performance requirements and sustains the system in the most cost-effective manor over its total life cycle.

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