Sustaining Engineering Informatics: Toward Methods and Metrics for Digital Curation[1]

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Abstract. Ensuring the long-term usability of engineering informatics (EI) artifacts is a challenge, particularly for products with longer life cycles than the computing hardware and software used for their design and manufacture. Addressing this challenge requires characterizing the nature of EI, defining metrics for EI sustainability, and developing methods for long-term EI curation.

Introduction

Engineering informatics (EI) is the discipline of creating, codifying the syntax and semantics of, exchanging, sharing, processing, making decisions about, storing, and retrieving digital objects characterizing the multi-disciplinary domain of engineering. This is a hard problem, as it requires combining a diverse set of emerging theories and technologies: e.g., information science, information technology, product engineering, and various engineering specialties.

Even without addressing issues specific to engineering, the general problem of long-term digital preservation is complex and open-ended. Issues include:

- Limited institutional support for archiving
- Limited understanding of long term archiving requirements
- Lack of a cost/benefit model to rationalize archiving
- Lack of formal methods and standards tailored to specific application domains for long term retention of knowledge
- Inefficient archival procedures
- Lack of clear policy guidelines
- Lack of clear metrics and archival methodology.

Engineers, in addition to the aforementioned issues, want the digital models and systems they build today to be extensible and reusable by subsequent generations of technologists. But even though many products have lifecycles spanning multiple decades (e.g., aircraft, ships, power generation equipment), design repositories and

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[1] Mention of commercial products or services in this paper does not imply approval or endorsement by NIST nor does it imply that such products or services are necessarily the best available for the purpose.

product lifecycle management systems assume that data is always readable. [1] This assumption is dicey at best when a digital product model has a longer lifespan than the data formats, application software and computing platforms used to create the model. And data must be writable as well as readable if a digital product model or its supporting information needs editing at some point during the product's lifecycle.

To address these challenges, we aim to characterize the nature of EI, develop methods for sustaining long-term usability of EI artifacts and define metrics for digital curation[2]. Our immediate focus is on archiving engineering information from Computer-Aided Design (CAD), Computer-Aided Engineering, Computer-Aided Manufacturing, Product Lifecycle Management and related software applications used in creating engineering documents. These digital documents are of many different formats, both proprietary and standards-based. This underscores the complex nature of the problem of digital format sustainability.

We outline a technical approach and roadmap which, if followed, could be a significant contribution to the digital archiving of EI. It is expected that these results could lead to standards for creating engineering-oriented digital object prototypes [2] –domain-specific realizations of digital object structures – and the process for creating and using these archives. The methodology and metrics could also be applied to other scientific disciplines, such as, chemistry, biology, and other areas where critical information must be "future-proofed."

Our approach is based on an ongoing study of end-user access requirements and existing models of archiving in the literature, including standards efforts and other methods deployed in digital libraries and in governmental archives. As part of this activity, we are creating a set of long-term sustainability criteria and a classification system for digital objects relevant to engineering. This effort will serve as the basis for evaluating the archiving of the different kinds of digital objects present in the engineering community.

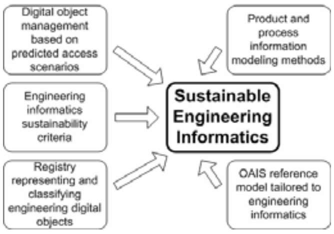

Fig. 1. Overview of EI sustainability approach.

Figure 1 summarizes key inputs. To achieve EI long-term sustainability, we consider the following ingredients to be necessary:

- Representation methods for both product and process information
- A strategy based on anticipation of future access requirements for managing archived digital objects

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[2] The Digital Curation Centre (http://www.dcc.ac.uk) defines *digital curation* as "maintaining and adding value to a trusted body of digital information for current and future use; specifically, the active management and appraisal of data over the life-cycle of scholarly and scientific materials."

- Sustainability criteria and metrics tailored for EI
- A registry representing and classifying EI digital objects
- Extensions to the Open Archival Information System (OAIS) reference model [3] to address issues specific to EI.

The rest of this paper is organized as follows. The next section provides a summary of related work. Next we present our ongoing efforts to develop sustainability metrics and classification criteria. We then suggest next steps toward achieving long-term sustainability for EI.

Related Work

There are five main strands of related work. Our ongoing activities and roadmap for the future aim to synthesize these related efforts to create a customized framework for the EI domains. Evaluation of the developed framework can then be accomplished through a prototype implementation and test bed for creating an EI archive. In the sciences and engineering, digital representations often have an underlying information model. It is thus important to determine sustainability factors for such structured digital objects. Taken a step further, it would be of great benefit to establish sustainability metrics for other aspects of an archival system besides the digital formats used, e.g., to be able to directly measure the quality of an ingest process or an access mechanism.

The first strand of work by Kahn and Wilensky [4] addresses the problem of distributed digital object storage and the infrastructure facilities required for its management. They define a model akin to the Domain Name Server (DNS) model for internet address resolution through the use of a Uniform Resource Identifier (URI) which they call a digital object identifier (DOI). Their model goes beyond just indexing the object for retrieval but also has other facilities such as a retrieval access protocol that manages the retrieval process using the DOI to retrieve the objects from the distributed store. In this model objects may be replicated for reasons of efficiency of retrieval. Their model also includes features for creating mutable and immutable objects allowing for modification of the digital object content without changing the URI when the object context is in flux. The digital object can be rendered immutable for permanent and unalterable digital object storage. When an object is immutable it can be replicated across the network without fear of future inconsistency. The Handle System (http://www.handle.net), a service providing unique, resolvable identifiers for Internet objects, is an implementation of Kahn and Wilensky's research results.

The second strand of work for indexing and managing digital objects comes from projects such as Pergamos [5] from the University of Athens, Carnegie Mellon University's Typed Object Model (TOM) [6], and Fedora [7]. TOM and Pergamos employ type-object taxonomies to allow for the identification of the given digital object format, the possible translations among these different formats, and the ability to retrieve the digital object based on the end user tool that is available for displaying the content. Fedora uses semantic web technologies to represent distributed information and to associate digital objects with web services. These projects, which build on the digital object framework of Kahn and Wilensky, form the infrastructural pieces for constructing and managing a digital archive but are generic architectures that are not specific to the EI world.

Pergamos creates a software environment for storing digital objects using the idea of a digital object prototype (DOP). Pergamos uses the digital object type model but does not enforce a strict hierarchy of types. Types are treated as prototypes and hence modifiable to suit end users' needs. Once a prototype is defined, there is strict adherence to the prototype specification in the definition of the digital object instances. There is a model that allows for the composition of the digital objects. Pergamos is based on a flexible information model for creating DOPs and instances, thereby allowing for a structured organization of the digital objects themselves. Like Fedora, Pergamos is compatible with the creation of a distributed object store that is critical for engineering and science informatics.

The third strand of work comes from information modeling of product and process information in EI. In the EI world there is a necessity to manage different data structures, formats, and compositions that are particular to engineering. For example, an assembly of a collection of parts, a configuration of a product and a configuration of information, for say tolerance or assembly analysis, are specific information models for specific tasks in engineering. To represent EI we need product and process information models that cover the entire life-cycle of the product. The National Institute of Standards and Technology's (NIST) Core Product Model [8], Open Assembly model [9], and other work in part-part relations and compositions and the work of the MOKA project [10] can form the basis for the information models that can be used to guide the creation of appropriate DOPs corresponding to the different levels of abstraction in the information model. DOPs provide a domain-specific realization of digital object types and classes in the context of digital libraries. The range of information exchange between participants in a design has also led NIST to the creation of a typology of standards according to the information model and content exchanged based on the expressivity of the information model.

The fourth strand corresponds to the work on the reference model for the process of archiving digital objects. The OAIS Reference Model [3] is a generic model for archiving that is achieving wide acceptance in a variety of domains. An engineering-specific application of OAIS is LOTAR [11], a proposed standard for creating archival information packages using the Standard for the Exchange of Product Model Data (ISO 10303) – informally known as STEP [12]. Commercial products based on LOTAR are in development in the aerospace industry. One such effort [13] uses STEP to represent geometry and product data management information.

The fifth strand of work involves standards and tools for managing the multitude of digital formats in an archival system. XML-based methods for packaging digital objects include METS (the Metadata Encoding Transmission Standard) [14] and the PREMIS data dictionary [15]. Software tools for identification, validation, and characterization of digital objects include JHOVE (JSTOR[3]/Harvard Object Validation Environment) [16] and DROID (Digital Record Object Identification) [17]. Several projects are developing format registries using these tools [18,19,20].

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[3] JSTOR is an acronym meaning "Journal Storage". Thus, JHOVE is an acronym containing another acronym!

The Library of Congress's digital formats registry [21] is particularly relevant to our work because it provides sustainability criteria, as discussed in the next section (see *Sustainability and Classification of EI Digital Objects*).

The related work presented above provides the strands of research that are critical to the realization of a framework for archival of digital objects in engineering and science. The challenge in EI is to integrate these strands to creating a truly distributed, user-managed (without requiring computer programming) and context-sensitive model for archiving digital objects.

Present Efforts: Toward Sustainability Metrics

The ability to replicate the behavior of the artifact or the experiment in the validation of science and engineering knowledge is crucial. This requires that the information be available in the best form for retrieval and reuse. The need to know a designer's intent becomes important in the context of redesign and reuse of existing parts. The creation, storage and use of information and data are distributed over space and time. Another important aspect of engineering archiving is the ability to store the digital objects at different levels of granularity and abstractions as required by the design decision-making tasks. Without such an ability to compose different digital objects for archiving it would not be possible to maintain the ability to encode reuse or rationale-based access needs.

We therefore consider end-user needs from the point of view of *reference*, *reuse* and *rationale* – the "3Rs" – to better understand the level of granularity and abstractions required in the definition of digital objects. By "end-user" we mean what the OAIS reference model refers to as the *designated community*.

We are also classifying the digital standards that are used in the design, manufacturing, and throughout the life-cycle of the product, using a previously-developed typology [22]. This effort will yield results regarding what standards are used, where they are used, and how are they expected to be used from the end-user perspective. This work can also be used to define the DOPs that are specific to the standards. We also focus on critical issues like original quality of digital formats in archiving, information loss due to transformation from one digital format to another, and importance of standards-based formats for archiving. Our goal is to define better sustainability metrics and clear policy of digital curation.

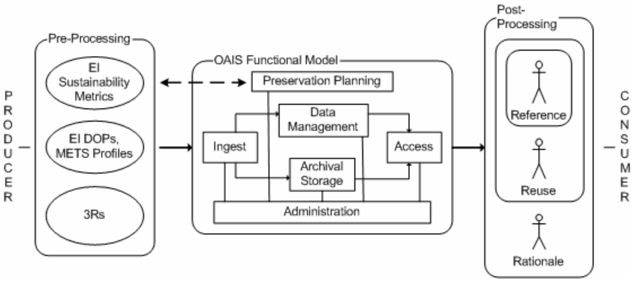


Fig. 2. Enhanced OAIS functional model.

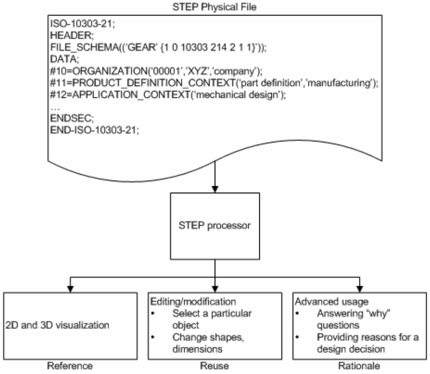
In a nutshell, our approach amounts to enhancement of the OAIS functional model to include pre-processing based on EI sustainability criteria plus DOPs and post-processing based upon the 3Rs as shown in Figure 2. The post-processing portion of the figure illustrates the hierarchy of access requirements for the 3Rs. The capabilities needed for reusing information are a superset of those sufficient for merely referencing the information. The access requirements for understanding rationale subsume those for reuse.

The 3Rs: EI Designated Community Requirements

The 3Rs – reference, reuse, and rationale – define a taxonomy of designated community access scenarios. By *reference* we mean the ability to read the digital object and produce the digital object for proper reproduction in a given display medium (computer display, paper, etc.). We use the term *reuse* to mean the ability to refer to and modify the digital object in an appropriate system environment (software and hardware). The *rationale* is the highest level of access in which the end user should be able to refer, reuse and explain the decisions about the content of the digital object.

The primary driver for the 3Rs is the special retrieval needs for each of these scenarios. For example a collection intended primarily for reference may need to be organized differently than one intended for reuse, where not only the geometric aspects of the product are sought but also additional information regarding manufacturing, part performance, assembly and other aspects. In a similar vein, rationale information may have to be packaged differently in that it may include requirements information along with other performance data on the part or the assembly. Given the range of uses and perspectives of the end-users, their needs will have a large impact on the process of archiving and retrieval.

Figure 3 illustrates these terms using as an example a STEP representation of a gear object. STEP physical files use an ASCII format defined in ISO 10303-21 [23]. The STEP processor can be any software application capable of interpreting and/or generating STEP physical files, for example a CAD tool capable of importing and exporting STEP files, or a visualization tool that can import STEP data.



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ISO-10303-21;
HEADER;
FILE_SCHEMA(('GEAR' {1 0 10303 214 2 1 1}'));
DATA;
#10=ORGANIZATION('00001','XYZ','company');
#11=PRODUCT_DEFINITION_CONTEXT('part definition','manufacturing');
#12=APPLICATION_CONTEXT('mechanical design');
…
ENDSEC;
END-ISO-10303-21;
```

Fig. 3. STEP and the 3Rs.

Toward an Archival information Metrology for EI

A standardized EI digital object within a specified set of conventions has a form (syntax), function (scope) and the ability to convey as unambiguously as possible an interpretation (semantics) when exchanged. The design of a standardized digital object in the context of information metrology is dictated by the following parameters:

1. ***Language***: the symbols, conventions and rules for encoding and expressing content. Examples include first order logic, OWL (Web Ontology Language) [24], and UML (Unified Modeling Language) [25].
2. ***Process-able Expressiveness***: the degree to which a language mechanism supports machine understanding or semantic interpretation. Expressiveness is closely connected to the scope of the content that can be represented and to the precision associated with that content. Support of standardized exchange requires a set of complementary and interoperable standards.
3. ***Content***: the information to be communicated. Content includes the model of information in the domain and the instances in the domain and explicates the relationship between the message and the behavior it intends to elicit from the recipient. Examples of content include STEP [12], NIST Core Product Model (CPM) [8] and its extensions [9].
4. ***Interface***: *User interface* concerns efficiency of communication between the system and humans. *Software interface* concerns accuracy and completeness of communication between systems.

By analyzing the 3Rs using the above four parameters, we can build formal definitions of reference, reuse and rationale and determine the end-user requirements for EI. Engineering digital objects need to be shared in a collaborative and secure manner across the global enterprise and its extended value chain. It is absolutely critical that the sharing mechanism preserve semantic correctness and be efficient, inexpensive, and secure. In order to create such a sharing mechanism, consistent standards, measurements, and specifications are needed for understanding significant relationships among the concepts. It is therefore essential to understand the interactions among the theory of languages, representation theory, and domain theory. Creating a science of EI metrology will require a fundamental and formal approach to measurement methods, testing, and validation analogous to formalisms used in the physical sciences.

Sustainability and Classification of EI Digital Objects

There are a number of potentially useful ways to view the classification of digital objects realized by thousands of digital formats currently in use. One way is through the 3Rs. Another way is by focusing on type of domain. One can also classify digital formats based on whether their content includes a model of the object being represented. For example, a bitmapped image of a part has no object model, but the same part represented using STEP does.

Yet another way is by considering sustainability factors such as those enumerated by the Library of Congress (LC) [21]. These are:

- **Disclosure** – availability of documentation specifying the format and validating software
- **Adoption** – a format's popularity
- **Transparency** – ease with which a digital object may be analyzed using generic software (as opposed to specialized tools)
- **Self-documentation** – inclusion of technical and administrative metadata within the digital object
- **External dependencies** – degree to which using a digital object requires specialized software or hardware
- **Impact of patents** – presence of patents related to a digital format
- **Technical protection mechanisms** – technical methods such as encryption that restrict access to the digital object.

A cursory application of the LC criteria to STEP yields the following observations:

- **Disclosure** – Because STEP is an international standard, documentation is available. However, the official specifications must be purchased from ISO or national standards bodies, and are not available for free on the Web. That said, websites with useful tutorial information exist, but you have to know where to look. Software for validating STEP data also exists, both free/open source and commercial.
- **Adoption** – STEP has been adopted by CAD vendors for exchanging geometry, but has not been as widely adopted for other STEP domains such as product data management.
- **Transparency** – Although it is theoretically possible for a human to analyze STEP data given a physical file and the EXPRESS [26] (a language STEP uses for representing information requirements) schema governing the file, doing so is extremely difficult for a realistically complex data set. Specialized software is needed.
- **Self-documentation** – Because the STEP representation is so rich, digital objects represented using STEP achieve a high degree of self-documentation. Still, it is sometimes useful to add additional annotation using logic-based languages such as OWL [24].
- **External dependencies** – Most CAD vendors have a least some ability to import and export STEP data.
- **Impact of patents** – None.
- **Technical protection mechanisms** – None.

In order to gain an understanding of how best to use the LC criteria to develop sustainability metrics, it would be useful to apply the criteria to other EI formats besides STEP and to look for commonalities and gaps. This would then lead to insights regarding additional EI-specific sustainability factors which, in concert with formal definitions for the 3Rs, would lay the groundwork for the activities described in the following section.

Next Steps

The next steps to developing EI sustainability metrics are to create a framework and test bed based on the DOP work and OAIS, along with the EI modeling requirements derived from our present efforts. The framework should include not only the model for the distributed organization of objects but also the model for creating DOPs in engineering using the information models and an OAIS-based process for defining technologies for creating archival packages in the form of DOIs.

The test bed should verify and validate the framework for a product model that covers as much of the product information as possible and is reasonable for testing the framework. The framework will be the basis for designing an EI test bed.

Framework for EI

The EI archival framework should be based on Kahn and Wilensky’s DOI methodology as the lowest level model for distributed management, DOP type-object modeling as the next level of detail, and should be combined with product information models and an archival process based on the OAIS standard.

A series of workshops held at NIST and University of Bath over the last two years provide a source of requirements. [29,30,31] Workshop discussions attempted to balance the desire for good metadata from those accessing the archive against requirements for ease of use from those populating the archive. The need for both human effort and automation as well as the need for both technology and policies in achieving success should also be addressed. The underlying objective should be to understand the needs of the EI designated community and, using the classification of engineering standards that exist for modeling of information for a product life cycle, to arrive at a framework for EI.

The framework design should include a detailed analysis of the LOTAR approach and different example case studies of the OAIS reference model involving other projects in the sciences and engineering. Examples include efforts such as NASA’s National Space Science Data Center [27] for satellite image data and the Centre de Données de la Physique des Plasmas [28] for data generated by plasma physics experiments.

The framework should be customizable to different types of engineering information, based on our EI sustainability metrics.

EI Test Bed

The test bed should be a venue for experimenting with and validating the OAIS reference model for archiving EI beyond geometry (to include product structure, assembly, tolerancing, and other areas) based on the proposed methodology and engineering-related archival standards. The suggested approach is to add EI extensions to the OAIS information and functional models and then to implement a pilot archival system employing the extensions.

An OAIS-based information model based on a taxonomy of engineering access scenarios employing the 3Rs should:

- Capture the taxonomy of engineering end-user scenarios
- Define the level and content of a digital object based on the taxonomy of access scenarios
- Classify engineering digital objects based on the 3Rs and sustainability criteria
- Attempt to model the content information in the information model, based on EI sustainability factors.

An OAIS-based functional model for EI should address a full range of engineering archival information preservation functions including ingest, archival storage, data management, administration, preservation planning and access. The functional model should:

- Tailor the OAIS functional entities – ingest, archival storage, data management, administration, preservation planning and access – to meet the needs of EI
- Support preprocessing of the digital information for archival based on sustainability metrics and driven by the EI-customized OAIS information model. Preprocessing should identify and model all actions undertaken on the submission information package prior to archiving
- Support post-processing of the digital information, identifying and modeling all actions performed on the archival information package prior to dissemination. Post-processing should be based on content information, metrics, and the end-user requirements.

Using the EI-tailored OAIS information and functional models, a pilot archival information system can then be built employing the 3Rs, sustainability metrics, and the DOI and DOP methodologies. The pilot can also serve as a means of determining how easily the digital format identification, validation, and classification tools discussed in the *Related Work* section (fifth strand) can be adapted for use with EI formats.

Expected outcomes of the pilot EI archival system would be:

- A collection of sample data that can be used for testing performance of EI archival system ingest and access
- Identification of designated user committees for EI
- Increased awareness of the need for long-term digital information retention and sustainability.

Conclusion

Archiving engineering information and data poses immense challenges in light of technology changes in both hardware and software. Traditional methods that were used in the world of paper are no longer applicable, and a proliferation of digital objects has flooded the engineering workspace in the last 20 years. Initially most engineering information was focused on geometry and some on the development of specific analytical tools, such as finite element analysis and other mathematical models of the artifact being analyzed. During this period, the data formats used have evolved independently to serve specific applications. These developments have led to major problems in maintaining engineering information for products with lifecycles measured in decades. Any technical approach proposed has to be cognizant of the organizational and technological dimensions of the problem. In the engineering-oriented digital archiving workshops conducted at NIST and the University of Bath with wide participation from government, industry and academia, it was argued that archival models should be such that facilities for archiving are available at the source of information creation. The argument for this approach is that archiving after the fact is often time-consuming and seldom undertaken. This observation and need has important implications for the design of a framework for archiving.

The focus of this paper has been to create a technical approach that takes into account that the problem of long-term EI sustainability starts at the point of creation of the digital objects and ends in delivering the right information for the task at hand (reference, reuse, and rationale) to the end user. The problem is a socio-technical system design problem that requires cognizance not only of the social needs and mechanisms of archiving, but also of the technical possibilities of achieving the archival goals. We have characterized the dimensions of the problem and identified five strands of related work that will inform the design of an archival framework. Last but not least we have identified a set of issues that need to be addressed in the design and testing of a framework for the archival of engineering informatics.

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