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A Framework for Spacecraft Information Modeling

François Lévy[1] and Georgi Petrov[2]
synthesis int'l, Houston, TX, 77004

Michael Fox[3]
Professor of Architecture, Cal Poly Pomona, Pomona, CA. 91768
FoxLin Architects, 390-392 Camino De Estrella, San Clemente, CA 92672

and

Marc Cohen[4]
Space Cooperative, Palo Alto, CA 94306

This paper brings a space architects' perspective to applying Building Information Modeling (BIM) to the design of crewed spacecraft and space habitats. The contributions of mature BIM to terrestrial architectural and engineering design are examined, as well as the applicability of BIM lessons learned to spacecraft design that might inform a Spacecraft Information Modeling (ScIM) framework. Specific instances in which BIM frameworks such as Levels of Development (LOD), Industry Foundation Classes (IFC), and Construction Operation Building Information Exchange (COBIE) may be applied to human spacecraft design are suggested. An organizational study of the relevant SciM framework and taxonomies to enable greater crewed spacecraft design efficiencies and optimization for risk mitigation, mass and mission cost is undertaken. Such a framework considers semantic object classification and relationships by location, typology, function, and material. As a proposed design methodology, a ScIM solution for human spacecraft design integrates the life support system with other spacecraft systems: primary and secondary structure, non-structural elements, spacecraft utilities, and architectural specialties. An example of a previously-design spacecraft is mapped onto a similar ScIM framework, concluding with suggestions for further research in bringing BIM-like processes to crewed spacecraft design.

Nomenclature

AEC	=	architecture, engineering, construction (industry)
AGC	=	Association of General Contractor of America
AIA	=	American Institute of Architects
bim	=	building information model (digital artifact)
BIM	=	Building Information Modeling (process)
BREP	=	Boundary REPresentation
CADD	=	computer-aided design and drafting
CAFM	=	computer-aided facilities management
COBie	=	Construction Operations Building Information Exchange
ECLSS	=	Environmental Control and Life Support System
GSA	=	General Services Administration (United States)
HVAC	=	heating, ventilation, and air conditioning
IE	=	Information Exchange standard
IFC	=	Industry Foundation Classes

[1] Architect, 2124 East Sixth Street, Suite 107, Austin, TX 78702, francois.levy.architect@gmail.com.
[2] Architect and Engineer, 2303 29th Avenue, Astoria, NY 11102.
[3] Architect.
[4] Architect and Co-Owner, Space Cooperative, marc@space.coop.

ISO	=	International Standards Organization
ISS	=	International Space Station
LOD	=	Level of Development
ME	=	Model Element
MEP	=	Mechanical, Electrical, and Plumbing
NBIMS-US	=	National BIM Standards (United States)
nD	=	n-dimensional
PLM	=	Product Lifecycle Management
PxP	=	BIM Project eXecution Plan
ScFC	=	Spacecraft Foundation Classes
ScIM	=	Spacecraft Information Modeling
STEP	=	Standard for the Exchange of Product Model (ISO-10303)
SysML	=	Systems Modeling Language

I. Introduction

IN terrestrial architectural projects, BIM (Building Information Modeling) is a digital design, documentation, construction, and facilities management workflow that uses data-rich 3D and 4D building objects shared amongst stakeholders to create, assemble, edit, and distribute federated models across multiple design disciplines. Such projects, representing the evolution of centuries of architecture and engineering, can be massively complex systems, incorporating civil, mechanical, electrical, plumbing, and material engineering concerns, as well as novel architectural expressions and computational structural solutions. BIM has grown both in modeling sophistication, data manipulation, and interoperability. At its best, BIM enables new design opportunities, simulates building performance, allows greater design process efficiencies, and reduces construction errors. BIM's development has paralleled design process in the automotive and aerospace industries, and has gained widespread acceptance among architects, engineers, and general contractors.

Building Information Modeling (BIM) has become a common digital design process in terrestrial architectural design. As of 2015, in the US 92% of large architecture firms (50+ employees) used BIM for their projects.[1] While possessing a significant technological aspect, BIM is neither a specific technology nor a particular digital tool. In this paper we distinguish Building Information Modeling (BIM), a technological and social process, from particular building information models "bims" as digital artifacts. Rather, BIM is a way of designing, documenting, testing, constructing, and operating built projects using digital tools and standards, as well as explicit social agreements between design, construction, and operational stakeholders. Given the breadth and variety of BIM adoption in the Architecture, Engineering, and Construction (AEC) industry, there is not an absolute definition of what does and does not constitute BIM. At minimum, BIM has the following characteristics[2]:

> **Geometry.** Two-dimensional geometry and three-dimensional geometry at minimum are incorporated in the bim[3] (see discussion of LOD 100 below), either in a single discrete model or in a federated model whose components are contributed by various members of the design team. Some BIM software and processes simulate the construction phases of a project; BIM over time is referred to as "4D BIM". More recently 4D bims have been used to explore project costs over time: so-called "5D BIM".
>
> **Data.** Bims are structured as databases that may be continuously queried and edited. Geometrical information intrinsic to model elements (MEs) can be queried and reported: dimensions, volume, bounding volume, surface area, location, and orientation. In addition a broad variety of data may be attached to an ME, ranging from physical properties such as density or thermal conductance, to building code-related classification like occupancy type, to economic factors like cost. Data from the model is valuable in many ways, from comparisons of schematic variations, to live feedback of volume, mass and surface area data that is extracted from the 3D model. The BIM approach can be used to qualitatively evaluate different floor plan layouts, and even material and weight choices based on quantitative data.

In addition, BIM is likely to include the following characteristics:

Interoperability. Many BIM implementations accommodate federated bims generated by distinct design disciplines, allowing architects, engineers and consultants to exchange building model data through the design process.

Parameterization. Many BIM authoring applications incorporate parameterized modeling, whereby model element geometry and dimensional relationship to other model elements are controlled by parametric constraints. At their most sophisticated, BIM processes incorporate graphical scripting or visual programming languages directly in BIM authoring applications such as Revit's *Dynamo* or Vectorworks Architect's *Marionette*. Commonly BIM processes make use of non-BIM modeling software that is nevertheless incorporated in the design workflow; one example is Rhinoceros' *Grasshopper* graphical scripting module.

Constructability. The bim can also be used as a diagnostic tool that is directly tied to fabrication. The model can be used post-construction for directly 3D printing replacement parts, for instance on deep space missions where resupply is not an option.

Note that in this paper, we refer to the process, building information modeling, as BIM, and digital artifacts of that process, building information models, as bims.

Figure 1. An early example of building information modeling: sectional perspective with dimension lines of the Massey residence, Los Angeles, CA. *Building model created in 1994. Credit: 1995 Cor-Tex / Neil M. Denari Architects.*

BIM constitutes a distinct advance beyond its predecessor in the design studio, CADD (computer-aided design and drafting). CADD tools from the 1970s onward employed vector computer graphics to represent architectural and engineering drawings. While CADD eventually developed 3D capabilities, it lacks the data attributes that are foundational to BIM. However, rather than being just an offshoot of CADD, BIM's development was influenced by Product Lifecycle Management (PLM) software from the aerospace, automotive, and product manufacturing industries, as well as advances in Object-Oriented programming[4]. The distinguishing characteristic of BIM is its reliance on organized, semantic databases to describe model elements, and the associated social collaboration that interoperable, data-rich modelsenabled[5].

Significantly, the commercial BIM software "ecosystem" includes numerous computer applications that are not intended to create BIM content; that is, there is more to BIM software than BIM authoring applications. Several other applications types fall under the BIM category yet are intended to view, validate, manage files for coordination and collaboration, and analyze bims. The latter category includes structural analysis, thermal and energy performance, and cost estimating. These other BIM applications increase the value of a given bim beyond simply creating a 3D model for visualization, extending BIM's usefulness to allow consultants and collaborators to contribute their expertise to the project effectively and efficiently.

This paper considers the benefits of a BIM-like design, construction, and operational process to spacecraft design, particularly for the design of crewed vessels. After briefly outlining key BIM standards and frameworks, we suggest a spacecraft design analog: Spacecraft Information Modeling or ScIM.

II. Precedent Frameworks

A. Levels of Development

One of the early critiques of BIM among design architects is that it is perceived to encourage users to implement detailed building component models prematurely. A concern is that designers may deploy pre-coded digital model components containing high levels of material, structural, and informational detail before appropriately considering and evaluating the full scope of necessary design decisions.

Yet in spite of BIM's ability to produce highly detailed building components, lower-fidelity modeling is also possible. Coarser models are desirable to allow incremental refinement of initial design decisions, allowing for iterative design processes to progressively refine models while testing milestone developments. For this reason, advantages remain for starting the architectural design process with lower-fidelity bims unburdened by dense geometric data attributes. Moreover, building information models need not be uniformly detailed; indeed given the federated nature of many BIM projects, uniform detail throughout built projects is neither realistic nor desirable.

As any other digital tool, it's important to deploy BIM appropriately in the design process[6]. In response to these concerns, the concept of Levels of Development (LOD) has evolved in order to codify a spectrum of degrees of detail required throughout the life of a project. The American Institute of Architects (AIA), Association of General Contractors (AGC), and the BIMForum, the U.S. chapter of buildingSMART international, jointly developed the LOD Specification to describe the detail level of BIM components and systems[7], referred to as Model Elements (MEs). Now in its fourth version, this document, the AIA's *G202 Protocol*[8] establishes definitions for increasingly granular levels of development, as well as a mechanism for identifying and assigning each design team member's detail level goal for their respective contribution to the federated model. Complementary protocols[9] allow the design team members to set expectations and coordinate deliverables in an orderly and communicative fashion:

> **LOD 100**. This level is the coarsest or most approximate early or preliminary Level of Development. At this level MEs, a graphic symbol or approximate massing may represent an ME by as a generic placeholder, though LOD 100 elements are not generally geometric representations. Since BIM components carry data as well as geometry, the LOD 100 standard also establishes data requirements of the component or system as derived from other model elements, such as cost per unit of area or cooling capacity per unit of volume for an HVAC system.
>
> **LOD 200**. A generic component, system, or assembly, represents the ME, which it models only approximately. LOD 200 MEs are placeholders that represent recognizable or merely establish the component's volumetric requirements (boundaries plus required clearances). LOD 200 data is similarly approximate and any information derived is imprecise
>
> **LOD 300**. The ME is specifically represented. Its quantity, geometry, location and orientation are explicit. Data may be attached to the ME. According to BIMForum:
>
>> *Quantity, size, shape, location, and orientation of the element as designed can be measured directly from the model without referring to non-modeled information such as notes or dimension call-outs. The project origin is defined and the element is located accurately with respect to the project origin*[7].
>
> **LOD 350**. In addition to LOD 300, the bim models the elements required for coordination with adjacent or contiguous MEs, including structural supports and MEP connections. Please note that for most architectural projects, design documentation generally goes no further than LOD 300 or 350. LOD 300 to 350 are in some ways analogous to the AIA's traditional Construction Document Phase, e.g. working drawings and specifications.
>
> **LOD 400**. The ME includes fabrication, assembly, and installation information. Data may be attached. LOD 400 models are akin to fabricator and sub-contractor's shop drawings that interpret the intent of the architect or engineer, who must review and approve the sub-contractor's or contractor's submissions.
>
> **LOD 500**. The ME constitutes a field-verified representation, analogous to an "as-built" or the AIA's post-construction "record drawing" of how the contractor actually completed the construction. LOD 500 is not a separate design-phase standard, except as a precursor to subsequent modification of existing structures. It is particularly useful for facilities management.

The LOD standard provides a guideline for qualifying the incremental maturity of a design. It establishes a framework for design team members to calibrate the level of detail of their deliverables as the design process proceeds. Deliverables from respective design disciplines can be assigned LODs according to the project design timeline, establishing expectations and responsibilities of design team members. Finally, the LOD standard allows for a clear set of expectations of what the client will receive at each stage.

B. Industry Foundation Classes (IFC)

Formally designated as standard ISO-16739, IFC is an interoperable BIM file format that includes both geometrical information and other ME data[10]. It is in part based on STEP (ISO 10303), and includes definitions for an ME's bounding box as well as body, the latter describable as a BREP (boundary consisting of surfaces), a Clipped Solid (the product of a Boolean operation like additive or subtractive modeling), a Swept Solid (a profile revolved along an arc path), and/or a Linear Extrude solid. In addition, STEP can accommodate a vector footprint, faceting, survey points, and mapped item representation.

IFC would be unremarkable if it were merely another 3D modeling format. Its significance to BIM, however, is two-fold. First, IFC allows non-geometric data to be attached to MEs. The data can include such variables as density, cost per unit of measurement, power requirements, fire rating, thermal conductivity, sound transmission, occupancy, and so on. It is also possible to add custom data fields that are specific to any project. Second, it is an open, non-proprietary format. The format is published and available to any software vendor or developer. No software uses IFC as its native format, and over 30 software applications are certified to reliably import or export IFC.

IfcValveType

Definition from IAI: The element type *IfcValveType* defines a list of commonly shared property set definitions of a valve and an optional set of product representations. It is used to define a valve specification (i.e. the specific product information, that is common to all occurrences of that product type).

NOTE: The product representations are defined as representation maps (at the level of the supertype *IfcTypeProduct*) which get assigned by an element occurrence instance through the *IfcShapeRepresentation.Item[1]* being an *IfcMappedItem*.

A valve type is used to define the common properties of a valve that may be applied to many occurrences of that type. Valves are typically is used in a building services piping distribution system to control or modulate the flow of the fluid. Valve types (or the instantiable subtypes) may be exchanged without being already assigned to occurrences.

The occurrences of the *IfcValveType* are represented by instances of *IfcFlowController* or its subtypes.

Property Set Use Definition:

The property sets relating to this entity are defined by the *IfcPropertySet* and attached by the *IfcRelDefinesByProperties* relationship. It is accessible by the inverse *IsDefinedBy* relationship. The following property set definitions specific to this entity are part of this IFC release:

- Pset_ValveTypeCommon: common property set for all valve types
  - Pset_ValveTypeAirRelease: property set for air release valve types
  - Pset_ValveTypeDrawOffCock: property set for draw off cock valve types
  - Pset_ValveTypeFaucet: property set for faucet valve types
  - Pset_ValveTypeFlushing: property set for flushing valve types
  - Pset_ValveTypeGasTap: property set for gas tap valve types
  - Pset_ValveTypeIsolating: property set for isolating valve types
  - Pset_ValveTypeMixing: property set for mixing valve types
  - Pset_ValveTypePressureReducing: property set for pressure reducing valve types
  - Pset_ValveTypePressureRelief: property set for pressure relief valve types

HISTORY: New entity in IFC Release 2x2.

EXPRESS specification:

```
ENTITY IfcValveType
  SUBTYPE OF (IfcFlowControllerType);
    PredefinedType           : IfcValveTypeEnum;
  WHERE
    WR1          : (PredefinedType <> IfcValveTypeEnum.USERDEFINED) OR ((PredefinedType = IfcValveTypeEnum.USERDEFINED) AND
                   EXISTS(SELF\IfcElementType.ElementType));
END_ENTITY;
```

Attribute definitions:

PredefinedType : The type of valve.

Inheritance graph

```
ENTITY IfcValveType;
  ENTITY IfcRoot;
    GlobalId                 : IfcGloballyUniqueId;
    OwnerHistory             : IfcOwnerHistory;
    Name                     : OPTIONAL IfcLabel;
    Description              : OPTIONAL IfcText;
  ENTITY IfcObjectDefinition;
  INVERSE
    HasAssignments           : SET OF IfcRelAssigns FOR RelatedObjects;
    IsDecomposedBy           : SET OF IfcRelDecomposes FOR RelatingObject;
    Decomposes               : SET [0:1] OF IfcRelDecomposes FOR RelatedObjects;
    HasAssociations          : SET OF IfcRelAssociates FOR RelatedObjects;
  ENTITY IfcTypeObject;
    ApplicableOccurrence     : OPTIONAL IfcLabel;
    HasPropertySets          : OPTIONAL SET [1:?] OF IfcPropertySetDefinition;
  INVERSE
    ObjectTypeOf             : SET [0:1] OF IfcRelDefinesByType FOR RelatingType;
  ENTITY IfcTypeProduct;
    RepresentationMaps       : OPTIONAL LIST [1:?] OF UNIQUE IfcRepresentationMap;
    Tag                      : OPTIONAL IfcLabel;
  ENTITY IfcElementType;
    ElementType              : OPTIONAL IfcLabel;
  ENTITY IfcDistributionElementType;
  ENTITY IfcDistributionFlowElementType;
  ENTITY IfcFlowControllerType;
  ENTITY IfcValveType;
    PredefinedType           : IfcValveTypeEnum;
END_ENTITY;
```

Figure 2. An example of an IFC specification, in this case, a valve. *From buildingSMART International Ltd., http://www.buildingsmart-tech.org/ifc/IFC2x3/TC1/html/ifchvacdomain/lexical/ifcvalvetype.htm, retrieved 1 May 2018.*

These characteristics—3D geometry; attached data; and an open, interoperable format—make IFC a critical format for a collaborative BIM process between multiple design disciplines.

C. COBie for terrestrial CAFM

Construction Operations Building Information Exchange **(COBie)** is a data standard created by the US Army Corp of Engineers as part of the larger US National BIM Standards (NBIMS-US). COBie is an information exchange aimed at a building's managed assets. It captures important data, typically for large facilities, that is important to the owner's operation of the facility throughout its lifecycle, from the Design, Bidding/Procurement and Construction Administration phases of a project to operations. Being the first formal buildingSMART IE (information exchange standard) adopted in the NBIMS-US, it has already made an impact in the way BIM is used to deliver many public sector projects, as well as large private sector facilities, like hospitals and higher education buildings. The US, the United Kingdom, and Singapore have already adopted buildingSMART IE as their common standard. The United States General Services Administration (GSA), US Government's landlord, provides the specifications for data exchange developed with that Administration's experience in building and managing hundreds of millions of square feet of facilities around the country and throughout the world.

COBie data is about the information ascribed to managed building assets like lighting, plumbing, various selection, and mechanical components. From a designer's perspective, COBie data is derived from construction document schedules: lighting schedules, plumbing fixture schedules, equipment schedules, room finishes, and so forth. COBie-compliant BIM-authoring software automatically assigns unique identifiers for all assets for scheduling purposes, and the user can assign them as well. The advantage to a building owner is that all assets are documented according to a predictable format, and hand-off manuals can be delivered electronically in a searchable database.

III. Applicability to human spacecraft design

As an acknowledgement of the legacy technology of paper drawings, BIM authoring software has been designed to accommodate accepted graphic conventions for visual communication in two dimensions (traditionally a sheet of paper or more contemporaneously a computer monitor) of 3D geometry. Such conventions include:

- Drawing in plan, elevation, and section;
- Delineating the plane of a section in a heavy outline and/or poché;
- Identifying distant elements of the geometry by lighter (thinner) lines;
- Silhouetting significant masses in a heavier (thicker) line;
- Distinguishing changes in topography by contouring planar breaks with heavier (though not the heaviest) lines;
- Dashing objects above or behind the view plane with one spacing of gaps and lines,
- While objects behind an obstruction are shown with a distinct dash pattern; and so on.

These practices are by now almost universally accepted conventions of producing architectural drawings, so ingrained in professional education and practice that any architect or structural/civil engineer in the world would instantly correctly interpret drawings produced according to these conventions[11].

While some of these graphical conventions to display two-dimensional views of 3D models may be appropriate to aerospace applications, it is not our intention to pattern aerospace design workflows merely on the product of architectural design efforts. Of greater importance in the context of this discussion is the nature of the contemporary BIM-enabled architectural design process. Key characteristics of that design process include:

Iteration. The first design decision in any project is that of defining the boundaries of the project. . These boundaries are multi-domain and multi-dimensional, from the property lines, to the floor area and height allowed by code, cost, and time of construction. Paradoxically, those boundaries may not be fully understood at the onset, and certain design limitations and parameters are only discovered once "design" is underway[12]. Design is thus inherently a non-linear process, whereby later design solutions may call into question the very assumptions or parameters of the design problem they were intended to solve.

Information. The aerospace industry has for decades now employed 3D computer modeling for design and documentation. These models focus in large part on the geometry associated with parts or sub-assemblies of vehicles: accommodating the geometry of parts within a given boundary constraint, fitting multiple parts against each other in order to alleviate interferences, and testing part installation by fit and sequence. This could be summarized as "fitting". Architectural BIM has similar or analogous concerns; what distinguishes it from strictly 3D modeling is that in addition objects and assemblies are data-rich. BIM model elements are both semantically distinguished (classified according to their role, function, or associated discipline) and have attached data such as thermal properties, fire resistance, cost, and so on. This information is part of the BIM file database, and can thus be queried, reported, and analyzed, offering opportunities to design for model element characteristics beyond their mere geometry[13].

Collaboration. We are centuries past the days of Vitruvius when an αρχιτέκτων ("master maker") was an architect, civil engineer, city planner, public health professional, and siege warfare engineer all in one. The highly complex, iterative, and potentially information-rich nature of design lends itself to the collaboration of large teams of design, construction, and facilities professionals and stakeholders each with their own expertise to contribute to the endeavor. Insofar as they enable collaboration in a neutral, non-proprietary and open framework, BIM standards play a vital role in the efficient and effective transfer and sharing of information among design stakeholders.

In its development, BIM authoring software was in part influenced by the modeling capabilities of automotive and aerospace design software[14]. While this type of preceding commercial software informed the development of 3D modeling in BIM, it did not address the collaborative needs of an industry[15] with disparate and more loosely tethered suppliers and contractors operating with fewer industry-wide standards. BIM's use in the AEC industry was initially championed by large-scale construction companies and building owners. These two groups saw BIM as a means of streamlining and reducing errors during construction, and improving facilities management.

Interestingly, the architecture profession resisted the adoption of BIM. We speculate that trained as they are to visualize three-dimensional objects and space by interpolating two-dimensional drawings, architects may have seen the advent of 3D modeling as an intrusion on their expertise. Moreover, BIM occurred to many architects as increasing their deliverable responsibilities and legal liability with little or no commensurate compensation or higher fees.

Nevertheless, it is BIM's frameworks for information management, whether geometrical data or otherwise, that makes it desirable as a digital design and documentation environment. The 3D modeling aspect of BIM is necessary and foundational, but alone inadequately represents the significance of BIM.

A. BIM frameworks mapped to ScIM

In terrestrial architecture, with the exception of the 500 specification, LOD is applicable to the design and documentation phases of a project, rather than procurement, construction, and occupancy. As a project matures in its design, many components and assemblies may be upgraded to higher LOD models. It may be tempting to think that by the end of design and documentation (delivery of construction documents), all project MEs are advanced to LOD 400. In practice, however, there is value in perpetuating certain model elements at a lower LOD. The computational cost of maintaining even a modest project's bim at 400 LOD would be prohibitive, and most software operations would slow to a crawl. It is neither necessary nor desirable for all MEs to be detailed to the level of a fabrication-ready model. Most commercially manufactured items are installed in buildings without any interaction with their subcomponents, or certainly not to the level requiring detailed modeling of every part and assembly within a piece of installed equipment. Rather, what's generally required are accurate—though not necessarily highly detailed—geometry, dimensions, and clearances for the ME, as well as connection types and locations to integrate the equipment into to building services—power, water, gas, etc.—as appropriate and required for the piece of equipment in question. That is, for even highly developed architectural models suitable for permitting, procurement, and construction, LOD 300 is adequate and even appropriate for most components.

Moreover, this conceptualization of the bim as just that—a building information *model*—assumes a certain level of abstraction that is not only convenient for the computational overhead reasons just cited, but is in service of a measured design process. Not knowing all the details of a component can be a setback at certain stages of the design process; what can be significantly worse is assuming a level of knowledge that is in fact not present. False assumptions in spacecraft design obviously can have catastrophic consequences, and having a schema like LOD with explicitly absent information where appropriate is useful in the design process.

Protocols like the PxP allow the design team to establish clear expectations for level of development of deliverables, helping distinguish which MEs are left at lower LODs pending further development, and which have reached sufficient albeit schematic maturation. A low-LOD element might be an indication to the designers that the ME in question may require further design attention; conversely, MEs may be deliberately left at a lower LOD if a higher fidelity model is not required.

Industry Foundation Classes, repurposed as ScFC (spacecraft foundation classes), could play an important role in expanding the interoperability of aerospace 3D models for design, analysis, procurement, fabrication, and maintenance. Structural classes could be expanded to include distinctions such as primary (pressure vessel) and secondary structure, as well as appropriate subcomponents. Non-structural elements would likewise be represented: racks, partitions, and stowage. ScFC services classes would include ECLSS, thermal loop, power distribution, data system, communications, and caution, alert and warning systems. ScFC architectural specialties for crewed vehicles and for habitats would be differentiated and identified with their own ScFC classes: windows, hatches, latches, grab-bars and handles, and miscellaneous hardware.

Adapting ScFC to spacecraft design would allow models and their data to be shared among design team stakeholders, such that various design parameters could be tested simultaneously. For example, a component's structural properties and mass, and how it fits and its fabrication is sequenced within a larger assembly, could be concurrently analyzed by one part of the design team, while its thermal performance could be assessed by other designers using different software platforms. While many software programs already allow file exchanges through commonly adopted file formats, an ScFC standard, like its IFC predecessor, would maintain a library of open, interoperable file formats accessible to any developer. Moreover, ScFC would help maintain compatibility of archived components and projects, allowing for longer useable life spans for project data in spite of evolutions in software platforms and changes in file formats over time.

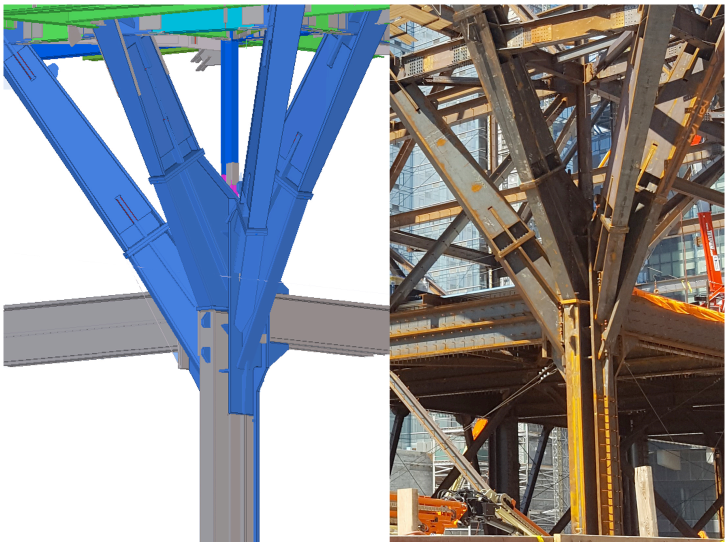


Figure 3. Structural bim of a complex steel connection developed in the commercial structural software, Tekla Structures (left). In addition to 3D geometry, the model contains information for all material grades, welds, weld preps, testing requirements, approvals and fabrication status. Right, the connection as erected on site. *Model by Skidmore, Owings & Merrill LLP; photo by Georgi Petrov.*

Like their terrestrial counterparts, crewed spacecraft and habitats require constant maintenance once occupied, only to a much higher degree. To illustrate this point, on the ISS, a core crew complement (three crew members) left little time for science[16], as most of the crew's time was consumed with operations and housekeeping tasks; a full crew of six (the current complement) on the other hand allows time for research. Given the greater efficiency and time savings that a CABM system offers terrestrial building occupants, it is reasonable to expect that numerous features of operations might benefit from CASM (Computer Aided Spacecraft Management) based on COBie.

B. Opportunities for improved processes

A great benefit of BIM comes from the enhanced collaboration processes between design and fabrication. This is true especially on projects with complicated geometry where conventional methods of conveying the design information are insufficient. Although traditional 2D drawings are still being produced in order to satisfy contractual and legal obligations, often the design is communicated through sophisticated BIM models[6]. Delivering a 3D model with elements that are tagged with relevant properties greatly reduces the time required by a contractor to make an accurate estimate of the quantities and effort that will be required to fulfill the project. This allows for a reduced time to complete the bid process, but more importantly it reduces the contingencies that would be typically built into the final cost of the project. The emergence of cloud computing has recently started to take the process one step further. If the BIM model is shared on a common server (i.e. in the cloud) then both the design and the fabricator can be working on the same model simultaneously. This further accelerates the sharing of information while greatly reducing errors. A designer can be modeling part of the structure while the fabricator is editing the portions that are already completed for their fabrication and constructability needs. The ultimate result is an accelerated start of construction with increased accuracy. Given the historically high costs of aerospace projects, any workflows that accelerate and streamline the design and construction process can have positive impact on project timelines and costs.

Previous research has underscored the value of an interoperable approach to design and construction in space habitats, specifically using a common database for bi-directional access by disparate design team members and their respective software platforms[17]. In terrestrial architectural and engineering practice, federated bims whose sub-models are contributed by various design team members are commonly managed and interference detected through the use of commercial software like Navisworks or Solibri. These models rely on IFC as their common file format, and this format is non-native to any BIM application. Moreover, IFC components currently are non-parameterized. While it is theoretically possible for BIM software to substitute a native object for an imported IFC one, the difficulty in editing an imported IFC ME preserves each disciplines authority over its contribution to the federated bim; architects cannot easily or inadvertently alter the structural model, for example. It remains to be seen whether true multi-directional editing of bims through the medium of a common, bi-directional database increase liability and the potential for error beyond an acceptable limit.

C. Previously designed spacecraft case study

This interdisciplinary academic project lead by one of the authors was carried out as part of the NASA sponsored X-HAB (vertically-oriented habitat) program[18]. The design team used an online collaborative workflow for the design of a deep-space habitat, including an innovative BIM output method and a direct digital fabrication processes linked to diagnostic sensors. The X-Hab was volumetrically constrained and was required to accommodate all consumables needed, without resupply. This project's design approach had two key features:

1) To compare alternative architectural designs in order to optimize the most elegant engineering/architectural solution within a constraint-driven approach;

2) To benefit very long duration space missions design through the inventorying and locating of consumables, dynamically managing their relationships by means of a real-time automated diagnostic.

The project's key areas of focus included:

- a collaborative online workflow
- a BIM constraint-driven design approach
- full-scale physical prototyping
- an investigation into the benefits of fabrication and parts replacement in deep space missions.

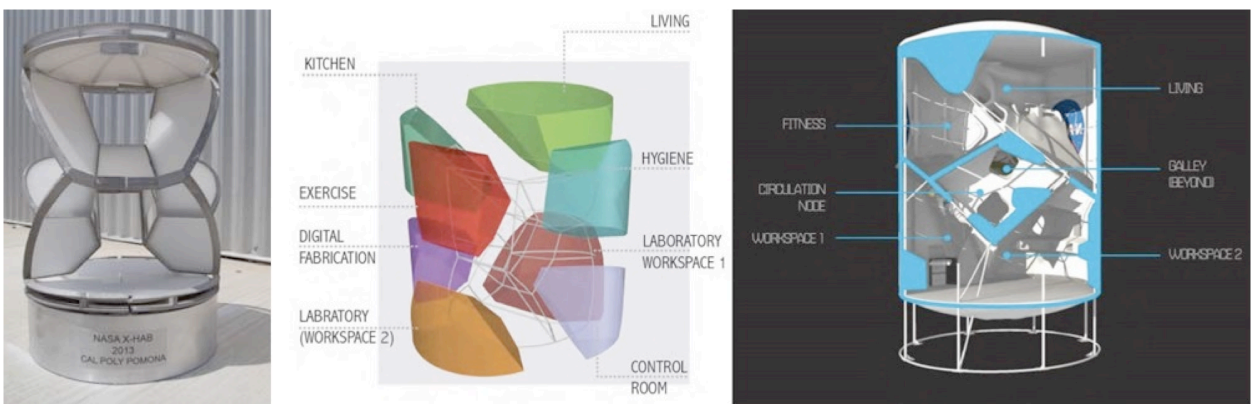
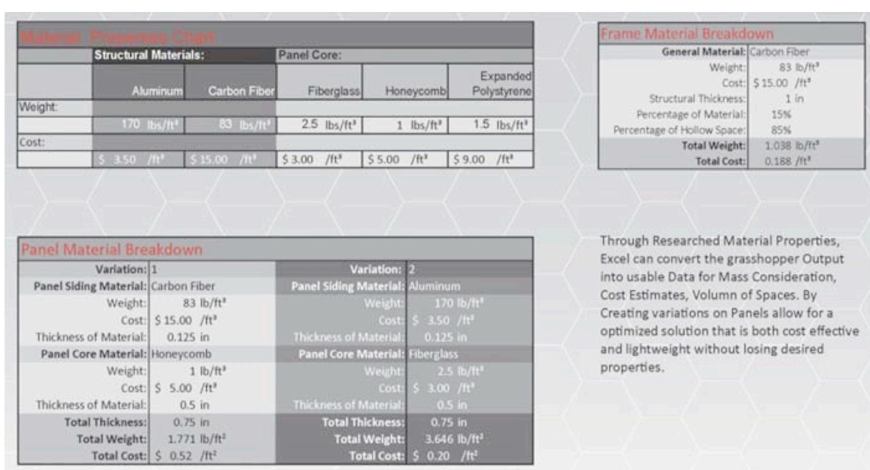


Figure 4. Model and diagrams of final 3D programmatic organization.

Design Process: The workflow primarily involved commercial software applications: SketchUp, Grasshopper, Excel, Firefly and Rhino, with documentation in Revit and AutoCAD. We began with traditional BIM software (Revit) for design explorations, and quickly turned to a more dynamic modeling software (Rhino) using a graphical scripting plug-in (Grasshopper). We thus used parametric modeling software in a BIM



	Structural Materials:		Panel Core:		
	Aluminum	Carbon Fiber	Fiberglass	Honeycomb	Expanded Polystyrene
Weight:					
	170 lbs/ft³	83 lbs/ft³	2.5 lbs/ft³	1 lbs/ft³	1.5 lbs/ft³
Cost:					
	$ 3.50 /ft³	$ 15.00 /ft³	$ 3.00 /ft³	$ 5.00 /ft³	$ 9.00 /ft³

Frame Material Breakdown

General Material:	Carbon Fiber
Weight:	83 lb/ft³
Cost:	$ 15.00 /ft³
Structural Thickness:	1 in
Percentage of Material:	15%
Percentage of Hollow Space:	85%
Total Weight:	1.038 lb/ft³
Total Cost:	0.188 /ft³

Panel Material Breakdown

Variation:	1	Variation:	2
Panel Siding Material:	Carbon Fiber	Panel Siding Material:	Aluminum
Weight:	83 lb/ft³	Weight:	170 lb/ft³
Cost:	$ 15.00 /ft³	Cost:	$ 3.50 /ft³
Thickness of Material:	0.125 in	Thickness of Material:	0.125 in
Panel Core Material:	Honeycomb	Panel Core Material:	Fiberglass
Weight:	1 lb/ft³	Weight:	2.5 lb/ft³
Cost:	$ 5.00 /ft³	Cost:	$ 3.00 /ft³
Thickness of Material:	0.5 in	Thickness of Material:	0.5 in
Total Thickness:	0.75 in	Total Thickness:	0.75 in
Total Weight:	1.771 lb/ft²	Total Weight:	3.646 lb/ft²
Total Cost:	$ 0.52 /ft²	Total Cost:	$ 0.20 /ft²

Through Researched Material Properties, Excel can convert the grasshopper Output into usable Data for Mass Consideration, Cost Estimates, Volumn of Spaces. By Creating variations on Panels allow for a optimized solution that is both cost effective and lightweight without losing desired properties.

Figure 5. Integrated BIM Excel output interface.

workflow using the live integration of Excel; the latter was used for output of data from Grasshopper, allowing for comparisons of schematic variations. Real-time feedback of comparative volume, mass and surface area data was extracted from the 3D model. For example, by creating variations of panels we were able to optimize a solution that was both cost- and mass-effective without loss of structural strength. Rhino was then used to fix the mutable geometry from Grasshopper to create static geometry as a basis for further 3D geometry and rendering. It was also used to extract points to be modeled in Revit or other modeling software. Firefly (a plug-in for Rhino that links Grasshopper to micro-controllers) was also tied to the model to create real-time sensor diagnostics from the physical counterpoints.

We used BIM to pursue alternative architectural designs within a constraint-driven approach, evaluating different layouts: comparing concentric/symmetrical pie-slices with off-center circulation for variety in crew cabins and other rooms; evaluating the functionality of various galley and wardroom designs; optimizing work areas in labs and maintenance work stations, etc. We undertook a trade and analysis cycle—uncommon in architectural design but very common in engineering—as a process approach. Through our systems engineering approach, students generated competing ideas, only some of which were advanced to final design development.

This BIM approach allowed us to quantitatively compare alternatives and evaluate the relative merits of design variations, ensuring that we were able to select the most efficient and effective system design. Every decision was reciprocal in our parametric process, maintaining the traceability of design decisions back to the fundamental requirements and providing a documented, analytical rationale for choices made in system development.

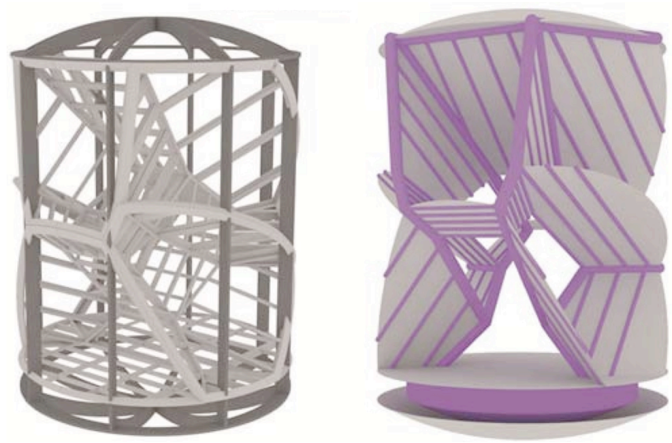


Figure 6. Structure and systems integration diagrams.

Concept Parametric (BIM) Model and Systems Engineering: After a comprehensive quantitative comparison and evaluation of interior layout alternatives, we selected the most efficient and effective system design. All systems and sub-systems of the final design were resolved, including structure, ECLSS, and water reclamation systems. This final design was subsequently developed, using a parametric model to optimize the space between habitable volumes. From a dedicated volume at the base of the habitat, MEP and ECLSS systems were distributed alongside structural members and between habitable volumes, forming a branching network with ancillary branches extending into the partitions.

At this stage we also developed construction drawings for the full-scale prototype mock-up. As part of our BIM approach, using Excel we built in linking with System Engineering modeling techniques such as SysML systems modeling language and CORE software to track requirements, dependencies, subsystem integration, interfaces, etc.

Physical Prototyping: A vertical section of the physical vertical habitat mockup was constructed at full-scale, allowing analog simulations of construction and occupancy using test devices. All modules were prototyped at a low-fidelity using cardboard and plywood to further study the habitat's volumetric relationships. It was important that the habitat mock-up be robust enough to enable real human presence and interactions to able to meaningfully test ergonomics and mobility within the mock-up.

Sensing and Direct Digital Fabrication. The bim was also used to drive digital fabrication of components. Additive printing devices were integrated in the iterative design process, directly tying the bim to fabrication. BIM is relevant to very long duration missions without resupply; the computational model of the habitat includes every integrated habitat component and piece of equipment. While the architectural bim is very useful for facilitating a comparative design process and through construction, we propose that BIM is also ideal for facilitating dynamic systems management during occupancy. Diagnostics that will tell the crew how well each component, system, and subsystem is functioning and anticipate when a part may require replacement or a backup system be brought on line so that the other can be shut down for maintenance. Further, all the equipment on the long duration habitat must have a system of Integrated Vehicle Health Monitoring, or Integrated Habitat Health Monitoring that could be plugged into the BIM of the habitat.

Figure 7. Images of final full-scale mock-up.

The model allowed us to digitally fabricate components with embedded diagnostic sensors using additive manufacturing; several parts were prototyped as functional components within the larger full-scale physical mock-up of the habitat. For example, the handhold/foothold was ergonomically designed to be used in several different configurations, and could be entirely fabricated within the habitat using in-situ materials and a 3D printer. Its embedded sensors were linked to the "live" bim via Firefly to report occupancy and stress, indicating crew and equipment locations, and how well the component was functioning, in order to anticipate when a part might require repair or replacement, and this sensor information was conveyed graphically within the habitat bim.

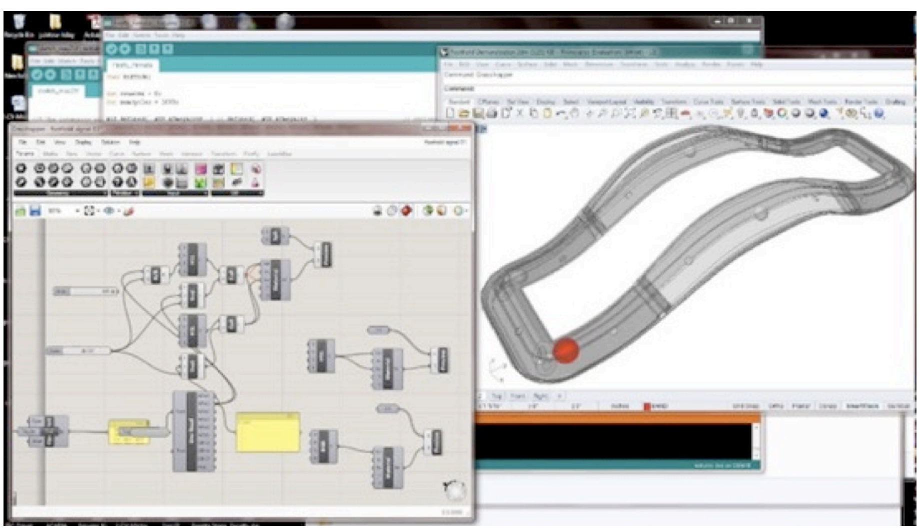


Figure 8. Prototype of physical diagnostic sensors.

This example project makes two important and distinct contributions to design and computation:

1) As a BIM process capable of linking with other System Engineering modeling techniques for tracking the requirements, dependencies, subsystem integration, and interfaces; and

2) In demonstrating a practical application for a post-construction "live" bim to investigate both occupancy and stress diagnostics.

IV. Conclusion

BIM frameworks offer opportunities for designing with data, stakeholder collaboration, 3D and 4D construction, and facilities management. The promise of BIM goes far beyond the avoidance of error that is the touchstone of System Engineering and other "glass box" systematic methods. BIM offers the potential for new, higher-level syntheses of design elements and processes to create heretofore unimagined designs and systems.

In the history of human space exploration and habitation, the demarcation between a human-rated vehicle and a habitat has at times been blurred, with vehicles like the Apollo lunar module for example doubling as a habitat, and habitats like ISS having design commonalities with space vehicles. Presumably such typological ambiguity may only continue as mass-sensitive missions are designed to make full use of payloads, incorporating vehicle components in habitats. Given the convergence of vehicular and habitation hardware, it may be logical to adopt a common digital design framework for human-rated assemblies to help ensure greater interoperability. Still-evolving BIM frameworks (IFC, LOD, COBie) represent a highly mature, robust, and tested set of standards that may have benefit to the design, construction, and operation of human-rated space vehicles and habitats.

Such standards are neither quick nor easy to implement. It has taken years for BIM stakeholders—encompassing design professionals, construction interests, research and academic institutions, government entities and software vendors—to develop common and interoperable frameworks. Given the highly specific nature and requirements of architecture for aerospace, it will not be sufficient to merely adopt terrestrial BIM standards, alter a few letters of some acronyms, and re-brand BIM for space. The equivalent constituencies in Space Architecture must lay broad field of groundwork, and commit to the formation of a consensus set of frameworks to effectively serve the interests of space architecture and the astronaut crews who will serve as the ultimate end-users.

In the nearer term, future research could address specific frameworks outlined above and develop them in greater depth, with a closer examination of the particular needs of human-rated aerospace design, construction, and operations in order to more closely pattern a set of appropriate spacecraft information modeling standards.

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