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Virtual Construction of Space Habitats: Connecting Building Information Models (BIM) and SysML

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Current trends in design, construction and management of complex projects make use of Building Information Models (BIM) connecting different types of data to geometrical models. This information model allow different types of analysis beyond pure graphical representations. Space habitats, regardless their size, are also complex systems that require the synchronization of many types of information and disciplines beyond mass, volume, power or other basic volumetric parameters. For this, the state-of-the-art model based systems engineering languages and processes - for instance SysML - represent a solid way to tackle this problem from a programmatic point of view. Nevertheless integrating this with a powerful geometrical architectural design tool with BIM capabilities could represent a change in the workflow and paradigm of space habitats design applicable to other aerospace complex systems. This paper shows some general findings and overall conclusions based on the ongoing research to create a design protocol and method that practically connects a systems engineering approach with a BIM architectural and engineering design as a complete Model Based Engineering approach. Therefore, one hypothetical example is created and followed during the design process. In order to make it possible this research also tackles the application of IFC categories and parameters in the aerospace field starting with the application upon the space habitats design as way to understand the information flow between disciplines and tools. By building virtual space habitats we can potentially improve in the near future the way more complex designs are developed from very little detail from concept to manufacturing.

Nomenclature

AES	=	NASA Advanced Exploration Systems
AIAA	=	American Institute of Aeronautics and Astronautics
BIM	=	Building Information Model
CAD	=	Computer Aided Design
CAE	=	Compputer Aided Engineering
CAM	=	Computer Aided Manufacturing
DOD	=	Department of Defense
IAI	=	International Alliance for Interoperability
IFC	=	Industrial Foundation Classes
ISO/PAS	=	International Standards Organization / Publicly Available Standards
ISS	=	International Space Station
JPL	=	Jet Propulsion Laboratory
MBE	=	Model Based Engineering
MBSE	=	Model Based System Engineering
MEL	=	Master Equipment List
MPLM	=	Multi-Purpose Logistics Module
NASA	=	National Aeronautics and Space Administration

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OBDC = Open Database Connectivity
PEL = Power Equipment List
SysML = A system engineering modeling language
TRL = NASA Technology Readiness Level
VSC = Virtual Space Construction
WBDG = Whole Building Design Guide

I. Introduction: MBE for complex systems and space habitats

Design and implementation of complex engineering projects involves different areas of the engineering process, from architecture and systems engineering to the engineering development of components, structures or subsystems to manufacturing. Currently in engineering there are trends to apply a model based approach to both the system engineering level (MBSE) as well as the engineering level (MBE) in general in order to reduce time and cost, increase complexity, improve design process, or better meet requirements to mention a few. The work presented in this paper show a portion of the applied research conducted to find and develop new workflows and techniques to use this MBE approach to the design of space habitats[1]. This approach also applies to other complex space hardware. For this, a design process/technique known as Building Information Model (BIM) is the correct choice for the task, a process well known in other industries such as construction and architecture and this time used in a space architecture simulated project within the requirements and needs of the aerospace realm. In essence, this approach presents some achievements part of ongoing work and applied research to tackle several information flow issues well known in the field. This project started as part of the research activity conducted at the Jet Propulsion Laboratory (JPL) NASA/Caltech for the NASA Advance Exploration Systems[2] (AES) program.

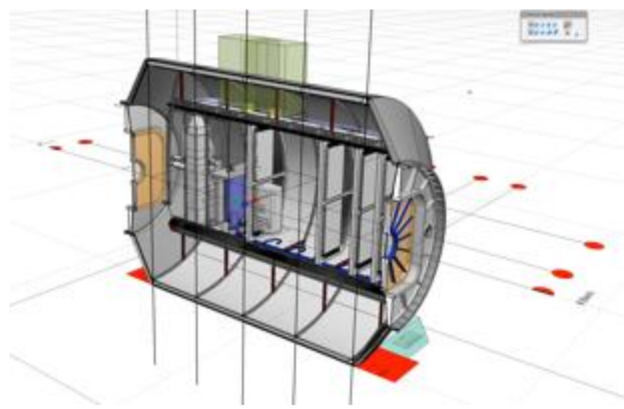

Figure 1. BIM models of an ISS Derived Module. An example of BIM applied to aerospace design

A. BIM today

Building information model techniques and processes today could be describe as ***"the process involving the generation and management of digital representations*** *of physical and functional characteristics of a facility/model/system…"* according to the National BIM Standard[3] (US) or also as ***an integrated - concurrent - team approach to all phases of a project including early conceptual design, planning, construction, operations and management,*** based on the Whole Building Design Guide (WBDG) definition originally for Department of Defense (DOD)[4]. In general and for the purpose of this work the Building Information Modeling (BIM) technique is a way to combine the basic geometrical paradigm of Computer Aided Design (CAD) with the management of information and database in one single interdisciplinary, collaborative, and concurrent modeling environment.

The purpose of this paper is not to explain the basics of BIM but to point out the strong points applied to the development and design of space architecture hardware. The most important aspects in the application of BIM to aerospace design processes are:

- It allows development of smart geometries. In essence, custom information + parametric geometrical components
- Models are scalable, modular, and more affordable (better return)
- Work can be re-cycled by developing better and more complete repositories beyond only geometrical
- This approach also improves productivity and faster completion
- BIM models integrate all sorts of information types and disciplines:
    - *Architecture*
    - *Concept Design*
    - *Systems Engineering*
    - *Power*

- ○ *Thermal*
- ○ *Mechanical*
- ○ *Electrical*
- ○ *Structural*
- ○ *Management*
- ○ *Cost*
- ○ *Procurement*
- ○ *Operations (integration)*
- ○ *Etc.*

- The design environment can be concurrent and collaborative (as well as platform/software independent)
- These techniques also allow automatic document generation including both 2D and 3D documents
- Models and be exported to other software packages providing a good foundation for simulation, etc.
- In essence BIM models integrate:
  - ○ *3D + info + management + cost + operations Approach*

B. Space Architecture and complex systems

In the design, development and manufacturing of space habitats there are similar to any other complex engineering problem with many issues regarding the design process itself. In the experience during several years of this work at NASA a few of them seem to be the most relevant such as:

- The use of different platforms, operating systems, and software packages among centers and collaborators
- The connection between requirements (e.g., capture in SysML models) and mechanical and architectural design
- Review and tracking of versions and modifications
- Integration of different disciplines
- Information flow and collaborative participation
- Etc.

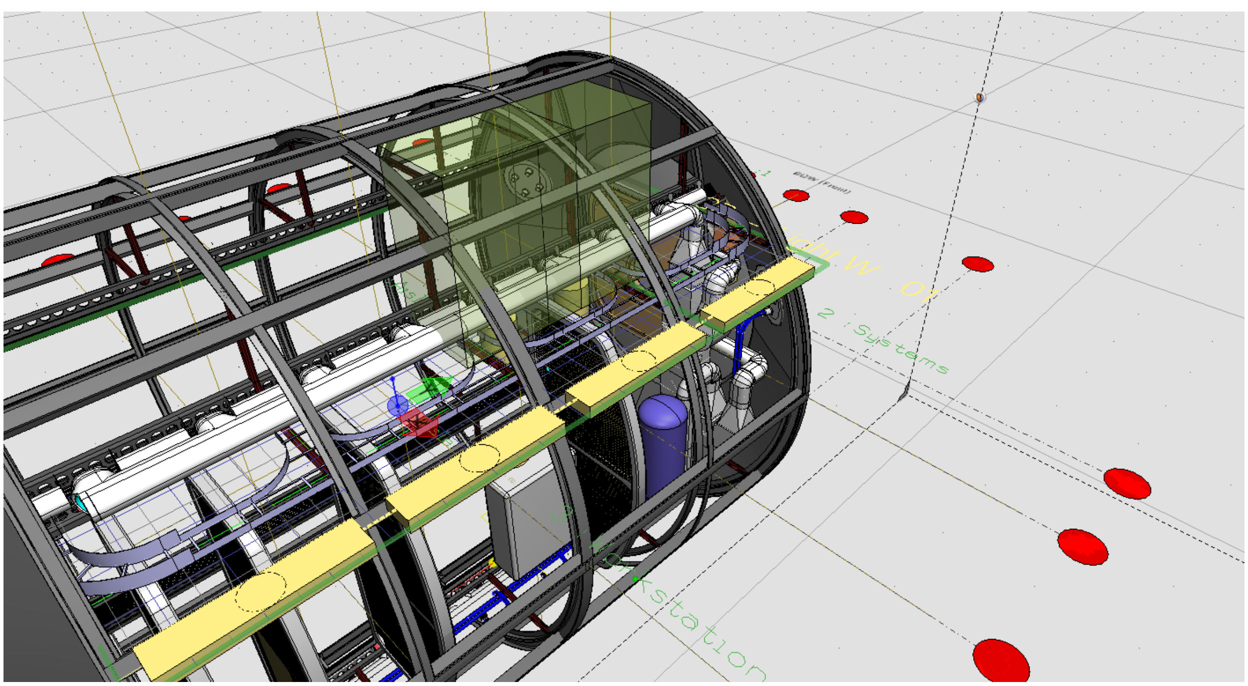

Figure 2. Perspective of a derived ISS module developed as a BIM model.

Beyond these typical issues in any architecture and engineering process there is also the integration of technologies and concepts often in the realm of cutting edge technologies or eventually with potential low levels of NASA Technology Readiness Level (TRL). The objective therefore is to address the integration of different tools for design, modeling, etc. in one linked model able to address trough a specific customized workflow addressing those aforementioned issues.

Implementing BIM techniques and processes into the current workflow of software and techniques allows to address some of them and to provide a strong foundation to mitigate those of a more complicated nature. Figure 1 and Figure 2 show some illustrations of the project this papers presents as an example of this approach.

II. Virtual Space Construction Process (VSC): BIM approach for aerospace design workflow

A. From requirements to implementation

Once some of the issues selected as targets have been defined and capabilities of new types of design processes using BIM identified the next step was to develop a conceptual workflow to see what parts of the developing lifecycle could be covered (Figure 3) as well as the information flow (Figure 4).

This research defines a Virtual construction Process as one using a BIM foundation that addresses a complete lifecycle of space hardware and system development potentially in the following areas:

- **Requirements** (SysML Model)
    - *Requirement*
    - *Systems Engineering*
    - *MEL*
    - *PEL*
    - *Etc.*
    - *Tradeoff*
    - *Traceability*
- **Configuration** (BIM, CAD Geometry)
    - *Concept Design*
    - *Planning*
    - *Architecture*
    - *Visualization*
    - *Engineering Design*
    - *Document creation*
- **Systems** (BIM, CAM)
    - *Structural (also loads)*
    - *Mechanical*
    - *Electrical*
    - *Detailing*
    - *Etc.*
- **Simulation**
    - *Thermal*
    - *Energy*
    - *Fluids*
    - *Stress*
    - *Custom Analysis (E.g. Radiation Harness)*
    - *Etc.*
- **Manufacturing** (BIM, CAE, CAM)
    - *Rapid Prototyping*
    - *3D Printing*
    - *Mock up development*
    - *Construction*
    - *Robotic Implementation*
- **Management**
    - *Phases*
    - *Procurement*
    - *Cost*
    - *Collaboration*
    - *Content Control*
    - *Briefing*
- **Operations and Integration**
    - *Hardware Integration*
    - *Testing data*
    - *Virtualization*
    - *Human factors*
    - *Virtual reality*
- **Database / Knowledge**
    - *Model Recycling*
    - *Database upgrade and update (database survival)*
    - *Maintenance*

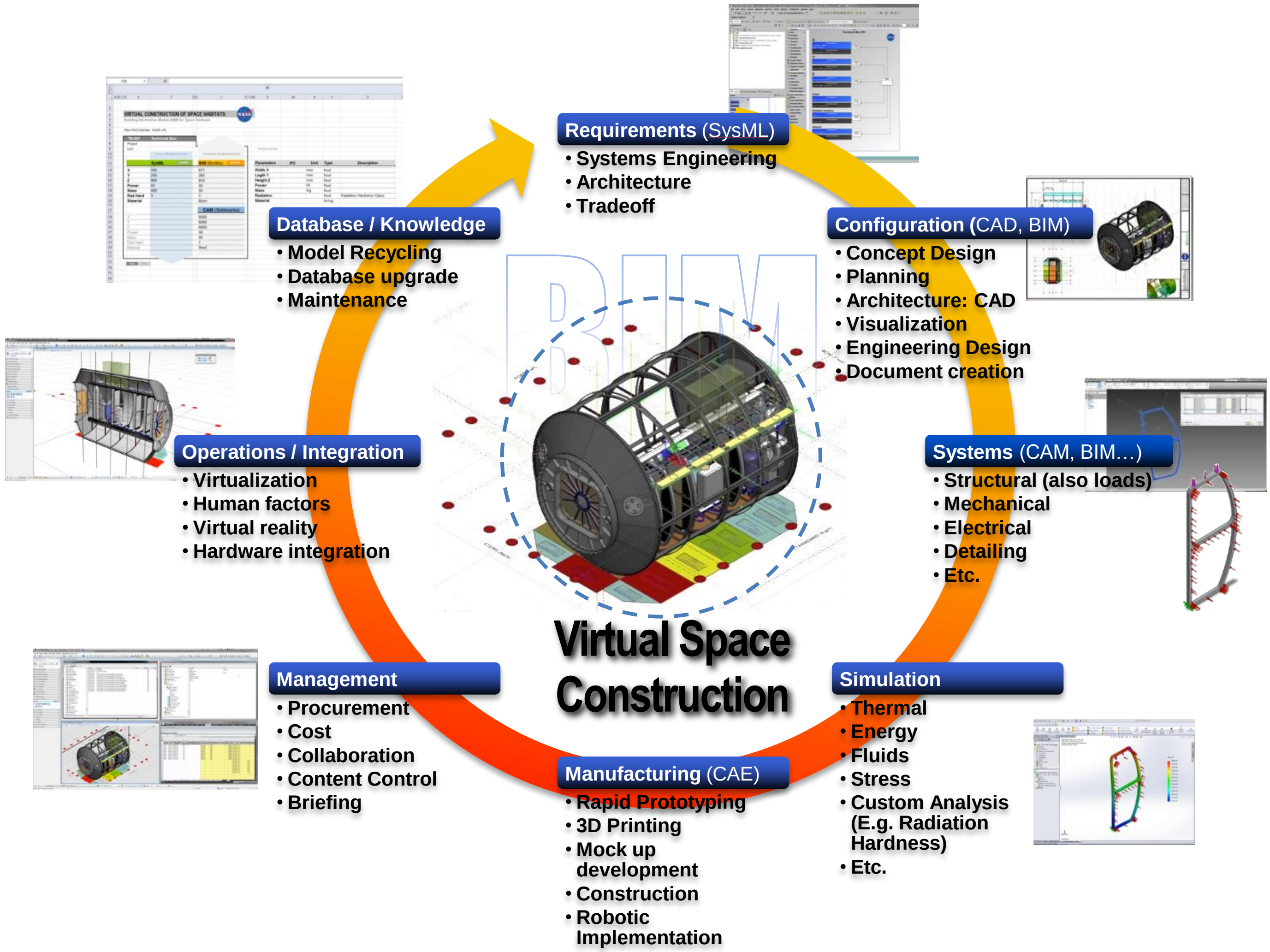

Figure 3. Lifecycle of aerospace hardware development potentially covered by a virtual space construction process

B. SysML

As part of the cycle of developing space hardware as well as space habitats a vital aspect is the systems engineering work behind it.

From capturing complex relationships between data and requirements to capturing requirements themselves, SysML[5] is one of the possible tools used at NASA and JPL for this purpose. The objective of this paper is not an explanation of SysML, but to understand the flow of the information to realize that the system engineering level and the interaction between parameters is key to a complete VSC process.

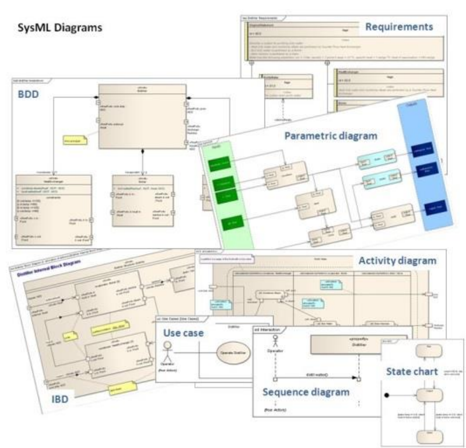

Figure 4. SysML diagrams. Public Domain.

BIM models can include many types of information within the model and, unlike CAD or Computer Aided Manufacturing (CAM) that information is scalable and customizable. However this information cannot be used to operate or develop complex relationships, therefore a model based engineering tool/language like SysML provides the foundation for the interaction of it. SysML and

BIM become the tail and the head of the same coin, a complete virtual construction process.

C. Data, information and design flow

In order to achieve this approach an information flow was created in order to share information between the different software packages involve. This workflow is the key of the process and had a few requirements concerning its development:

- Platform independent / operating system independent (Macintosh, Windows, Linux, etc)
- Scalable
- Expandable
- Exportable
- Information flows bidirectional in both ways
    - *From the SysMl (MBSE) side*
    - *From the BIM-CAM side (MBE)*

Any component is based on information that has been parameterized, whether this is a dimension or the material it is made of, collected and managed by a database. This "middle man" in the example provided by a spreadsheet and in general using any OBDC database allows to manage the information, capture time changes, detect what version is newer, or simply provide a source for a backup at any time.

The flow of information (Figure 5) not only goes between requirements and design sides, at any time we can pinpoint the cycle, read the values of the parameters relevant to us and use other software packages to perform analysis, construct mechanical models, etc. The architecture of this information flow has several components:

- A – SysML Model
- B – Database (Microsoft Excel Spreadsheet in this example)
- C - BIM Model (In this case using a federated model created with Bentley AECOSim)
- D – CAM Studies (Using Solidworks in this example)
- E – Simulation (Using Bentley Energy Simulation in this case).

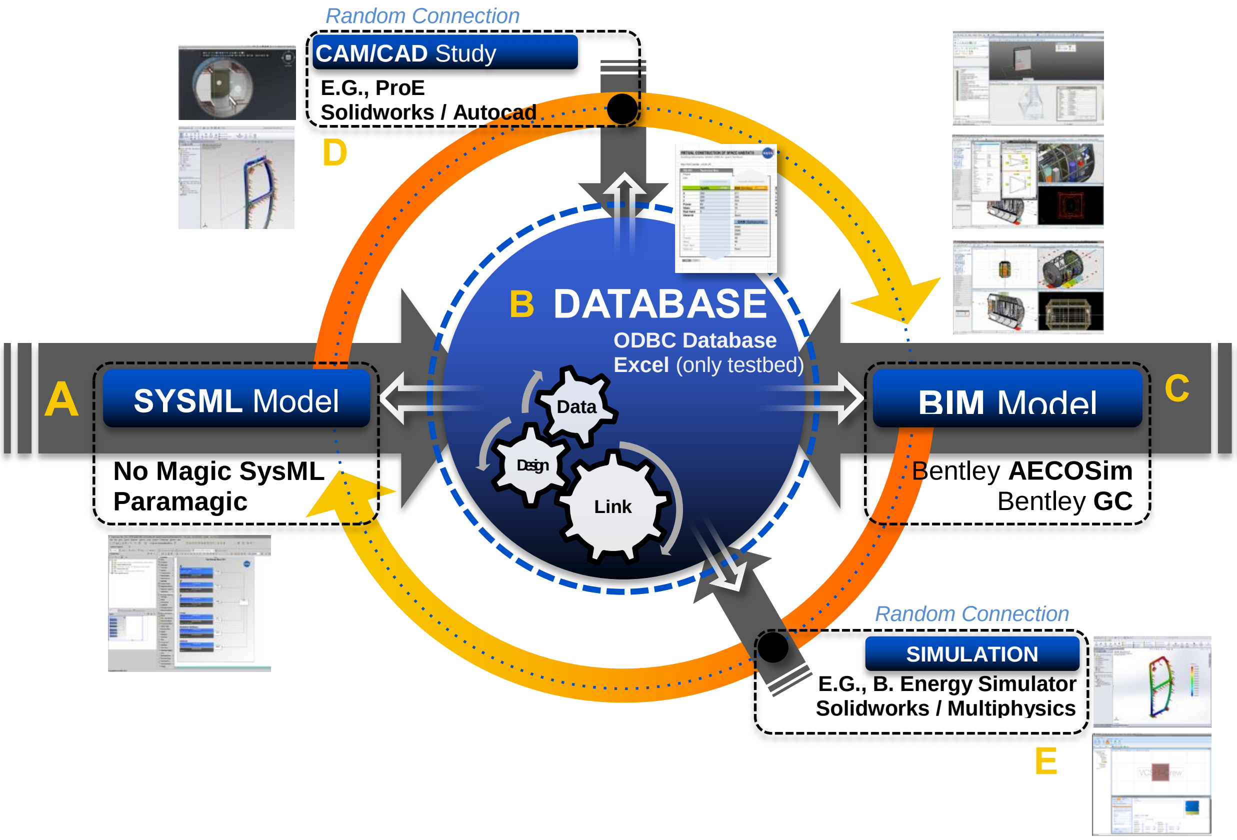

Figure 5. This shows the architecture of the information flow for a VSC process

III. IFC for space architecture and aerospace

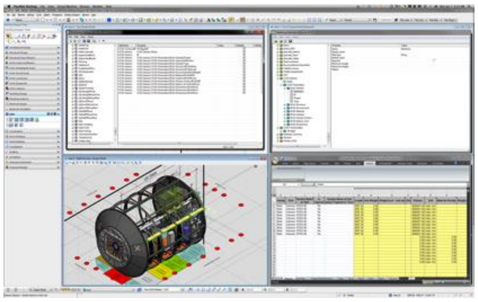

Figure 6: information input windows

With the idea of sharing parameters that define all levels of information in a project, also comes the idea of what they are to define to allow a proper exchange of information. Developing standards is basic in order to make the most of the building information modeling tools as well as other model based engineering techniques. With this objective in mind, the conducted research started to look into the development of IFC standards for Aerospace in general and space architecture in particular. This is an ongoing task currently. "**Industrial Foundation Class (IFC) Standard"**[7] is a neutral and open specification to transfer and share information. This is implemented by using object-based file formats that present data model. This is an effort independent from any private company or software vendor that has been developed by building SMART International Alliance. The objective is to improve and facilitate the exchange of information between disciplines in architecture and engineering. Building Information Models can use this format and therefore could potentially lead to a set of standards also within the aerospace sector. The following are representing just a few of the proposed fields, relevant to space architecture projects that have been considered within this investigation:

Structure (IfcSAS)

- Mass
- Loads
  - *Launch / Flight / Reentry*
    - *Tensial (Axial)*
    - *Compressive (Axial)*
    - *Shear stress*
    - *Momemtum*
    - *Torque*
    - *Pressure Load*
    - *Ultimate load load – Crash*
    - *Ground Integration Load*
    - *Pressure Load – Launch*
    - *Pressure Load – Flight*
- Fatigue
- Impact resistance
- Damage tolerance
- Mechanical Stiffness

Environment (IfcSAE)

- Radiation Hardness (Shielding)
- Radiation behavior
- Thermal expansion
- Thermal shrink
- Thermal load
- Thermal shock resistance
- Creep
- Atox Reaction
- Degradation
- Corrosion
- Micrometeoroid shielding/tolerance
- Dust particles Resistance
- Vacuum behavior

Interior Architecture (IfcSAIA)

- Type

* Subsystem

Material (IfcSAM)

* Material
* Composite
* Conductivity
* Material outgassing
* Fire resistance rating
* Thermal resistance
* Material elasticity

Dimensions (IfcSADim)

* Volume
  * *Stowed*
  * *Deployed*
* Dimension
  * *Stowed: X, Y, Z*
  * *Deployed: X, Y, Z*

Human Factors (IfcSAHf)

* Human Rated
* Habitability
* Accessibility

Systems (IfcSASys)

* Type
* Subsystem
* Components
* Category
* Power
  * *Generated*
  * *Consumed*
  * *Stored*
* TRL
* Interface
* Connection type
* Conducts

Table 1: example database values

Concept	IFC SA Name	Prefix	Name	Suffix	IFC Value	Type of Value	Min	Max	Default Value	Units	Comments
General (IfcSA)											
Mass	IfcSASMass	S	Mass		IfcMassMeasure	Decimal	0	1000	0.0	Kg	

V. International Space Station (ISS) Derived module: VSC Example

D. Description

The following example presents a derived Multi-Purpose Logistics Module (MPLM) module[6] from the International Space Station (ISS) developed using a Virtual Space Construction approach (BIM-SysML-CAM). This hardware is not real flight hardware but follows many of the design principles required for a space habitat. For the design of the VSC model part of the following systems and components have been designed and implemented:

- Volumes and areas (Architecture)
- Air flow and management
- Electrical
- Mechanical (nonstructural)
- Structure
- Control and managing devices

Requirements:

- Customized IFC parameters[7] for space habitats
- Human factors considerations
- Real ISS measurements
- Random access frameworks for storage and internal space organization.

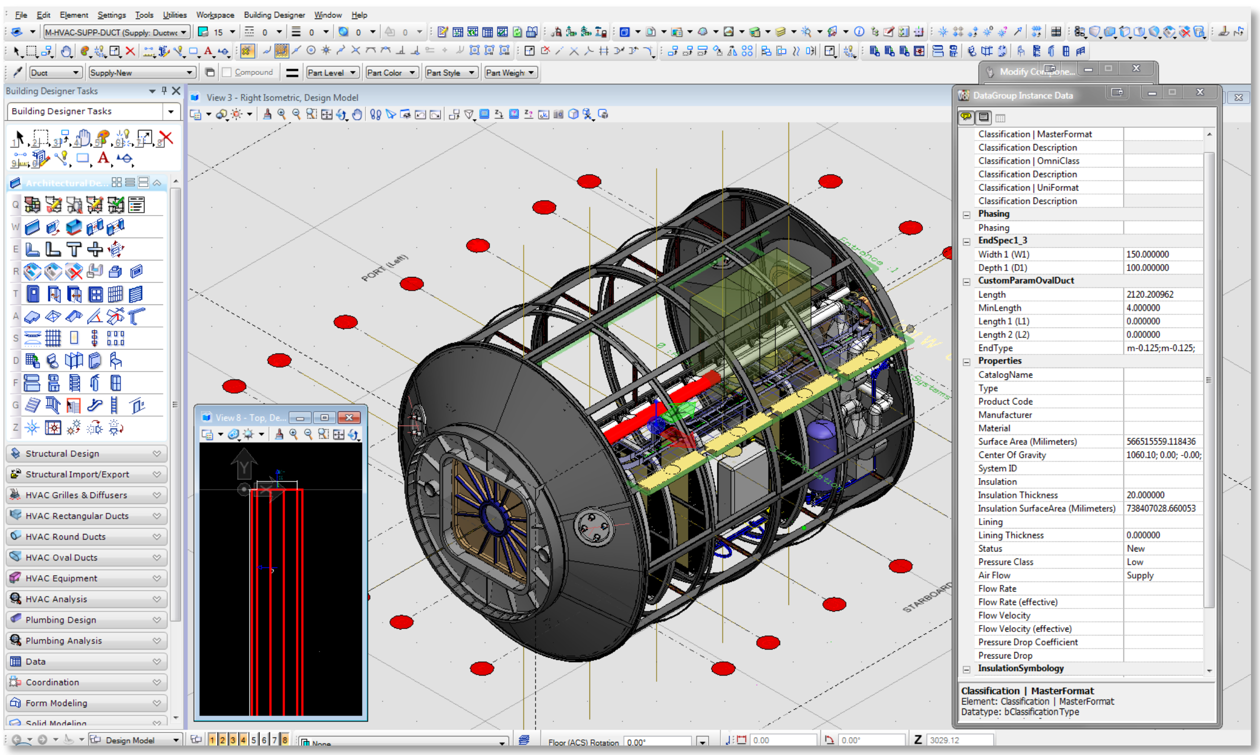

Figure 7. Derived ISS module using BIM in Bentley AECOSim.

E. Workflow

To illustrate the workflow of information as describe in Figure 5, the following snapshots will show some key points in the design process.

First of all a technical box with X, Y and Z dimensions and a set of specific parameters (Power, Radiation Hardness and material) is determined using a SysML model (Figure 8, Figure 9). At this point setting requirements is as easy as changing the value of those parameters. Then that information is exported to an excel spreadsheet (Figure 10) acting as database. This database manages the flow of information and history tracking. From the database the BIM software reads the value of parameters. The Generative components module (Figure 11) of

Bentley AECOSim BIM authoring software allows not only using the value of the parameters to change the dimension and data of the technical box but also to modify those parameters interactively. If the yellow points are brought together, the dimension will change responding to the drags in the technical box (Figure 11, right side) and the values in the database will also change. If from the requirements standpoint some specific values are determined but the design process needs changes, this information will be updated and then infused again to SysML. This way a bidirectional connection between the SysML model and the BIM component has been established from using direct data input or graphic modeling input.

Once a component is completed following this approach, it is integrated in a linked BIM model (Figure 12). For this case Bentley AECOSim has been selected as the software for the task, but the BIM model can of course be modified using competitor BIM software. Once all the components are integrated either by importing CAD components, BIM components or directly developed in the BIM software, there are several functions that can be done:

- Space planning (Figure 12)
- Populate each component with customized information (Figure 13)
- Structural component design and automatic MELs (Figure 14)
- Architectural parametric components design
- Integration of different parametric systems (Figure 15)
    - *Structural*
    - *Mechanical:*
        - *Water*
        - *Ventilation*
    - *Electrical system (not shown in this paper but developed as well)*
- Clash programmable detection (Figure 16)
- Document generation, visualization and templates (Figure 17)

Besides the BIM model this workflow for a complete virtual construction process also shares information with CAM software like Solidworks (Figure 18) and imports CAD models without parameters from other environments like Autocad (Figure 19). Since the geometry of the elements is known as well as the parameters that specify the values for the parametric features this information can be shared with other types of software. For instance recreating the random access framework in a solidworks environment we can also include loads and test vibration, stress, etc. This way test can validate the design and provide feedback into the database. This can also be achieve using energy simulators to see the flow of energy for different geometries and materials (Figure 20)

On this paper only specific parts of the model are shown and presented however the steps described applied to any other type of components design with the same workflow.

The linked model described (Figure 6) is has been developed using the following software:

- MBSE: No Magic SysMl and Paramagic plugin
- BIM: Bentley AECOSim
- CAD: Autodesk Autocad
- CAM: Dassault Systems Solidworks
- Simulation: Bentley Energy Simulator

1. SysML

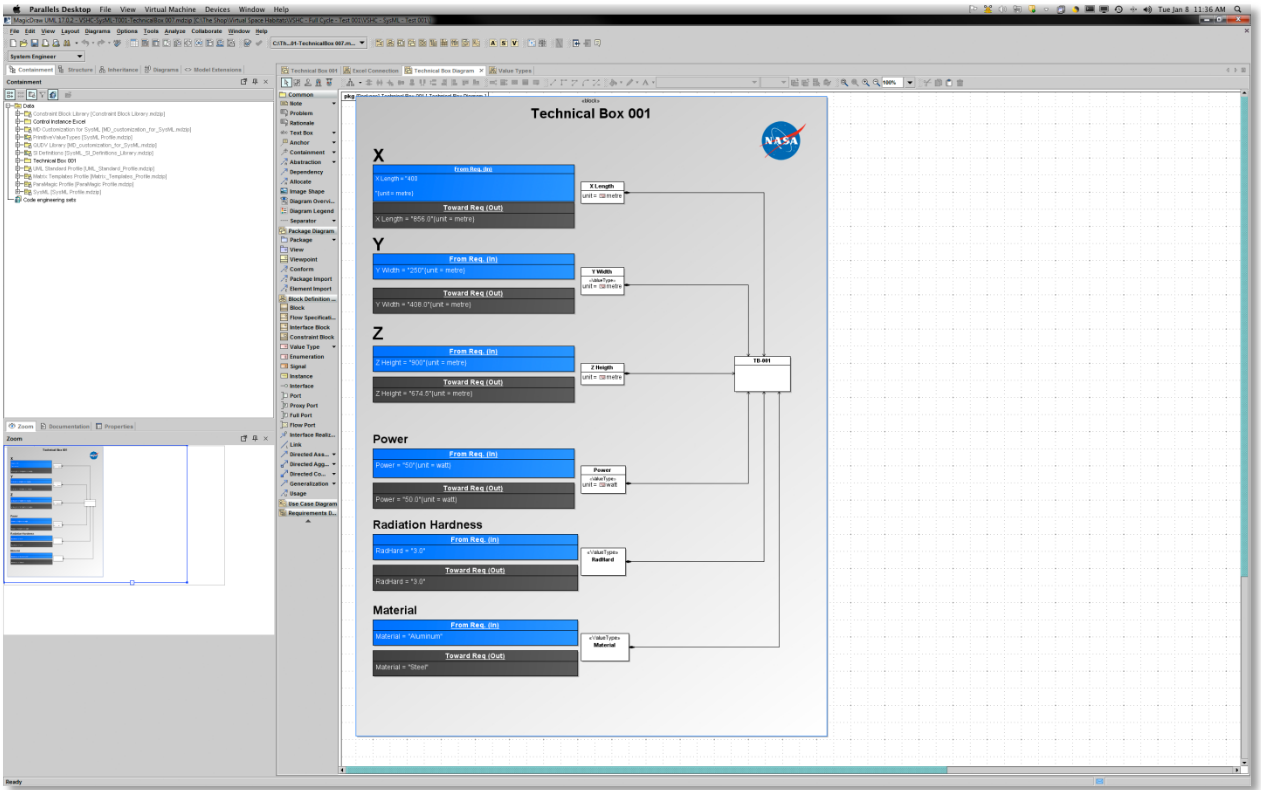

Figure 8: SysML Model for a technical box with some custom parameters

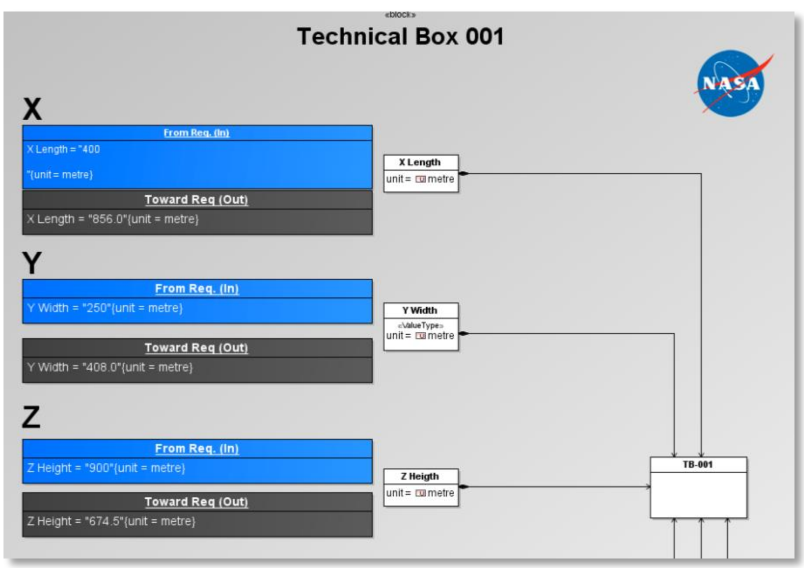

Figure 9: close-up view of the SysML parameters

2. *Data Base*

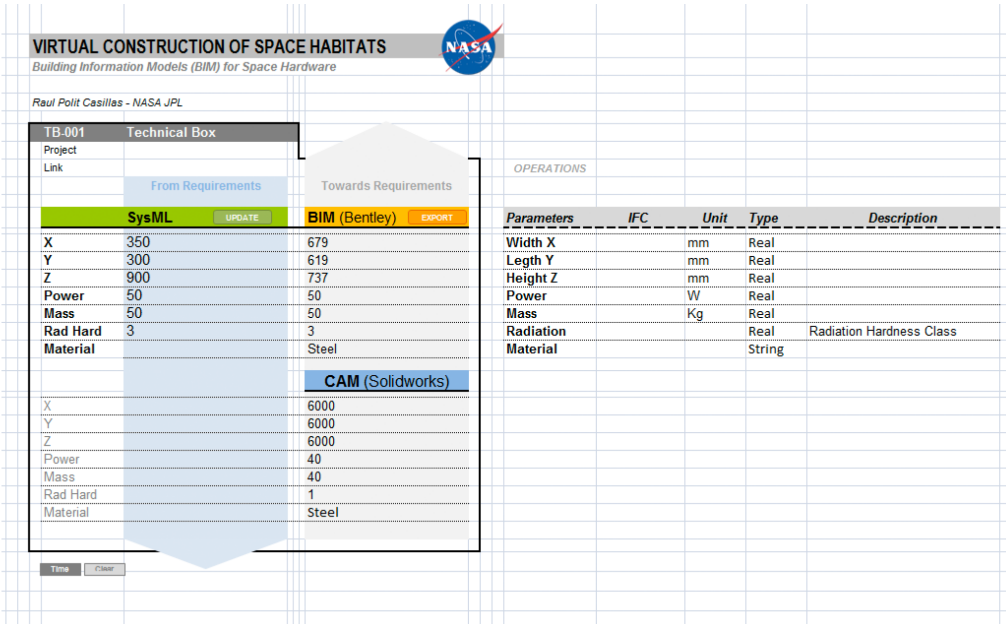

Figure 10. Excel Spreadsheet acting as a middle man database.

3. Generative Components - BIM

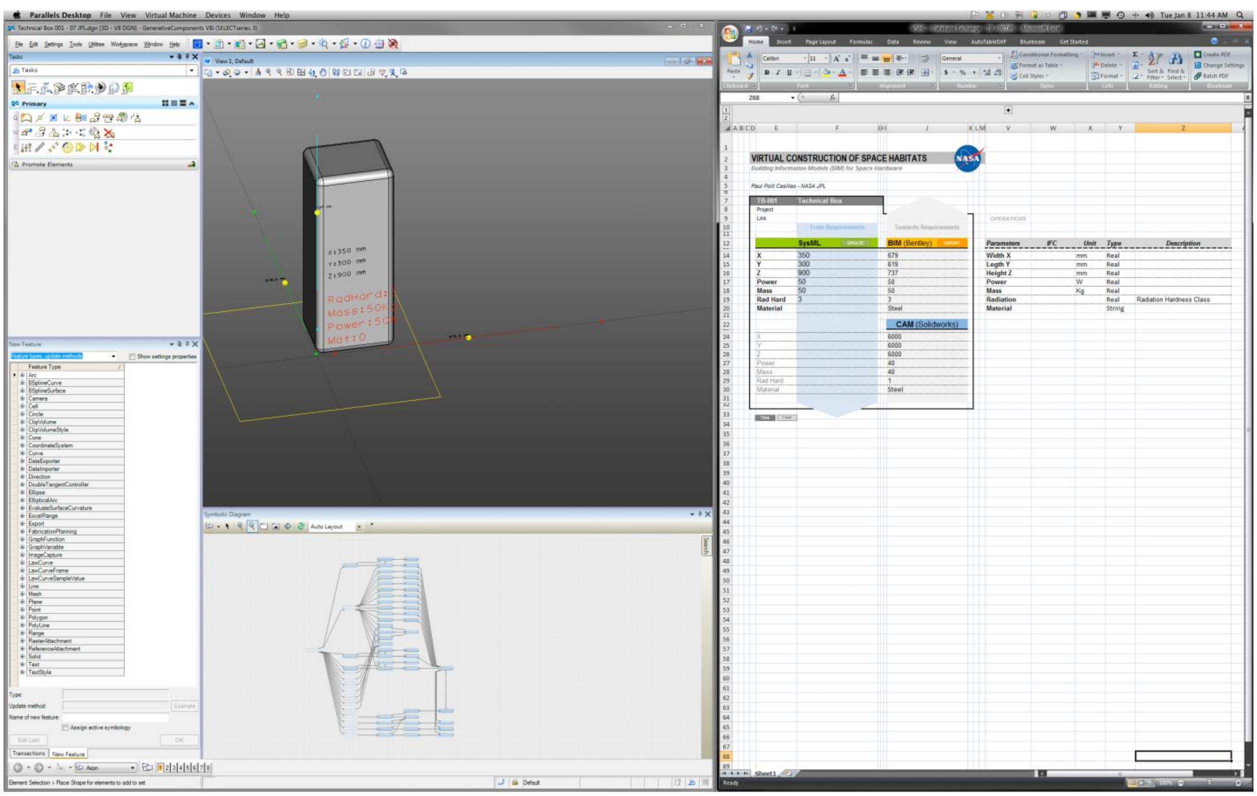

Figure 11. Left: Generative Components BIM model. Right: Spreadsheet updating values automatically.

5. *BIM Full Model*

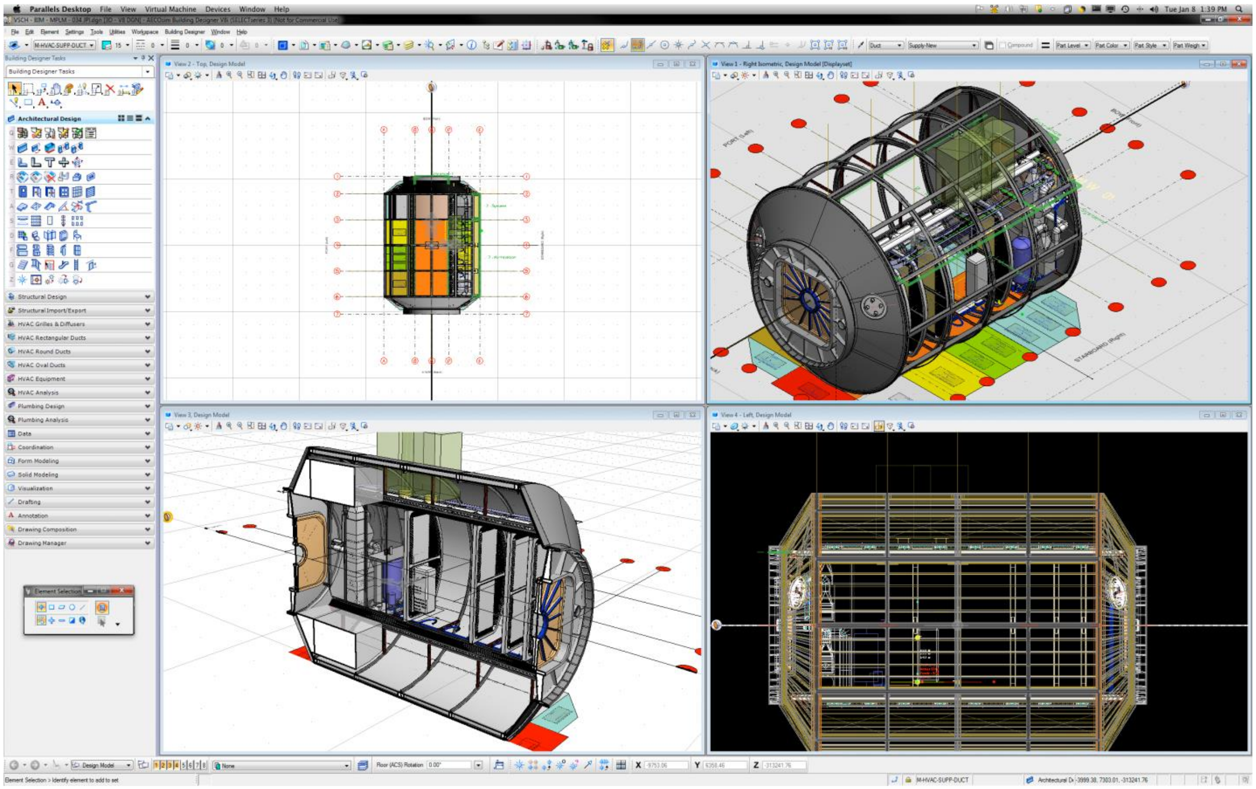

Figure 12. Full model of the ISS Derived MPLM Module using BIM.

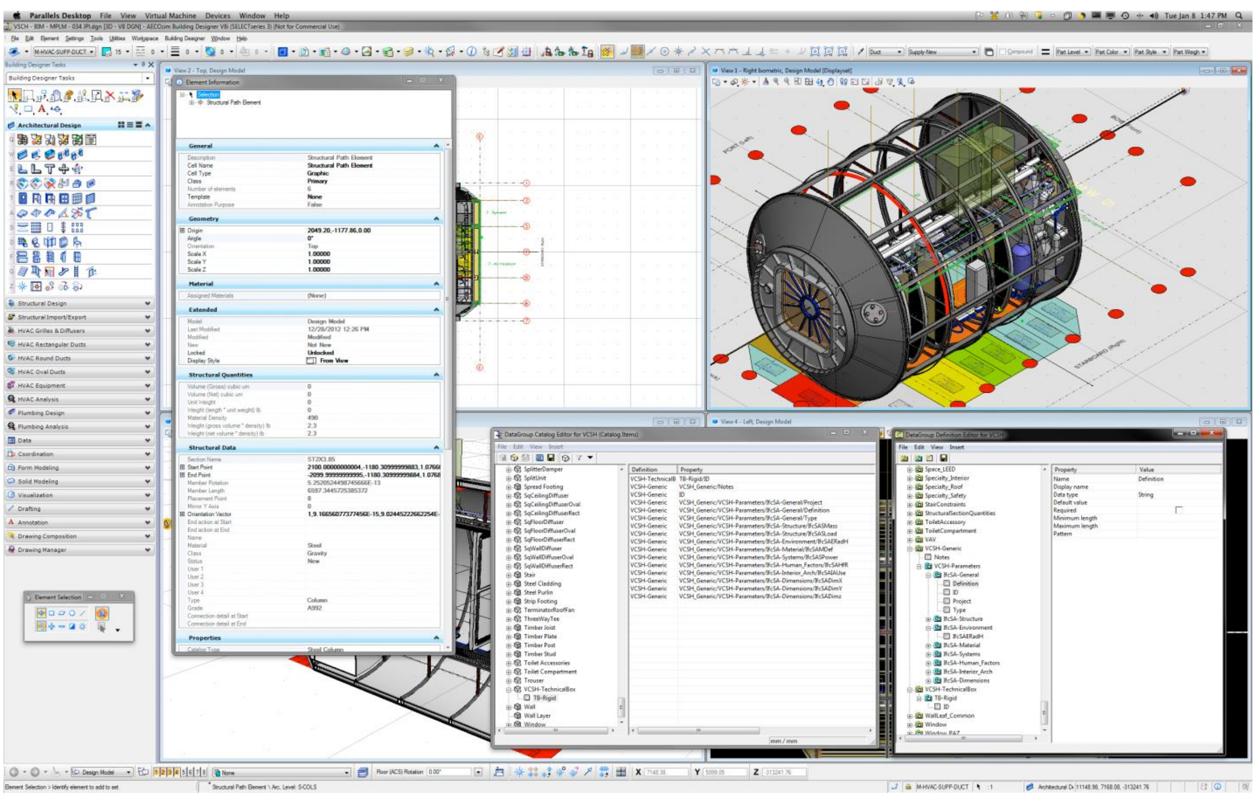

Figure 13. Custom IFC values for some of the BIM components.

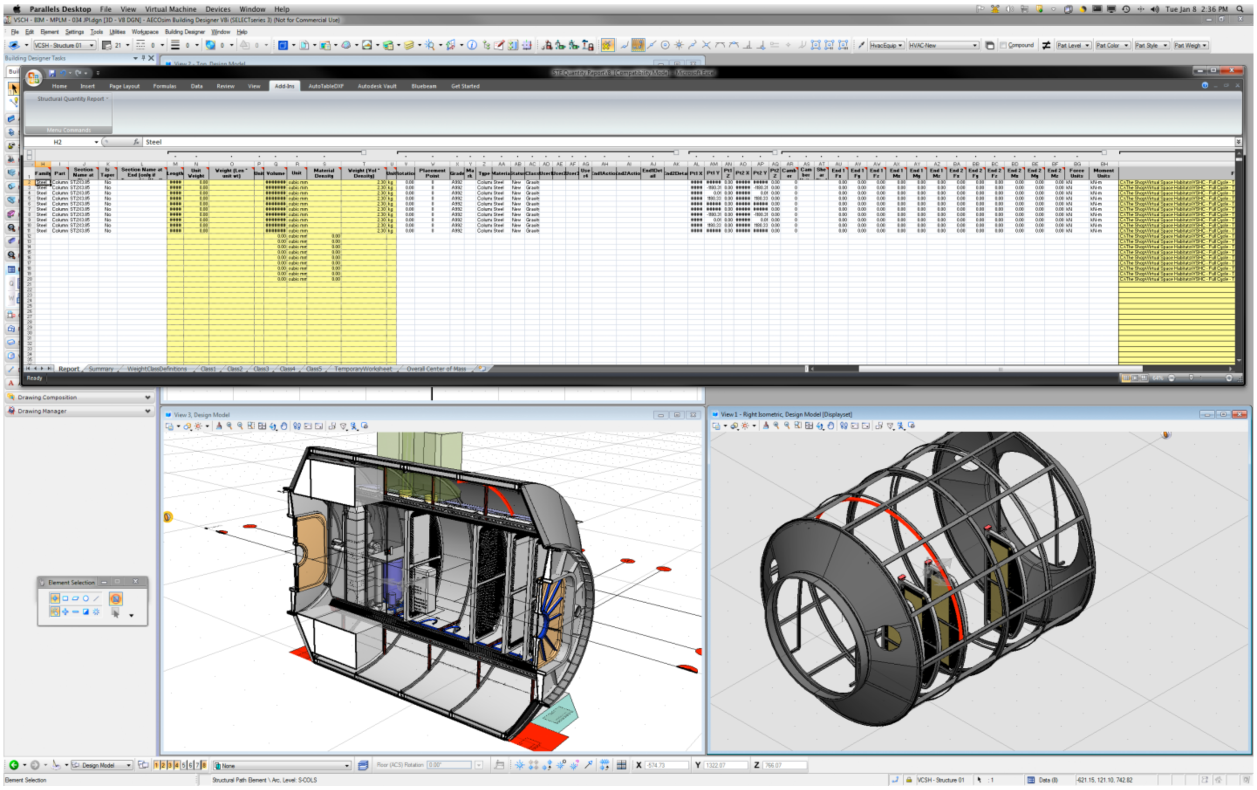

Figure 14. Structural MEL in excel automatically created from the BIM model.

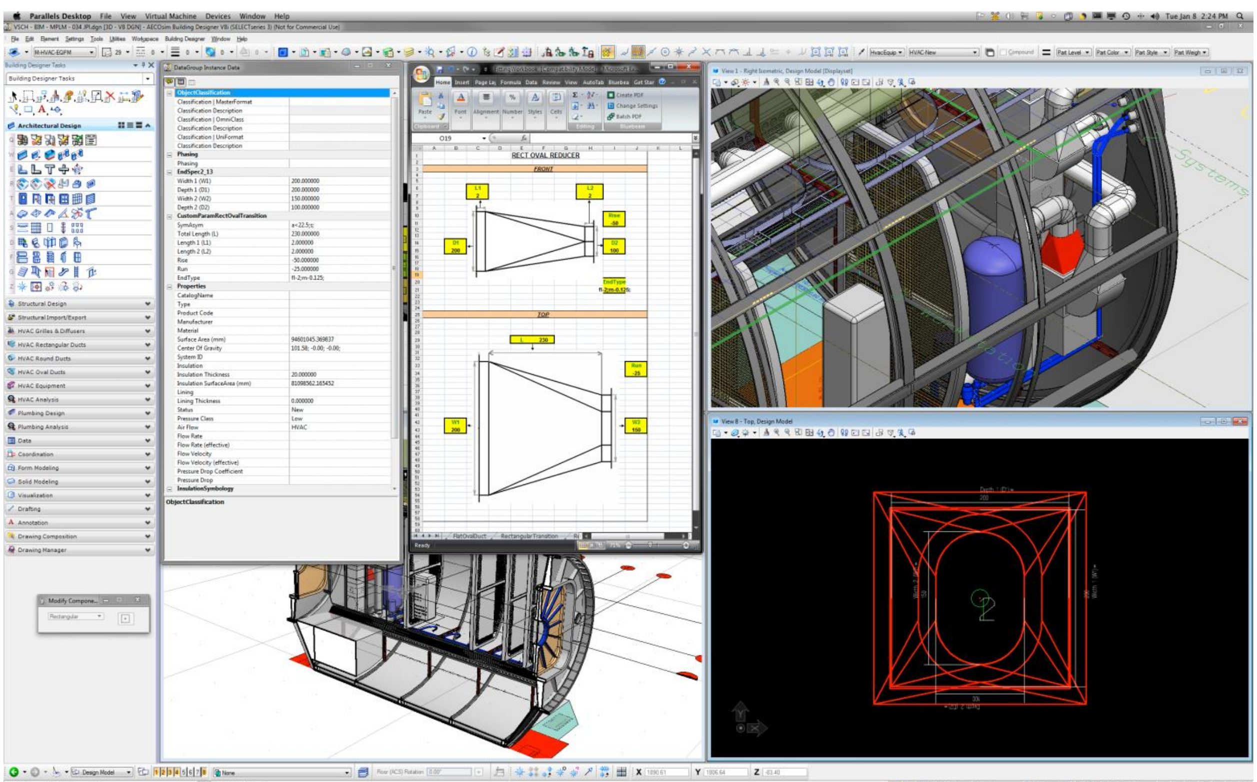

Figure 15. Component can be modified using linked excel spreadsheets generated by the software.

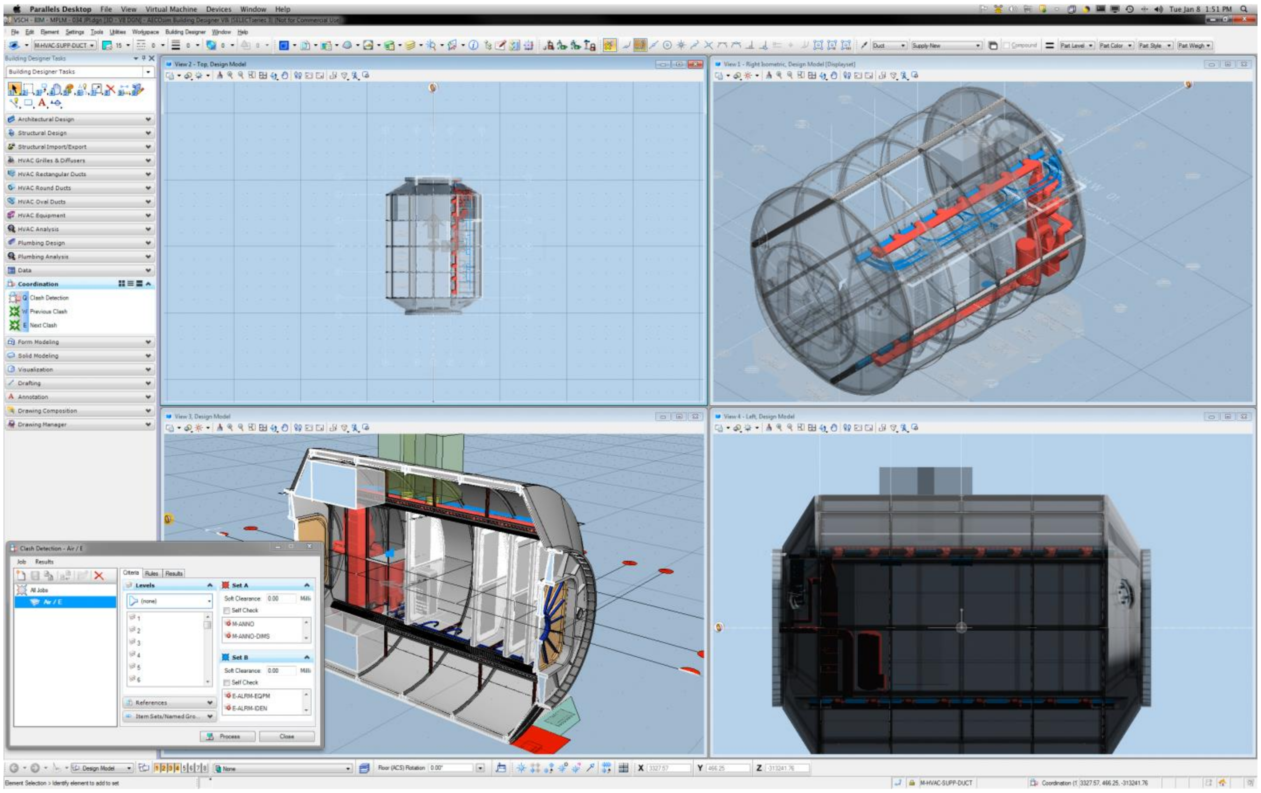

Figure 16. Clash detection between ventilation and electrical system.

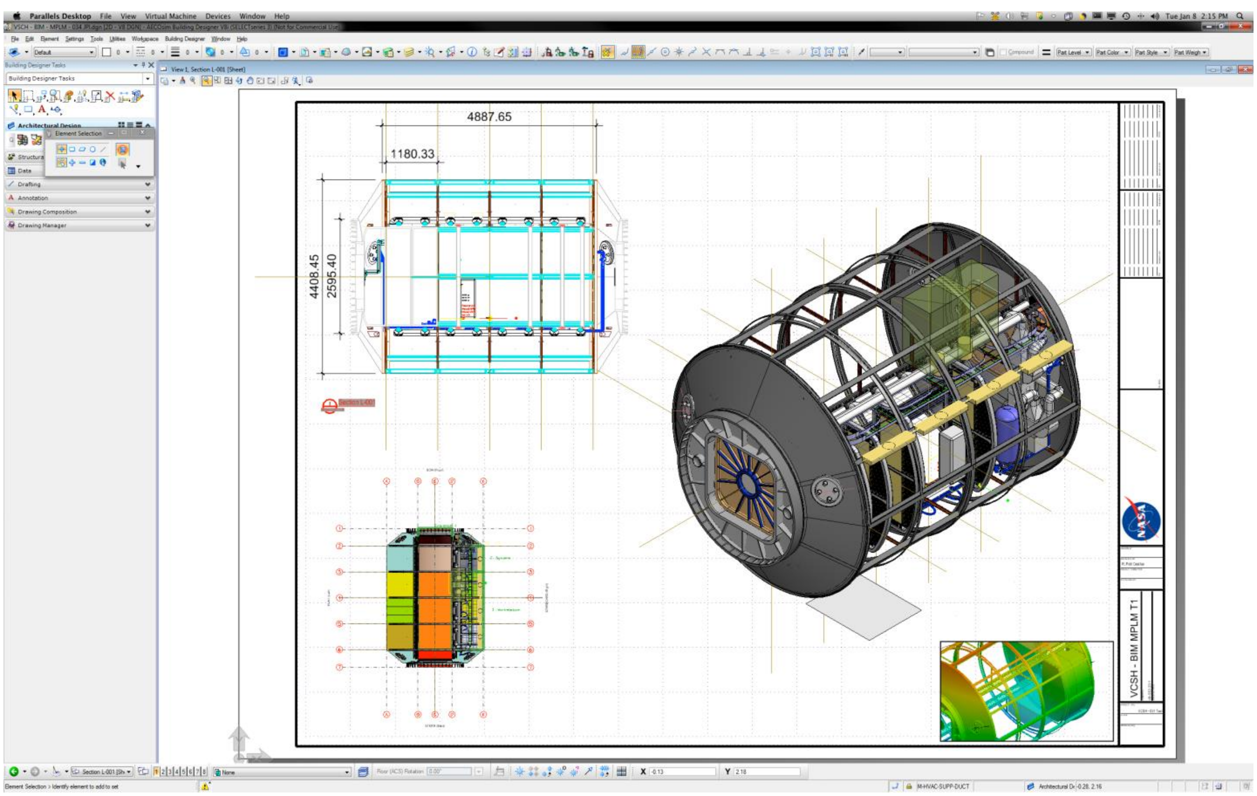

Figure 17. Generation of documents from the BIM model integrating different sources of information.

7. CAM/CAD

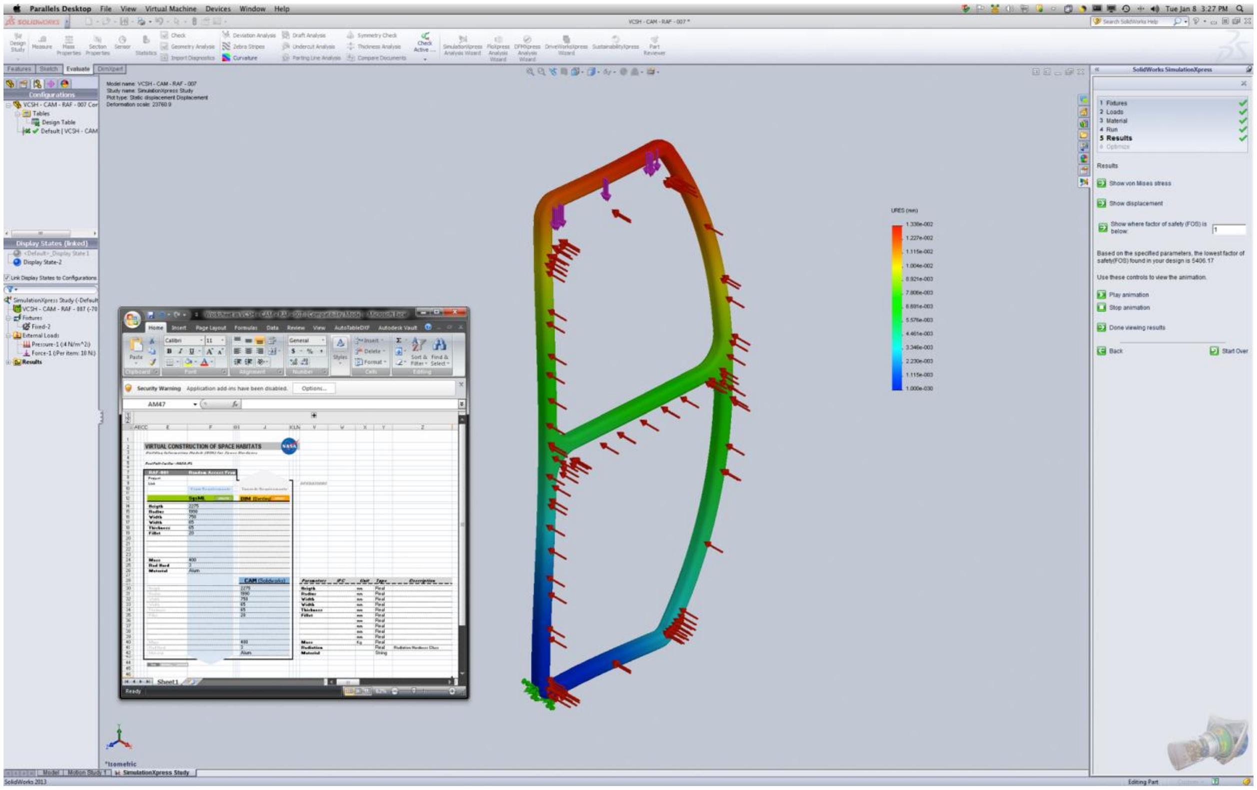

Figure 18. CAM model in Solidworks of one of the BIM components and stress analysis of it.

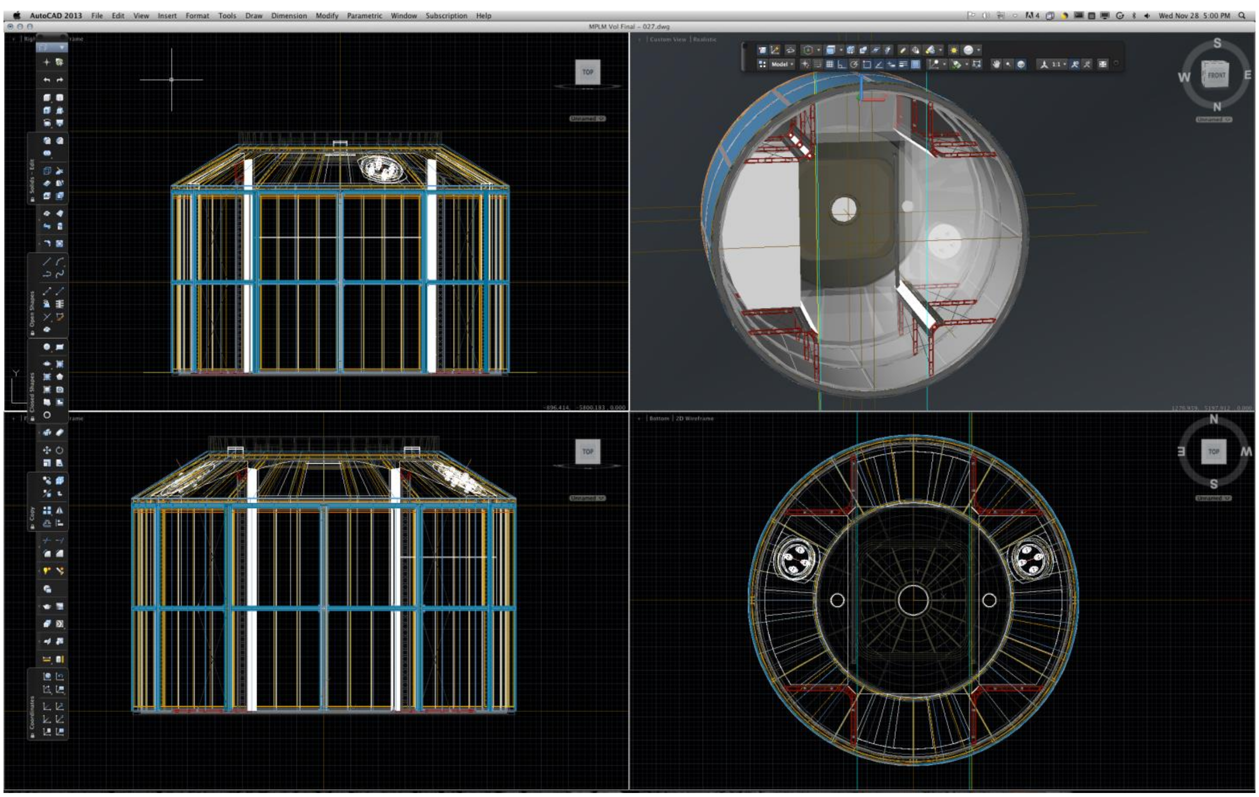

Figure 19. Imported CAD model from Autocad into BIM.

8. Energy Simulation

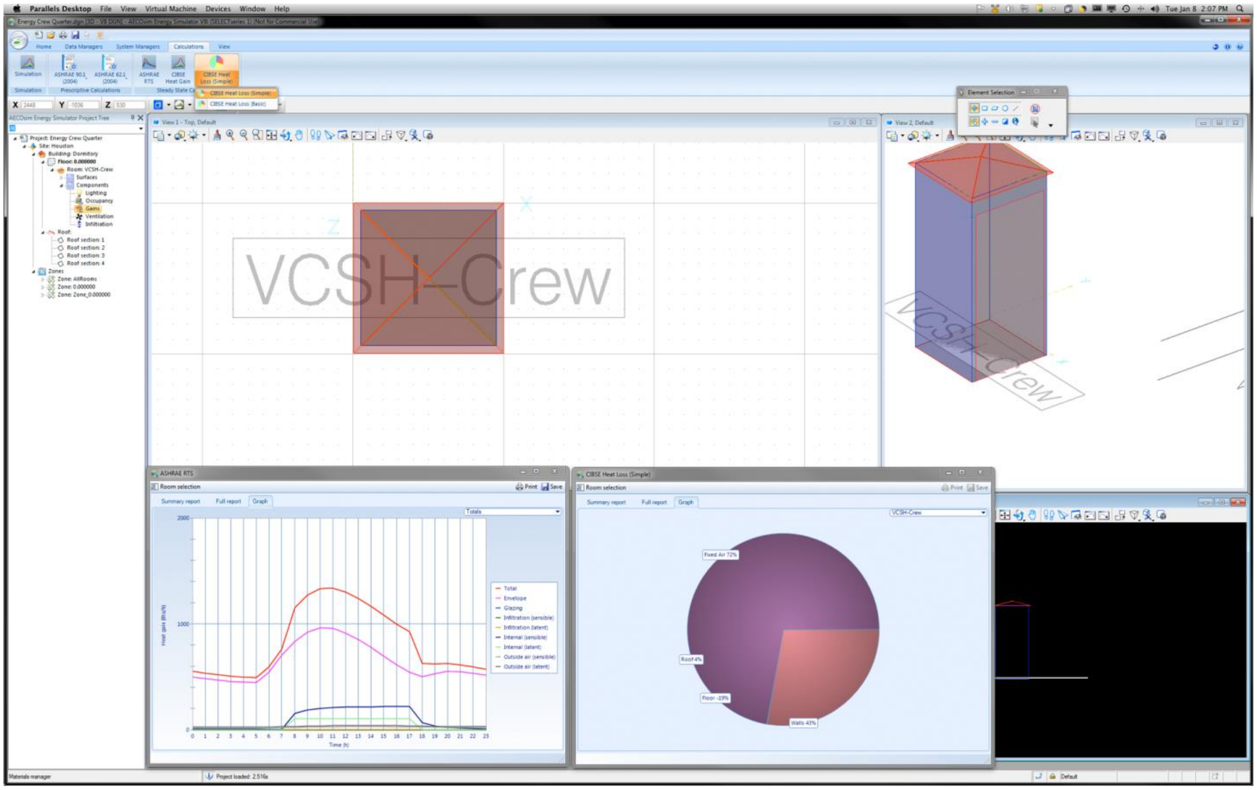

Figure 20. Bentley Energy simulation model for the volume of a single crew cabin.

VI. Conclusion

This study shows that a two-way connection between SysMl and CAD models can be done through BIM, and even more this cycle could include the flow of information between other types of software like CAM, CAE or simulation software. This part of the current ongoing work has great potential to change the way we think and design space habitats as well as other complex systems in aerospace. As a summary this are the benefits of the approach developed by the authors:

- Capability to create smart and complete models very quickly, regardless of the scope
- Integration of many disciplines (mechanical, electrical, architecture, structural, etc.) within the same model
- Reinforce more extensive management
- Possibility to develop virtual models with physical parameters
- Collaborative and concurrent
- Database survival: no need of different versions, etc.
- Complete workflow SysML/CAD/CAM/BIM/Simulation linking all the parts
- Recycling work (modular): the more modeling done the better reusable database becomes available
- It uses a proven expertise in the field of complex architecture
- Potential strong link between requirements (SysML) and design software (following industry trends)
- More affordable and complex studies can be completed faster
- Unprecedented fast early formulation design beyond sketches
- Fosters Innovation

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