Space Vehicle-Building Design Process Issues and Models. A framework

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Abstract: Human-crewed Space missions have had a renewed interest in recent years related to long-term strategies for humankind's sustainability. It involves avantgarde scientific fields and deals with the vital problems of shielding astronauts from the hostile extra-terrestrial environment as well as to provide them comfort in order to guarantee an acceptable life quality during the Space missions. Due to these peculiarities, all extra-terrestrial dwellings are characterised by high level of technologies, punctual controls and constant maintenances. Moreover, Spacecrafts are not fully considered as "buildings" despite the crews' long permanence and activities inside them. So far, the stringent conditions have required that their design and construction process must be tackled by mechanical and aerospace industries. From the perspective of long period missions, it is necessary to involve architects and building experts in order to enhance the user experience through the definition of more habitability and liveability requirements in Spacecrafts. This research wants to involve the participation of architects and building experts during the design process of a Space Vehicle-Building (SVB) by detecting a framework for Space architecture and construction Design Processes.

Keywords: Space architecture; Building Information modelling; design and construction process.

1. Space Favourable Times

This paper aims to propose a framework for the *design and construction process* of dwellings for human activities in an extra-terrestrial environment. In the perspective of long period missions, it is fundamental to consider the dualism of those particular dwellings, which are both vehicles and buildings and therefore extend the concept of 'building' to manned Space vehicles: the Space Vehicle-Buildings.

Recently, there has been a favourable momentum for space missions, and the theme has gained hype on media as well as it has been financed by factories and private firms. The main Space agencies from all over the world have forecasted the extension of the human presence from low-Earth orbit to the Moon, Mars and deeper Space destinations as a long-term goal and set it as a strategic plan for the next generations (Schaffer, 2008). According to planned missions to the *red planet*, the duration of the journey has been estimated 180 days each way together with 60 days of *in loco* mission (Baldelli et al., 2016). Astronauts are going to spend almost all the time on space vehicles and that is the reason why spacecrafts should provide an effective journey at no expense of the physical and psychological wellness

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of the crews that eventually leads to the success of the mission (Martinez, 2007). As a key issue of this challenge, it is important to take carefully into consideration the human living requirements in an extra-terrestrial environment.

Since 70's Spacecrafts have been considered as new typology of habitation for astronauts. The architecture of dwelling for humans in low-orbit or in general extra-terrestrial environments, has been defined by Harrison (2010) as "the theory and practice of design and building environment for humans in outer Space". At the same time, Häuplik-Meusburger and Bannova in "Space Architecture and Habitability: an asset in Aerospace Engineering and Architectural Curricula" (2016) have highlighted the role of Architects and Building Experts during the design process of Space architecture. Simultaneously, the *process* of designing and constructing Space architectures has to manage a higher level of complexity so consequently more efficient processes have to be applied.

This paper focuses on manned Space Vehicle-Building – from now on SVBs – which allow crews to stay a long period in the orbit, like the International Space Station, or Space vehicles used for reaching far destinations (Figure 1).

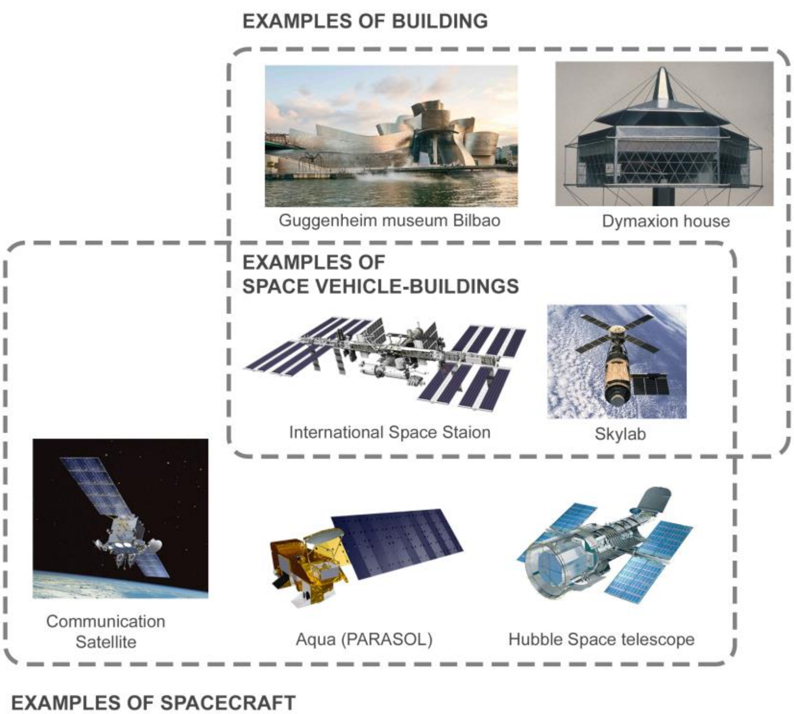

Figure 1 : Examples of Space Vehicle-Building – SVB.

SVBs are very complex engineering systems that deals with many scientific disciplines (Won et al., 2001). Their design, construction and development must consider the dual characteristic of being a vehicle and a building at the same time. The design and building processes of SVBs should therefore take into account not only this dualism, but all disciplines equally important; so to be effective it is needed a synergic collaboration between Architects, Engineers, Health experts and so on. For this reason, the design process should consider problems of coordination between specialists in a *Collaborative* design paradigms (Gianfranco Carrara. et al., 1997; Gianfranco Carrara and Fioravanti, 2002).

To work on an enterprise as such it needs a great effort in coordination, especially when the project is progressively defined, under unexpected and unavoidable changes. As a matter of fact, in advanced, intertwined and ever-changing fields from components, technologies, economic factors, changes are normal conditions (Moayeri et al., 2017). In fact, the key factor of project delays, loss of its quality and arising costs in both Aerospace and AECO sectors is represented by unsuitable management, shortcomings and conflicts among involved actors (Penttilä, 2009; Xu et al., 2013).

According to above cited literature, it is vital to individuate an efficient collaboration strategy between involved disciplines. Further, a common platform of data exchange among actors is needed.

Moreover, the present methodology wants to propose an alternative design process which should enable designers to take advantage of BIM capabilities based on knowledge. Therefore, the BIM methodology needs to be extended to a wider field, introducing "Space Vehicle-Building Modelling (SVBM)".

2. SVB specifications

As mentioned before, although many spacecrafts can be considered as a dwelling due to the presence of astronauts for a long time period, it is also a vehicle that performs transportation functions. The Fig. 1 shows examples of buildings, spacecrafts and then SVBs. It is important hence to make many important considerations in order to identify and analyse those dissimilarities.

1. SVBs deal with objects which are endowed with a propulsion system that allows them to move from one point to their destination or maintain a certain position in an orbit. This is a fundamental difference from an ordinary building, and it induces to inquire about the stability of a vehicular-building during its movement. It is necessary therefore to simulate and analyse the whole entity under mechanical efforts and dynamic studies.
2. SVBs could be isolated systems that need to keep their tightness from their surrounding environment. Special equipment, like air and water recycling units, temperature and humidity controls, biological waste collections, must be integrated during the design and construction phase while they must be constantly monitored in their uses.
3. SVBs have to be built with modern and innovative construction methodologies. They must assure many performance requirements which are hard-to-reach using traditional technologies and construction methods. Materials like bricks or concrete have not been considered yet due their unit weight and/or their technical performances like isolation capacity.
4. Raw materials are difficult to be provided and take their time to be delivered. Sustainability principles in Space Vehicle-Buildings are therefore essential and must be taken into consideration. Renewable energy sources like the solar one must be part of the whole building system.
5. Due to cargo restrictions and/or less weight efforts, Space Vehicle-Buildings often deal with limited habitable volume which is defined as "the free space that one can maneuver around within a spacecraft. This excludes any volume occupied by equipment" (Porter & Bradley, 2016). Together with the point 2, space limitation and its closure are key factors that determinate an Isolated and Confined Environment (ICE) which compromises a dwelling's liveability performance (Häuplik-Meusburger, S. et al. 2017).
6. SVBs that leave the Earth's atmosphere are subjected to zero or microgravity condition. This means that there could not be a reference plane which is commonly defined "floor one". Since in

zero gravity environment it is possible to move among all x, y and z directions, each surface could be used.

7. In order to face up the particular and lethal environment in outer Space, it is necessary to provide dedicated shelters. As a matter of fact, outer Space is featured by radiation exposure and possible collision of meteorites.

By defining those dissimilarities of a Space-Vehicle Buildings from terrestrial ones, it is possible to have a better comprehension of these objects. Furthermore, these features contribute to delineate the field of investigation for Space Architecture.

3. State of the art

In Aerospace and Mechanical Industries, the design framework is mostly supported by the software CATIA, developed by Dassault Systèmes which allows to cover the entire process life cycle of the project (Daneshjo et al., 2012). It was born as a CAD based platform with considerable experience in simulations, then moved to a more mature mechanical information system that was integrated with Computer Aided Engineering (CAE) and Computer Aided Manufacturing (CAM) systems (Naprstkova, 2011). Furthermore, it was endowed with several sets of human ergonomic models which can simulate an optimal utilization of the design (Yogasara, 1999).

Afterwards the CATIA, Gehry and Partners pioneered its use in architecture and eventually has been exploited in AEC field by Gehry Technologies, founded in 1990s. The developed software 'Digital Project', allows an accurate control of complex projects and makes possible a considerable effort/cost reduction of the design process (Shelden, 2002). An outstanding example has been the Walt Disney Hall in Los Angeles where by means of the design process the curved façade skin have been approximated by large flat tiles 50%, simple curved ones 45% and double curved ones 5% (Dillet, 1994) that led to a considerable cost reduction. In the perspective to provide a valid design support to all building, BIM methodology implementation has been adopted by 'Digital Project' (Gehry et al., 2020).

As a matter of fact, the increasing performances required in contemporary AECO industries make buildings become more and more complex systems. For this reason, the BIM methodology has gained momentum inasmuch it allows "the generation and management of digital representation of physical and functional characteristic of a facility" (BuildingSmartAlliance, 2015). Moreover, the requirements from AECO sector pushed forward the development of BIM methodology which is able to manage the 5^{th} (costs) and 6^{th} (energy and sustainability) 'dimension' (Charef et al., 2018).

Aziz et al. (2016) have suggested the benefits of applying BIM methodology to Facility Management (FM), which are: effective operational costs, shorter times for decision making, more resources for decision making, better documentations, collaboration and work flexibilities, clash detections and updated information .

The managing of these characteristics and functions are vital in a complex system like Spacecrafts (Won et al., 2001), and in particular in a SVBs, which involves even more professions. So far, the strategy of managing different disciplines that deal with processes, models and tools to handle complex engineering projects is called System Engineering (Guo, 2010).

In particular, Polit-Casillas and Hove (2013) from Jet Propulsion Laboratory of California Institute of Technology, have experimented the application of BIM methodology together with the Systems Engineering Language (SysML) for a virtual Construction of Space Habitats. The authors have defined the Virtual Space Construction Process (VSC) which is a specific BIM based approach for aerospace design workflow (Figure2). It is possible, therefore, a bi-directional connection between complex-relationships management based on system engineering language like SysML and CAD models through BIM environment. The researchers have then reported the modelling process and many technical simulations of Multi-Purpose Logistics Module (MPLM) from the International Space Station (ISS) using the VSC approach.

The mentioned evidences show that BIM methodology is a promising methodology during the design process for complex buildings. Together with other benefits from application of this methodology, BIM should be considered as a valid, although limited, *design* support of Spacecraft dwelling and it should be adopted in Space architecture.

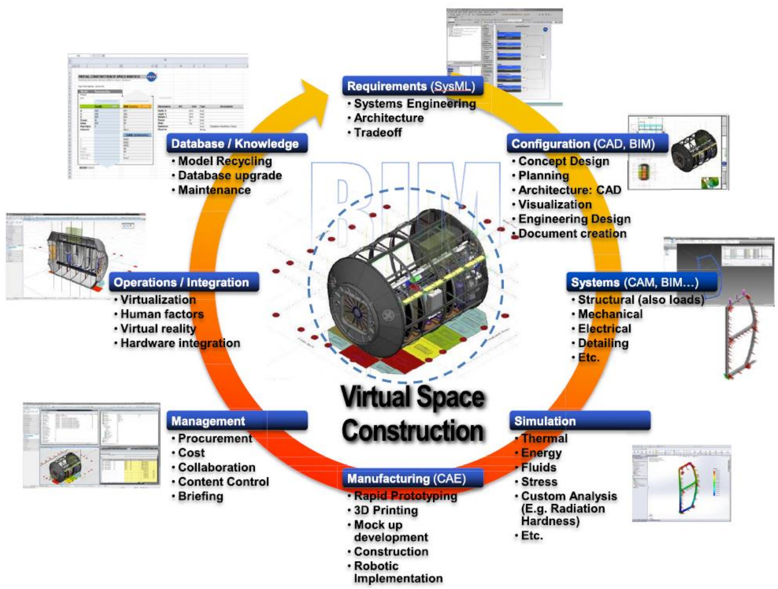

Figure 2: Lifecycle of aerospace hardware development according to VSCP (Virtual Space Construction Process), Polit-Casillas and Howe, 2013

Nevertheless, there are strong differences between a terrestrial building and a Spacecraft. Considering those dissimilarities and recognizing the livability and habitation issues are essential requirements of a manned Space vehicle, this paper is going to introduce a framework for Space architecture: The Space Vehicle-Building Modelling, SVBM.

4. Proposed model

4.1. Involvement of Architecture and Building experts in Space Architecture

The application of concepts of Knowledge, Semantics and Ontologies is vital in the design and construction process of a *Collaborative design* (Carrara and Fioravanti, 2009), which is strongly required in Space Architecture. This is the reason why the proposed model wants to extend the BIM methodology, which is a well-known design strategy among AEC industries, for SVBs. The dissimilarities from ordinary buildings, reported in the above paragraph, must be considered during the design and construction process and so does in the proposed methodology, which becomes “Space Vehicle-Building Modelling”, SVBM.

SVBM must be able to communicate with Aerospace and Mechanical knowledge and, at the same time, enable the management of habitability and liveability requirements by Architecture and Building experts. To facilitate the communication, a common data exchange format is needed.

The Figure 3 shows the data-exchange flow between operators, which are represented by the Aerospace and Mechanical industries, the Architecture and Building experts and the Manufactures, can be supported by Industry Foundation Classes (IFC) format (“View and Convert 3D CAD files”).

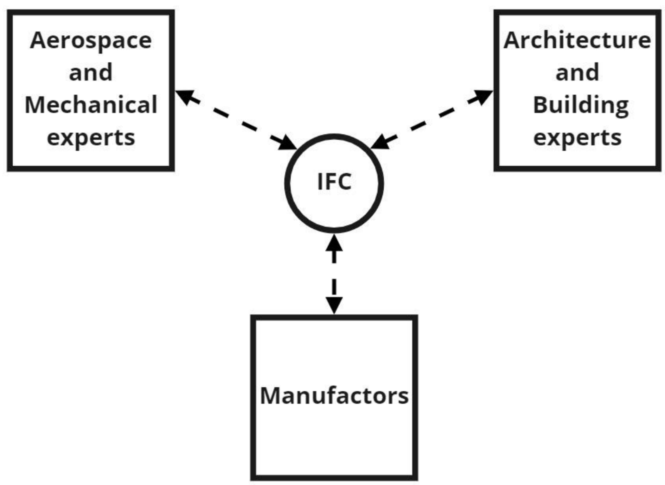

Figure 3: Communication between operators

4.2. Role of SVBM

It is a common agreement about benefits of using a BIM methodology in the AEC industry where data can be queried during a building’s whole life cycle by involved actors. The interoperability capability at data level of this methodology allows experts from different disciplines to manage the same building objects, to improve dialogues among them and to speed up the decision-making process. Thus, the proposed framework wants to take advantage of those benefits during the design and construction process of SVBs.

In the *design phase*, a common platform of SVBM methodology should be based on Knowledge, making the interdisciplinary collaboration easier, reducing the incongruence and facilitating the multidisciplinary collaboration (Fioravanti, 2006). The benefits can be the reduction of time and effort during the design phase as well as the raise of quality of the project. Moreover, the knowledge-based platform, together with concepts of *Agents*, will enhance the level of accuracy of performance simulations, allowing a more realistic testing result (Simeone et al., 2013). In the second place, the enhancement of collaboration between all involved disciplines can speed up the processes as well as economic benefits in design investments.

During the *construction phase* the SVBM should represents a dynamic and interactive model allowing a more accurate realization, coordinate the time schedule and reduce the construction cost. (Chen & Luo, 2014).

There can be several applications of SVBM during the *operation* phase. For instance, it can enable interactive data storage and visualization, trough incessant data updating by users and/or devices allowing an efficacy facility management. In Space Architecture, which is featured by extreme conditions, it could be vital making the dwellings able to interact with its users, environmental conditions and the maintenance survey. This implementation has already been used in building exploiting data input through sensors, algorithms as “black-box” that elaborates data and then actuators as output (Trento et al., 2019).

4.3. SVBM conceptual framework

The Figure 4 shows the conceptual framework of SVBM during its lifecycle.

The Knowledge from specific disciplines constitutes the base for definition of requirements, which by means of synthesis and performance simulations, reaches the modelling of the final elaboration of entities. A SVBM should therefore be a composition of ontologies and semantics that expresses the meaning of instances.

The SVBM should provide a dynamic and interactive data visualization and extrapolation of objects. Inasmuch it is endowed with Knowledge, this methodology should behave like an intelligent database allowing users to simulating and obtain needed information during the design, construction and utilization phase.

A SVBM model needs to be continuously updated in every phase of its life cycle. All changes during the design phase, variations during the construction, and data gathering during the utilization should be recorded.

The enhancement of the SVBM model may contribute to reach Knowledge achievement. The data gathering during the life cycle, including the design strategies, construction technologies, functional usages and members behaviors, could be recorded in order to enable new acquaintances in Space Architecture and therefore, development of further Knowledge.

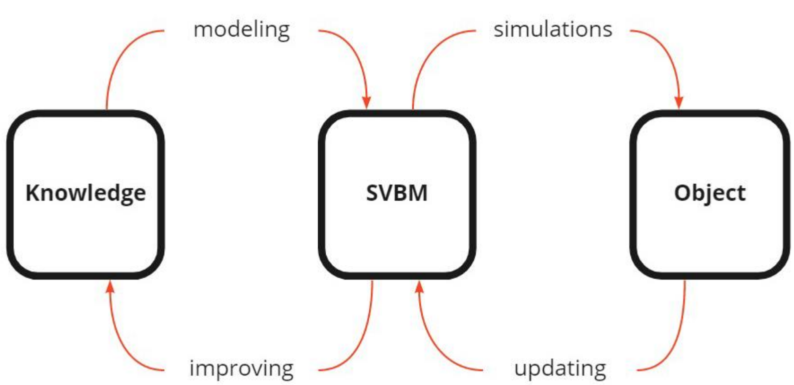

Figure 4: Conceptual framework of Space Vehicle-Building Modelling – SVBM.

4.4. SVBM requirements

The dissimilarities of SVB obtained in the previous section represent the definition of this new typological habitations. Moreover, they constitute also arguments that must be tackled with an appropriate design strategy. The proposed methodology, SVBM, should take advantages from advanced design strategies and capabilities from traditional BIM, at the same time fulfill new requirements.

1. The integration with a mechanical system has been partially tackled in the AECO sector, for example by Calatrava's motion buildings. In SVBs, the entire system could be dynamic. Therefore, the interoperability issue, through IFC, with mechanical/rockets engineering sector is vital.
2. Due to the limited available spaces in SVBs, each piece of the technological systems has to be designed as an integrated and multipurpose entity. In order to allow prompt maintenance, SVBM should be endowed with an integrated sensors network and an automatized reacting system that interacts with users' needs and environment changes.
3. The integration with innovative construction methods and building management is demanded.
4. The SVBM requires a performative energy control and simulation strategy.
5. In order to take into consideration human factors, the SVBM should allow complex model analysis like human behaviour simulation and perceptive studies through advanced design strategies and technologies, i.e. agent-based intelligences, Augmented Reality, Virtual Reality.
6. The micro or zero gravity environment allows users to move equally among all 3 axes, SVBIM should consider this feature and consequently evaluate related issues like the colocation of the reference plan.
7. The SVBM should allow to verify structure and radiation exposure resistance as well as other simulations of external hazards that may compromise the safety and liveability of SVB.

To manage a complex system like SVB, a unifying rule is needed in order to make collaboration between disciplines efficient and possible. This goal could be reached through a *Knowledge*-based structure as defined by Carrara and Fioravanti (2009). The SVBM methodology is therefore the very first step toward a more advanced design support tool.

5. Future developments

The proposed framework needs to be supported and validated with a real project. This work must be achieved only with the support of the Aerospace and Mechanical Industry which can provide more accurate technical information which are hardly procurable. Only through a synergic cooperation between actors, this framework based on collaboration of each environment can be tested.

During the definition of SVBs, the authors have noticed that part of the considerations made in this research could be extended to a wider field. Although this work starts with focusing on Space Vehicle-Buildings, it is possible to apply achievements of this research to many other manned vehicles. As a matter of fact, the points 1-5 of the Space Vehicle-Buildings definition could also describe Isolated and Confined systems like submarines and airplanes which operate in harsh and particular conditions. All these habitations must perform human accommodation duties in an uncommon environment, and, at the same time, need to provide functions of a vehicle. This means that this framework is worthy of further researches due to its possible future application and benefits. It is possible then to think about a more general definition of Vehicle-Buildings as well as their framework, VBM.

6. Discussion and conclusion

From the perspective of further exploration in outer Space, it is reasonable to imagine extra-terrestrial human settlements for the following generations. According to todays' technologies, moving from Earth to other planets requires several months and Space pioneers are going to spend a huge amount of time on their Space vehicles. Spacecrafts with crews should be therefore designed in order to maximize safety and livability. This research proposes to recognize manned Space vehicles as field of investigation of Space architecture and therefore to be considered as a new typology for human dwelling where design and constructive methodologies used so far cannot stand the pace with encountered problems.

The result of this research is the definition of a conceptual framework for Spacecrafts of next generations, which are different from an ordinary habitation. These dissimilarities then have been then considered as the requirements of this advanced methodology.

The proposed framework aims to involve the systemically participation of architects, building experts and health experts, into the design, construction and operating processes of SVBs. The collaboration of these professions, which have already started to contribute in this avantgarde field, is essential in order to develop a possible scenario of a futuristic human settlement and therefore, the extension of human presence in outer Space.

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