Physical or Virtual? :
Effectiveness of virtual mockups of building envelope systems

Minjung Maing[1]

Introduction.

Within the building design to construction process, mockups of some form will be used and the selection of mockup types will depend on factors of Owner's requirements and risk adversity, project budget, schedule, and confidence in the building envelope systems. This paper will refer to mockups as representative sections of building envelope systems. The building envelope is often the portion of a building that undergoes the most number of mockups and/or testing throughout the design and construction process. In today's practice, building envelope mockups typically refer to physical mockups, which are physical replicas of some portion of the building design. However there are technological capabilities present with the given advanced software tools to create its virtual version – virtual mockups – as well as ongoing research.

The building envelope poses many design decisions as the design progresses. The effective conversion methods of its design to fabrication and subsequently installation, is ever pressing as the building industry strives for efficient building practices and building designs. The versatility and powerful digital design tools (such as CAD, CAE, CAM, mechanical production and simulation tools[2]) available today allow for more flexibility in the design itself. In some cases it leads to custom building envelope systems, but does not necessarily play a big factor on how mockups are to be used throughout the design process. The reason being mainly the disjointed process in current practices in which skin system fabricators and installers are not able to match up to the level of digital visualization competency as the design team utilizing building information modeling (BIM).

[1] Assistant Professor, Georgia Institute of Technology School of Architecture (maing@coa.gatech.edu)

[2] CAD – Computer Aided Design; CAE – Computer Aided Engineering; CAM – Computer Aided Manufacturing.

This paper discusses the different types of mockups, their impact and implementation on projects with examples followed by a comparison summary. The intent is to provide a general overview to allow the building team to make intelligent and conscious decisions of mockup selection for given project conditions.

Types of mockups

A mock-up is defined as a full-sized structural model built to scale chiefly for study, testing or display[3]. In building design, various mockups are used to study the building envelope and verify constructability, targeted performance compliance, and visual appearance. It is a step in the design and/or pre-construction phases used to primarily aid in the visualization of the building, material textures, design (performance) requirements, design intentions and team coordination. Complex building types, especially healthcare projects, include mockups of various aspects of the building design, such as of interior patient rooms, equipment layout, security prototypes, and building envelope systems. The building envelope mockups referenced in this paper, due to its well-defined scope of portraying some part of the layer that separates exterior and interior environments, can be applied to a wide range of different building types of varying degrees of complexity.

A mockup of a building envelope is a replica of what will go on the building face – facade – which is where many architects place great emphasis during the design phase. The building envelope is not limited to the vertical plane but also includes the horizontal plane (roofs, plazas, podiums, integrated gardens) and all planes in-between which create the separating medium between inside and outside. Whether the mockup is planar or multi-planar, the areas of importance, and of concern, are:

- Constructability / Assembly – sequencing of work, transitions between planes and different materials, and corners of components.
- Structural performance – testing of structural connections
- Environmental performance – testing of thermal, air and moisture infiltration and exfiltration.
- Planning – effective coordination and collaborations, and scheduling.

How each mockup is used is based on its type, purpose and its inclusion point in the project schedule. Figure 1 summarizes some of the different types of mockups and their functions within the building design process.

[3] Definition from Merriam-Webster (http://www.merriam-webster.com)

Types of Mockups *Type* - Function	Implementation
Visual mockups - Requested by the Owner/Architect to aid in the discussions of material effects and color selection. The size of these mockups range from handheld sizes (12 in. cubic feet) to one-story height mockups. Although rare, depending on the uniqueness of the envelope design and how they are fabricated, there could be smaller scale versions (similar to large study models but with actual material representation) prior to doing full scale mockups.	Between schematic design (SD) and design development phase (DD)
Prototype mockup – Primarily used when developing and testing custom assemblies. Used as testbed for ideas.	Design development phase (DD)
Performance mockup –A full scale mockup of selected envelope systems to test: 1)Integration of assemblies; 2) Engineering performance in air and moisture infiltration, structural performance, thermal efficiency.	Pre-construction and during shoring construction.
Field mockup –On-site mockup prior to installation on the building and built adjacent to the building. Continued through the end of the building envelope installation.. –Sample reference – training, knowledge transfer.	Construction Administration (CA) and Construction phase (Contractor)
In-place mockup –The first group of components installed on the building will be reviewed to set standards of workmanship and resolve any uncertainties of installation quality assurance.	Construction Phase – during installation of building envelope.
Virtual mockup – – Digital representation of portion and specific location on the building envelope. – Implementation point within a long period range.	From design development to pre-construction and beyond. *(to be discussed in Virtual mockup section of this paper)*

Figure 1. Type of Mockups

The Case for Mockups

Building Information Modeling (BIM) creates a significant shift in the way we practice with the aim to facilitate improved collaborations and efficient exchanges throughout the building process. The ability to embed different types of information or parameters into the building model and the ability to better represent the building envelope are beneficial but underutilized. The main reasons being the fluency of this process is still very much under-developed in envelope design and much of the building envelope fabrication and installation industry has not completely transitioned their processes to integrate with BIM. To some extent, for projects that use standard (off-the-shelf) components and refrain from complex forms and integrations, the fabricators acknowledge less demand for process integration and adoption of BIM. However there are concepts and project delivery methods that lend well to an integrated process and need to be considered.

To understand at what point mockups can conjunctively coexist with BIM, one needs to recognize the Level of Development (LOD) categorization, which is derived from a concept of defining the level of detail and information placed on BIM models. The LOD levels primarily coincide with practices within the schematic design phases through to construction phases as described below. The categorization of the grain of the model helps to identify at what point the mockup can be prescribed since different project delivery types and design problems can have varied LOD definition use through the design phase.

LOD 100 – During conceptual design phase: model elements are shown as conveying information of volume, area.
LOD 200 – Design and model elements have more definitions: models of generalized systems.
LOD 300 – Construction information of generalized system is inserted into the model. Suitable to generate traditional construction documents.
LOD 400 – Virtual representation of specific systems and direct translation with construction and fabrication.
LOD 500 – Model is accurate to how the building was built (as-builts).

A building envelope mockup will typically utilize information developed at LOD 400 level. The potential of a virtual representation of a mockup – virtual mockup – is the high-resolution problem-solving possibilities if LOD 400 study models of identified locations were introduced earlier in the design phase. In a recent workshop where contractors were asked about their opinions to the concept of virtual mockups and LOD, the response was the early implementation of high detail studies would be helpful to the design team in working with the construction/fabrication team to promote an efficient workflow.

In one scenario, there are digital tools which are promoting better virtual representation opening doors to better modeling of building envelope systems. In an alternate scenario, there is a move to require more physical mockup and testing of building envelope systems. So the question becomes what is considered necessary and what can we gain from virtual representations that can either substitute information and process data gained from physical mockups. The main strengths of building mockups is the arena of exchange it creates to study the building envelope, beyond the 2D construction details, to ensure that the design and construction teams are convinced of its constructability, functionality and quality. Better utilization of mockups would be to understand the capabilities of physical and virtual mockups, to streamline this verification process and make cost effective decisions of mockup selection.

Design phase implementation

The approach of designing building envelope systems are varied and heavily based on intended aesthetics, budgeting and decision making. Although the design itself is driven by the Architects' vision and concept, the decision maker is primarily the Owner. The Owner may or may not be strongly influenced by the design team who advocates for mockups but in essence decides on the proposed mockups and approves its implementation into the design process.

An overview of current practice trends provides an understanding of how mockups are implemented into the design and construction process. Building envelope commissioning is rapidly emerging as not just a standard for best practices but as part of building codes (for example, 2010 California Green Buildings Standard Code), with the goal to improve building efficiency and project delivery. The main framework for building envelope commissioning is to assign performance metrics to projects, through developing a Basis of Design (BOD) during pre-Design and an Owner's Project Requirements (OPR) during the subsequent design phases. The BOD of the project, per the National Institute of Building Sciences (NIBS) Guideline for Building Envelope Commissioning provides "narrative descriptions of building exterior enclosure systems (e.g., roof, exterior walls, floors, windows, skylights, atria, thermal mass, etc.)" and the OPR provides performance criteria for each of the identified systems. The Commissioning Plan, a continuation of the OPR, then serves as an expanded reference for expected performance of the building envelope and bridges the transition from design and construction to occupancy and operations phase activities.

Due to problematic building envelope systems, the industry acknowledges the high-risk aspect of this interface separating inside from outside. Whole Building Design Guide (WBDG)[4] prescribes mockups, in this case physical mockups, as giving information and assurance of constructability and performance of the building envelope system. The referenced physical mockup in this guide is the performance laboratory mockup, which is the most thorough out of the physical mockups in terms of verifying the designed systems and also the most costly option among the mockup types. The high cost stake makes it a difficult decision for the project team. Informed decisions of mockup selection are therefore beneficial to avoid redundant budget use.

Figure 2 shows a general workflow – a series of processes described through associated activities of relevant participants – of project execution for building envelope systems illustrating extreme scenarios of the design process. The upper workflow is for very budget conscious projects where no mockups are specified. Consequently the project team also selects standard pre-engineered and pre-certified systems, relying on these certifications for product quality and successful installation. The lower workflow shows the other extreme scenario where costs to do these mockups are minimal in

[4] administered under National Institute of Building Sciences (NIBS).

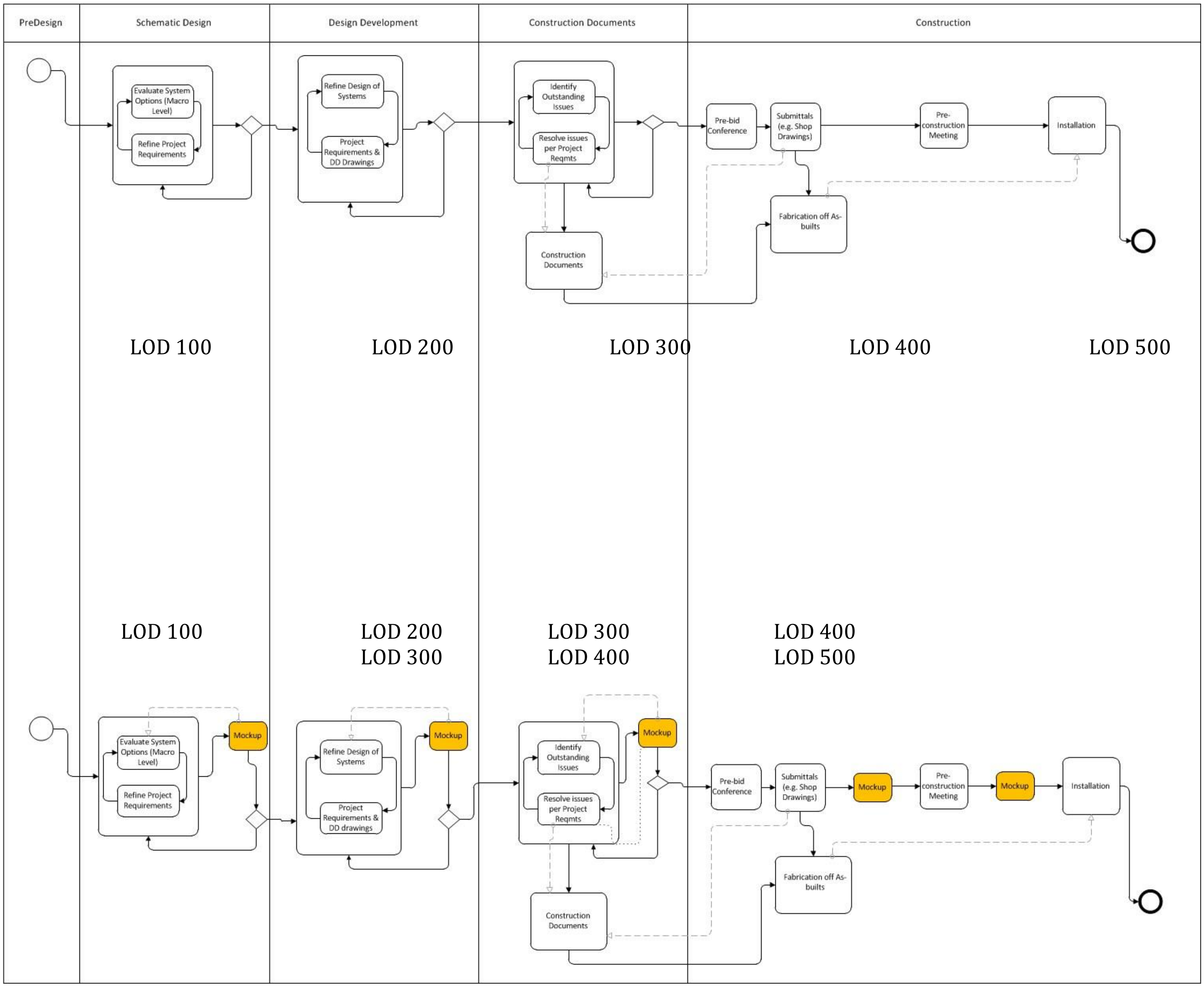


Figure 2. Design to construction process and mockups with the most cost-sensitive project at the top and least cost-sensitive at the bottom. With the least cost-sensitive project (high budget), there are mockups implemented at every phase that play a significant role in decision making.

retrospect to the high-budget building envelope design. The important thing to note is the LOD at each phase and how this is changed by the interjection of mockups within the design process. The mockups referenced in these diagrams are physical mockups that are static and exist outside of the design iteration process. These mockups are not expected to be interchangeably used with the design and modeling process but mainly used as a performance checklist at its implementation points.

Conventional vs. Custom systems

The major intended outcome from mockups in a project is for involved parties to obtain a sense of confidence that the designed envelope systems are constructible, meets the design intent and performs. The first questions the mockup answers are “Is the designed building envelope system constructible per the drawings?” and equally important “Do the installers, sometime different tradespeople, know how to build it together effectively?” By effectively we refer to a reasonable installation time and sequence with proper installation of all elements including the integration of components that join the different assemblies together.

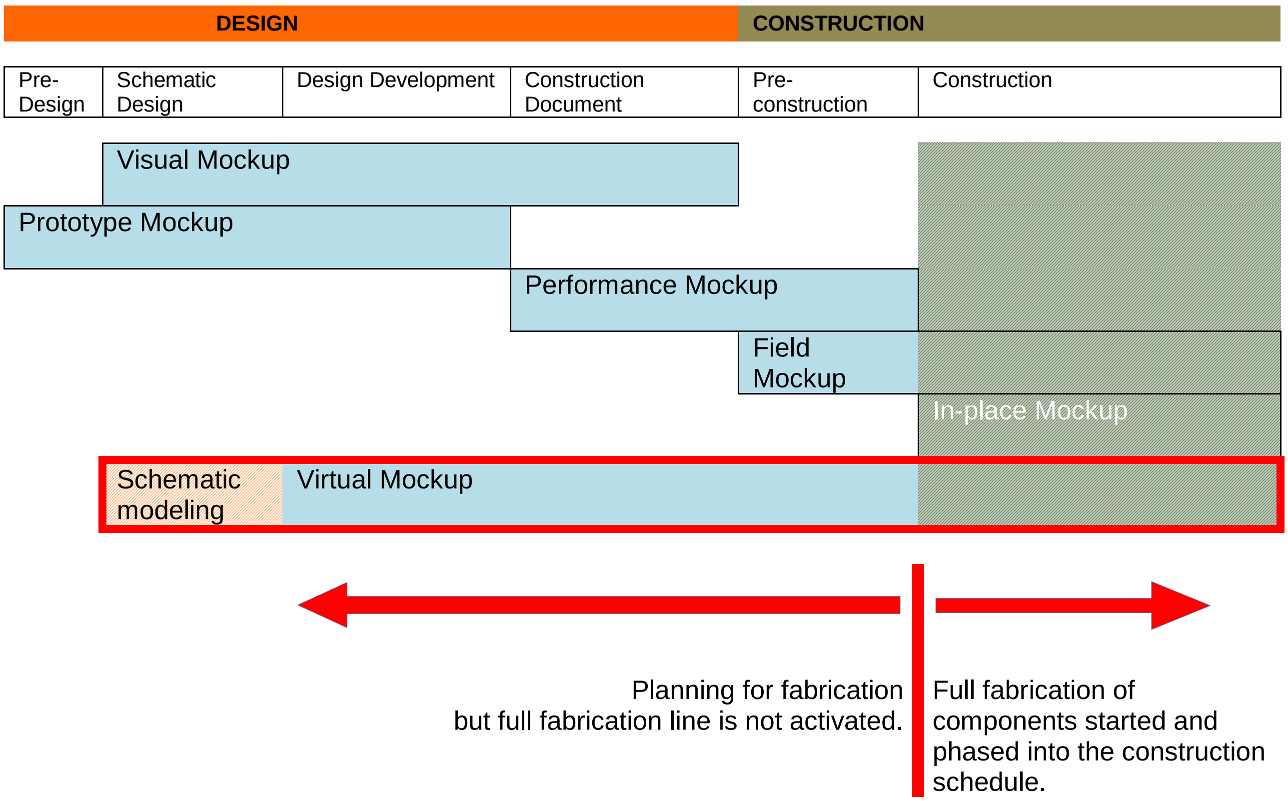


Figure 3. Implementation of various mockup types and critical points of fabrication schedule within the design and construction project timeline.

The functions of the different mockups are suggestive of when they can have the most impact on the project. The size of the mockup and their implementation timeline has close correlations with their cost. Design teams should consider three main conditions as they weigh the decision of mockups:
1) the building envelope systems (**ENVELOPE**);
2) when and how to use mockup (**TIME**/**SCHEDULE**);
3) costs of mockups (**COST**).

For an overview Figure 3 shows when the various mockups are typically implemented and where fabrication of the components commences. This diagram applies to the design-bid-build project delivery method, however only slight variations apply to more integrated project delivery methods where integration of the multi-disciplines occur earlier during the design phase.

ENVELOPE: Understanding the building envelope system can answer the question of which mockups are more appropriate and which mockups would be redundant. Building envelope systems can be categorized as conventional or custom systems regardless of material type. Categorizing the building envelope into these two major categories based on their configuration can give the designer prior knowledge and performance expectations of the building envelope system. Conventional systems are material assemblies that are composed of primarily standardized components for mass production and standard repetitions in its assembly. Conventional, or more commonly termed “off-the-shelf” components and their assemblies are marketed as products, individually tested by third party testing facilities and include manufacturer’s warranties. For example, all AAMA-certified (through American Architectural Manufacturers Association - AAMA - standards) curtain wall systems are performance tested at third party testing facilities and come with manufacturer-approved installation standards and AAMA certification labels.

Custom envelope systems are project-specific and can vary in the range of customization from different edge treatments to specially fabricated components and unique installation procedures. This is the case for where new prototypes transpire from the design process and where emerging materials are integrated into the building. The lack of precedence in terms of its performance during the installation as well as exposed to the environment makes a custom envelope system require additional steps to gain confidence in its design and implementation.

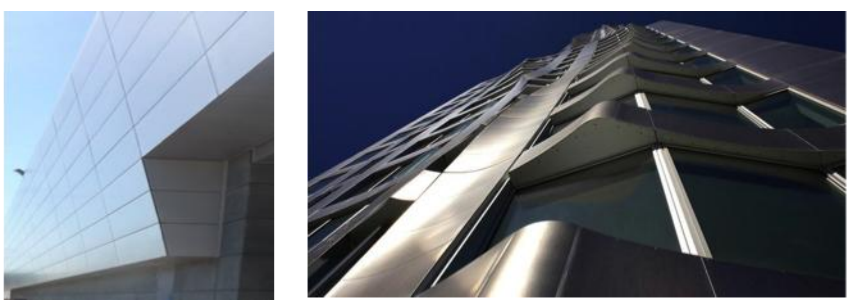


Figure 4. Metal exterior panel installation: (a) conventional standard assembly and (b) custom metal panel installation.

An example of conventional and custom systems for metal panels are standardized installations shown in Figure 4a and the unique forms of the outer metal panel as shown in Figure 4b.

TIME/SCHEDULE: The building process is fraught with repetitious processes due to reworking from miscommunications or lack of information. Mockups are used as stepping stones to fill in some of the information gaps – incomplete construction documents. To get maximum usage out of mockups, their inception throughout the design and construction process is important. As outlined in Figures 1 and 3, use of mockups are type-dependent, which has a noted time frame for implementation of when they are considered effective. For instance, visual mockups are most effective earlier in the design phase so that the designer can commit to the selection of material, color, texture and its appearance and not hold up procurement scheduling. Once the envelope is categorized into either customized or conventional systems then the next set of decisions are what is the project schedule, and how best to ensure no major holdups from poor and missing 2D details.

<u>COST:</u> Cost is driven by how much risk and upfront costs the fabricator is willing to take and in some cases need to take to stay competitive for the project. A general of understanding would be for full scale mockups that utilize non-standard components, and require small batch production mainly to purpose a mockup, the project team will need to carry the burden of a heavy cost premium versus a less costly option of a mockup that utilizes standard components or mass produced components. Performance mockups, therefore, have a high cost premium for fabrication of parts due to the small batch production for custom envelope systems. The scenario being that any changes due to failure during the performance mock-up will make the small batch not useable for the larger scale production on the final project.

Given these three driving considerations, it is important to know that they are not exclusive but highly cross dependent. The discussion of which mockup to include should conjunctively evolve around envelope systems, time framework and cost which exist under the umbrella of owner requirements and expectations. To make a comparison of physical and virtual mockups, it is important to understand their impacts on the design to construction process. The following sections will summarize processes for these mockups and provide a comparison outline to highlight the advantages and disadvantages of physical and virtual mockups.

Physical Mockups

Physical mockups are considered the visual, prototype, performance and field mockups. This section refers to performance and field mockups to discuss the benefits of physical mockups as compared with virtual mockups, since these mockups require a high level of resolution in the building design. These mockups, if implemented, are built in the later stages of design, when the Architect has decided on building form, materials and the design project team has transitioned to refining (finetuning) the design.

Performance mockups are constructed in a third party certified testing lab facility – not on the project site – and require a full set of construction documents, procurement and fabrication, installation and testing requirements. Since it is a full-scale replica of a portion or segments of the building, it is common that the performance mockup also serves as a last-round visual mockup; the final check on design aesthetics for the architect. The criteria for a performance mockup (set by AAMA) are that upon successful completion of testing, documentation of the tested building envelope system is finalized and the design in terms of constructability, coordination and the specified performance requirements is validated. As-built drawings of the tested systems are recorded. The responsibility of full implementation into the project is given primarily to the construction team in coordination with the fabrication and design teams. In effect, the fabrication of the finalized design does not happen till after successful completion of the performance mockup.

Field mockups are usually a step inserted into the building envelope installation schedule and have minimal impact on the preparation and initial costs. It does not require separate documentation and are based on the approved project construction documents, including approved shop drawings. Implementation occurs during pre-construction, after procurement, and during or after fabrication of the building envelope systems. The distinction of the implementation schedule is dependent on whether it is installed on the building ("in-place" field mockup) or on a separate structure adjacent to the jobsite ("pre-installation" field mockup) (See Figure 5).

Figure 5. Field mockups are built on-site and differ in whether it is a pre-installation or a first in-place installation: a) Left image shows a "pre-installation" field mockup built adjacent to the building and b) Right image shows a field mockup which is "in-place" meaning that it is installed on the building and if approved will be a permanent installation.

Both the performance and field mockups verify constructability, however their main difference is the scope of testing. The performance mockup is placed in a certified testing facility to perform tests of air and moisture infiltration under different loading conditions, structural performance and thermal efficiency of the proposed systems. The field mockup, placed on-site, test air and moisture infiltration under different loading conditions. There is assumed confidence in the structural and thermal performance of the proposed systems. One can then deduce that basic selection of a physical mockup is based on a need for verification of constructability and assembly for assured performance in air and moisture infiltration.

Virtual Mockups

The concept of virtual mockups is, similar to physical mockups, an accurate replica of a portion of the building envelope systems in the virtual environment. BIM, integrated project teams (i.e., Integrated Project Delivery (IPD)), and Virtual Design and Construction (VDC) tools create a design process that relies on information exchange and interoperability at early stages of the design with common goals to improve efficiency for better performing buildings. A virtual representation of the building envelope at the level of detail that allows for the study of constructability, work sequence, scheduling and performance provides many promising potential savings in time and cost, improved coordination and design flexibility.

Projects that have used detailed virtual representation to better document the building envelope have described benefits in cost savings in comparison with physical mockups. An example of a type of virtual mockup and how it was used, is presented in a drawing sheet by Mortensen Construction (General Contractor), shown in Figure 6. The general contractor states that they utilize virtual mockups for high-risk planning (building

Figure 6. Mortensen Construction (Contractor) used Google Sketchup to model select building envelope corner section for coordination between design and construction teams.

envelope), integrated work planning, construction sequencing, and team communication and collaboration. The 3D digital representation at high-level detail (LOD 400) facilitates collaboration, productivity and ultimately improves the construction process.

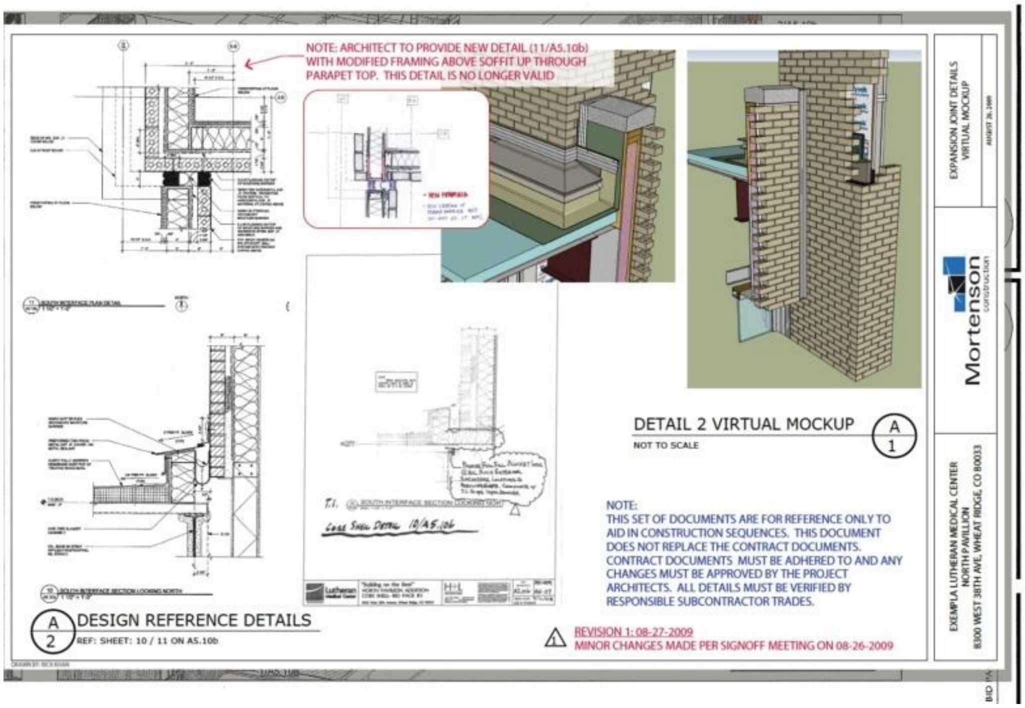


Figure 6. (Cont.)

The cost savings comparison given by Mortensen Construction projects states more than twenty times savings with 4 virtual mockups versus the same 4 sections built as physical (field) mockups. Since the element of time was not included into the physical mockup cost (which would actually make the cost of physical mockups much higher), the main conclusion would be that planned properly the virtual mockup can have significant savings in cost and time compared to its physical mockup counterpart.

In another example, with a different project team, the project was on an accelerated timeline and the Owner and Contractor wanted to try an alternative to physical mockups to understand the building envelope system and integrate it with their BIM model. A similar initial attempt was made to model a portion of the building envelope system virtually in two different ways for different systems (Figures 7 and 8). After reviewing the building envelope systems, project conditions and process, the question of how a virtual mockup should be modeled was posed. The models shown in Figures 7 and 8 were studied and there were either no component parameters attached to the objects besides their dimension, or the placement of detailed information was excessively represented leading to large file sizes. The virtual mockup was viewed as a compilation of systems and the configuration of the compilations would be unique to the project but the systems were not necessarily unique to each project.

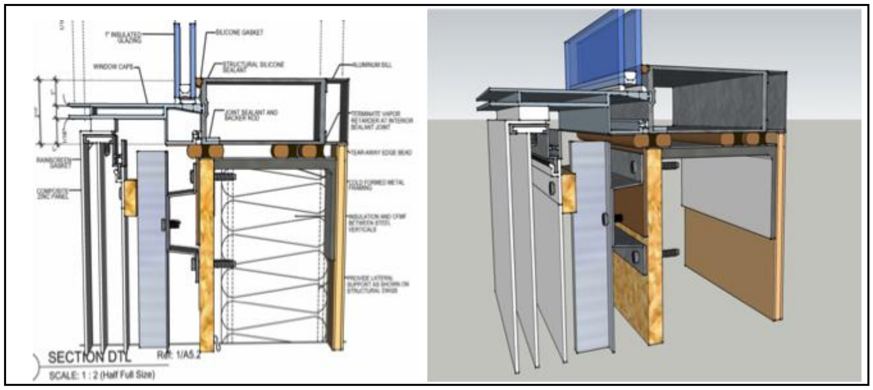


Figure 7. Window to metal panel interface shown in a) 2D detail and b) 3D detail. (This was modeled in Google Sketchup.)

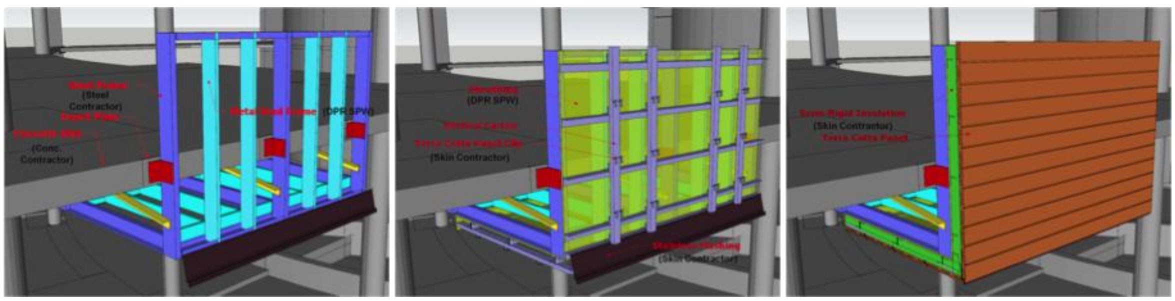


Figure 8. These series of images show progression of installation from framing through to the exterior cladding materials. (This was modeled in Autodesk Navisworks.)

To be able to embed information of components as parameters and able to have automated references, modification updates the building envelope systems were approached as mechanical products and the virtual mockup as a mechanical assembly, with parts, subassemblies and master assemblies. Parts were categorized as the individual pieces at the component level: anchor plate, bolts, sheathing panel, glass, and metal panel etc. Subassemblies were categorized as unit assemblies such as windows, doors, and metal panel system utilizing the modeled parts including clips needed for structural attachment etc. Master assemblies were the compiled model where all the relevant subassemblies were put together similar to how each trade would come in and install their portion of the physical mockup. The interfaces of the subassemblies became the main areas of resolution in the master assembly, analogous to the constructability and coordination issues that are typically raised during physical mockups. Views of the master assembly models of varying sizes are shown in Figure 9.

Once the parts were modeled the assembly of these parts raised issues of integration and constructability and revealed areas lacking continuity and requiring additional components or special machining not shown on the project 2D shop drawings. It became an analysis of not only assembly but of performance requirements – air and moisture resistance review. Knowing the need for additional materials and special machining early in the design phase is critical to better implement into the budget or design other solutions for a 3D mechanical solution (Figure 10).

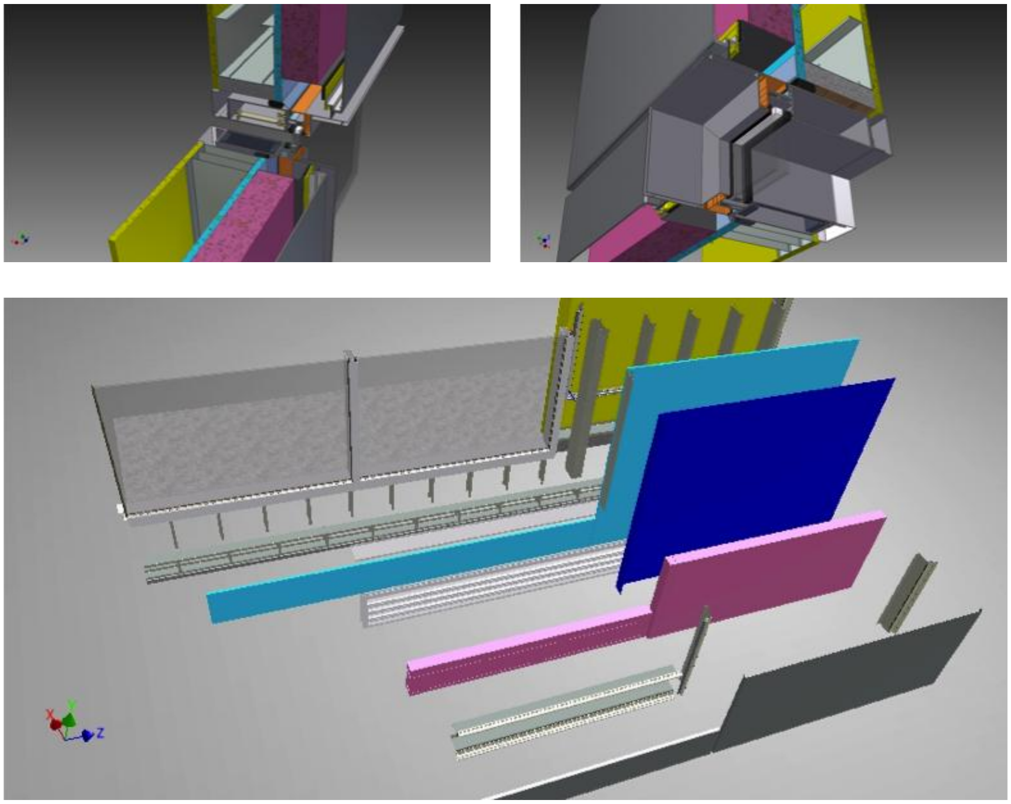


Figure 9. Virtual Mockups of window and adjacent metal panel system shown: (a) and (b) window corner virtual mockup to study corner interface; (c) exploded virtual mockup to show the layers that make up the selected building envelope section (Modeled by Georgia Institute of Technology Digital Building Lab)

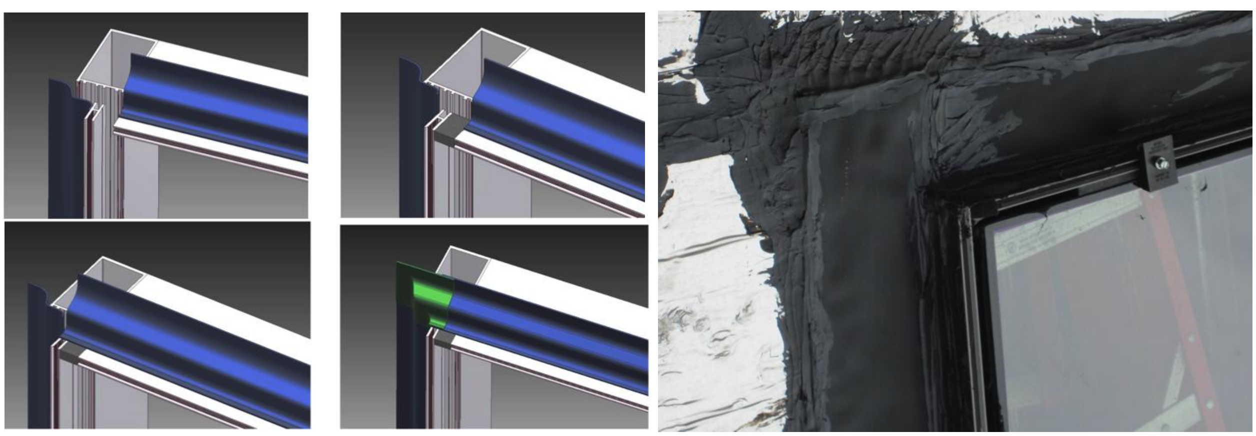


Figure 10. Virtual representation of the fabrication and installation process of the binding strip revealed that there would be issues with material buildup, of two materials overlapping within the glazing pocket. This issue was later discovered during the installation process with excessive build-up of material where the pressure bar would have need to be installed.

Through this method of modeling, a part library was formed and subassemblies were able to be shared allowing for possibility to form different combinations of master assemblies that would be specific to each distinct project condition without having to start from the very beginning of the modeling process.

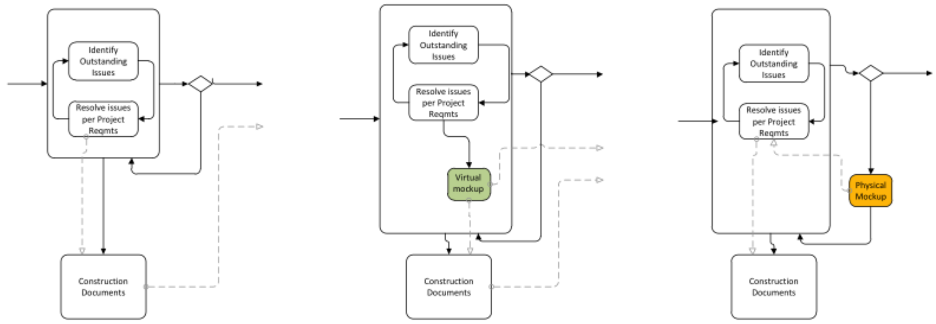
Comparison of Physical and Virtual Mockups

Physical mockups are static reference points and, depending on the level of design and performance resolution, may incur a large cost penalty for major reworking leading to major delays in scheduling. In addition, once the physical mockup is completed, it is difficult to include future design changes and any impact of value engineering on the systems will invalidate the physical mockup. Physical mockups are most effective when the design team provides coherent drawings, and fabrication and construction teams are well coordinated. This allows the mockup to serve as a step in the design to construction process, to reassure all involved participants of their understanding of how the envelope should be installed to meet its performance requirements. Performance mockups provide more in-depth examination of the building envelope and would certainly be useful for unique prototypes, however its use on conventional systems is redundant and purpose questionable.

Virtual mockups are non-static and allow for studying and manipulating the design with higher level of understanding of assembly, material characteristics, as well as understanding its translation into effective performance and construction processes. Since it is in the virtual environment, it lacks the materiality and tangibility of its physical counterpart. However, it offers consistency in transfer of knowledge between involved participants in developing the virtual mockup through to its installation on the building. With an interactive model there is mobility of information and easy accessibility of visual information for both design and construction teams.

In addition to the direct effects on the making process, the virtual mockup can have implicit effects on the design process and imposes better building practice by allowing design teams, preferably in conjunction with construction teams, to design and study the building envelope system at greater depth earlier in the design process. Implications are:

1. Allows design team to study their building envelope three-dimensionally (3D detailing) and include 3-D detailing, where practical, and determine relevant details.
2. Promotes better communication through visual representation, not relying on physical representation (physical mockups), and creates feedback structure with design, fabrication and construction teams.
3. Emphasizes integration of project team, exchange of ideas, and building information.
4. Allows design team to understand levels of design flexibility throughout the design process.



a) b) c)

Figure 11. Comparison of workflow at construction document phase of: a) where no mockups are prescribed; b) virtual mockup is used and it becomes part of the iterative design process; c) physical mockup is used and it is used as a "go-no-go" checkpoint outside of the iterative design process.

The striking difference in process and the area of biggest potential and benefit is the impact of physical versus virtual mockup in integrating with the design process (Figure 11). The physical mockup is less flexible and used as final decision checkpoints whereas virtual mockup allows for the resolution of problems before, during and after documentation, fabrication and first on-site installation. Virtual mockups can assist to address the issues of constructability, assembly, planning, and sequencing before a first-in physical field mock-up. The proposition of virtual mockups does not propose that it should completely replace physical mock-ups but proposes to better utilize performance mockups and give alternatives to those projects that opt out of performance mockups.

Summary

As more projects utilize BIM tools and technologies, the need for better virtual representation of the building envelope will be inevitable. The concept of virtual mockups provides modeling environments to embed information and perform simulations without being attached to the whole building BIM model. Virtual mockups allow for in-depth hlgh-level detail study of building envelope systems and their interfaces without the high cost burden of some physical mockups. Physical mockups are undeniably beneficial however excessive use of these mockups can be better controlled and intelligent choices of mockup selection can be made based on awareness of versatility of various mockup types within project parameters (building envelope, time/schedule and cost). Virtual mockups can substitute or complement physical mockups, to make the use of physical mockups more efficient in highlighting issues incurred from field conditions (e.g. quality of field work), that is difficult to convey in virtual or performance mockups.

The use of virtual mockups will be most beneficial if implemented early in the design phase through to fabrication and construction sequencing to ensure that these high-level detailed mockups encapsulate elements of design flexibility and specifics of fabrication toleration, performance compliance, assembly and installation procedures.

Future Research

This paper includes research from an ongoing research project funded by Digital Building Laboratory at Georgia Institute of Technology. The goal of this and future research is to improve the model and information exchange of virtual mockups and to assess the level of virtual modeling to address different processes and collaborations. An analysis of the decision process of mockups in early design phases is in progress. A report of design-to-fabrication workflows through case studies will be completed outlining recent changes in practice driven in changes of exchange methods.

References:

Stroik, Brian. “Why a Mock Up, Because the Owner Expects it Done Right”, BEST2 Conference, Portland, OR: 2010.

Khan, Rick and Dace Campbell, “Constructability Review and Virtual Mockups”, presented at AEC BIM Forum February 2011. San Diego, CA: 2011.

Baker, M. “Using Physical Mockups to identify curtain wall design flaws”. Building Design and Construction. 2009.

Lemieux, D. J. & Totten, P. E., “Building Envelope Design Guide – Wall Systems,” Whole Building Design Guide (WBDG), National Institute of Building Sciences, 2009.

Knight, K. D., Runkle, J. A. & Boyle, B. J., “Procedures for Commissioning Building Envelopes,” 2008 Symposium on Building Envelope Technology, Roofing Consultants Institute, 2008.

Maing, M. “In-between: Designing joints within Facades”. 2009 Symposium on Building Envelope Technology, Roofing Consultants Institute, 2009.

California Green Buildings Standard Code. (CALGreen). California Building Standards Commission: 2010. (http://www.bsc.ca.gov/default.htm)

NIBS Guideline 3 Exterior Enclosure Technical Requirements for the Commissioning Process, National Institute of Building Sciences, 2006.