

# 3D Modeling and Virtual Mockup Building as Teaching Tools in AEC Materials and Methods Curricula

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A set of virtual mockup 3D modeling exercises is being presented in this paper for the curriculum of a typical construction materials and methods class. The goal of these exercises is to enhance students' spatial awareness of construction assemblies and therefore lay a better foundation for their success in higher-level courses and their professional practice. Furthermore, these exercises allow instructors to scale hands-on components of their classes and facilitate virtual/online learning in this topic. At present, these exercises have been implemented as supplemental material for a popular textbook in construction materials and methods and their effectiveness will be monitored.

**Key Words:** 3d modeling, mockup building, virtual classroom, materials and methods

## Introduction

Construction materials and methods classes are often exciting experiences for freshmen or sophomore students in all AEC (Architecture, Engineering, and Construction) programs. After all, these are usually their first experience with the “real subject” of their field of study: Buildings and materials are being explored and scientific topics are explained in a not-too-theoretical, applied context. In addition, processes are being taught that can be experienced either in a hands-on lab or on a construction site during an internship. And all of this occurs right after (or concurrent to) their introductory science and Gen-Ed requirements, which provides an often welcome “real world” contrast to those courses.

Given all of these positive aspects, it is surprising that materials and methods courses can be experienced by students as too theoretical and unstimulating. This is because a major detriment to student success is often their lack of an experiential reference when it comes to construction topics. For example, steel connections presented in a classroom can be quite a “dry” topic unless labs are provided where students can work with them in a scaled-down construction site environment. Alternatively, students that have worked on a construction site during a vacation job or an internship typically develop an easier understanding of the topics. However, the majority of incoming students does not possess this prior knowledge.

It has been argued (Glick et al., 2012) that three-dimensional understanding of the construction process, which in turn is based on the ability to visualize and comprehend spatial relationships is lacking in many incoming students. This then leads to problems in their understanding of key construction courses like construction materials and methods, estimating and project scheduling and likely further courses in steel, concrete or wood design and more. These problems with student understanding are typically being addressed with a variety of teaching tools: in-class demonstrations, materials and assemblies libraries, hands-on labs as well as site visits, images and videos. While all of these certainly add to a teacher's toolkit and greatly aid in the students' comprehension of the topic, three issues limit their applicability:

**Material weight and scale** are central problems to any hands-on course in construction technology. The materials that are commonly in use on construction sites are typically too large or too heavy for a safe lab in an educational setting. This is often compensated by the use of smaller cross-sections and material amounts, scale models or a switch to a different material (e.g. the use of the much lighter wood to represent heavier materials in mockups). This sometimes gives students a too scaled-down experience and reduces what might have been a commercial construction context to a residential construction context.

With increasing student numbers in these introductory classes, **scalability becomes an issue**. Where a lab is reasonably easy to set up with a small number of students, increasing the size of the student body leads to a higher demand on coordination: More TAs need to be hired and more materials need to be purchased. This also affects physical space requirements. The same is true for in-class demonstrations and the use of material and system libraries. Also, site visits, although they are exciting and educational events, are often limited in the feasible number of participants by simple practicality as well as liability constraints on the side of the construction company. All of this is complicated by generally dwindling financial resources, which make costly items like hands-on materials labs a taxing proposition.

Although in-person taught courses are often the preferred learning venue, it can be seen in many educational fields that **online course offerings are increasing**. (Allen and Seaman, 2010, Martin, 2012) Often, this approach provides a way to deal with the reduced financial resource environment and offers the possibility for additional revenue generation. And most recently, MOOCs (Massive Open Online Courses) have entered the academic landscape, providing a course environment (often without direct associated costs) to hundreds of thousands of students at a time. While these online courses might not remain in their current form forever, as an experiment they certainly illustrate both the need for scalability of course content and for digital, online-deliverable course content.

When it comes to learning construction methods and systems (and, of course, the materials that make up our buildings), it is crucial for a student to understand how things fit together. Every construction system is an assembly of subparts (e.g. beams, bolts, decking) and often a layering based on various functional requirements (e.g. air barrier, insulation, structural sheathing,...). This “tectonics of architecture and construction” can be as simple as the layering of beams or be of a complexity akin to assembling auto parts (as experienced, for example in Frank Gehry’s buildings). Therefore, it is imperative to devote sufficient teaching resources towards honing related skills in students. It can even be argued that digital curriculum elements should not only be concentrated in “drafting”-type classes, but rather need to be included throughout the entire curriculum, similar to writing and oral presentation requirements.

All of this is concurrent with an educational environment where the following tendencies can be observed:

Teaching methods are changing from pure lecture-methods towards an interactive, group-learning-based problem-solving-oriented classroom. Due to the nature of the construction process and the involved physical objects, construction materials and methods classes naturally lend themselves to these teaching approaches. Real-world scenarios can be included in a curriculum and – if desired – “flipped classroom” approaches can be followed (Mills and Treagust, 2003, Perrenet et al., 2000, Hmelo-Silver, 2004).

Over the past years, there has been a significant change towards **easy availability of high-quality digital tools**. Often, these tools are very low-cost or are being made available for free (without an associated direct cost) to the educational environment, while other times, they follow a public “freemium” model. Examples are:

- **Easily available 3D CAD software.** It is quite common for CAD software manufacturers to produce a scaled-down (and sometimes educational/personal-use only) version of large, commercial products. The most popular example for this might be Trimble’s (formerly Google’s) SketchUp, which now comes in a commercial “Pro” version as well as a free “Make” version that can be downloaded, learned and used easily (Trimble, 2014). Other examples are Autodesk’s commercial programs (e.g. AutoCAD, Revit, 3ds max), which now come with a free 3-year license for educational users (that can even be used in a non-networked classroom) and their freely available (or extremely low cost) proof-of-concept



Figure 1: Autodesk's FormIt on an iPad

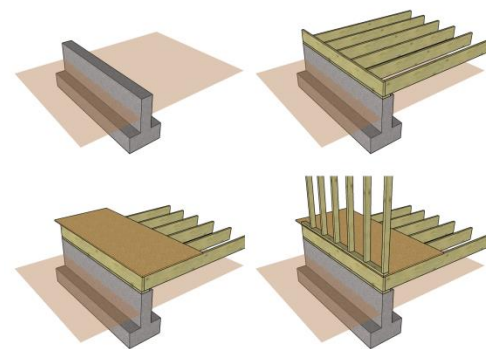
- programs such as FormIt (see *Figure 1*) and the maker-oriented 123D collection of apps (Autodesk, 2013).
- **The switch from 2D CAD to 3D CAD-based Building Information Modeling (BIM) software.** Pushed from both the industry as well as the software manufacturer’s side and following a demand for integrative digital tools, BIM software has been widely made available and is being increasingly used in the construction industry. Examples for this are Autodesk’s Revit platform and Graphisoft’s ArchiCAD. This has also come along with software manufacturers and educators developing curricula that focus on BIM’s innovative approach on object-oriented modeling as well as data-driven design (Joannides et al., 2012).  
However, while it is typical for BIM software implementations to include a 3D representation of the entire building and its materials, they do this only at a building element level (e.g. “a floor”) and not at the building component level (e.g. “a joist”). That level of detail is commonly included in these programs as non-visual data (e.g. the floor contains a joist “layer”) and as a 2D CAD detail for construction documents. Neither of these two explores assemblies at the component level and therefore does not help a student’s detailed understanding of construction material systems.
  - **User-interface methods for digital tools have improved.** While in the past, these consisted of the mouse-keyboard-digitizer combination in a command- or menu-driven software environment, users nowadays have much more interactive and natural tools at their disposal. Examples for these are human interface devices like 3DConnexion’s 3D mouse, Microsoft’s Kinect, the Leap Motion device, and tablets. On the software side, software code-based programming can be replaced by visual programming (as in McNeel’s Grasshopper and Autodesk Vasari’s Dynamo).
  - **It has also become easier to share 3D content, particularly on the web.** While in the past, 3D web-based content required browser plugins (e.g. for Adobe Flash or VRML), modern browsers have WebGL built in, a graphics engine that gives web content direct access to a host computer’s graphics hardware. WebGL makes it thus possible to display a 3D model in high fidelity on a website and let the user interact with it. Various approaches have been realized using this technology. Services like Sketchfab.com and sunglass.io serve as good examples here.

Given all of these technological advances, it is surprising that **CAD- and BIM-based classes are sometimes taught as a non-core topic**. Depending on the academic program, these classes might end up as professional electives or are omitted altogether and then assigned as remedial classes only as needed.

## Background

Part of the author’s teaching of an “Advanced CAD/BIM” class over the years included an exercise in which students were asked to create virtual assembly animations. As shown in *Figure 2* on a simplified model, assemblies not only had to be modeled using building components but the assembly process also needed to be illustrated as an additive animation process.

This exercise has proven very successful in supporting the students’ spatial comprehension of assemblies and thus understanding of topics that ideally should have been located in a construction materials and methods class. Having this exercise produce an animation also exposed any modeling flaws, which led to inherent error-checking during the assignment process, not unlike what is necessary for constructability testing.



*Figure 2: Animated assembly modeling*

Contrasting to this is an exercise where the author in the past asked students in a construction materials and methods course to complete a final project using materials and assembly knowledge gained in class. With varying backgrounds in representation (drawing or digital design), student work visual quality varied significantly with architecture students typically handing in the more error-checked and constructible designs and construction management and engineering students handing in what can be seen more as an unchecked “concept” design. Figure 4 shows a sample design from this course where the task at hand was to design a bus stop in certain materials (this group was assigned masonry).



Figure 3: Physical facade mockup

While the concept is certainly there, design and assembly details remain unchecked and materials are simply painted on as visual cue. A better spatial understanding of masonry layup (which certainly was taught in the course) would have led these students to question more the appearance of their design and produce a more realistic result.

In addition to these educational-setting examples presented above, reference should also be given to the common construction practice of building physical mockups of wall sections, façade sections and other complex assemblies (see Figure 3).

This process is often used to check appearance, constructability and sometimes building performance of the building elements in question. While physical mockup building is a hands-on exercise, its use in a lab environment is limited due to the aforementioned scaling problem and the materials and teaching resources required.



Figure 4: Sample student design from construction materials and methods course

### A 3D Model-based Exercise Curriculum for a Construction Materials and Methods Course

A total of 46 exercises were created based on the chapters in Edward Allen and Joseph Iano’s book “Fundamentals of Building Construction: Materials and Methods” (Allen and Iano, 2013). While the complete list is omitted here, sample exercise titles can be seen in *Table 1* for two of the chapters: Chapter 4 (Heavy-Timber) and Chapter 8 (Brick Masonry).

Chapter 4: Heavy-Timber	Chapter 8: Brick Masonry
4.1 Assemble a bent	8.1 Assemble water table detail using custom-shaped bricks
4.2 Assemble a pegged bracing connection	8.2 Create Flemish Bond using modular bricks
4.3 Assemble a timber frame (copy bents and fill in purlins)	8.3 Create intricate bond (various different coursings) using modular bricks
4.4 Assemble a glulam / CLT building	8.4 Create brick layout for first layer of complex shaped wall (steps, angles) and comment on where you will have to cut bricks
4.5 Assemble a glulam / open-web truss building	8.5 Assemble window opening detail using modular bricks and steel or concrete lintel
	8.6 Create intricate chimney-top detail using

	modular bricks (creative task)
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*Table 1: Sample exercise titles from two of the chapters*

This set of exercises was expressly developed with the following criteria in mind:

They were to use common and easily accessible CAD software, preferably free software.

They had to include somewhat simplified models of real objects so that the purpose of the exercise would not be overshadowed by a too-high demand on digital modeling skills.

A user should not need to learn too many 3D modeling commands so that software-learning would only be a short step towards being able to complete the exercises.

They were to encompass the entire breadth of the underlying construction materials and methods book.

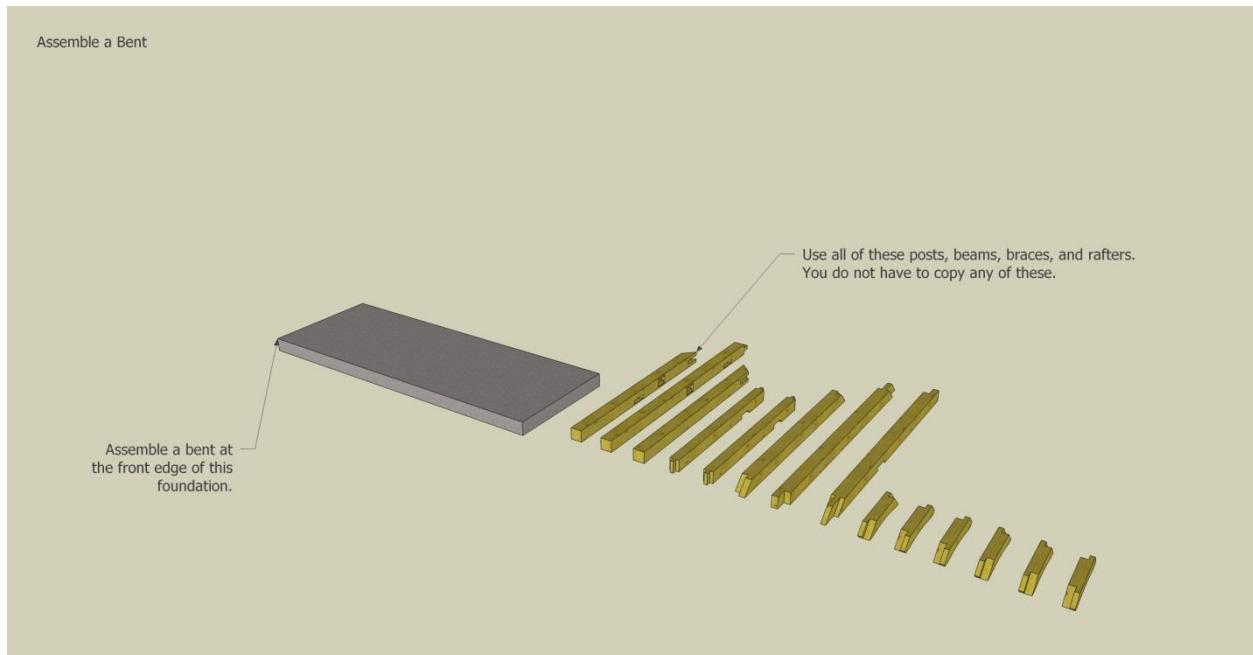
These goals were followed by choosing Trimble's SketchUp Make as the main software for these exercises. Among the available choices of common "generic" 3D modeling software applications (Autodesk AutoCAD, McNeel Rhino, Trimble SketchUp, AutoDesSys bonzai3d and form\*z, Nemetschek Vectorworks and others), SketchUp offered a free educational/personal version and has proven itself as a very intuitive and easy-to-learn software. Students often already have a basic understanding of SketchUp and instructional material (books and online videos) are readily available (see for example Schreyer, 2012). In addition, SketchUp models can easily be annotated in the 3D modeling space and results can be presented right inside the software. Many universities already have SketchUp Make installed on their lab machines and may also possess SketchUp Pro, an enhanced version of the same program, which can also be used to complete these exercises.

To make the exercises generally applicable, all exercises were also exported in Autodesk's DWG format, which any 3D CAD software typically can import. Furthermore, a short instructional video and a student handbook were produced that both taught the basics of SketchUp.

The exercises were then prepared so that students would work only with 3D "objects", removing the need for them to create "raw geometry" using basic modeling commands. Therefore, the only needed commands were MOVE, COPY, ROTATE, SCALE, SELECT, ERASE, and MEASURE, making the exercises true assembly processes.

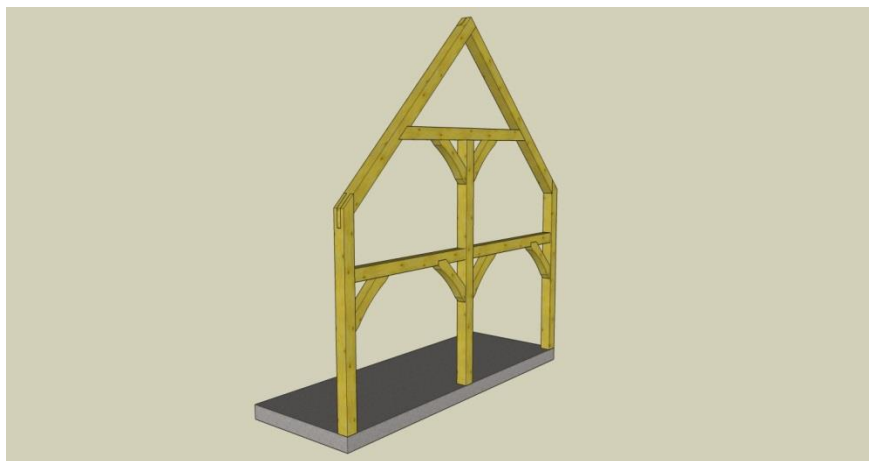
A sample exercise can be seen in *Figure 5*. In this exercise, the student is asked to assemble a timber-frame bent from a set of pre-cut timbers, some of which will need to be copied. In this exercise, no members need to be scaled, though.

All of the elements are textured with wood grain and a (locked) base is provided on which the structure is to be erected. Instructions for the student are included right inside the 3D model. Where necessary in other exercises, reference points are provided that help guide object placement.



*Figure 5:* Student instructions for a sample exercise

*Figure 6* then shows the completed exercise with all of the timbers in their correct places. This image is typically provided only to the instructor. However, depending on teaching intent, the instructor may choose to release these images to the students as well as a guideline for the exercise. In either case, the student must go through sometimes spatially challenging exercises such as in this case 45-degree rotation and snap-point positioning to get everything placed correctly.



*Figure 6:* Solved sample exercise

To maximize usability of the created content, all of the exercises were exported as short “turntable” videos where the camera moves around the completed model. Also a COLLADA version (via DAE files) of the completed exercises was produced, which can easily be used with WebGL implementations that allow these models to be posted to web services like the aforementioned Sketchfab.com and then embedded in any other website, for example a web-based Learning-Management System like Moodle.





Figure 7: Interactive WebGL browser view of timber frame model

To support project-based curricula and foster creativity, some of the exercises are left open-ended. For example, one of the exercises asks students to model an arbitrary concrete volume. They then must add appropriate formwork to this shape from a library of available parts (mainly plywood and studs). As part of such an exercise, students invariably run into problems where elements overlap and assemblies must be resolved in 3D space – just as would be the case on a construction site.

While this set of exercises is quite complete, instructors are certainly encouraged to go beyond them and use their students' newly-learned 3D modeling abilities for other virtual projects. Examples could be:

**Term design projects**, e.g. for a shed, a bridge or similarly-sized structures. These projects can even venture into questions of prefabrication and transportation or using software for materials estimating.

**More open-ended exercises.** These can build on and use virtual objects from any of the included exercises or be completely separate from them.

**Enhanced 3D student presentations.** Any of these tasks can be presented by the students to a class in a very interactive manner if the presentation is done in the 3D environment. When presented on a large screen, details can easily be explored (and mistakes can be found!) and the entire class can be better included in the 3D modeling thought process. For open-ended problem-solving tasks, this approach can even include a live-modeling design charrette-like presentation.

Students who complete all of these exercises in this process likely will have developed a better understanding of assemblies and building systems than could be gained from descriptive text and images alone. They will also have honed their abilities in spatial comprehension and should perform better in plan-reading and constructability testing exercises.

The digital nature of these exercises also solves many of the aforementioned problems that may be encountered in a materials and methods class: They allow a student to use “full-scale” steel beams without safety concerns. They also permit an instructor to scale up their course's hands-on component without the need for additional resources. Lastly they offer the possibility to include lab activities into an online course that can be scaled as needed.

## Implementation

Exercises as presented in this paper are quite easy to set up for a skilled instructor with good knowledge of 3D modeling and CAD software and instructors should very much be encouraged to adjust this approach to their individual needs. At present, however, this set of exercises has also been implemented for the 6<sup>th</sup> edition of Edward Allen and Joseph Iano's book "Fundamentals of Building Construction: Materials and Methods", published in October 2013 by John Wiley & Sons, Hoboken, NJ. (Allen and Iano, 2013). The exercises, all produced by this paper's author, are available through the Interactive Resource Center, an online repository that is included with new book purchases.

In light of the aforementioned background observations – and certainly also as part of a highly competitive publishing environment – textbook publishers have adapted their textbook offerings to include not only the core text but also offer interactive resource material that increasingly can be used online or on a student's computer.

Examples for these are:

- Question banks (that can be imported by the instructor into learning-management software)
- Online quizzes and flashcards
- Animations and full-color illustrations
- Videos, image and PowerPoint slide libraries
- Exercise books and teacher instruction material
- Interactive e-books

The exercise curriculum materials presented in this paper expand on these sometimes quite "static" offerings and attempt to remedy some of the aforementioned shortcomings of the various AEC curricula. If the time commitment for completing these exercises is made by an instructor, it is – as stated before – postulated by the author that the benefits will impact the entire AEC curriculum positively even beyond the construction materials and methods class itself.

Because of the recent publication date of the exercise material and this book, at the time of writing this paper no evaluations of student performance and survey results are available. However, student progress will be monitored over the spring semester 2014 and findings will be reported in a follow-up paper.

## Summary

A set of 3D modeling exercises have been presented that:

- Allow a student to use an easy-to-learn and free 3D CAD program (Trimble's SketchUp Make) to learn about building assemblies using only a few non-complicated commands.
- Allow a construction materials and methods course to have its students experience assemblies and systems without the need for expensive and time-consuming labs.
- Offer flexibility in scaling up class sizes (and creating online classes) since all of these exercises can be completed on a student's own computer.
- Introduce students to 3D modeling, which benefits spatial comprehension, understanding of constructability and inherent error-checking.

These exercises were included in the latest edition of Edward Allen and Joseph Iano's book "Fundamentals of Building Construction: Materials and Methods". Overall, these 46 exercises encompass the breadth of the book and include the main materials (wood, concrete, steel, masonry) but also non-structural assemblies like tiling, stairs, and curtain walls. Together with this book's other ancillary materials (question banks, image collections, animations, and presentations) and other instructor-specific resources, this set of exercises will certainly aid in a student's comprehension of this topic. Some interactive exercises are left open-ended and should even spark creativity and foster problem-solving skills.



## Acknowledgements

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## References

Allen, E., and Iano, J. (2013). "Fundamentals of Building Construction: Materials and Methods". John Wiley & Sons, Hoboken, NJ

Allen, I. E., & Seaman, J. (2010). "Learning on Demand: Online Education in the United States, 2009". Sloan Consortium. PO Box 1238, Newburyport, MA 01950.

Autodesk (2013). "Mobile Apps". Retrieved 10/24/2013 from <http://www.autodesk.com/mobile-apps>

Glick, S., Porter, D., and Smith C. (2012). "Student Visualization: Using 3D Models in Undergraduate Construction Management Education". International Journal of Construction Education and Research, 8:26-46, 2012

Hmelo-Silver, C. E. (2004) "Problem-Based Learning: What and How Do Students Learn?". Educational Psychology Review, September 2004, Volume 16, Issue 3, pp 235-266

Joannides, M.M., Olbina, S., Issa, R. (2012) "Implementation of Building Information Modeling into Accredited Programs in Architecture and Construction Education". International Journal of Construction Education and Research, 8:83-100, 2012

Martin, F.G. (2012) "Will massive open online courses change how we teach?". Communications of the ACM CACM, Volume 55 Issue 8, August 2012

Mills, E., Treagust, D. (2003) "Engineering Education – Is Problem-based or Project-based Learning the Answer?". Australasian J. of Engng. Educ., online publication 2003-04. Accessed 10/24/2013 from: [http://www.aeee.com.au/journal/2003/mills\\_treagust03.pdf](http://www.aeee.com.au/journal/2003/mills_treagust03.pdf)

Perrenet, J. C., Bouhuijs, P. J., and Smits, J. M. (2000). The Suitability of Problem-based Learning for Engineering Education: theory and practice. Teaching In Higher Education, 5(3), 345-358. doi:10.1080/13562510050084730

Schreyer, A. (2012). "Architectural Design with SketchUp: Component-Based Modeling, Plugins, Rendering, and Scripting". John Wiley & Sons, Hoboken, NJ

Trimble (2014). "SketchUp Make". Retrieved 1/23/2014 from <http://www.sketchup.com/products/sketchup-make>