Journal for Geometry and Graphics
Volume 19 (2015), No. 2, 301–316.

Computer Graphic Modeling for the Reconstruction of the Roman Colosseum

Adrian H. Tan, Frank M. Croft Jr., Fabian H. Tan

The Ohio State University, Department of Civil Engineering
2070 Neil Avenue, Columbus, OH, United States
email: tan.191@buckeyemail.osu.edu

Abstract. This research focuses on a digital step-by-step recreation of the construction process of the Colosseum, the famous ancient Roman amphitheater, demonstrating that the process of retracing the construction of such a large and complex monument presents a variety of challenges. Computer-generated imagery, or CGI, has been used to recreate ancient structures based on literature and archaeological evidence, focusing primarily on completed structures during their period of use. Given enough data, computer graphics can serve as a tool in simulating the construction of ancient monuments as well, though this approach warrants a balance between optimization and accuracy. Provided with extensive literary research and on-site analysis, the simulation discussed uses general-purpose engineering graphics software which provides an ideal balance of user-friendliness and complexity handling. The creation of the model, using the functionality of the software in question, reveals significant potential as an educational tool for understanding the enigmatic construction processes of the Colosseum, as a training tool for the construction operations of ancient edifices, and as an investigative tool for renovating such structures. Still, setbacks such as complexity spikes and erroneous feature mapping, owing to the dissonance between the computation capabilities of the hardware, the functionality of the software, and the data values provided need to be overcome.

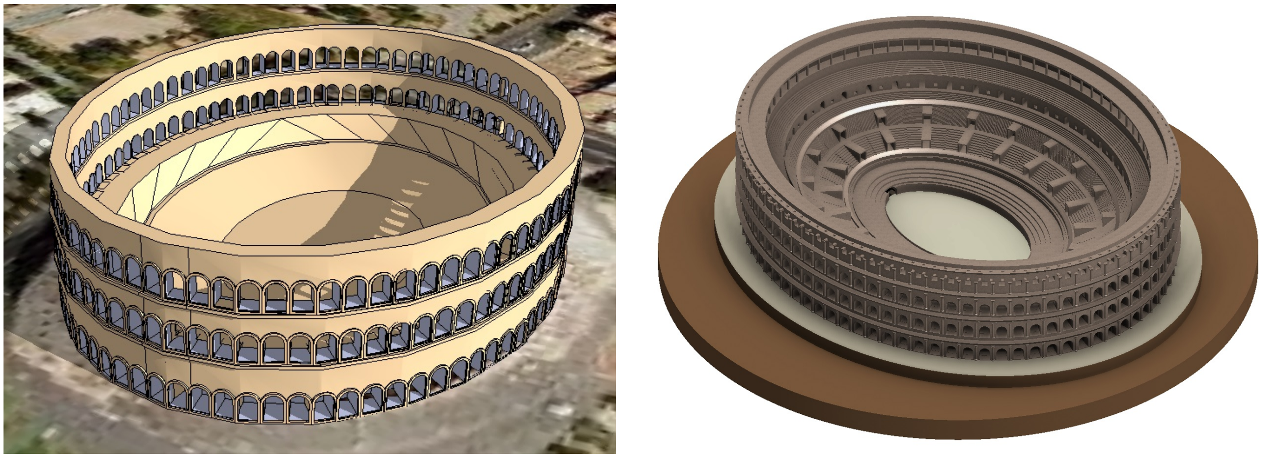
Key Words: Computer graphics, digital modeling, computer aided design, architecture, archaeology, Colosseum

MSC 2010: 68U07, 00A67, 51N05

1. Introduction

With the advent of modern technology, the creation and analysis of architectural blueprints and simulations is becoming a second-hand task, particularly in light of advancement in

ISSN 1433-8157/$ 2.50



(a) (b)

Figure 1: Two different possible graphics engines were tested for a prototype model of the Colosseum: Google SketchUp (a) and Autodesk Inventor (b). Google SketchUp can integrate the model into an environment, but at the expense of accuracy. Autodesk Inventor, while so far unable to reproduce backgrounds, can produce a more accurate model in the long run, which is why this engine was used for the final model.

Computer-Generated Imagery (CGI). One aspect of digital reconstruction involves the restoration of ancient structures and monuments, along with understanding of the processes that created them. The efficacy of computer simulation makes it a valuable utility in the analysis of engineering and construction in history; however, a potential point of contention concerns the extent of said efficacy, in that the software requires an optimum balance between data conservation and authenticity. This study demonstrates that although computer simulation via an engineering-geared modeling program can recreate the construction of ancient structures in accordance to historical records, it is not without its flaws and as such presents important implications regarding simulations of this nature.

1.1. Software selection

Several different programs and/or options can be used to create a simulation of the Colosseum among other monuments. The first option would be to create the model from the ground up, using programs written independently of existing interfaces. However, this approach is disadvantageous, since the matters of rendering objects in the first place must be addressed before any modeling of the Colosseum can take place, and the sheer amount of detail and coding involved would render this strategy impractical.

A less time-consuming method would be to use an existing graphics program, such as Google SketchUp or Autodesk Inventor, to create the simulation. This approach has the benefit of being far more flexible and faster to implement, because the baseline graphics programming has already been defined.

Several different graphics programs were considered for use in this study. Originally the intent was to create the model using Google SketchUp and superimpose it over a map of the surrounding landscape. However, the user interface does not support real-time adjustment of dimensions or automatic feature patterning, and therefore such a task would be fairly arduous at the minimum (Figure 1a). The most viable option, and the one that is used in the final model, is Autodesk Inventor. Here the model can be shaped more easily and may include a higher degree of complexity for less effort; the disadvantage is that backgrounds are more limited, but the model is intended to provide insight as to how the monument was constructed as well as how it would have appeared, so the surrounding landscape is a minor aspect compared to the model itself (Figure 1b).

1.2. Recent studies

Models of the Colosseum, as with other ancient monuments, do exist and have been created based on historical data. Many of these are reconstructed with varying degrees of accuracy, but what is important is that said accuracy applies mostly to the superstructure because it is the best-known aspect of this monument. Archaeolibri's model of the Colosseum is intended for professional use in archaeological guides, and as such presents an accurate restoration with realistic detail [1]. Another model, produced by Vision Publishing, superimposed digital imaging over a photograph of the modern Colosseum, filling in the gaps left behind by centuries of degradation [4].

One of the major implications of these models is that they show how the monument and surrounding locale appeared upon completion. What is important is that the construction process of the Colosseum, which is of similar importance, is usually overshadowed by the monument's appearance after completion and during its use. For a model that capitalizes on information pertaining to the construction of the monument, the foundation is subject to as much discussion as the superstructure. Starting from this point, the monument can be constructed and then broken down into stages as per the existing data, providing a picture of not only what this building looked like, but also how it was built.

2. Modeling process

The model used for this project was sculpted, modified, and finalized on Autodesk over at least eight months, partly due to the detailed research that was required to ensure its accuracy and partly due to the complexity of the monument itself. It is based on a combination of the reconstruction in *Rome's Museo Colosseo* and the 1725 print, *L'Anfiteatro Flavio* [3], modified to fit the dimensions of the existing arena and the exterior walls in the model.

The foundation was of the linear type, meaning the load of the elevation walls was distributed over their planimetric, or two-dimensional, outlining [2]. This means the substructure can be rendered using outlines of the foundation, and can be modeled in a similar manner to the actual building process. An ellipse of the same dimensions as the Colosseum was used as a starting point; the foundation walls were built upon this using extrusion features based on the wall outline (Figure 2).

There are two elliptical rings in the superstructure, the inner and outer. To create the level borders and the seats, sweep features, or profiles extruded along a path, were used along with cross-sections of the radial ribs and the building's internal structure, respectively, both obtained from site photos (Figure 3). The path was a projected ellipse derived from the wall extrusion, enabling an elliptical sweep (revolved features have a fixed axis and are used primarily for cylindrical features rather than elliptical ones).

The 80 entrances were created using a single Boolean difference extrusion and a procedural array — that is, a pattern of regularly spaced features along a given path. This enabled the creation of three rows of arches, resulting in an 80 by 3 elliptical array of difference extrusions (Figure 4). The windows on the topmost story were created in the same manner later,

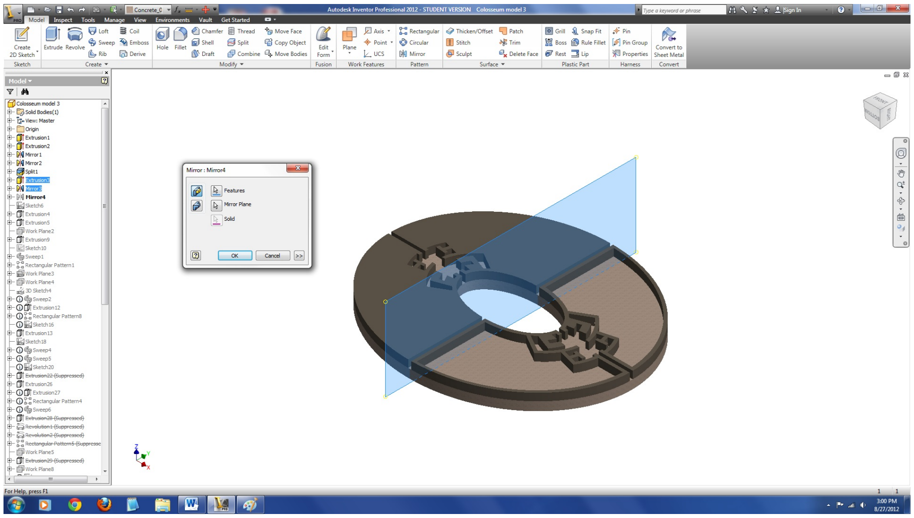


Figure 2: Foundation construction

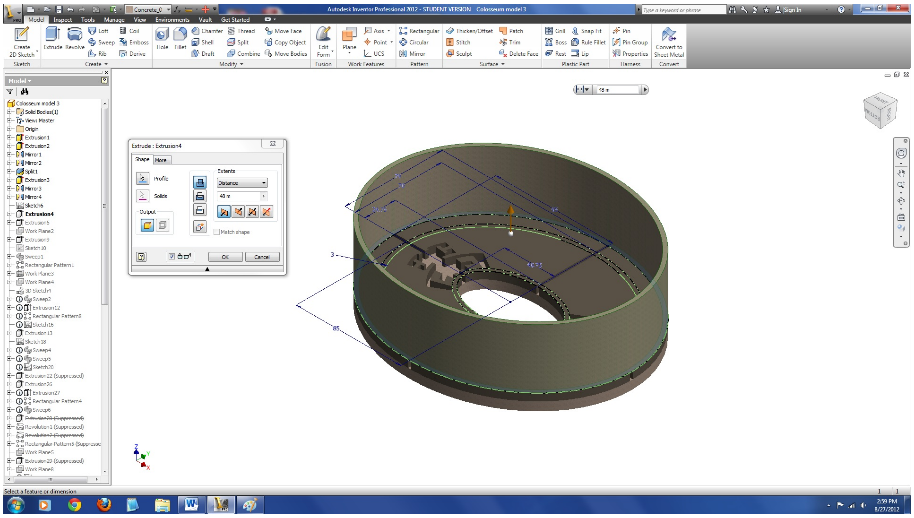


Figure 3: Extrusion features for walls

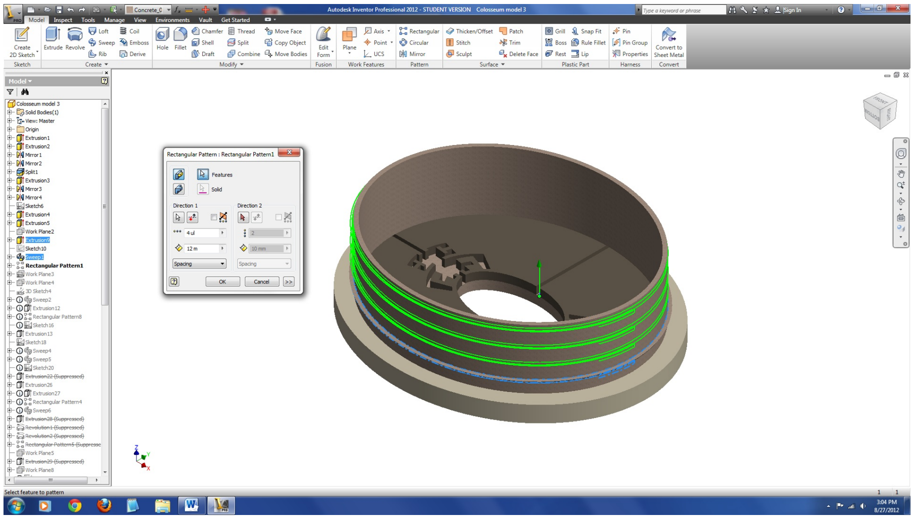


Figure 4: Entrance and archway construction

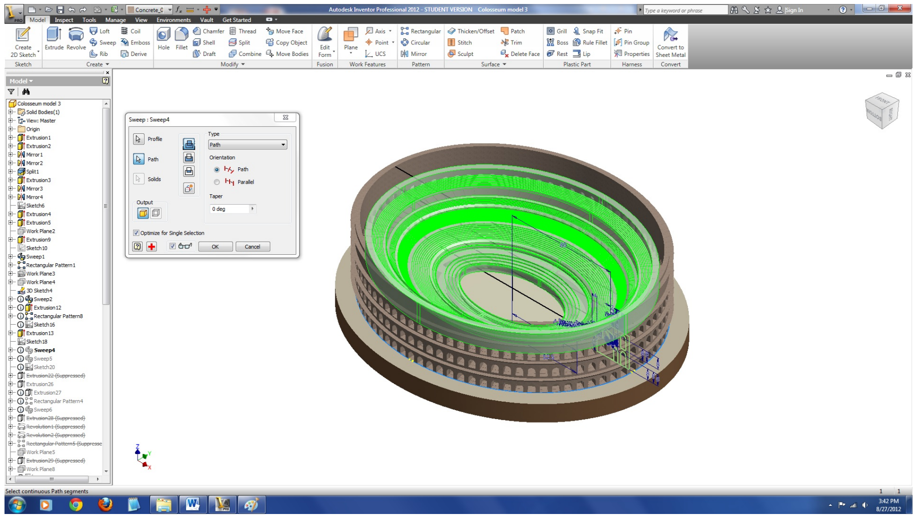


Figure 5: Seat tier construction with Sweep feature

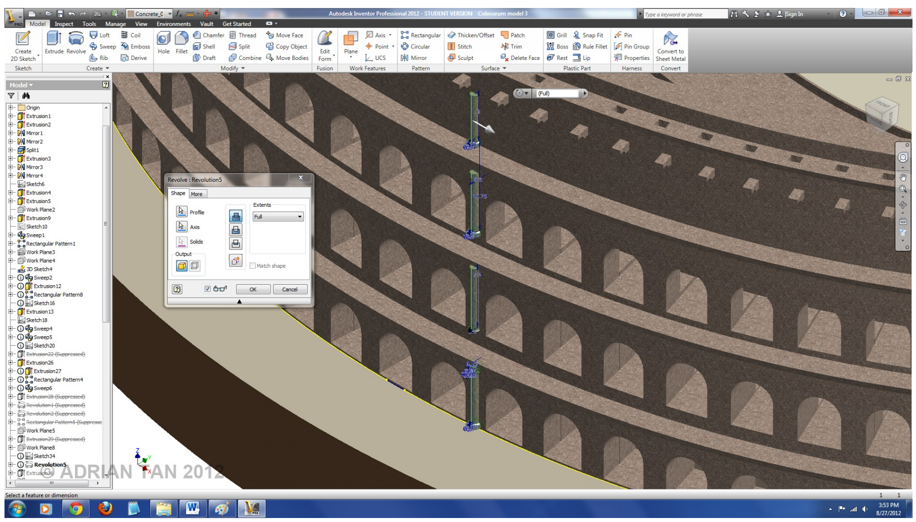


Figure 6: Pilaster construction

although only one row was required. The path for the elliptical arrays was later used for the seating sweep feature, as shown in Figure 5.

Each of the 80 arches is bordered by a pair of semi-columns; the risk of data lagging limited the detail to a stylized appearance as opposed to a more historically accurate version. A work plane was created at the midpoint between the two arches nearest to the YZ plane. Then four column cross-sections were created on the work plane, and all of them were used in a revolved feature (Figure 6). Finally, another linear array was used to duplicate all of the column features, using the same process for duplicating the archways (Figure 7). On a side note, there were reportedly statues gracing the second- and third-story arches; these were ultimately omitted in this project due to complexity constraints.

The passageways leading to and from the seats were recreated via procedural rectangular patterns of extrusion features. The passageways and windows leading to the third-story seat level were replicated through difference extrusions and patterned alternately. The doorways were patterned 40 times, and the smaller windows patterned 80 times, with every other

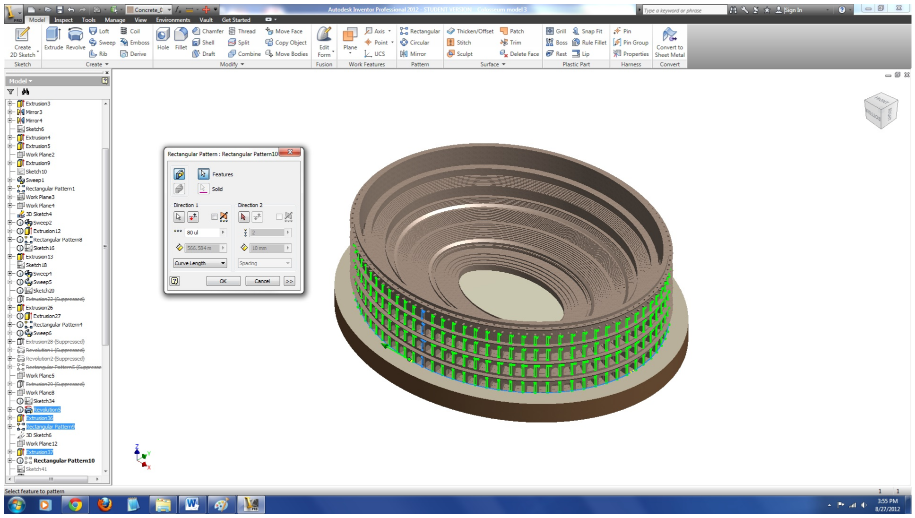


Figure 7: Pilaster patterning

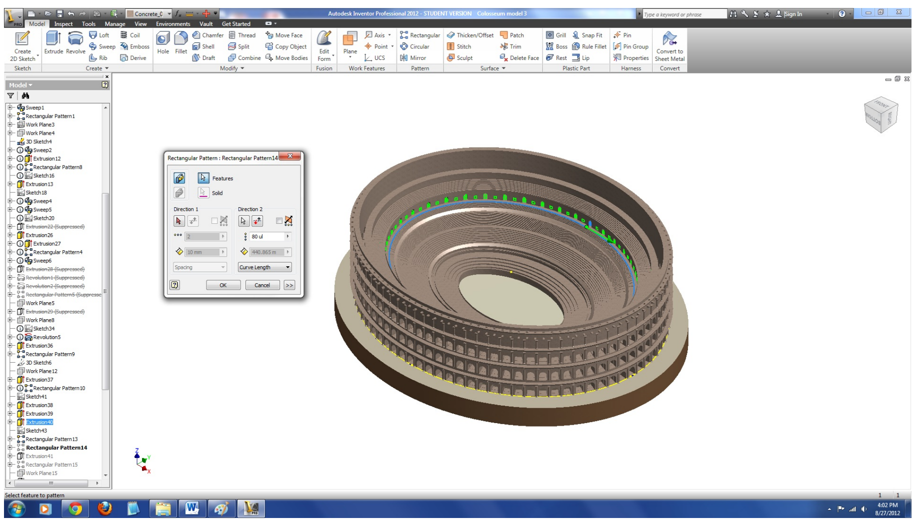


Figure 8: Passageway patterning

extrusion not affecting the model due to it extending into the area already removed by the doorway (Figure 8).

Each *vomitorium* was created using two extrusions: one to create the feature itself and the other to eliminate the stairs inside (Figure 9). These were elliptically patterned per the quarter-section view from Fontana's print [3] (Figure 10). The stairways were created using a different approach because a rectangular pattern would not have lined them up evenly between the *vomitoria*. Five stairways were created independently with five separate work planes based on axis points between each of the *vomitoria*. Then these stairways were mirrored on both the XZ and YZ planes to create 20 different stairways.

The final component of the superstructure was the *velarium*, which has left the least physical evidence. A common theory was that it was hung on a network of ropes tied to the 240 masts that would have fit into the corbels of the structure; however, other evidence suggests horizontal booms supporting a shorter awning (Figure 11). These two possibilities were reconstructed as an experiment by a team of experts under the surveillance of NOVA,

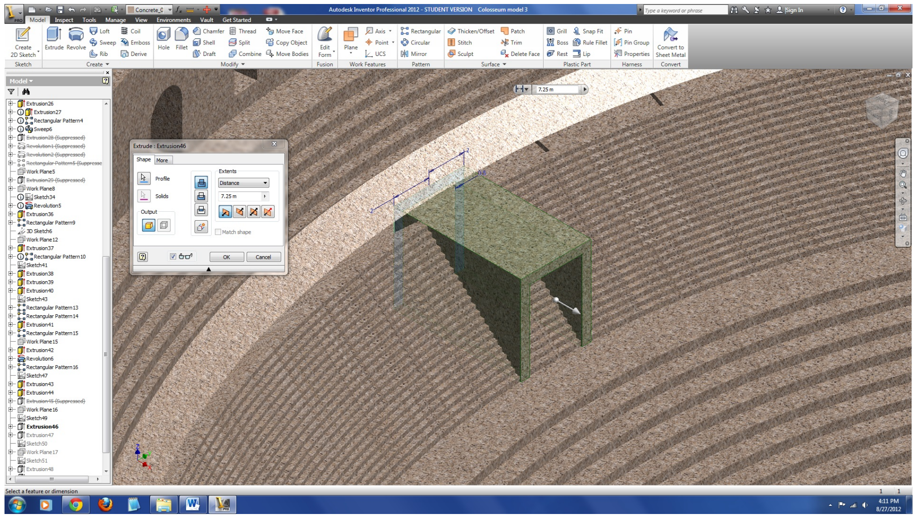


Figure 9: *vomitoria* construction

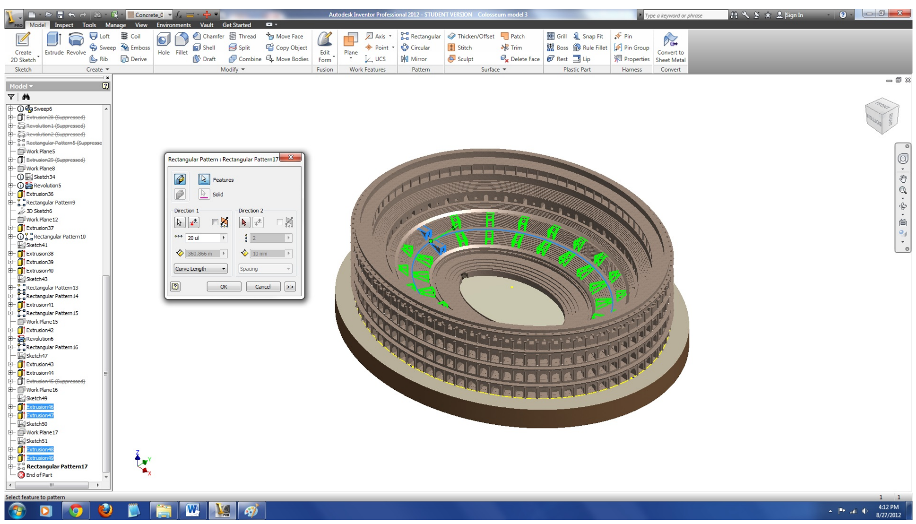


Figure 10: *vomitoria* patterning

the science television series. It was deduced that the mast system would have been more likely (Figure 12); though shorter, it would have been easier to retract, and was surprisingly effective as a sun shade [5].

Due to data constraints, a simplified version of the *velarium* was created for the project. The 240 corbels and the corresponding holes on the topmost exterior ribs were replicated via the same rectangular pattern approach used for the archways. The masts and booms were created with two revolved features (i.e. revolving a profile around a central axis) that were copied likewise. The *velarium* is an extruded feature, but with a nominal thickness (about 0.1 m or so) to pass off as a membrane, as surface features are typically translucent/transparent (Figures 13, 14).

The final phases of creating the simulation, the level stages and section view, were created from the finished model. The two main processes involved are respectively to subdivide the model into individual levels and to cut a section from the model before replicating the interior. The superstructure was divided via extrusion features that removed each of the stages, starting

Figure 11: A close-up of the fresco, *Brawl at the Pompeii Amphitheater*. Note the *velarium* structure outlined in red, over the top of the stadium. (Robert Etienne: *Pompeji, die eingeäscherte Stadt*, Ravensburg 1991. *Museo Archeologico Nazionale*, Naples.).

from the attic down to the ground floor (Figure 15). This is where the disadvantage with the method described became clear: the model was created in one solid piece, meaning that replicating the individual sections would require a more powerful engine to accommodate the increase in complexity.

For the section view in Figure 16, a segment of each of three revolved difference features

Figure 12: Two possible models for the *velarium*. The rope-supports are more vulnerable to high winds, while the masts are shorter but can be retracted in hostile weather (WGBH 2006).

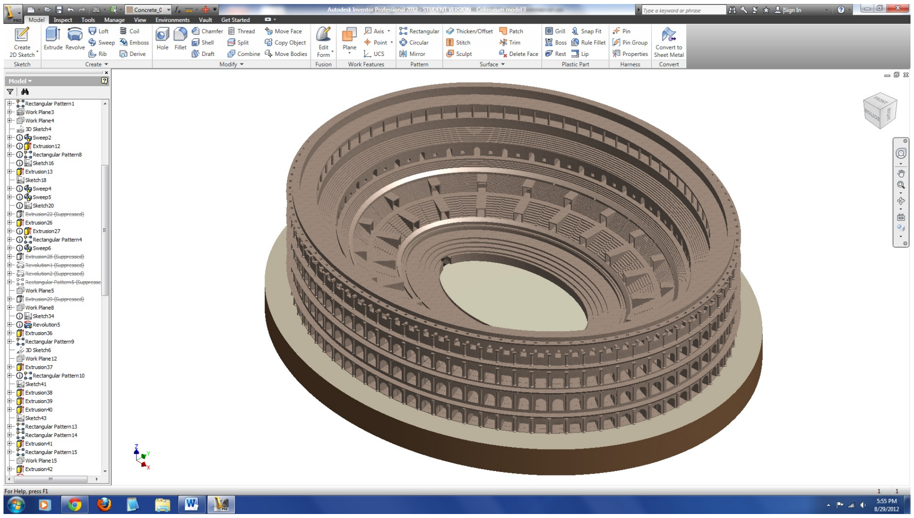


Figure 13: Colosseum without *velarium*

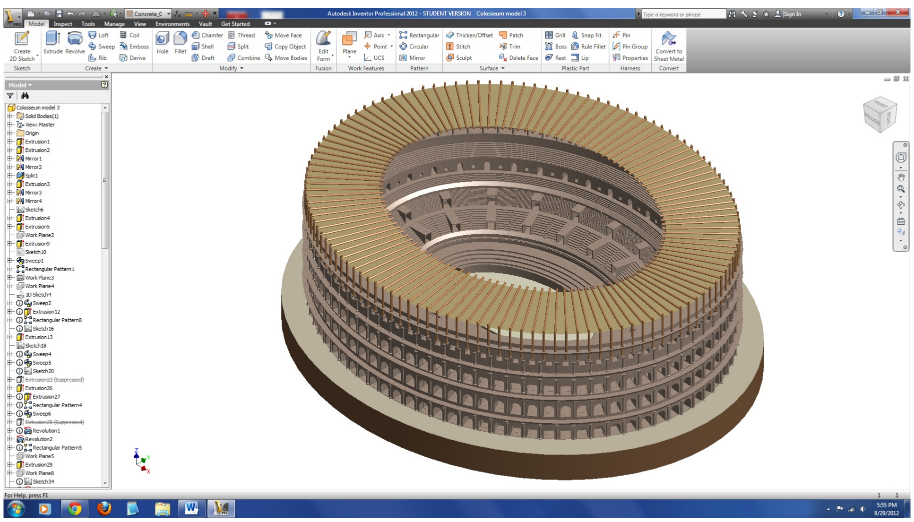


Figure 14: Colosseum without *velarium*

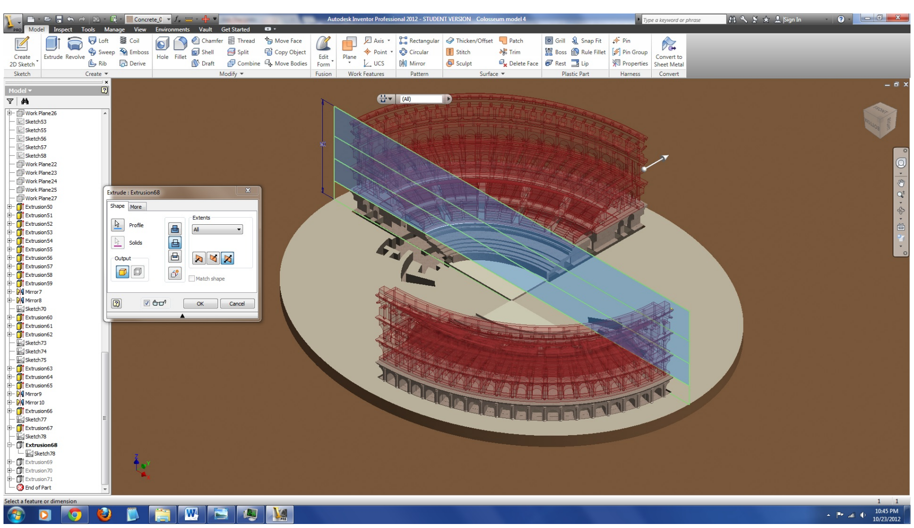


Figure 15: Reverse-engineering the model construction stages

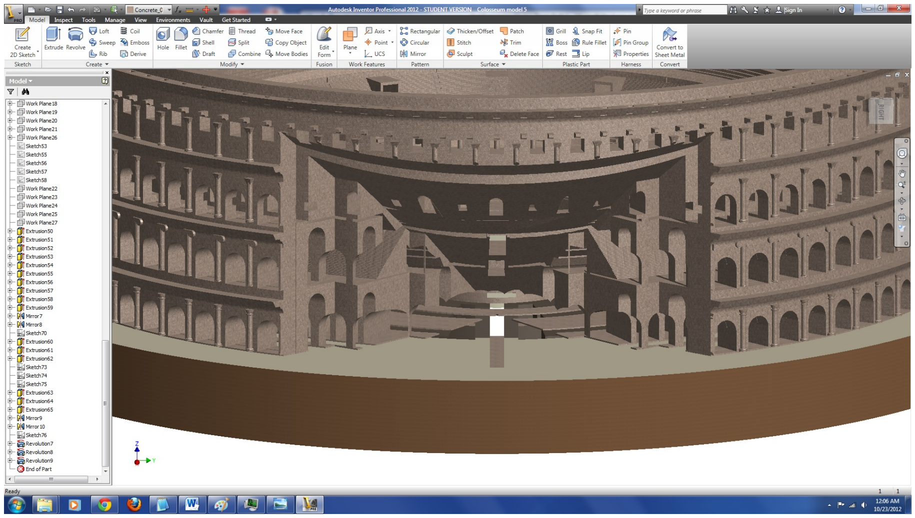


Figure 16: The inaccurate sectional view prior to modification

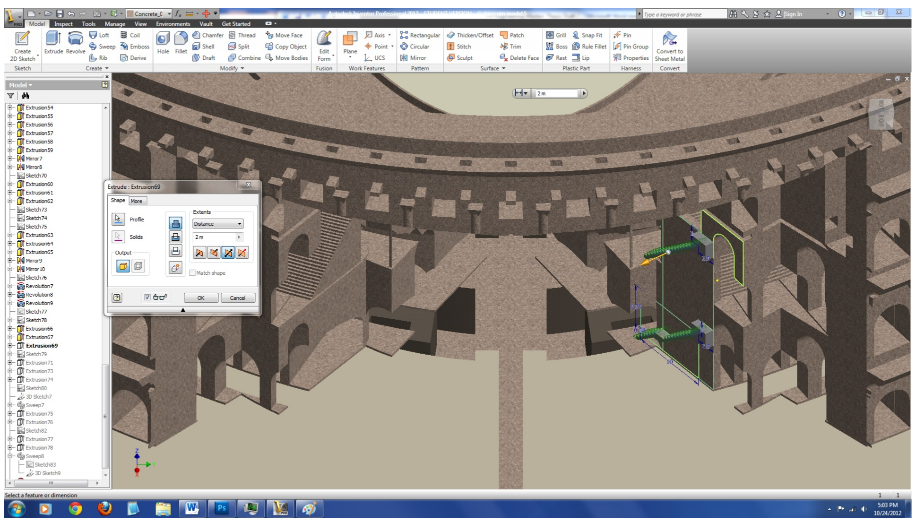


Figure 17: Extrusion of the dual stairways

was positioned so that the resultant slice could provide a cross-section of the model's interior without interfering with the seating. Compared to a scale model of the actual structure, the interior of the digital model would still be inaccurate, primarily because the stairways were not modeled during the initial sweep feature that created the interior and seating (Figure 16).

To remedy this for the section view, the stairways were created manually for each side of the split. In the figure, the right side has two stairwells, one on top of the other. These were created using a single sketch feature, which was marked with the Shared attribute meaning that the sketch could be used to create multiple features. The stairways are drawn in by hand, with excess line-work trimmed and open loops closed as necessary. Another set of extrusion features is used to create the stairways (Figure 17).

The completed model is shown in Figure 19. Notice that to complete the image, a ground object was added and preprogrammed shading was applied for realism.

The side of the section view that had two stairways in opposite directions connected by a landing was more difficult to construct because it required some modification of the

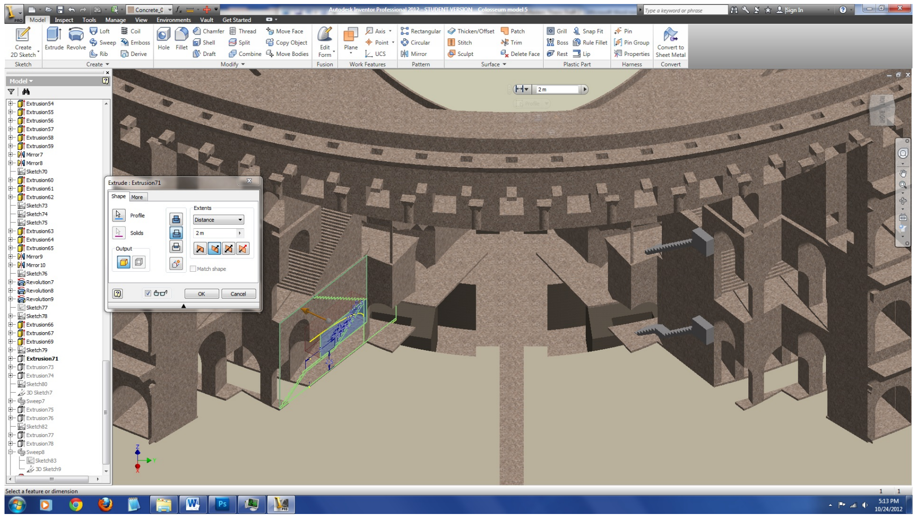


Figure 18: Removal of the filled interior space, to make way for the connected steps

cross-section to accommodate them. A series of extrusion features was used to clear out the protruding portions of the interior. Notably, the connected stairwells were created from difference extrusions because it was concluded that excess system lag could be reduced by creating them from the existing wall (Figure 18).

3. Analysis

The stages of the Colosseum erection as recreated by the model are shown in Figures 20 through 24. Two of the four sections have been removed, so the cross-section of the Colosseum during each stage is also visible. A number of views of the Colosseum model can be used to judge the integrity and reliability of the model in comparison to the actual monument. At

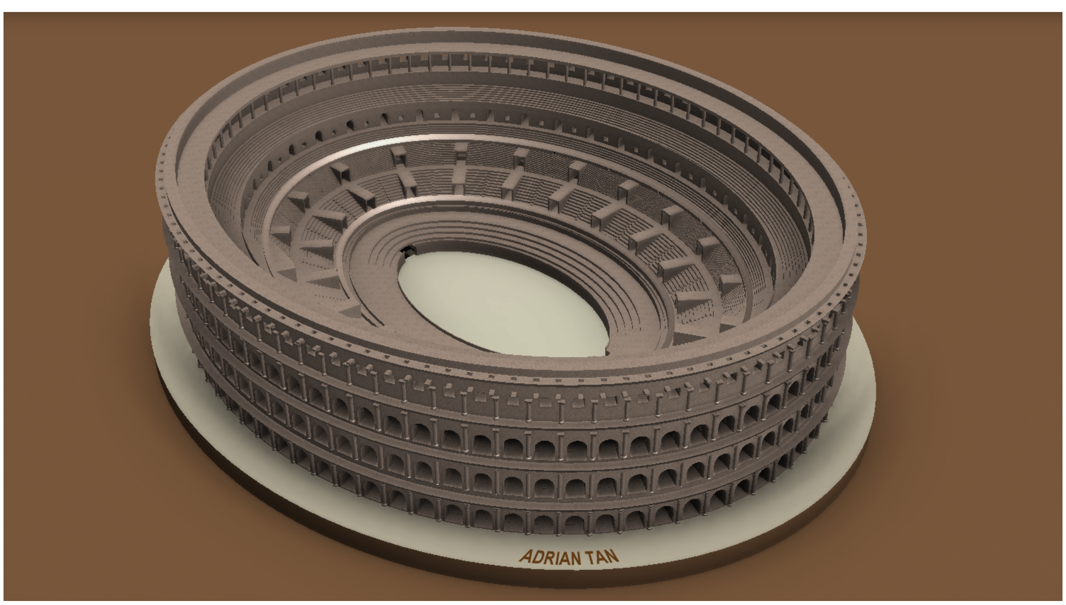
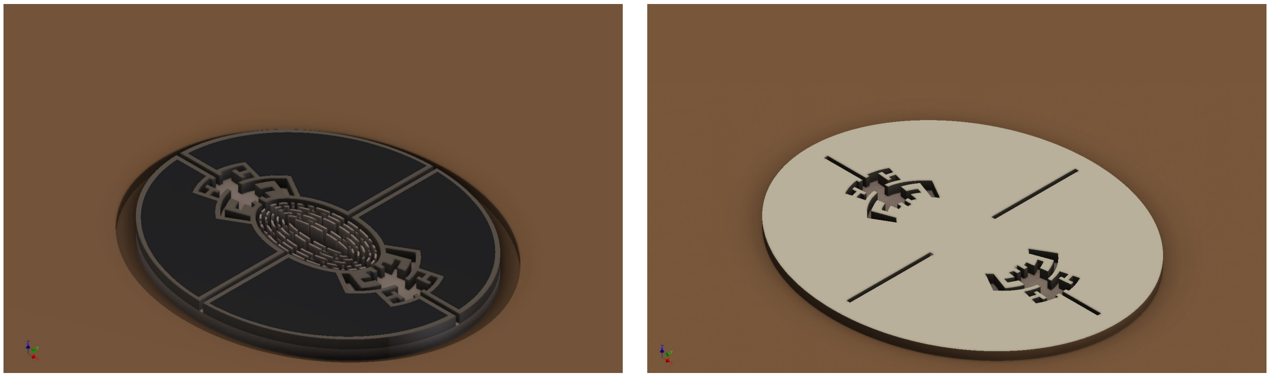


Figure 19: The completed Colosseum model, with perspective, preprogrammed shading and a ground platform



(a) (b)

Figure 20: The foundation prior to the first level of construction (a) without the floor surface/ arena and (b) with the floor surface/arena.

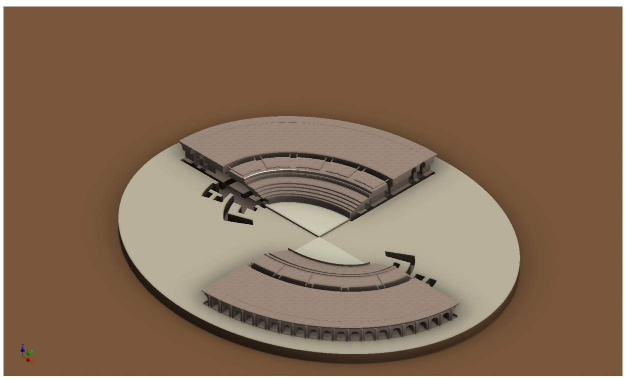


Figure 21: Cross-sectional view of the first level of construction

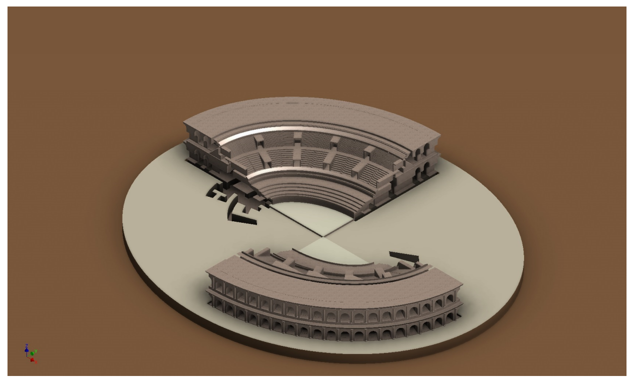


Figure 22: Cross-sectional view of the second level of construction

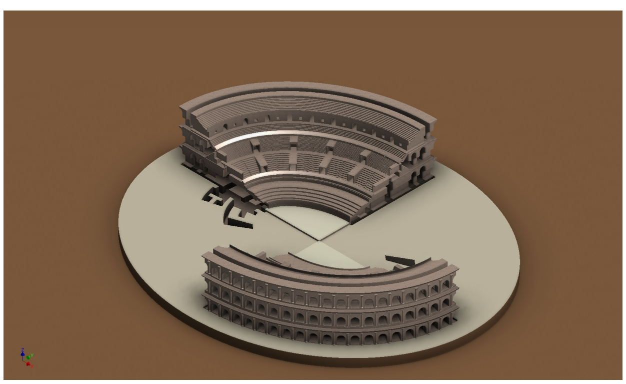


Figure 23: Cross-sectional view of the third level of construction

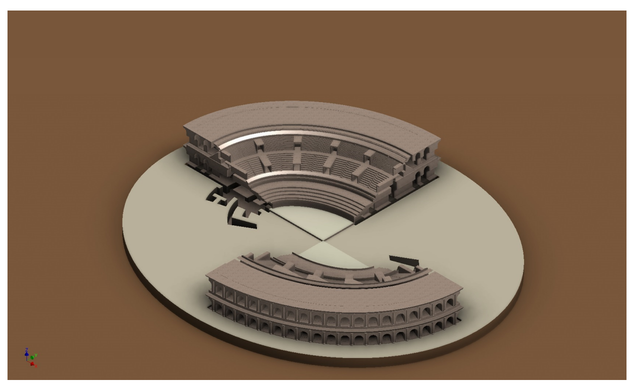


Figure 24: Cross-sectional view of the fourth level of construction

first glance, the exterior is similar to other restorations of the monument in terms of the outer decor, and the interior shows the *vomitoria* and stairwells in positions akin to the historical print used as a reference. However, despite resemblances to the actual structure, there are subtle differences which could potentially compromise the accuracy of the model.

For example, the floor of the arches is not on the same level as the radial ribs, but above

(a) (b)

Figure 25: A column abutment from the Colosseum interior (a) is compared with a corresponding structure from the model (b), which shows that the model column is relatively unrealistic, partly due to the lack of photorealistic texture.

(a) (b)

Figure 26: A comparison between one of the *vomitoria* in the Colosseum (a) shows that it does not have the attic overhead, as in the corresponding structure in the model (b).

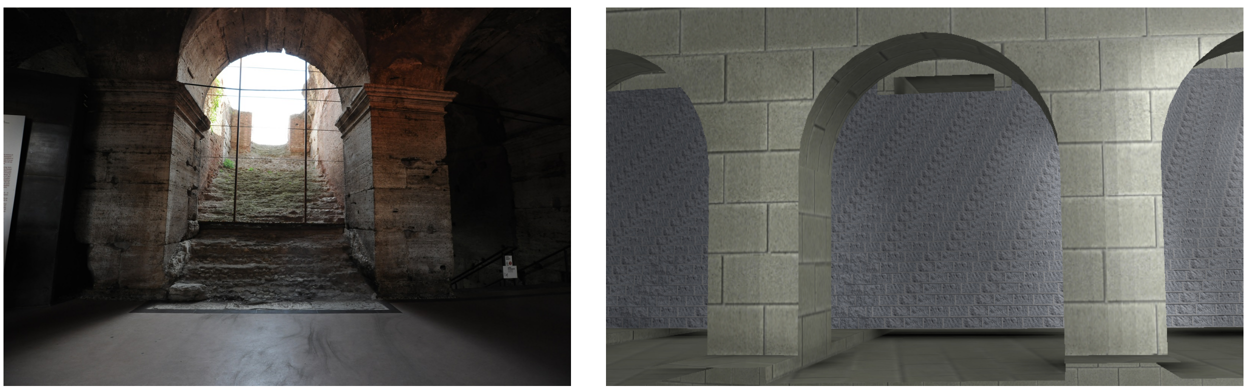
them because of the different distances for the rectangular patterns (Figure 25). Inside, the *vomitoria* are dead-ends because the stairways overshadow the passageways into the interior. Additionally, the second floor has raised areas between the archways, and the first floor is level to the ground plane.

The contrast between the interior of the digital model and the interior of the scale model shown in Figure 29 shows the contrast between the two models more clearly in the second animation. The initial zoom-in is directed towards the foundation of the model, which is obscured by the floor. This can be justified by Inventor recognizing additions in a part as union features, which is particularly important when the fact that this model is essentially one large, complex part is taken into consideration. And anyway, this is the least of the setbacks demonstrated in this animation.

The stairways in particular are not as well designed as other aspects of the model. The interior of the model is created entirely using sweep features to reduce complexity, but this is at the cost of accuracy. The interior would have had a complex network of stairs and passageways, but the paired stairways of the model section view run into the tops of the columns in front, and the walled stairway does not have entry or exit archways because it is too narrow to accommodate these.

(a) (b)

Figure 27: The arena of the Colosseum has degraded over time (a), and the same can be argued for the concrete that comprised most of the seating. However, the model (b) used a historical diagram as a basis, and may provide some ideas of the monument's appearance in its still pristine state.

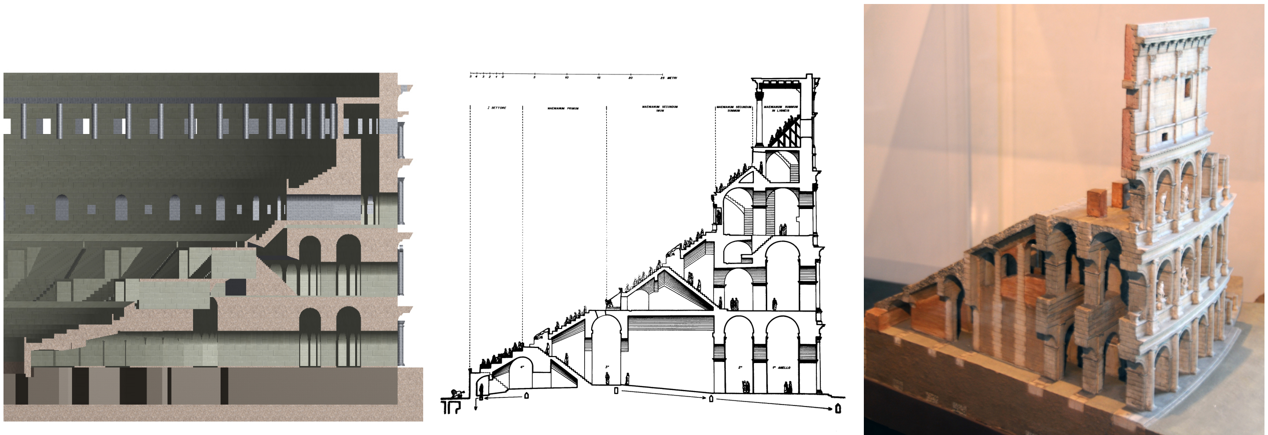


(a) (b)

Figure 28: A sample archway leading up to the seating (a) is further corroboration of the model's interior underdevelopment, as it clearly shows an opening towards the seating which, in the model, is covered by the stairway just behind it (b).

4. Discussion

As the modeling process demonstrates, this simulation can allow for relatively complex details such as the seating, *vomitoria*, and outer décor with simple extrusions, sweeps, and patterns. The model was constructed without having to divide or mirror a fraction of the component because the rectangular arrays can factor in an elliptical path, with the orientation of the components adjusted to the path. Likewise, sweep features can be used to render elliptical features such as the seat tiers and internal structure with a relatively simple series of steps. In theory this degree of complexity can be achieved with any similarly advanced graphics software provided that it has the functional capability of handling the large number of features required. The most significant problem with the modeling simulation would be handling the complexity, due to the sheer amount of data the system must process. At higher levels of complexity, if too many steps are taken at once, the program may stall or, in the worst case,



(a) (b) (c)

Figure 29: This series of cross-sections shows how the Colosseum model can reflect inaccuracies that may result from subjective viewpoints regarding the reconstruction. Miscalculations in the model mean that the seating in (a) has a lower slope than in the official cross section from the *Museo Colosseo* (b) and in the section scale model from the same museum (c).

crash altogether. This means the computer hardware requires further development to catch up with the software requirements and capabilities in order to make this simulation viable. The overall result is a trade-off between rendering capabilities and accuracy, which explains the relative simplicity of some of the more minor elements of the model, such as the outer pilaster caps.

Comparing some of the specific features of the model and the corresponding sites in the Colosseum, several further setbacks are revealed. Based on a historical source, the model does simulate the exterior adequately, but the same cannot be said with respect to the interior. This is especially apparent in the comparison shots shown in Figures 25 through 29; the model features are solid, monolithic structures without subdivision, and overlook key structural components such as keystones in archways, capitals in columns, and so on. So the model is not truly indicative of the appearance of the monument prior to substantial damage and/or renovations. That said, however, the methods of such a simulation can vary enormously. Given a more powerful engine, better software capabilities, and a more comprehensive data pool, it may be possible to recreate the Colosseum interior, but this would come at the expense of both accessibility and comparative ease of use.

The disparities shown in the previous pages suggest that depicting the construction process may be even more taxing than depicting the model itself. The processes for building the Colosseum demonstrate different methodologies with regards to the way the monument was erected, with the digital model being constructed starting with the full walls rather than in levels like the original monument. This is not to say that the ancient construction methods cannot be rendered digitally; it is simply less time-consuming but also less inaccurate to complete the structure before working the steps in reverse, based on the limited historical data that can be gleaned with regards to these methods.

5. Conclusions

Digital simulations of ancient monuments such as the Colosseum may provide a lucrative outlet for such complex structures that can be reconstructed with enough reference material and a bit of speculation. The Colosseum in particular has significance with regards to construction and architecture, with a number of sources providing historically accurate dimensions which can be used for the pictured simulation. And the Romans used a blend of several different styles along with innovations of their own to develop their own fashion of construction and engineering which remains influential. As such, it is expected that the Colosseum can be created in graphical form with enough detail to remain recognizable. Constructing the simulated model, like the actual monument, starts from the ground-up with a foundation built in a similar fashion to source records, while the superstructure uses processes that simplify construction but rely on dimensions with little regard for historical methods.

Where this idea falls flat, in the general sense, is in the simulation of the construction process. The procedures used to create the virtual model in the first place are not without their setbacks, the most notable of which is the increase in render time relative to complexity. More importantly, while this approach could work in theory, the very process of reverse-engineering the procedures could provide an entirely new set of problems, such as subdivision of the structure, recreation of individual features, and possible scaling of equipment and other utilities.

Despite the potential shortcomings of visual simulations of ancient construction, future research and development is nonetheless encouraged in this area of study. Advancements in both computer graphics and historical research may be beneficial in the virtual reconstruction of monuments such as the Colosseum. In due course, such reconstructions can provide an increasingly detailed look into the era when the respective structures were built, thereby enhancing public and academic knowledge of both these ancient monuments and their respective areas and time periods.

Acknowledgements

The author dedicates this paper to his parents, whose love, encouragement, and support have allowed the research required to be possible.

References

[1] C. Giuliana: *Rome Reconstructed.* Archaeolibri, 1996.

[2] C.G. Malacrino: *Constructing the Ancient World: Architectural Techniques of the Greeks and Romans.* J. Paul Getty Museum, 2010, pp. 120–122.

[3] P. Quennell: *Architecture of the Western World.* Newsweek, New York 1971, pp. 38–39.

[4] R.A. Staccioli: *Rome, Past and Present.* Vision Publishing, 2001.

[5] WGBH, British Broadcasting Corporation & WGBH Video: *Secrets of Lost Empires: Colosseum.* WGBH Boston Video, Boston/MA 2006.

Received August 06, 2014; final form October 12, 2015