A Computer-Generated Model of the Construction of the Roman Colosseum

Thesis

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ABSTRACT

This research focuses on the construction process of the Colosseum, the famous ancient Roman amphitheater, by digitally recreating the step-by-step processes that would have been involved in the construction process, 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 long been used to recreate ancient structures based on literature and archaeological evidence. Most of the simulations that are generated, however, focus primarily on the appearance of the structures upon completion and during use. Given enough data, computer graphics can serve as an effective tool in simulating the construction of ancient monuments as well, which is demonstrated via the digital (re)construction of the Colosseum as mentioned previously. Through extensive research and on-site analysis, enough dimensions for the construction process and the architectural features and concepts that such a simulation will likely entail can be obtained to create relatively accurate representations, which will in turn serve as a breeding ground for theories concerning their design, construction, and ability to withstand the test of time.

In this case, the background of the study is presented in the form of the history of Roman architecture in general and especially of theaters such as the amphitheater, the category which the Colosseum belongs to. This clarification provides a starting point for the research, and forms the precedent for most of the ideas that will be employed. The background of the simulation includes software, in this case Autodesk Inventor, which provides an ideal balance of user-friendliness and complexity handling. Coupling this is a structural analysis of the monument that provides the key dimensions and features that are present in the actual model.
With this in mind, the creation of the model, using the functionality of the user interface, is compared to the actual construction, revealing a critical dissimilarity. The model renders the superstructure as one continuous feature, with all the levels being created at once instead of in stages as per the original construction process. In addition to this setback, the modeling procedure is also affected by other complications, most notably the linear correlation between complexity and render time. Large amounts of features such as those seen in the Colosseum would cause the program to potentially stall in a bid to process the corresponding amount of data, which may be due to the dissonance between the computation capabilities of the hardware and the functionality of the software.

Technical complications aside, the simulation also shows mixed results conceptually. With technology advanced enough to handle the complexity, the construction stages could theoretically be rendered, but they must be reverse-engineered from the completed model. This precludes using the simulation as a direct influence in both historical studies and civil/green engineering, and furthermore, it fails to take into account the labor, expenses, and sustainability issues regarding the structure. Thus, this simulation is best applied not as a direct reference, but rather as a demonstration of the concepts behind it.
To my parents
VITA

2007

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Fields of Study

Major Field: Civil Engineering and Geodetic Sciences
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Regarding this thesis, I am grateful towards Dr. Frank Croft who, as my thesis advisor, has been very patient with me and has allowed me to explore a research topic related to my expertise and interest in combining engineering graphics, history, and civil engineering; I am fortunate to have him as my thesis advisor. I also wish to convey my heartfelt thanks to Dr. William Wolfe, who was not only instrumental in getting me into the Civil Engineering Department, but also nurtured me with all his invaluable comments and questions during my biweekly presentations in the construction program. Similarly, I wish to convey my thankfulness to Dr. Rick Freuler for being my committee member; as one of the best teachers in the country, I wish to thank him for his willingness to provide assistance in this study.

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CHAPTER 1:
INTRODUCTION

1.1. Background

Construction is an ancient field, having combined science, engineering, and art since the Neolithic age. 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 Computer-Generated Imagery (CGI). One aspect of construction involves the restoration of ancient structures and monuments, of which only few survive relatively intact, along with understanding of the processes that created them. Digital restoration of these monuments would therefore be very beneficial to the study of construction in ancient history.

1.2. Goal

The efficacy of computer simulation makes it a valuable utility in the analysis of engineering and construction in history. This thesis is intended to demonstrate that computer simulation can be used to recreate the construction of ancient structures in accordance to recorded details. As our understanding of history changes with ongoing research, recreations of constructed works must be increasingly updated with the availability of additional historical data. With this in mind, computer graphics can be valuable in the analysis of antiquity, and it is much anticipated that in the future, it will become an invaluable tool in this field of study.
1.3. Objective

At the current rate of development in computer graphics, it is easy to create simulations of any given structure using advanced computer imagery and research on ancient construction. Therefore, with a combination of historical references for the various dimensions and specifications and state-of-the-art CGI, reproductions can be formulated that are not only accurate but also adjustable should new data become available. Ancient monuments in particular can be restored based on up-to-date information obtained from both actual sites and historical and academic documents, such that they can be digitally rebuilt from the ground up as done by their builders, and therefore visualize them, in the truest sense, when these structures were at their finest and most majestic. The objective of this study is to simulate the step by step construction process, from the substructure (foundation) to the superstructure, of the Colosseum of Rome, one ancient landmark of particular significance, restoring it digitally to its original appearance, so as to replicate how the people of their civilizations presumably constructed it as well as how they would have seen it during its heyday.

1.4. Tasks

For this project, computer simulation is used to recreate one particular monument, the Colosseum of Rome. Considering the capabilities of today’s graphics programs, the creation of accurate models of both of these structures can be considered a relatively simple task, particularly due to the measurements that many references supply, and partly due to the constantly increasing proficiency of the hardware and software
involved. Thus, CGI is a very useful and helpful utility concerning this undertaking, with regards to both artistic quality and historical accuracy.

The first task in achieving this objective is visiting the Colosseum in Rome, so as to gather measurements from both historical documents related to this structure and from the structure itself. Several site visits to the Colosseum in Rome, in addition to several research sessions to other similar amphitheaters such as in Capua, Pompeii, Catania, and Agrigento in Italy, have been conducted by the author in relation to the subject matter.

The second task in this research is an analysis of the design, materials, and construction operations related to the model. Although evidence related to these topics was previously scant and fragmented, the sequence of steps in construction could still be recreated accurately. The process of construction could be broken down into the substructure and superstructure stages, both of which have been analyzed for the sake of the model. In contrast to some other monuments such as the Pantheon, the Colosseum, despite its iconic status, has not had as much of its original detail preserved, as is evidenced by the fact that only part of its outer wall remains standing. Despite their marked difference in overall appearances, however, all monuments have a substructure, i.e. the foundation, and a superstructure, i.e. the walls and roof (or awning, in the case of the Colosseum), and part of the reason that their respective facades differ may be that different parts of the superstructure may or may not have survived into the present era and were also subject to reconstruction in the meantime.
The third task is the production of digital models based on the data obtained. A preliminary model of the structure has already been created for the sake of the study, although it must still be refined with more accurate dimensions once these are obtained through research and analysis. The model of the Colosseum, in contrast to models which could be constructed for other monuments such as the Pantheon, can be used for study of cylindrical monument construction, as well as the structural stresses and failures observed when these types of monuments are subjected to stress from the external environment.

The fourth and final task is an assessment of the construction methods and implications of ancient construction. Of particular note would be the complexity of the monument and how it relates to modern construction. Certain features can be used as a starting point; the archway, for example, was prevalent throughout the monument and in general it was and still is practiced on a large scale in architecture. Discussing the complexity could be used as a basis for updating the model and the concepts that it demonstrates with current innovations and modifications. In this way, modern engineers can learn from the past in general, and therefore build a brighter, more energy-efficient future using ancient civilization as a basis.

1.5. Thesis Organization

From this point forward, this study will be divided into four chapters:

Chapter 2 will serve as an overview of Roman history in general. This should provide a background regarding Roman history for the uninitiated. It should also be useful for
examining the history of specific aspects of Roman culture such as architecture and construction, to simplify comprehension of these concepts for the sake of the analysis.

Chapter 3 examines the history of Roman architecture, and the architectural history of the ancient Roman theater/amphitheater, which will provide the historical precedent for the construction methods of the Colosseum. The generic history will cover the origins of Roman construction, including its progenitors and the influences that shaped it into the style that is recognized today. Common materials and resources used in construction and some techniques that were employed up to and including the Colosseum construction will also be explained. In addition, the amphitheater is a specific type of building, part of the theater category; as such, the history of the theater and amphitheater will also be clarified. Comparisons between Greek and Roman theaters will feature as part of the history and influence; for example, Greek theaters were primarily built on an incline and only featured a half-section, whereas Roman theaters came in both the standard half-encircling version and the full-encircling amphitheater version. Differences such as these can distinguish the specifics about the monument in question, and can thus provide a general idea of the appearance of the completed simulation model.

Chapter 4 discusses the background of the simulation. This includes technicalities related to the software used, recent findings regarding this prospect, and an in-depth structural analysis of the Colosseum. As this simulation will be implemented on an advanced graphics program with a user-friendly interface, the variety of software options allows for a suitable selection. Discussion will also be reserved for current
findings of similar topics, in this case existing computer-generated models of the Colosseum; highlights will be made of what these simulations have in common and what aspects have yet to be addressed. Lastly, the structural analysis aims to provide key figures regarding the shape, structure, building plans, and layout of the Colosseum, so that the model can replicate it accordingly.

Chapter 5 explains the simulation, particularly the software processes that go into the completed model. Afterward the study will focus on the construction processes that created the Colosseum, and in light of this, a discussion of the viability and feasibility of the simulation will follow. The software implementation will build the model using a series of stages and commands on the desired interface, which will elucidate how the model is constructed digitally. This is followed by the construction process of the Colosseum, which is used as an analysis of its complexity and as a comparison with the simulation, to provide an idea of where the model stands in terms of viability. This chapter concludes with a discussion on two levels. The first will be an examination of the model’s standpoint compared to other methods of analysis, along with how it stacks up against models used to plan and construct modern structures. The second is an in-depth investigation into the advantages and disadvantages that both the model the model’s historical precedent would have had from a historical perspective. The relationships between the two regarding the viability of each, including complexity and possible effort/resources involved, will also be featured prominently in this analysis.

Chapter 6 examines the conclusions drawn from the study. Some suggestions for improving the simulation along with its viability in the field of civil engineering are also
proposed to address the setbacks that may be turned up by this study. A summary of what the study has achieved will be given first. Then, conclusions will be drawn concerning how viable the simulation is, whether it can be applied to current studies, and if so, how. Finally, recommendations will be made regarding the application of this study and the concepts behind the simulation to modern construction and civil engineering.
CHAPTER 2:
A BRIEF HISTORY OF ROME

2.1. Pre-Roman Locale and Natives

While this analysis focuses primarily on Roman architecture and the Colosseum, a brief overview of Roman history should provide some background for the uninitiated. To start off, Roman civilization is primarily centered on the Mediterranean peninsula known as Italy, which covers some 301,338 square km (116,347 sq mi) of land with a temperate seasonal climate and is populated by around 60.8 million inhabitants. Rome has retained its role as the capital of Italy and, for a long time, a political and religious center for European civilization. But to understand Rome as a whole, let alone the related construction aspects, it is imperative to comprehend the origin of Roman civilization.

It is difficult to trace precisely when the first hominins arrived in Italy, but there is evidence to suggest that the peninsula has been inhabited since the Paleolithic period: stone tools in Pirro Nord (Puglia Region) date back to as early as between 1.0 and 1.7 million years ago (Arzarello et. al. 2011:6). Of more immediate importance, however, is the advent of humans in the Neolithic realm, which led to the development of the various cultures that existed prior to, and may have influenced, the Roman civilization that would one day settle upon this Italian soil. Northern Italy was the first region of the peninsula to see human populations large and complex enough to serve as a breeding ground for culture in any reasonable capacity. There are a few prominent examples of these: the Camuni of Valcamonica, Lombardia, who carved the famous rock engravings
known from this region; the Terramare ("marl-earth") of the Po River valley, Emilia, named for its extensive lacustrine (marl) deposits and characterized by extensive evidence of pile dwellings (Haverfield 2008 p. 55); and the Villanovans of the Po valley, Etruria, Emilia Romagna (at Verucchio), and Campania, who were famous for their cinerary "hut urns" (Figure 2.1). The last in particular was one of the most extensive, and it is possible that it may have been an ancestor to the Etruscan tribe that would in turn give rise to the ancient Roman civilization someday.

![FIG. 2.1: A pair of Villanovan hut urns. These urns give an idea of the structures that were constructed in the era when this tribe was at its dominant stage. (Museo Civita Romana)](image)

Towards the end of the Neolithic period, Italy became increasingly colonized by the pre-Roman tribes, most notably the Pelasgians of south Italy, who presumably migrated here from the Greek region of Arcadia (Ridpath 1885 v.1:607). In due course, other civilizations also staked out the peninsula, notably the Minoans and Greeks; the latter group may have absorbed the Pelasgians. By the 8th century BC, the region was already colonized by such tribes as the Latins, the Sabines, and the Etruscans themselves. While
the Latins were considered the main tribe (Sanderson et al. 1899 v.1:177-9), the Etruscans were likely the oldest, probably second only to the Pelasgians. The Etruscans were also the most advanced technology-wise, but their origins and culture are still subject to much debate due to the paucity of evidence. Nonetheless, their technology has proved influential to modern science, engineering, construction and architecture both directly and indirectly, which would make the pursuit of their origins more valuable. Evidence suggests that their culture, language, and other aspects were neither Greek nor Italian in character, and several explanations for this inconsistency exist. Herodotus stated that the Etruscans migrated from Lydia (part of Turkey, named after its legendary king) to escape famine (Herodotus/Carter 1958:1.7); modern scholars used to express doubt in the veracity of this report, due to genetic evidence that the Etruscans may have been related to the Tuscans who occupied the same territory (Vernesi et al. 2004:694–704). Nonetheless, recent evidence from DNA tests has moved their origin to the Near East, in Anatolia (Achilli et al. 2007:759-67). Etruscan-written inscriptions of their origin have yet to be found that could confirm this, but regarding their genealogy, the newfound accuracy of Herodotus’s report gives it at least some degree of merit.

As the Etruscans set root in Italy, so other civilizations followed their lead. The Greeks began building colonies in the southern coast between the 8th and 5th centuries BC, appearing in Sicilia, Campania, Lucania, Bruttium, Calabria, and the Gulf of Tarentum. Collectively known as Magna Grecia, or Greater Greece (Caldwell 1956 p. 328), they advanced significantly even prior to the advent of the Roman kingdom. In
fact, Dionysius suggested that several Greek colonies not only sporadically colonized Latium but may have also given rise to Rome itself, though this claim is subject to some controversy (Rolin 1768 v.1 p.3). Regardless, the settlement that would one day become the city of Rome was founded along the Tiber River, near Tiber Island.

The final major tribe that helped influence the early Roman civilization was the Latin people. Their culture, the Latial culture, is categorized by modern scholars into five different periods, from the 11th to the 7th century BC (National Roman Museum-Diocletian). Period I, from the 11th to 10th century BC, began with settlements in the Alban Hill east of Rome; speculation of simple, roof-thatched residences is backed up by baked-clay hut-urns known from this period (Figure 2.2). Period IIA, from the 10th to 9th century BC, saw the spread of agriculture throughout the areas, and village
communities in Gabii, Satricum, and Ardea. Period IIB, during the 9th century BC, is known from evidence of settlement organization; settlements around Rome grew larger during this time, such as in Fidenae, Tivoli, Palestrina, and the Capitoline, Palatine, and Velia Hills. Period III, from the 8th to 7th century BC, was the era of cultural transformation, in which the advent of social classes made the Roman society significantly more sophisticated. Finally, Period IV, during the 7th century BC, showcased the completion of social class division, with wealth being used to develop urban centers throughout the Roman kingdom, including Rome itself.

2.2. The (Rumored) Origin of Rome

As colorful as the actual history of Roman Kingdom is, discussion of it invariably gives way to the legends surrounding its actual founding. The most famous legend is that of Romulus and Remus: reportedly, their mother was forcibly converted by her uncle Amulius to a Vestal Virgin but was later seduced by the god Mars. Once the children were born, they were abandoned to die, but were found and raised by a she-wolf (Figure 2.3) and fostered to adulthood by the shepherd Faustulus and his wife. Once they amassed a following and overthrew Amulius, they set off to found a new city, but eventually argued over the position of founder which led to Remus being killed off. Romulus founded the new city, named Rome after himself, as a haven for landless refugees, and since most were single men, Romulus arranged the abduction of the Sabine women, leading to conflict with the Sabines that ironically united both tribes. It is said by some sources that after a long life as the commander of Rome, Romulus ascended to the heavens and became the personification of the Romans, Quirinus.
The problem with legends such as these is that scholars of the day not only believed them, but often refused to question them. Such was the case for the greatest Roman historian of the time, Livy (59 BC – AD 17), who wrote in his The Early History of Rome (Livy: 1.1, Selincourt 1971:33-34) that he supported the mixture of facts and myth, and also showed prejudice against foreign peoples, concepts, and ideas. Nowadays, the facts regarding Roman civilization must be separated from myth through the analysis of physical evidence - which is the subject of the remainder of this study.

For a map of Italy and the territories that will be discussed from this point onward, see Figure 2.4.

FIG. 2.3: The famous bronze statue of the Capitoline Wolf nursing the infant Romulus and Remus resides in the Musei Capitolini in Rome. Most literature regarding the history of Rome is a mixture of truth and legend, which makes it difficult to determine actual events without genuine physical evidence.
FIG. 2.4: This map of Italy shows the provinces that will be discussed in future sections. The capital and focus of this study, Rome, is highlighted by the green star symbol.
3.1. **History of Roman Construction**

While it is commonly thought that Roman construction and architecture evolved entirely from the style developed by the Greeks, the latter are in fact only one of the many influences towards the former, particularly because the original Roman Kingdom, which lasted from 753 BC – 509 BC, evolved in a unique historical environment that Greece was never able to successfully colonize. The original inspiration for this architectural style, in fact, may have come from the ‘native’ tribes that the Romans contended with, most importantly the Etruscan civilization, although the latter did have trading links with ancient Greece and therefore could have also had its share of Greek architectural influence (Ward-Perkins 1974:11).

Etruscan civilization originally relied on simple structures, as evidenced by the hut-shaped funeral urns found in Villanovan tombs. Different types of tombs emerged later on, built or hewn from tuff found on site: circular tombs reminiscent of prehistoric tumuli; grid patterns dividing tombs into blocks containing several family tombs; and hollowed out cliff-face or ground-level tombs that belie a complex arrangement of chambers, lobbies, and corridors – the last of which reveal important developments in the evolution of the Etruscan private dwelling (Stierlin 1996:15-6). Evidence also suggests that the Etruscans were inspired by the Greeks in terms of temple design and also architecture in general, albeit with some modifications. The three-part interiors with single entrances in Etruscan temples differed from the continuous interiors and
fore-and-aft entrances of Greek temples, for example (Moffet 2004:111). Other aspects of Etruscan construction, such as residential dwellings, have yet to be discovered, but it is likely that the Romans must have had plenty of Etruscan construction and architecture alongside the Greek predecessors as inspiration for their own building style.

Aside from the Etruscans, other peoples left their mark on Roman construction and architecture. By the fifth and fourth centuries BC, another native tribe that would become assimilated to the empire, the Volsci, raised great acropolises (summit cities) made from polygonal stone walls, also derived from the Greeks. Though these elevated fortifications did not succeed in keeping the Romans at bay, they did help in another way, by providing base models for large-scale military construction. Volsci-inspired defenses encircled the city of Cosa, for example, founded by Rome in 273 BC to guard the ports of Orbetello and Monte Argentario, complete with forum and acropolis in a rectangular grid pattern, and the Comitium, the location of the original founding of the city, consisting of a circular area surrounded by raised seating (Stierlin 1996:19).

Meanwhile, Greek construction and architecture was intended for functionality as well as artistic purposes. Part of the reason that Greek construction is so prevalent is that this construction style spread throughout the civilizations that were subjugated by this nation – the only major exception being Egypt which, indeed, was one of the influences behind this movement (Ward-Perkins 1974:9). The Greeks also engaged in commerce with Egypt, Mesopotamia, Asia Minor, and Cyprus (Moffet 2004:39), further
promoting the diffusion of Greek architecture throughout most of the Classical world and allowing it to become instantly recognizable today (Figure 3.1).

Roman art and construction, however, were different. The Roman civilization was formed in a world already influenced by the Greek style, via both indirect and direct contact. It was true that the Romans became a liability in the eastern Hellenistic realm, but it was also true that the Greeks influenced the Romans in a positive fashion (Watkin 1986:42). Indeed, it is likely that the Greek style inspired the Roman style to some extent, although the latter did derive from a complex, continuous historical development which would make explanations related to this prospect more complex. For all intents, though, it can be said that Greek construction along with its other artistic
styles was free to develop within its own premises, a luxury that the Roman style did not
have (Ward-Perkins 1974:9).

Though the Romans were known as engineering pioneers, the earliest history of
Roman building did not specifically take engineering into account. Early structures were
basically oval huts of timber, wattle, and thatch, and reconstructions can be seen in
various early Roman settlements (Figure 3.2). More advanced and durable structures
began to appear in the 6th century BC, but these were mostly constructed with religion
in mind. One of the first was the Temple of Jupiter, Juno, and Minerva on the Capitoline,
which was completed in 509 BC (Stamper 2005:6). It was stated to have been
revolutionary in many respects, such as the dressed stone foundation and terracotta-
faceted timber superstructure, as well as its use as a monument instead of a primitive
sanctified enclosure. It was a far cry from the standard Greek models, however, with its
relatively low profile, triple-cell (inner chambers dedicated to the deity in question),
and expanded rear wall that enclosed the building. These were modifications to the
Greek design made for Etruscan tastes. Low-slung buildings such as these remained the
standard as late as the second century BC (Ward-Perkins 1974:11).

As Roman civilization expanded, however, its skill in construction in turn became
more advanced. This led to a new range of building types and thus to the increasing
development of construction techniques as yet unheard of in Hellenistic culture (Watkin
1986:42). As a general rule, however, most early buildings were still built from local
resources: timber frameworks and roofing; terracotta roof tiles; stone blocks for
monumental work; sun-dried brick superstructures; and mortared rubble as space-filler.
FIG. 3.2: A reconstruction of an early Roman hut based on remains found in Fidenae, Italy. This was a simple structure, due to the likely limitations of building space and materials during this period. Exterior (a) and interior (b).
The latter two were especially common, since they could be used in many types of construction works and were easily created from local resources.

Near many Roman sites, there were good supplies of fine clay and tuff, a soft volcanic rock that could be shaped into construction blocks for construction. North and east of Rome, however, the stone was mostly limestone which is not as easy to carve into regular shapes and was therefore used as is. Limestone buildings were thus constructed along the limestone fractures, resulting in polygonal formations. The rectilinear and polygonal styles coexisted for some five hundred years due to the disparity of the materials available at each site, before more adequate transportation for hewn stone blocks was developed (Ward-Perkins 1974:11). Similarly, mortared rubblework and later concrete varied based on the materials available. Styles of concrete included the primitive and irregular *opus incertum*, small-blocked *opus quasi-reticulatum*, checkerboard-patterned *opus reticulatum*, horizontally brick-faced *opus testaceum*, mix-and-match *opus mixtum*, and row-alternating brick-faced *opus listatum*, among others (Gallico 2000:74-5). The style of the facing depended on the stone used in its respective construction, and it can be said that the variations in the local stone used in each building resulted in similar variations in the corresponding facing and brick arrangements (*Figure 3.3*).

While Rome was a centerpiece for development in Roman construction, it was not the only hub of influence within the kingdom-turned-republic, and likewise, the Etruscans within its boundaries were not the only sources of inspiration. Several newly founded colonies also became factors in this regard; most of the buildings within these
FIG. 3.3: Three different forms of Roman concrete: a) *Opus incertum*, b) *opus reticulatum*, c) *opus testaceum*. The examples shown here are from the Pompeii archaeological site.

colonies no longer stand due to external circumstances, but excavation has revealed some important clues. The town of Cosa, founded in 273 BC, provides some of the most well-preserved of these: the layout of the city derives from Greek colonies to the south, the masonry is from Central Italian tradition, and the buildings themselves are Roman in design (Ward-Perkins 1974:15). This would make colonies such as this a “melting pot” of various construction styles, including the one synthesized by the Romans themselves.

By the second and third centuries BC, Rome was capital of a republic that encompassed most of Europe. Roman construction during this period was used as a statement, conveying the power and resources the republic enjoyed. Structures of all kinds – palaces, baths, temples, bridges – were constructed in lavish detail during this
time. Soon, early in the 4th century AD, Rome experienced a growth in the urban population, and in turn, a spike in architectural development. Innovations in construction provided grand public entertainments, such as races and gladiator battles, for which massive monuments such as the Colosseum were constructed. The use of the arch in construction, known to the Sumerians and Etruscans, was perfected at this time, becoming the basis for vaults, domes, and even whole structures. In contrast to the rectilinear methods of the Greeks, who devoted their buildings to religious rather than public use, the Romans used this new and versatile tool to refine the many practical aspects of public building design. As said building design was taken to new, unprecedented levels, the usage of stone in construction became impractical, and more innovative developments were made on materials that were stronger, but lighter than stone. Modern engineers know the most important of these developments as concrete, originally consisting of lime, volcanic dust, and water poured over crushed stone, resulting in a mixture that set to rock-hard consistency but could be poured in a plastic state to accurately fill spaces within brick or stone facings, and as in the case of later monuments such as the Pantheon (Figure 3.4), create the precise shapes of vaults, domes, and even entire structures at once (Milo 1999:16-8).

Even with all these innovations, the Roman civilization could not maintain its grip on Europe forever. The late fourth and fifth centuries AD did herald the decline of the Roman Empire, but theories vary regarding the cause. Raeburn (1980:76-79) argued that external raids and immigration broke down borderline frontiers, effectively kick-starting the slippage of its power upon the territory that the Roman Empire had held for so long.
FIG. 3.4: The exterior and interior dome of the Pantheon. This concrete dome is one of the largest in history, and the largest free-standing structure of its kind known. Exterior (a) and interior (b).
Worse still, the oppressions of imperial tax collectors and other corrupt members of the higher-class further aided in decaying the empire from the inside-out. On the other hand, Gibbon (1946:1220-1221), a prominent Roman historian, suggested that the spread of Christianity and of barbarians to Italy were the primary factors behind the fall of Rome. He cited Christianity in particular as a major influence, even more so than foreign invaders, because it suppressed the Roman notions of direct action in favor of indolent pacifism, inevitably leading to conflict between the respective dogmas that ultimately caused the already crumbling empire to finally collapse.

In any case, the lesser-privileged, therefore, had to retreat to larger, well-fortified estates, which ensured their safety in return for labor, and eventually converted them into medieval serfs. Floor mosaics from Tunisia display vivid images of heavily fortified mansions (Figure 3.5), in which both serf and owner sought refuge – perhaps a throwback to the fortresses of the Volsci. Thabraca is also home to another of these strongholds, including towers as well as a closed lower story, very much like medieval castles. The last function of Roman construction of antiquity, therefore, appears to be the protection of refugees from the horror of Rome’s depravity.

The common feature it shares with the previous developments is that unlike Grecian construction, Roman construction kept in mind the housing of large numbers of people – a need which persists to the modern era. So the Roman Empire, from its humble days as a simple kingdom to its final gasp in the Middle Ages, has provided what may possibly be the greatest triumphs of construction, architecture, and engineering, triumphs which continue to influence architects all over the modern world (Figure 3.6).
FIG. 3.5: These mosaics from Tunisia (a), (b), and (c) display heavily fortified towns. These would have been common refuges for all classes of society during the last turmoil-riddled vestiges of the Roman Empire. (Bardo National Museum 2009)
FIG. 3.6: Fascist architecture, which enjoyed a comparatively brief stint during World War II, was inspired by the architectural style of ancient Rome. Two examples of this are the Palazzo della Civiltà Italiana, also known as the "Square Colosseum" (a), an icon of Fascist architecture no doubt inspired by its namesake, and likewise, the exterior of the Museo della Civiltà Romana (b), modeled after Roman aqueducts. (Tan 2011)
3.2. Engineering of Roman Theaters

3.2.1. Introduction

Temples were one of the great marvels of Roman construction; theaters were another. Whether Roman theaters were wholly inspired by Etruscan or Greek theaters is up for debate, but it can be asserted that the Greeks did indeed influence the Romans to some degree in terms of theatrical construction and design.

3.2.2. Greek Theaters

Greek theaters were originally built on a large scale to accommodate the large number of people on stage, as well as the large number of people in the audience. Already skilled in mathematics and science, the Greeks utilized acoustics to enable the stagehands to be heard by all audience members, even in the top seats. The first seats in Greek theatres were constructed from wood, but around 499 BC, they were constructed from stone inlaid into a natural ground slope, forming more permanent and stable seating.

The first Greek theaters were relatively small, especially by the standards of later monuments, but even these early models demonstrated the capacity to fit entire villages or even towns in a single place. Among the earliest of Greek Theaters, the ancient theatre at Delphi, like the other structures of the Delphi complex, was built as a commemoration to the god Apollo, the patron of music and theater. Originally built in the 4th century BC, its 35 tiers have a capacity for
5,000 (Sweet 1987:192). Later examples occur in Athens, the capital of ancient Greece, which had multiple theaters scattered throughout the city – particularly in the Acropolis, the central hub of Athenian society. Located here is the Theater of Dionysos, which is one of the earliest preserved theaters known (Figure 3.7). It was most likely built in the fifth century BC, following the collapse of the bleachers of the Athenian agora which prompted the moving of the dramatic and musical contests to the theatrical construct.

**FIG. 3.7:** The Theater of Dionysos is one of the earliest open-air theatres preserved in Athens. It has been speculated that the theater was built in the fifth century BC, but the only certain evidence points to it merely existing since the fourth century BC.
FIG. 3.8: The Odeon of Herodes Atticus, Athens, was built in 161 AD, long after the diversion between Greek and Roman theaters. Since the Hellenistic Greek civilization was stationed in Greece instead of Italy, it evolved separately from the Roman era, producing its own styles of construction, art, and architecture.

The Theater of Dionysos is sometimes confused with the nearby Odeon of Herodes Atticus (Figure 3.8), which was built in 161 AD by the eponymous aristocrat as a site for musical events, and could seat 8,000 (Leake 1821:61). The oldest orchestra in the theater precinct is thought to have a diameter of around 28 meters, although there is some debate relating to its actual dimensions (Bieber 1961:54-55, 63).

Theaters such as these were very common throughout most of ancient Greece. Despite their variety, however, most of them shared a similar design, consisting of a semicircular arrangement of seats around a central orchestra, which in turn had a skena (background plate) behind it – a forerunner of the modern backstage area. Greek theaters typically were built on the side of an
incline for easier foundation construction, did not have a roof, and were not enclosed, so the audience could see the surrounding landscape as well as the stage. This design would be the standard for theaters throughout ancient Greek history, and it would not be until Roman construction diverged from the Greek style that the Roman theaters would undergo substantial changes in appearance.

3.2.3. Greco-Roman Theaters

Though they were technically a separate civilization from the Greeks, the Romans did not construct entirely different theaters of their own invention, but borrowed from the sophistication of Greek design. There are transitional stages, in fact - the Greco-Roman theaters represent a conversion from pure Greek to (mostly) pure Roman theaters. While they were similar to Greek theaters, they were built on the top of the hill instead of being hewn out of it, and the decorations were more elaborate in a similar fashion to other types of building modeled off of Greek designs (Colliery 1899:47).

A fine example of this transitional stage can be found in the Greco-Roman Theater of Catania, Sicily (Figure 3.9). Built during the Hellenistic period, it eventually fell into disrepair until the Roman era, when a new Roman design was constructed over its remains in the first century AD. Following its decline between the 6th and 7th century AD, and in the advent of the Middle Ages, it was used as a foundation for other structures; the Church of Saint Francis of Assisi still backs the cavea, or spectator seating, of the Greek-Roman Theatre today.
FIG. 3.9: The Greco-Roman Theater of Catania. Notably, traces of marble seating are present in some areas (circled in red and inset).

Later attempts to preserve it proved futile until around the middle of the 20th century, when most of the buildings above it were demolished.

The cavea, open to south-east and having a diameter of 98 meters with an original capacity of 7000, is divided into three parts: the ima (lower), the media (middle), and the summa cavea (higher). Like other Greek theaters, it partly rests on the natural slope, but is also supported by walls horizontally crossed by ambulatories, linked together by stairs, with access to different areas. The 22-meter-wide orchestra, at the foot of the cavea, still has the original marble flooring, although it was badly restored in the 4th century AD. The building stage, closed at its sides from parascaenia (the walls used as backdrops), probably had a monumental frons scaenae, or backgrounds, adorned with marble columns and statues, a Roman development that was also influenced by Greek theatre.
Another Greco-Roman Theatre occurs in Taormina, also located in Sicily. Built primarily of brick, it probably dates to Roman times, but the plan and the arrangement are more similar to those of a Greek theater.

3.2.4. Early Roman Theaters

Roman theaters were initially planned in a similar manner to Greek theaters; once they fully diverged from the Greek style, however, they evolved in their own way. Some were styled after the standard theaters; others, as will be discussed in the next section, were shaped differently. In standard Roman theaters, as in Greek theaters, the arrangement of tiers did not form a complete circle, but unlike Greek theaters, they were built on their own foundations instead of natural inclines, and were enclosed on all sides rather than partly open to the surrounding area (Sear 2006:1).

While early Roman theaters were made from wood, the most well-known ones were constructed from stone because stone theaters were more stable than wooden ones and could withstand longer periods of use – and in fact, the transition from wood to stone seating was likely made precisely for these reasons. One theater in Petra, Jordan, took this tradition even further: according to Browning (1989:138), the cavea, which could seat between 3000 and 4000, was carved into the very cliff it still rests upon today (Figure 3.10).
This theater in Petra, Jordan, was carved entirely out of the stone cliff upon which it is set.

Of course, while the Petra theater has the luxury of being nestled into a cliff face, most Roman theaters were situated on less abrupt changes in the landscape and therefore were constructed from stone blocks stacked on top of one another. Jordan in particular is a hotspot for this type of structure, as it was annexed to the Roman empire in 106 AD (Reid 2005:24) and enjoyed a state of prosperity under its care. In the case of Jerash, another city in Jordan, Browning (1982:36,50,125-6,175) reports that in fact two theaters were constructed - the North Theatre in 163 AD, remains in disrepair despite partial restoration in 1925, while the South Theatre between 81 and 96 AD, which has thankfully survived in better conditions (Figure 3.11). And another city in Jordan, Umm Qais, also contains two theaters, one of which is the world’s only basalt theater known (Figure 3.12).
FIG. 3.11: The South Theater in Jerash, Jordan. This is the more intact of the two theaters that exist in this city.

FIG. 3.12: The theater in Umm Qais, Jordan. Notice the black volcanic basalt that comprises most of this structure.
Yet another theater from Jordan comes from the outskirts of Amman. This theatre, built during the reign of Antonius Pius (138-161 BC), could seat about 6,000 (Figure 3.13). Rooms behind the side entrances, or paradoi, led to the orchestra and stage, and rooms behind these now house the Jordanian Museum of Popular Traditions and the Amman Folklore Museum on either side.

Within the Italian peninsula, one of the first non-wooden, permanent Roman theaters was the Theatre of Pompeii (Figure 3.14). Again, the seating capacity was 5,000 people, and in some foreshadowing of the awnings of amphitheatres, a velarium (awning) stretched over the cavea to protect the audience from the sun and rain, which was operated by sailors and withdrawn when the winds became too strong (Luciana 2003:34-35). The theater of Pompeii is also notable for its quadriporticus, a nearly square courtyard adorned with 74 Doric columns.
and with an entrance marked by three Ionic columns near the north corner. This structure dates to the 1st century BC, making it one of the oldest known in Italy; following the earthquake of AD 62, caused by the awakening of Vesuvius, the complex was turned into barracks for gladiators, rather like those of the Colosseum, constructed on two floors with a guard post set up near an entrance doorway. One source provides speculation of the quadriporticus even being a gladiator training school, or *ludus* (Luciana 2003:66).

The Theatre of Pompeii should not be confused with the Theatre of Pompey, which is located in Rome. This site, which is considerably more famous than the Theater of Pompeii, was built over seven years, starting from 55 BC, and gained fame – or rather infamy – as the site of Julius Caesar's murder by the *Liberatores*, a self-designated group of members of the Roman Senate and elite. Notably, the
Romans used a concrete foundation for this theater. Vaulted corridors were also built underneath the seating for access to each section of the auditorium, allowing safe access to upper levels and allowing the theatre to fill and empty efficiently. The arch, which had been innovated by the Sumerians/Etruscans and improved by the Romans, was also put to good use, for it allowed the Romans to create larger structures than the simple rectilinear construction of the Greeks would have allowed. The stage is also attached directly to the auditorium, making an enclosed single structure, as opposed to Greek theatres which separated the two, which made for better acoustics and crowd control.

FIG. 3.15: The Theater of Marcellus, in Rome.
A similar case can be argued for the Theater of Marcellus, also in Rome (Figure 3.15). At 111 m in diameter, it could originally hold about 11,000 spectators (Roth 1993:230-231). It was built primarily of tuff, brick-faced concrete, and travertine, but recent restoration has begun replacing the travertine with brick facing.

This construction style was copied for nearly all future theatres within the ancient city of Rome and throughout the empire, and would become the forerunner of an even more famous and universally recognized theater type: the amphitheater.

3.2.5. The Roman Amphitheater

The origins of the amphitheater, an entirely Roman institution (the term is derived from ancient Greek *amphi*, meaning “around,” and *théatron*, meaning “place for viewing”), are still relatively unclear. Records pertaining to amphitheaters tend to ignore the origins of the group as a whole, but records do indicate that the first amphitheater-like structure was constructed out of wood in the middle of the Roman Forum in the second or first century BC (Bomgardner 2000:59). Originally, it was argued that the amphitheater was of an Etruscan origin, based on finds in Campania dating to the 4th century BC, but the evidence for amphitheaters there is merely circumstantial and only dates from circa 70 BC.

While the most familiar amphitheaters are the ones resembling the Colosseum, they were in fact constructed in a variety of ways, based on the landscape available on site. Not all amphitheaters were constructed on level
ground: some were built in naturally occurring pits and hillsides which required some variation in the design. **Figures 3.16 and 3.17** provide six different arrangements of amphitheater based on the ground plane of the building site.

**FIG. 3.16:** Different methods of amphitheater placement were based on alignment with the surrounding landscape. Early prototypes embedded the amphitheater into the ground. These include: direct excavation of the cavea (a), partial excavation and sculpting the cavea over the excavated soil (b), and building the cavea over an excavated arena (c).
FIG. 3.17: Continuation of Figure 3.16. Later amphitheaters set the amphitheater arena on or above the ground. These include: partial erection on an inclined ground plane (a), erection upon a natural hollow (b), and finally construction of the entire structure on a level plane (c).

The amphitheater in Figure 3.16.a) is carved directly into the ground, without any superstructure erection. This has the advantage of a stable foundation and no need to haul in materials except for the seating, but the site must be a semi-conical pit for this arrangement to be feasible. In Figure 3.16.b), the cavea is created by excavating the arena, then piling the spoil-heap into a ring and mounting the seating on top of it. Again, this requires minimal use of material, but the balance between the cut and fill regions means a pre-existing hill of the proper size should be scoped out for a proper build site. Figure 3.16.c) shows a more proactive approach, excavating the arena and erecting the seating, which
does not require a pit or hill but does require material to be imported for the cavea. Taking this arrangement further, Figure 3.17.a) depicts an amphitheater embedded into the side of a cliff, reducing the cost by erecting a partial cavea but again necessitating a suitable cliff-side for this arrangement to be feasible. Figure 3.17.b) puts the cavea and arena in the middle of a naturally occurring pit, but modifies the seating so the angle of the slope does not matter, producing more versatility but requiring more foreign material. Notice that only Figure 3.17.c), full erection on level ground, requires full construction of the cavea and arena. This was a more common method than most because in many places where the arenas are found, the land is relatively flat. Since the elliptical sloped seating of previous theaters was the best arrangement for maximum acoustic potential, the lack of a naturally occurring elliptical pit meant that the amphitheater was expected to form the shape by itself.

Under imperial rule, from Augustus onwards, amphitheaters were constructed from stone, which is more durable and long-lasting than wood. The earliest known example, in Pompeii, was built in the same year as the one in Campania, and was used for gladiator games until 79 AD, when it was buried by Mount Vesuvius (Figure 3.18). More recent instances are also known: the amphitheater in Capua, which was dedicated by Antoninus Pius, built during Augustus and later restored by Hadrian; the Catania theater (Figure 3.19), which could seat as many as 17,000 spectators during its use, though part of it was blocked off in the early 17th century by a volcanic rock base for the neighborhood
of Via Grotte (Vecchio 2011:274); and the amphitheater in Verona (Figure 3.20), constructed in AD 30, which is the third largest of its kind known and has been used for many purposes, from bullfighting to opera (Birmingham 2012:195).

FIG. 3.18: The Amphitheater of Pompeii, the earliest known stone amphitheater (a). The interior has become covered in vegetation over the centuries, but the structure remains relatively intact otherwise (b).
In due course, the phenomenon of the amphitheater became popular enough that like its half-enclosed precedent, it soon appeared throughout the
Roman Empire, not just within Italy. The El Djem amphitheater in Tunisia (Figure 3.21) is the largest amphitheater in North Africa, capable of seating 35,000 spectators (UNESCO 2003:370). Somewhat humorously, it is as recognizable in the cinematic industry as in the archaeological field, having served as one of the settings in the 1979 Monty Python film, *The Life of Brian*, and on a more serious note, as a setting in the Academy Award-winning film *Gladiator* – as a substitute, ironically enough, for the larger and inordinately more famous Flavian Amphitheater, also known as the Colosseum, for despite its iconic status, the latter could not be used as a stage set directly for legal reasons.

![Image of El Djem amphitheater](image)

FIG. 3.21: The Amphitheatre of El Djem, Tunisia.
3.2.6. The Colosseum of Rome

Founded by Emperor Vespasian, in 75 AD, this 622-foot-by-528-foot ellipse of stone was the largest of the ancient amphitheaters. Estimates vary concerning its seating capacity; The International Library of Technology (1899:48) gives a relatively high estimate of approximately 87,000 seats alone, and 100,000 including with standing room, whereas Milo (1999:16) predicts a more modest total estimate of about 50,000. Whatever the audience capacity, the Flavian Amphitheater was a landmark of Rome even in ancient times.

The Flavian Amphitheater was built starting from AD 72, under Vespasian, with the opening ceremonies under his son Titus in AD 80. Built from travertine and brick, this mighty arena’s outer elevation comprised four stories reaching up to a total of 47.8 meters (Hopkins 2005:2). Inside, the seating and wooden arena belied a complex network of chambers where the contestants would await their battles. This was the epitome of Roman amphitheaters, the largest of its day and indeed of antiquity in general. Even today, the iconic image of its remains reminds us of the glory of Roman construction and building design (Figure 3.22).

Although the Colosseum is familiar to modern people in its ruined state, its appearance was drastically different in ancient times (Figure 3.23). The travertine would have been carefully cleaned and polished, statues would have lined the outer archways, and the Colossus of Rhodes, which would one day be cited as one of the theories as to the modern name of the Colosseum, would have stood tall and majestic by its side. The Colosseum would have also had a
velarium or awning on its top, like other amphitheatres, to shield spectators from the sun.

For a map of the Empire during the Colosseum construction, see Figure 3.24.

FIG. 3.22: The Colosseum as it stands today. The outer ring has largely deteriorated, and recent restoration has preserved the inner ring with modern materials.

FIG. 3.23: A reconstructed model of the Colosseum as it would have appeared in ancient times. (Museo della Civiltà Romana, 2011)
FIG. 3.24: This map, placed over a layout from Google Maps, depicts the extent of the Roman Empire during the later rule of Vespasian, circa 74-79 AD, while the Colosseum was under construction. Notice the city of Rome flagged in the center. (Google Maps 2012)
3.2.7. Summary

While it is true that the Roman style of theater construction is different from that of the Greeks in some ways, it is also similar with respect to others. By adapting the existing finesse of Hellenistic construction and architecture, and by adding their own innovations, the Romans created theaters that blended artistic quality and precision design.

A list of the theaters discussed in this section, along with their respective regions and approximate dates of construction, is shown in Table 3.1. A list of amphitheaters, regions, and construction dates, is shown in Table 3.2.

TAB. 3.1: A chronological compilation of ancient Roman theaters. Note that the monuments listed here are the ones discussed in this study, meaning this compilation may not be comprehensive.

**TIMELINE OF ROMAN THEATERS**

<table>
<thead>
<tr>
<th>Monument</th>
<th>Location</th>
<th>Construction Date</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Taormina, Sicily</td>
<td>7th century BC</td>
</tr>
<tr>
<td>Theater of Dionysos</td>
<td>Athens, Greece</td>
<td>5th Century BC</td>
</tr>
<tr>
<td>Theater of Delphi</td>
<td>Delphi, Greece</td>
<td>4th Century BC</td>
</tr>
<tr>
<td>Theatre of Pompeii</td>
<td>Pompeii, Italy</td>
<td>1st century BC</td>
</tr>
<tr>
<td>Theatre of Pompey</td>
<td>Rome, Italy</td>
<td>55 BC</td>
</tr>
<tr>
<td>Theater of Marcellus</td>
<td>Rome, Italy</td>
<td>13 BC</td>
</tr>
<tr>
<td>South Theater</td>
<td>Jerash, Jordan</td>
<td>80-90 AD</td>
</tr>
<tr>
<td>Odeon of Herodes Atticus</td>
<td>Athens, Greece</td>
<td>161 AD</td>
</tr>
<tr>
<td>North Theater</td>
<td>Jerash, Jordan</td>
<td>163 AD</td>
</tr>
<tr>
<td>Umm Qais Theater</td>
<td>Umm Qais, Jordan</td>
<td>2nd century AD</td>
</tr>
<tr>
<td>Theater of Catania</td>
<td>Catania, Sicily</td>
<td>2nd century AD</td>
</tr>
</tbody>
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TAB. 3.2: A chronological compilation of ancient Roman amphitheaters. Note that the monuments listed here are the ones discussed in this study, meaning this compilation may not be comprehensive.

**TIMELINE OF ROMAN AMPHITHEATERS**

<table>
<thead>
<tr>
<th>Monument</th>
<th>Location</th>
<th>Construction Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amphitheater of Campania</td>
<td>Campania, Italy</td>
<td>1st century BC</td>
</tr>
<tr>
<td>Amphitheater of Pompeii</td>
<td>Pompeii, Italy</td>
<td>1st century BC</td>
</tr>
<tr>
<td>Verona Amphitheater</td>
<td>Verona, Italy</td>
<td>30 AD</td>
</tr>
<tr>
<td>Flavian Amphitheater</td>
<td>Rome, Italy</td>
<td>70 AD</td>
</tr>
<tr>
<td>Amphitheater of Capua</td>
<td>Capua, Italy</td>
<td>1st century AD</td>
</tr>
<tr>
<td>Amphitheater of Catania</td>
<td>Catania, Sicily</td>
<td>2nd century AD</td>
</tr>
<tr>
<td>Amphitheater of Catania</td>
<td>Catania, Sicily</td>
<td>2nd century AD</td>
</tr>
<tr>
<td>Amphitheatre of El Djem</td>
<td>El Djem, Tunisia</td>
<td>238 AD</td>
</tr>
</tbody>
</table>
CHAPTER 4:
COLOSSEUM SIMULATION: BACKGROUND

4.1. Software System

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 4.1.a). In the same vein, Autodesk Maya and Cinema4D were also considered, but despite their modeling capabilities, both were rejected on the grounds that they rely on procedural modeling and polygonal meshes to create solid features, entailing in a more complex modeling process.
FIG. 4.1: 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.
Among the choices available, 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 4.1.b).

Regarding this subject, it should be noted that in theory, given the time, resources, and hardware/software capabilities, any computer graphics program can be used to create a monument or structure as large and complex as the Colosseum. Autodesk Inventor was selected primarily because of its capability to render models directly, rather than through wireframe models. Autodesk Inventor uses ShapeManager, the proprietary geometric modeling kernel of Autodesk which in turn is derived from the ACIS geometric modeling kernel. This kernel combines wireframe, surface, and solid modeling to simulate solid parts and structures more easily than wireframes alone. This would be more advantageous because editing the structure directly will allow for greater complexity in the model, which will allow for a more detailed and accurate result. Other factors to take into consideration are the relatively low learning curve, partly owing to a user-friendly interface that enables a higher degree of comprehension and dexterity with regards to the software functions, and in this case availability, as it was at the time of this writing one of the graphics programs used in the various College of Engineering programs of the Ohio State University, such as the First Year Engineering Program.
4.2. 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. A model found online shows a less sophisticated structure which faithfully replicates the superstructure exterior and most of the interior, but lacks the interior passageways that are patterned throughout the seating (Belcher and Stewart, 2012). Archelobri’s model, on the other hand, is more thorough with significantly more detail, and indeed, the model that it depicts is intended for professional use in archaeological guides that intend to showcase accurate restorations (Archeolibri, 2010). But these models show how the monument 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.

The substructure, which is one of the main reasons the Colosseum remains standing, is commonly forgotten in models and simulations pertaining to it. This would not the case for a model that capitalizes on information pertaining to the construction of the monument, as will be discussed. In this case, the foundation is subject to as much discussion as the superstructure in historical records, since it is similarly rich in history and complexity alike. Starting from this, the monument can be built as usual, but can also be 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.
4.3. Historical Data

Although the Colosseum is indeed an iconic monument, it has only partially withstood the test of time, and today its ruined state leads to many questions. Among the most important are what it would have looked like in life, but also how it was constructed in the first place. The simulation discussed seeks to answer both of these questions by reconstructing the Colosseum using source-accurate techniques and historical methods.

4.3.1. Soil and Environment

With regards to a historically authentic simulation of the Colosseum, the site and environment are the first aspects to consider. Soil conditions could make or break any monument, but especially one this large. The Colosseum rests in a natural flat area on the floor of a low valley between the Caelian, Esquiline and Palatine Hills, penetrated by a partially canalized stream. Following the Great Fire of Rome in 64 AD, the site was used as the site of Emperor Nero's portico villa, the Domus Aurea, complete with an artificial lake, fed by an extension of the Aqua Claudia aqueduct, up front and center. The Domus failed to reach completion and was soon destroyed after Nero’s suicide in 69 AD (Claridge 1998:267). The Colosseum would occupy the area that had been previously allocated to the Domus lake, and would be built over a decade starting from 70 AD (Stierlin 2002:89-90).

On this note, soil conditions are one of the first and foremost topics to discuss for sites such as the Colosseum and the aforementioned lake bed. This warrants a brief history of the soil conditions of Rome in general. The information provided is
taken from the studies of Rodolfo Lanciani (1897:1-6), an Italian archaeologist and a pioneering student of ancient Roman topography, whose greatest work was the production of a map of the ancient city of Rome.

The geography of Rome mainly revolves around the Tiber River, which starts in the Apennine Mountains and flows some 406 kilometers (252 mi) to the Tyrrhenian Sea. Prior to the peninsula’s colonization, during the Quaternary period, the river was much larger and more powerful, separating the primeval Ciminian Forest from the Alban volcanoes. As the river broke up into smaller streams, it fragmented the eastern locale into the smaller islands that would become the hills of Rome and other promontories. West of this the Vatican and Janiculum regions were less irregular, as they were shaped by the main current of the river without separate branches. By the time mankind had arrived in Italy, the Tiber had diminished into its historical proportions, but the valley bases remained subject to flooding and therefore accumulated alluvial deposits. As a result, the hills have since lowered and the valleys have become filled, making the region steadily more level over time. Soil borings conducted in 1872 (Lanciani 1897:2-3; Canevari 1875-6 p. 429), however, revealed that the region was once a series of narrow dales enclosed by cliffs as well as the evergreen Ciminian Forest, and because of the Tiber flowing through the area, it remained plagued by swamps and streams that would have made the soil unstable and unsuitable for large-scale settlements (Figure 4.2).
FIG. 4.2: The Tiber River as seen today. The diluvial deposits that surround this river are remnants from when it inundated most of the region which make the soil unstable and unfit for constructing buildings in general without a foundation design to evenly distribute their weight. Also notice the Ponte Rotto on the left, which was built on the diluvial soil of the Tiber Island in the 2nd century BC.

The geological formations of Rome are also of interest in this explanation, because they determine the availability of both suitable construction sites, if any, and materials that would be locally available. The four main types found in the Roman area are limestone, argillaceous, volcanic, and diluvial. Limestone formations are best known from Corniculum, the ancient town in Latium. Argillaceous formations are found in the Vatican and Janiculum ridges, or clay hills, which may have been quarried for clay to make bricks. Volcanic formations are categorized as deposits of either tuff or the related pozzolana. Tuff of the lithoid (red), granular (yellow), or lamellar (gray) varieties is found in San Saba, in Monteverde outside of Porta Portese, and in Sant'Agnese outside of Porta Pia, while pozzolana occurs near
the Tre Fontane abbey. Lastly, diluvial deposits, which are formed by consolidation of sediments deposited in floods, are found in most areas near the Tiber (which presumably flooded the land out of sheer size prior to the arrival of mankind), such as Monti Parioli, Villa di Papa Giulio and Acqua Acetosa, Ponte Molle and Ponte Nomentano.

In light of all this, it appears that some of the materials for the Colosseum specifically appear to have been in good supply, but Lanciani (1897:369) points out that the site selection was still a risky choice. Even before Nero’s lake bed was put in place, the territory bordered by the Caelian, Oppian, Velian, and Palatine hills, which it was intended to occupy, was already unstable. The swampy environment and presence of local springs created a risk of flooding if precautions were not taken. One excavation in 1875-78, which failed to include proper drainage, resulted in severe flooding of the dig site, leaving substructures in over three meters of river water without an outlet to drain from. In light of this, the best choice for the Colosseum foundation would most likely have been a deep, wide slab of solid concrete which distributed the weight of the superstructure evenly and keep the monument from sinking.

Considering the poor soil conditions that the Tiber in general would have provided, one obvious question would have been how the Romans would have felt when they discovered the problem, and how they would have handled it. In fact, evidence suggests that the Romans were well aware of this setback – and as can be expected, they were quick to not only express their dismay, but to also work around
the difficulties it would have entailed. As discussed by Malacrino (2010:118-119), a solid foundation was the first and foremost priority, and according to Vitruvius (ca. 85 – 15 BC), one of the most prominent Roman architects of his day, the most common way of handling it was to excavate down to bedrock (as seen in the Casa Romuli in Figure 4.3) or at least a strong layer of clay. This was accepted as the standard in foundation preparation, and just as well, since structures that failed to comply by this rule did not last for long. The historian Tacitus (*Annals* 4.62-3) explains that, for example, the Fidenae amphitheater was not set on stable ground, and the joints of the wooden superstructure were not secured; almost inevitably, the stadium collapsed after being overcrowded of spectators, killing or injuring around fifty-thousand in the process. Likewise, Pliny the Younger (*Epistles* 10.39)
criticized the then-unfinished theater at Nicea as a waste of expenses due to the building already sinking into the presumably damp, soft soil it was built upon, and possibly being constructed from weaker stone than usual.

However, a much more pressing and important question concerns the cause of such untimely circumstances. In retrospect, the answer may have come from the Roman civilization itself, specifically its expansion process. Most of Italy was presumably covered in forest prior to mankind’s colonization, but in light of the need for farmland and city space, it was the most logical choice for the Romans to remove any trees and vegetation that impeded their progress. Despite the short-term benefit, the effect of this would have ultimately been detrimental, because the soil which had been previously kept in place by plant roots and enriched by detritus (non-living particulate organic material, typically fragments of dead organisms which would have served as fertilizer) would not only be poorer in nutrients post-deforestation, but more importantly, it would also be more vulnerable to runoff and erosion (Shipley & Salmon 1996:159). This, coupled with the swamp-like conditions the Tiber presumably provided, would have made the soil softer and less capable of supporting the buildings above it.

The types of soil and geological deposits within and around the Roman locale, and the locations of each, are listed in Table 4.1.
TAB. 4.1: The four main types of Roman soil. Volcanic is counted twice because the two different resources it yields come from different quarries.

### Soil Types of Rome

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Location</th>
<th>Resources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limestone</td>
<td>Corniculum (Latium)</td>
<td>Limestone, foundation</td>
</tr>
<tr>
<td>Argillaceous</td>
<td>Vatican, Janiculum</td>
<td>Clay (bricks)</td>
</tr>
<tr>
<td>Volcanic</td>
<td>San Saba, Monteverde, Sant’Agnese</td>
<td>Tuff</td>
</tr>
<tr>
<td>Volcanic</td>
<td>Tre Fontane</td>
<td>Pozzolana</td>
</tr>
<tr>
<td>Diluvial</td>
<td>Monti Parioli, Villa di Papa Giulio, Acqua Acetosa, Ponte Molle, Ponte Nomentano</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Reference: Lanciani 1897, p. 5-6
4.3.2. Materials

Environmental conditions notwithstanding, the Romans were competent in construction. This is because they used numerous resources to erect their signature structures and monuments, taking care to flag potential setbacks (such as a sturdy foundation in poor soil – the solid concrete slab that supports the Colosseum will be explained in detail later) and work around them accordingly. For the sake of this study, three specific materials will be highlighted: travertine, tuff, and concrete.

The first stone within the Roman locale to be used in monuments was travertine (Figure 4.4.a), *lapis tiburtinus*, from the plain quarry below Tibur (Tivoli). It was valued for both its strength and its ability to be shaped into neat blocks, but unlike previous stone materials it could also be used as facing because of its resistance to weathering and its attractive appearance (Ward-Perkins 1974:13). Travertine is a porous, yet durable form of limestone deposited by geothermal mineral springs, particularly hot springs; the travertine from the Tivoli quarries is particularly suitable for monument construction because its porous, off-white exterior hardens under exposure, and because it was hard enough to remain wear-resistant but soft enough to be easily shaped by carving tools.

Because of its durability and attractive appearance, travertine was used in a majority of Roman buildings prior to the advent of white marble as a material. Even when marble saw increased in its use, travertine remained a reliable and invaluable resource; Emperor Augustus relied on this stone alongside white marble for building and restoration purposes, for example. Along with the Colosseum, travertine was
also used for such structures as the theatre of Marcellus, the Arch of Drusus, the tomb of Cecilia Metella, Temple of Vesta in Tivoli, and the so-called Temple of Sybilla Tiburtin; the Tivoli travertine is still used to this day as a building material (Porter 1907:18).

The second stone of choice for use in Roman construction is referred to as tuff. It is sometimes referred to as “volcanic tufa”, but it differs from true tuff, which is more closely related to travertine; the volcanic stone, which consists of consolidated volcanic ash, is referred to as tuff in this study to avoid confusion (Figure 4.4.b). It is softer, more porous, and less attractive than travertine, but has the advantage of being easier to carve into shape, and still strong enough to be used in internal construction. Multiple types of tuff appear throughout the volcanic regions of Italy, with each individual type forming from a different distribution of volcanic ash; differences in color, coarseness, and compactness depend on the distance the ash has traveled from the source prior to settling (Frank 1924:11-12).

Tuff is obtainable in Campania, which is known for the red and black varieties, and in Umbria, Picenium, and Venetia, which produce the even softer white strain (Vitruvius/Morgan 1960:49). Because of its abundance, tuff was used in a wide variety of ancient Roman buildings, most notably for construction skeletons, though this did not preclude entire structures being built from it. Tuff comprised the whole port of the island of Ventotene, for example, and closer to home, the Servian Wall, built to defend Rome in the 4th century BC (Heiken 2006:130). It could also provide a cosmetic touch if need be: the facing pattern known as opus reticulatum employed
FIG. 4.4: Two types of stone were used to build the Colosseum. Travertine (a) is durable and attractive enough to serve as an exterior finish, while tuff or "volcanic tufa" (b) is relatively softer, making it easier to carve into the desired shape. (Museum of Natural History, Cleveland OH, 2009)
small rectangular tuff stones to create its namesake diamond pattern (Gallico 2000:74). The tuff that was commonly used in Roman construction, no doubt including the Colosseum, was trachyte tuff, known in Italian as *peperino* (Porter 1907:16).

The third major material that was used in the Colosseum is of a manmade composition, albeit one created from natural resources. In its most authentic state, Roman concrete was primarily “pit sand”, a form of clean, fine-grained volcanic sand. Combined with quicklime made from powdered limestone, and poured over a primitive ‘aggregate’ of marble or pumice rubble, the resultant compact, monolithic, cohesive mass set to immense strength and hardness, even when underwater – until the discovery of Portland cement in the 19th century, this was the strongest and best binder material known, and without lateral thrust it could be set in the form of a solid dome without difficulty, making the presence of buttresses in Roman domes and vaults a superfluous precaution.

The origins of concrete in general and of Roman concrete specifically remain uncertain, but there is evidence that it existed in the fourth, third, and second centuries BC, and that it was in Italy in which it was first developed on a major scale. Early house walls were composed of crushed limestone, plaster, and later small chunks of rubble. Later evolution of this concept resulted in the development of the concrete arch, which was created by pouring liquid concrete into a timber framework. Tinkering of the concrete arch resulted in the concrete vault, a basic structural unit which was a longitudinal extension of the round arch; this was often
lightened by coffering, negatives of depressions built upon the mold into which the concrete was inserted. Further tinkering still with this new medium would enable structures to reach unprecedented sizes and shapes, because the concrete could encompass a larger area, take up less weight, and remain as strong as stone; the Colosseum employed three sets of arch-bearing piers and, more importantly, an extensive network of concrete-cored arches and vaults, a system that was repeated in numerous smaller amphitheaters throughout the Roman Empire (Raeburn 1980:67-8).

A full list of resources used in the construction of the Colosseum is shown in Table 4.2, shown below.

**TAB. 4.2**: A list of the materials that comprised the Colosseum. In this case, known quantities are applied to resources that were applied in bulk; constituents that do not have a known quantity shown were likely used in relatively small percentages, mostly for ornamentation and utilities rather than the structure itself.

**MATERIALS OF THE COLOSSEUM**

<table>
<thead>
<tr>
<th>Material</th>
<th>Usage</th>
<th>Quantity (if known)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement/Concrete</td>
<td>Foundation, upper floors, vaulted arches</td>
<td>250,000 cubic meters</td>
</tr>
<tr>
<td>Travertine (limestone)</td>
<td>Main pillars, ground floor, external wall</td>
<td>100,000 cubic meters</td>
</tr>
<tr>
<td>Volcanic tuff (peperino)</td>
<td>Minor pillars, radial walls/skeleton</td>
<td></td>
</tr>
<tr>
<td>Iron</td>
<td>Clamps for binding travertine</td>
<td>300 tons</td>
</tr>
<tr>
<td>Tiles</td>
<td>Floors and walls</td>
<td></td>
</tr>
<tr>
<td>Bricks</td>
<td>Walls</td>
<td></td>
</tr>
<tr>
<td>Marble</td>
<td>Seating, statues and ornaments, drinking fountains, covering for outside walls</td>
<td></td>
</tr>
<tr>
<td>Lead and terra-cotta pipes</td>
<td>Water and Sewer system</td>
<td></td>
</tr>
</tbody>
</table>

References: Hopkins & Beard 2011, pp. 127,146; DuTemple 2003, p. 36
4.3.3. Planning and Specifications

The dimensions of the Colosseum have already been described in Section 3.2.6; however, this section details the planning of the monument in general. The first issue with the actual construction, as with buildings in general, would be the planning stage, concerning how the building is placed relative to the surrounding area and particularly accommodating its size and the problems that came with it. The construction area had already been selected and was of the appropriate size for this structure, but its scale also created a few issues regarding its design. The circumference would have been calculated by contemporary trigonometry to be 1885 Roman feet (Hopkins & Beard 2011:143), translated to 557.96 meters via Hosch’s (2010:206) estimate of the Roman foot as 296 mm. As the structure would have been ringed with eighty external arches which spanned 6 meters each, this warranted a slight reduction in the perimeter to 1835 Roman feet (543.16 meters) by reducing the size of the arena instead of the auditorium (Hopkins & Beard 2011:143). This maintained a relative equilibrium between scale and familiarity which enabled the work to be carried out by artisans and their foremen.

Evidence regarding the work organization comes from the fact that upon inspection, the vertical jointing patterns of each arch are distinct, as are the stairways, suggesting that each construction team operated independently of the others. However, the arch-stones are all relatively similar, and the outermost ground-floor annular corridor varies by only 1 percent around its perimeter. So despite the apparent independence among the building teams, it appears that they
all relied on the same specifications and could work with precise measurements where it counted.

But hard evidence such as was presented above, while conclusive in many respects, may not necessarily answer every question concerning this landmark. Although it is to be somewhat expected for an ancient monument, for example, it still remains puzzling that there are few hints, if any, about both the identity of the true designer of the Colosseum and the true dexterity of the workforce that erected it. Ground plans preserved in inscriptions and three-dimensional hard-copy models provide insufficient clues, and current knowledge of the builders’ aptitude and viewpoint regarding both practicality and technical calculations is primarily a matter of speculation. Anecdotes regarding the architects of the time do exist: One story goes that Apollodorus’s plans were rejected by Trajan, and when the latter was succeeded by Hadrian, the new emperor’s plans were scorned by Apollodorus in return – condemning him to execution (Dio Cassius LXIX.:4). But other scholars disagree with this account. Both the identity of the Colosseum architect and his relationship with the emperor are likely to remain unclear without verifiable records (Hopkins & Beard 2011:142-145).

4.3.4. Substructure

The area beneath the visible part of the Colosseum consists primarily of the foundation which will be discussed in the reconstruction process. There is one area of interest, however, that should be discussed in depth. At the center of the substructure, below the arena was an elaborate underground structure, known as
FIG. 4.5: The hypogeum as seen today. The arena has decayed completely, and that the structure beneath is clearly visible at this level of deterioration.

the hypogeum (Curl 2006:880), which is today clearly visible due to degradation of the arena (Figure 4.5). This consisted of a two-level subterranean network of tunnels and cages where contestants were held between matches. Animals and performers were brought through the tunnels from nearby stables or the barracks at the Ludus Magnus to the east. Separate tunnels were provided for the elite citizens and the gladiators to enter and exit the Colosseum without passing through the crowds. Eighty vertical shafts provided quick access from the hypogeum to the arena for caged animals and scenery pieces, alongside larger hinged platforms for large animals. A series of aqueducts also allowed rapid flooding of the arena, enabling mock sea battles and other naval displays. The entire system was restructured on
numerous occasions, and at least twelve different phases of construction can be seen today (Claridge 1998:281).

The hypogeum was actually larger than the arena above it, though that may merely be due to the store rooms and the corridor leading to the Ludus. A system of revolving capstans (vertical-axled rotating machines used to apply force to ropes or cables) and pulleys is stated to have hoisted the animals up onto the arena (Figures 4.6 to 4.9). This would have required a large selection of labor such as slaves, animal trainers, and stage-hands to bring the animals into the lifts and onto the arena. The conditions would have been cramped, unsanitary, and possibly dangerous, no doubt due to such limited space. Worse still, the beast masters could not err in their duties; Suetonius (Holland 1936:236) describes how Caligula (AD 12-41) had one hapless trainer flogged with a chain for several days before he was finally killed when the emperor tired of the stench of his rotting brain. In short, being a Roman animal trainer was difficult, dangerous work.

Health issues aside, the engineering of the hypogeum has also been subject to a great deal of controversy. One school of thought suggests that the original building plans did not include this system; the fights were held at the bottom of the pit that would later be covered by the arena (Fea 1813). Another argument is that the substructure was contemporary with the original building, since the angle of the seating would preclude viewing of the bottom of the pit in its entirety; this is supported by a Roman inscription stating that the arena was damaged in an earthquake, which could only have happened with supports holding it up (Bianchi
1823:127-154). A consensus was proposed by the Spanish priest/antiquarian Juan Masdeu, who confirmed that the arena and hypogeum were later additions. This could also partly explain the reports of mock naval battles mentioned in Dio’s description: with a viable system of water delivery (though probably not from the Tiber, due to its link to the sewer system), they could have been plausible at least prior to the arena’s installation (Hopkins & Beard 2011:136-142).

FIG. 4.6: Two scale models of the underground lifting system in the Colosseum. (Museo Colosseo 2011)
FIG. 4.7: A lifting mechanism from the Colosseum, with some weights to the left. The rope is a modern addition which points to where the pulley was inserted. (Museo Colosseo 2011)
FIG. 4.8: A close-up of the lifting mechanism in Figure 4.7. Note the wooden pulley wedged in the center groove. (Museo Colosseo 2011)

FIG. 4.9: A scale model (a) and an illustration (b) of the lift systems that transported cages up and onto the arena; note direction of lifting via the red arrows. Recreation of this mechanism is not needed, since the simulation focuses on construction techniques.
4.3.5.  **Superstructure**

Because of its elliptical structure and sheer size, the Colosseum presented unprecedented structural problems. These were solved by skilled engineering that made extensive use of concrete barrel vaults in a honeycomb structure (Figure 4.10), though much of the upper structure is of travertine and tuff masonry (Rodgers 2006:275). The essential constructional units are the concrete-cored piers, arches, and barrel-vaults; though the arch was not a Roman invention, its exploration in construction is primarily a Roman innovation. The amphitheatres of Verona and Pula reduced the pilasters to shallow relief, stressing the pattern of the non-Greek arches and fully exploiting the functional potential and grandeur of *opus caementicium* (Raeburn 1980:68).

![Fig. 4.10: A series of archways from the Colosseum interior. Note the vaulted ceiling, a derivation of the arch system.](image)
Like most modern superstructures, the Colosseum was constructed in levels, or stories. The Colosseum had been completed up to the third story by the time of Vespasian's death in 79 AD, and the top level was finished and the building inaugurated by his son, Titus, in 80 AD. The outer perimeter alone is estimated to have required 100,000 cubic meters of travertine, with 300 tons of iron clamps holding the blocks together. The radial ribs and vaults supporting the ceiling required similar amounts of tuff and brick-faced concrete. Despite its grandiose scale, however, the basic design was the same as that of other buildings of its type, including the smaller amphitheaters located elsewhere within the same city as the Colosseum. The surviving façade of the outer wall consists of three stories of superimposed arcades, topped with a podium serving as the base for a tall attic, with windows interspersed at regular intervals, and framed by arrays of semi-columns - one Tuscan, one Ionic, and two Corinthian. Each of the arches in the second- and third-floor arcades would have framed statues, probably honoring divinities and other figures from Classical myth.

The Colosseum's huge crowd capacity meant the venue must be filled or evacuated quickly, and the solution to this issue is similar to one used in modern stadiums. The amphitheater was ringed by eighty entrances at ground level. The four axial entrances were most likely used by the elite class, and were richly decorated with painted stucco reliefs, though only several fragments remain in the north entrance. The other 76 entrances were numbered as a guide to their designated sectors, starting from the first arch to the right of the south axial
entrance. Many of the original outer entrances have disappeared with the collapse of the perimeter wall, but entrances XXIII (23) to LIV (54) still stand. Spectators accessed their seats via vomitoria (plural of vomitorium), passageways that opened into a tier of seats from below or behind (Figure 4.11). These quickly dispersed people into their seats and, likewise, could permit exit or evacuation within only a few minutes (Claridge 1998:276, 282). Owing to this, the term vomitorium derives from the Latin verb vomeo/vomere/vomitum, "to spew forth" (so despite the similarities in etymology, and despite the common misconception, the vomitorium has nothing to do with vomiting).

FIG. 4.11: One of the vomitoria of the Colosseum. Passageways such as these ensured a rapid entrance and/or dispersal of audience members at the start and conclusion of each show, and also regulated evacuation in case of emergency.
At the center of the stadium, the elliptical arena measured 87.4776 meters (287 feet) by 54.864 meters (180 feet). It was surrounded by a protective wall separating the central area from the podium where the Roman nobilities, including the emperor, witnessed the Colosseum’s daily battles (Quenell 1971:36). The arena itself would have been covered with sand, possibly for traction and to soak up the blood spilled in battle, and was presumably ringed with a mechanism to protect the spectators in its immediate perimeter. One rustic poem suggests a series of ivory rollers around the edge of the arena to prevent a foothold, along with an extra fence erected within this boundary, with a safety net extending to the podium (Hopkins 2005:135).

The final component of the superstructure was the velarium, which has left the least physical evidence. A common theory was that it was comprised of a network of ropes tied to the 240 masts that would have fit into the corbels of the structure, with a large awning that was held over most of the seats; however, other evidence suggests horizontal booms supporting a shorter awning (Figure 4.12). These two possibilities were reconstructed as an experiment by a team of experts under the surveillance of NOVA, the science television series. The mast system was found to be shorter, while the rope system swayed loosely and nearly came loose from its supports in rough weather. It was deduced that the mast system would have been more likely (Figure 4.13); though shorter, it would have been easier to retract, and was surprisingly effective as a sun shade (WGBH 2006).

FIG. 4.13: Two possible models for the *velarium*. The model on the left, supported by ropes as per the commonly depicted hypothesis, is more extensive but more vulnerable to high winds. The model on the right, supported by masts as per the Pompeii Amphitheater painting, is shorter but could be retracted in hostile weather (WGBH 2006).
CHAPTER 5:  
THE COLOSSEUM SIMULATION: ANALYSIS AND DISCUSSION

5.1. Modeling Process

Creating the Colosseum model on Autodesk Inventor, while feasible, requires software capable of handling a high degree of complexity. This is not just because the model has to conform to historical data, but also because the sheer amount of features will cause later tasks to lag and possibly stall the program. Nonetheless, with a powerful enough CPU, Autodesk Inventor can be used to theoretically recreate the Colosseum, along with other ancient Roman monuments and indeed other ancient monuments in general, with enough time and research data.

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 sheer complexity of the Colosseum.

5.1.1. Foundation

The Colosseum’s foundation was of the linear type, meaning the load of the elevation walls was distributed over their planimetric, or two-dimensional, outlining (Malacrino 2010:120). 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 an extrusion feature based on the wall outline. The sections within the foundation
walls were “filled” with extruded features (profiles extruded along a finite distance) representing four layers of foundation concrete, thereby raising the elevation up to the ground floor (Figure 5.1).

5.1.2. Walls and Seats

There are two elliptical rings in the superstructure, the inner and outer; both were rendered using extrusion features. 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 5.2). The path was a projected ellipse derived from the wall extrusion (Figure 5.3, 5.4), enabling an elliptical sweep (revolved features have a fixed axis and are used primarily for cylindrical features rather than elliptical ones).

5.1.3. Entrances, Arches, and Windows

The 80 entrances were created using a single Boolean difference extrusion and a single array – that is, a pattern of regularly spaced features along a given path. A sketch that included the outline of the Colosseum was used to determine the horizontal direction of the array, with the alignment adjusted to the direction of the array path. The vertical direction enabled the creation of three rows of arches, resulting in an 80 by 3 elliptical array of difference extrusions (Figure 5.5). The windows on the topmost story were created in the same
manner later, although only one row was required. The path for the elliptical arrays was later used for the seating sweep feature, as shown in Figure 5.6.

FIG. 5.1: Foundation construction.

FIG. 5.2: Extrusion features for walls.
FIG. 5.3: Level divisions.

FIG. 5.4: Internal structure construction.
FIG. 5.5: Entrance and archway construction.

FIG. 5.6: Seat tier construction with Sweep feature.
5.1.4. **Outer Décor**

Each of the 80 arches is bordered by a pair of semi-columns as discussed in Section 3.2.b. 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 5.7, 5.8). Concerning the column tops, the Tuscan style was the simplest as it could be integrated into the revolved feature. For the Ionic style, a 3D sketch was used to project the edges from two adjacent arches and connect them to form the horizontal axis for the work plane, which was used to create the sketch for the required extrusion feature. The Corinthian style was created via an extrusion, starting from the top of the topmost column, with the taper option enabled for gradual narrowing of the cross-section; since there are two sets of Corinthian columns, a linear array was used to duplicate them. Finally, another linear array was used to duplicate all of the column features, using the same process for duplicating the archways. (Figure 5.9) 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.
FIG. 5.7: Pilaster construction.

FIG. 5.8: Close-up of pilaster showing Revolve feature.
5.1.5. Vomitoria, Passageways, and Stairwells

The passageways leading to and from the seats were recreated via 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 extrusion not affecting the model due to it extending into the area already removed by the doorway. (Figs. 5.10 to 5.13)

Each vomitorium was created using two extrusions: one to create the feature itself and the other to eliminate the stairs inside (Figure 5.12). These were elliptically patterned per the quarter-section view from Carlo Fontana’s 1725 print, L’Anfiteatro Flavio (Quennell 1971:38-39). The stairways were originally
intended to be patterned in a similar manner to the vomitoria, with an ellipse formation. However, the resultant even spacing was unable to line up all the stairways evenly between the vomitoria. Therefore an additional approach was used. 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 same process was repeated for the doors leading to the stairways, except with a single difference extrusion instead of two union features (Figure 5.14).

FIG. 5.10: Passageway patterning.
FIG. 5.11: Window patterning.

FIG. 5.12: Vomitoria construction.
FIG. 5.13: Vomitoria patterning.

FIG. 5.14: Stairways and work planes.
5.1.6. *Velarium*

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 created using union and difference extrusions respectively and 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 .1 m or so) to pass off as a membrane, as surface features are typically translucent/transparent (Figures 5.15, 5.16).

**FIG. 5.15: Colosseum without velarium.**
5.1.7. Recreating the Construction Stages and Section View

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 foundation was constructed in the same manner as in the historical literature, but the superstructure had to be divided via extrusion features that removed each of the stages, starting from the attic down to the ground floor (Figure 5.17). 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.

FIG. 5.16: Colosseum with velarium.
For the section view in Figure 5.29 (bottom of page 115), a segment each of three revolved difference features was positioned so that the resultant slice could provide a cross-section of the model’s interior without interfering with the seating (Figure 5.18). With the features stacked over each other, the end result looks similar to Figure 5.29 at first glance. However, a closer examination reveals that in comparison to the scale model, the interior of the digital model is not accurate, primarily because the stairways were not modeled during the initial sweep feature that created the interior and seating (Figure 5.19).

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 (Figure 5.20). Using this feature, the sketch is used to create the wall that separates the stairwells from the next archway via an extrusion feature. 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 5.21).

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 cross-section to accommodate them. A series of extrusion features (Figure 5.22) was used to clear out the protruding portions of the interior. Notably, the connected stairwells were created from difference
extrusions, and a difference sweep, because it was concluded that excess system lag could be reduced by creating them from the existing wall (Figure 5.23).

**FIG. 5.17:** Reverse-engineering the model construction stages.

**FIG. 5.18:** Removing a section from the model for internal examination.
FIG. 5.19: The inaccurate sectional view prior to modification.

FIG. 5.20: Sketch of dual stairways. Note the wall outline overlaid over the stair shapes.
FIG. 5.21: Extrusion of the dual stairways.

FIG. 5.22: Removal of the filled interior space, to make way for the connected steps.
FIG. 5.23: Clearing out the space near the connected steps.

FIG. 5.24: The completed Colosseum model, with perspective, preprogrammed shading and a ground platform.
The completed model is shown in Figure 5.24. Notice that to complete the image, a ground object was added and preprogrammed shading was applied for realism.

5.2. Construction Process

Ordinarily, it is preferable that the construction procedures be placed at the beginning of this chapter; however, since the objective of the study is to simulate the construction processes as well in comparison to the historical sources, it could serve a better purpose for the readers to offer the construction techniques as a comparison to the construction of the model, which is why this discussion follows the modeling process. Modeling the Colosseum with the current graphics software is feasible within the proper data constraints, and can be done in less than a year with the proper data. Constructing the Colosseum, however, spanned a longer time period, with different methods applied on the field as opposed to on the computer system.

5.2.1. Foundation Excavation and Formation

The Colosseum placement with respect to its environment has been discussed previously, so the focus should be upon the construction of the foundation. It has been mentioned that the Colosseum occupied the area that had been previously allocated to the Domus lake. Once the site was drained, it was excavated down to the clay bed, upon which an elliptical ring 60 meters wide, 6 meters deep, and encircling an ellipse of 196 by 164 meters was exhumed – entirely by manpower. The perimeter walls were constructed within
this excavation: the outer spanned 539 meters, the inner 199 meters; both were three meters thick and 12.5 meters high. The space within these walls, all 250,000 cubic meters, was filled with *opus caementicium*, or Roman concrete, with embedded leucitite chunks, resulting in a very stable foundation (Hopkins & Beard 2011:146-147). Notably, Roman concrete could not be poured in the same way that modern concrete is; the mixing was more similar to that of brick mortar than modern concrete and thus the low moisture content would have essentially made the concrete too dense for pouring of any degree. Instead, the leucitite chunks were laid as aggregate, and the mortar was mixed on site and then pounded into the aggregate for close compaction, resulting in a solid, wear-resistant foundation.

The Colosseum’s foundation was comprised of two superimposed structures formed in this manner (*Figure 5.25a*). On top of these structures, two 6-meter elliptical concrete rings, each about 6.3 meters high and embedded with yellow tuff and brick-facing walls, denoted the upper part of the foundation (*Figure 5.25b*). The upper rings were interrupted by axial covered passageways (*cryptoportici*) and annexed spaces dividing the foundation into four distinct quadrants, forming a permanent formwork for the four superimposed layers of concrete that formed the foundation’s upper walls (*Figure 5.25c*). This is when the foundation reaches the elevation for the superstructure and ground floor (Malacrino 2010:120-122).
FIG. 5.25: Construction of the Colosseum substructure. The foundation, a concrete ring 60 meters wide (a), served as the base for a series of partitioning concrete walls (b), which held the concrete below the ground floor (c). The hypogeum (d) was added later on, to serve as a support for the arena and to house the participants between battles.

Inside the inner brick-wall ring, the hypogeum (Figure 5.25d), which was subdivided into a series of corridors, measured at 76 meters by 44 meters and was delimited by the same brick-wall ring. The longitudinal axis of the hypogeum was oriented in the East-West direction as were the rest of the foundation walls. Constructed from tuff blocks and bricks, the hypogeum walls subdivided the space into twelve corridors of varying length and width, notably including six elliptical corridors running parallel to the encircling wall and nine linear ones parallel to the longitudinal axis (Beste 2003:1). The internal structure of the
hypogeum was added after the completion of the Colosseum, constructed by Emperor Domitian shortly after he rose to power.

5.2.2. **Superstructure - First, Second, and Third Levels**

Apart from its size, the main interest of the Colosseum superstructure is the evidence it provides for Roman construction methods in general. Foundation aside, its success as a monument was largely due to choice of materials – and the local resources were more than enough to provide for the specifications. The main load-bearing skeleton was from stone masonry with a travertine exterior and tuff interior while concrete was limited to vaults and upper internal walls. At higher levels, in order to reduce downward thrust, the walls were made from brick and concrete, and the seating was constructed from timber; most of the vaults were also constructed from pumice to further reduce weight (Quennell 1971:38). To expedite the construction process, the site was broken down into four different sections, each in turn erected via an organized construction subdivided by way of materials. So whereas other buildings were lost due to being created from brick-faced concrete, the Colosseum relied on a combination of organized construction and sturdier, more durable materials to remain standing long after the fall of the Roman Empire (Ward-Perkins 1974:94).

Unlike the model superstructure, which is constructed with a single feature with additional elements added later, the actual superstructure was constructed in a similar manner to modern buildings, with each level being constructed with the features it entailed. The arena itself was built directly over the hypogeum
which has been discussed in Section 4.3.4, and covered with sand to presumably absorb whatever blood may have been spilt (Claridge 1998:279).

One of the most notable aspects of the Colosseum superstructure, as with Roman construction in general, is its extensive use of the Roman arch, a hallmark of this style of architecture. It should be noted that Greek and Etruscan forerunners to the Roman arch do exist, such as drainage channels of the Etruscan states. The arch was however primarily a Roman achievement. In arches constructed from concrete, as can be seen in the Colosseum, the facing was made of bricks, most of them extending only 12 to 15 centimeters (5 to 6 inches) into the concrete behind them. However every sixth or seventh brick reached to the back of the arch, keeping the concrete in position (Raeburn 1980:69).

The construction of Roman arches was a precise operation. Each arch was mounted on its respective formwork or a temporary structure to support the arch during construction. This was comprised of at least two arches joined crosswise by a curvilinear mantle over the clear span, or the width of the arch. Corbels were used to support the formwork and in many constructions, these were designed to serve as decorative cornices. Arches could be made out of concrete, brick-faced concrete, brick, or stone blocks; the former two could be made in one solid piece, but the latter two required a keystone so that the friction generated by said keystone along with the voussiers, or arch wedges, could stabilize the structure. Some arches such as in the Baths of Caracalla did
not require keystones, instead using a progressive projection of the brick rows. For additional stability, abutments were also provided to further distribute the stresses the arches transferred down their curved top sections. The Colosseum arches used primarily brick-faced concrete and travertine arches, with columns in between serving as the abutments (Figure 5.26).

FIG. 5.26: A selection of Colosseum archways as seen today. The disparity between the materials for the different levels was intended for structural stability: tuff and travertine below provide a heavy, stable base, and concrete faced with brick at higher levels keeps the weight at higher elevations to a minimum.
FIG. 5.27: This model (a) and drawing set (b) depicts two of the arches from the Colosseum. The keystone and central column/abutment are shown in brown for clarity.
A related case could be argued for the construction of vaults, which are closely related to arches and rely on a similar concept. (The Colosseum also has this type of structure within its walls, but these vaults are not monolithic, meaning they did not consist of a single structure). Indeed, it was likely difficult, if not impossible, to construct monolithic vaults that could remain standing without external support, at least from stone. Thus the builders of this type of structure inserted parallel or crossing stiffening ribs made from brick to control and reinforce the vault (MacDonald 1976:148-50).

Figure 5.27 depicts two supporting arches from the interior of the Colosseum. Different parts of the arch in Figure 5.27.a are highlighted with red labels and arrows, with the most significant support portions colored accordingly. The dimensions in Figure 5.27.b are approximated from on-site measurements, rounded to the nearest tenth to account for variations between individual structures.

The first floor of the Colosseum, the Podium, was reserved for the most prominent government officials, such as the emperor, senators, and dignitaries. Upon the first floor, in the immediate perimeter of the arena, special boxes were provided at the north and south ends respectively for the Emperor and the Vestal Virgins, providing the best views of the arena; flanking these at the same level was a broad platform or podium for the senatorial class, who were allowed to bring their own chairs. The Colosseum had been completed up to its third floor by the time of Vespasian’s death in 78 AD. This was the floor which held the
maenianum secundum, originally reserved for ordinary Roman citizens or plebeians. It was divided into two sections: the lower part (immum) for wealthy citizens; and the upper part (summum) for poor citizens. Specific sectors were provided for social groups such as boys with their tutors, soldiers on leave, foreign dignitaries, scribes, heralds, priests and so forth, with inscriptions identified the areas reserved for particular groups (Claridge 1998:278-9).

FIG. 5.28: Travertine was easily obtainable from the Roman quarries. Blocks were carved from the quarry (a), rolled onto logs (b), and wheeled to pulleys that hauled them into transit (c).
Though many different materials were used to create the superstructure of the Colosseum, its structure was constructed primarily from travertine, the same stone that was used for its outer façade. Blocks of this material were used to raise a framework of concentric piers and arches, which were connected by a series of lateral walls, which in turn were built from tuff on the lower floors and brick-faced concrete on the upper levels (Quennell 1971:38). As shown in Figure 5.28, each of these stones was chiseled from the Tibur quarry, splitting off as a rough six-ton block (Fig 5.28a). The stone was then rolled onto logs (Fig 5.28b), hoisted with pulleys onto an oxcart (Fig 5.28c), and sent thirty kilometers to Rome along a specially built road. Two hundred carts of stone entered the city during each day of the Colosseum's construction. Other materials included tuff, obtained a few kilometers from the city, bricks and concrete produced on site, and with aggregate from the demolished Domus.

As each travertine block arrived, it was chiseled into the proper shape for installment, and hauled into place by a wooden crane with a block and tackle mechanism. These cranes were massive, sometimes twenty meters high, and were positioned both inside and outside the Colosseum. Using pulleys along with hand-cranked winches (Figure 5.29.a) or treadmills in the case of the larger versions (Figure 5.30), a single crane could lift and place blocks weighing tens of tons upon the monument's walls (Homer-Dixon 2008); as such, notches were carved onto the blocks before installation, so that the winch clamps could attach to them and lift them more easily (Figure 5.29.b). It is also probable, considering
FIG. 5.29: Reconstruction of a lifting mechanism employed in the construction of the Colosseum. The crane (a) was equipped with a set of tongs that clutched a matching set of notches in each stone block. Notches for cranes/scaffolding, indicated by red arrows, were carved directly into the blocks, and are still visible in the internal walls today (b).
similar practices in modern construction, that wooden scaffolding was also set up for workers to guide blocks into place upon the higher elevations, and it is likely that the larger holes in the stone blocks were carved for the purpose of fitting the mandatory support structures. Once guided into place, the stone blocks were then bonded together with iron clamps, mostly pre-manufactured but sometimes repaired and altered on site. About 300 tons of iron was used in the first level alone, and molten lead was also poured into the clamp holes to prevent shifting and rusting (DuTemple 2003:35-36).
FIG. 5.31: The construction of the Colosseum floors mandated use of wooden cranes on multiple levels. Construction of the first floor involved cranes on the ground (a), but building the second floor required wheeling them onto the first floor (b).
FIG. 5.32: A stylized, speculative rendition of the Colosseum wall erection process. Notice the winch cranes could have been used to provide concrete for the higher levels as well as lift the building blocks.
As the first floor was completed, the Romans rolled their cranes up the sloped seating to hoist stone blocks to the higher floors (Figures 5.31, 5.32). However, as the elevation increased, concrete faced with brick began to replace travertine and tuff because it was lighter and therefore did not have to bear as much weight at higher levels. The concrete was likely mixed at ground level, and then carried upwards by ropes or workers up stairways and scaffolding to the higher levels (Homer-Dixon 2008).

The second level of the Colosseum was constructed in a similar manner to the first level, but with a critical difference: the space between the piers was filled with brick-faced concrete instead of tuff. Thus two parallel brick walls could be built, and filled with concrete to form the wall cores. This was convenient because higher levels needed to weigh less to reduce stress on the lower levels, and higher levels additionally needed to bear less weight, enabling the use of weaker but lighter construction materials (DuTemple 2003:42).

5.2.3. Superstructure - Fourth Level and Roof

The fourth and final level was completed by Titus in 80 AD. It was later refurbished by Domitian with another level, the *maenianum secundum*, in the *ligneis* or attic. This was the highest area of seating and consisted of 10-11 terraces of wooden seating which gave it its name. During its construction, the workers installed a row of eighty columns, each shaft alone weighing nine tons, along the inside edge of the gallery, supporting a roof of travertine to shelter the lowest classes, such as slaves and women, which sat at this level (Homer-Dixon
Corinthian pilasters also divided the final level into 80 compartments, each with a small opening. On the outer wall of this level, the corbels and matching openings supported the masts for the *velarium*. Since the corbels and pilasters could not have been installed after the wall was assembled, it is likely that they were laid while it was erected in a similar manner and skill to façades on other buildings of the era (Claridge 1998:279,282).

The stages of the Colosseum’s erection are shown in Figures 5.33 through 5.37. Two of the four sections have been removed, so the cross-section of the Colosseum during each stage is also visible. Figures 5.38 shows a sectional view of the structure at completion, including the interior stairwells. A time-lapse animation of the construction of the Colosseum, with all stages including the hypogeum and arena, is also provided.
FIG. 5.33: The foundation prior to the first level of construction (a) without the floor surface/arena and (b) with the floor surface/arena.
FIG. 5.34: Cross-sectional view of the first level of construction.

FIG. 5.35: Cross-sectional view of the second level of construction.
FIG. 5.36: Cross-sectional view of the third level of construction.

FIG. 5.37: Cross-sectional view of the fourth level of construction.
FIG. 5.38: A comparison between a sectional view of the digital model upon completion (a) and a sectional view of a scale model (b). The stairways were added in after the section was cut, instead of during the construction process of the model. Additionally, the section removal process removed the interior columns entirely in the digital model, whereas the scale model retains the column bases as sector markers (Museo Civlta Romano).
5.3. Model Analysis in Animation Form

Provided with this study are three animations of the model for this simulation, described in Section 5.1. The views of the Colosseum model provided by these models can be used to judge the integrity and reliability of the model in comparison to the actual monument.

5.3.1. Creating the Animations

Creating the provided animations requires use of the Inventor Studio environment. In the 2012 version used in the study, this is accessed by opening the Environments tab on the search bar and clicking the Inventor Studio option (Figure 5.39); in older versions, it is accessed through the Applications tab. Once the Inventor Studio environment has been activated, the current view can be copied into the starting position for the camera used to create the animation by right-clicking the Camera icon on the object tree and selecting the option to create a camera from the current view. The camera can then be moved around the structure using the animation timeline slider by zooming, panning, and rotating as with the current view, writing each camera action to the timeline as needed (Figure 5.40). When the path is decided, an animation render can then be produced using the Render Animation option (Figure 5.41). The video size, camera, frame rate, time range, and save file can be customized for optimum quality of the output rendered. Note that there is a Preview/No Render option; this allows for the animation to be recorded without rendering each frame, thus
reducing rendering time even for large assemblies such as the model discussed previously.

FIG. 5.38: Opening Inventor Studio; this is the environment used to create the animations.

FIG. 5.39: Inventor Studio can be used to create animations that involve moving the camera around a stationary model. The cameras are circled in red; the slider and the option to write an action with a certain camera (icon next to the selected camera) are circled in blue.
FIG. 5.40: Rendering the animation. Options can be tailored to suit the quality of the animation in terms of visuals or frames-per-second. The Preview: No Render option is circled in green.
5.3.2. **Animation 1: Exterior**

This animation serves as an overview of the external characteristics of the model. The exterior is similar to other restorations of the monument in terms of the outer décor, and the interior shows the vomitoria and stairwells in positions akin to the historical print used as a reference. However, although the monument does resemble the actual structure at an outward glance, there are subtle differences which could potentially compromise the accuracy of the model. Firstly, the arches and pilasters in the model are positioned differently than in the corresponding exterior. In the Colosseum the floor of the arch is on the same level as the radial ribs that indicated the levels; in the model, the former is above the latter because of the different distances for each rectangular pattern that produced the three rows of arches from the single row of entrances ([Figure 5.41](#)). Near the top of the model, the corbels that held the *velarium* masts are spaced unevenly with respect to the windows, as there should be three corbels per section of attic, due to the even spacing of the corbels relative to the ellipse instead of the windows ([Figure 5.42](#)).

The animation zooms in towards the interior after this quick overview. Here is where the disparity between simulation and reality becomes clear. The vomitoria are dead-ends because the stairways overshadow the passageways into the interior, and also because the extrusions regarding them are not deep enough. Additionally, the floors are incorrect: the second floor has raised areas between the archways, and the first floor is level to the ground plane.
5.3.3. **Animation 2: Interior**

The contrast between the interior of the digital model and the interior of the scale model shown in Figure 5.38 shows the contrast between the two models more clearly than in the exterior overview 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 animation shows each of the stairways, demonstrating that these in particular are not as well designed as other aspects of the model. The interior of the model is created entirely using sweep features, instead of individual rooms and walls, to reduce complexity. This is at the cost of accuracy because in reality the interior has a complex network of stairs and passageways that would have led spectators to various areas around the seating. The paired stairways of the model section view, however, are dead-ended because they 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.

5.3.4. **Animation 3: Construction Stages**

This is essentially a repeat of Figures 5.25 and 5.33-37, in animated form. Note that this animation was produced on Windows Movie Maker because Autodesk Studio does not accept imported .PNG screenshots.
5.4. Discussion: Modeling and Construction

5.4.1. Findings

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, 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 5.41 through Figure 5.51; 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, as no program can ever simulate a photorealistic rendering of the true form of the structure. 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.

Generalizing from this, it can be stated that while the model is ideal for authentically simulating a speculative restoration, it may not be as ideal for reconstructing it via ground-up means. Such a simulation will inevitably take up large amounts of data, and more complex operations may be required to accommodate additional insights. This is important because the model is actually dynamic, and may have to be revised as more information is revealed.
FIG. 5.41: 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. Not only is it monolithic, without subdivisions, but it also omits important architectural details, such as the “flaring” of the top portion that would reinforce the column via stress distribution. Of course, part of the realism can be rectified through the use of photorealistic textures, especially masonry, though the mandatory use of a polygonal texture map may complicate this idea to some degree.
FIG. 5.42: A comparison between an archway from the Colosseum (a) and one from the simulation (b) is another example of how the uniformity of the modeling process comes at the cost of details. The model arch is built from one solid piece with textures overlaid upon it, rather than separate units, thus complicating demonstration of the actual construction methods.
FIG. 5.43: A quick 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). The model also lacks the brick facing of the actual structure, though this can be theoretically remedied via texture mapping.
FIG. 5.44: 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) was created using a historical diagram as a basis, and may provide some ideas of the monument’s appearance in its still pristine state.
FIG. 5.45: This stairway system (a) shows that the interior of the model differs from the actual system by a significant margin, warranting the creation of a separate part to simulate the structure (b). This is because the interior cross section actually varies depending on the location within the structure, meaning the interior cannot be accurately rendered with a single sweep feature as was attempted in the model.
FIG. 5.46: 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).
FIG. 5.47: The views from the second level of the Colosseum in (a) bear a passing resemblance to a similar view from the model in (b). However, it appears that the vomitoria are not as closely spaced, and the third floor lacks passageway openings. As the seating in the actual site has degraded, it cannot be compared to the equivalent in the model, which was based off a restoration from before the degradation of the monument.
FIG. 5.48: As before, the degradation of the concrete makes the actual Colosseum (a) look significantly different from the model (b). Disregarding details, however, the use of a historical model as a basis for the digital one can be cited as a reason for how the patterns of the archways and relative positioning to the *vomitoria* look relatively similar.
FIG. 5.49: One of the few similarities between the model and the real monument is in the passageways leading out of the seating. The “walls” pictured in (a) are really the internal structures which would have supported the seating; the reason the actual structure looks different is simply because the seating has been lost over time. Note that this applies only to the exterior, however, as the interior seating is solid due to being created from a sweep feature (b).
FIG. 5.50: Shown above is another example of the presumed similarities, degradation aside, in the passageways leading out of the seating. The actual site is pictured in (a); the model version in (b) has seating, which has degraded in the actual monument, and more importantly, a solid interior owing to the sweep feature. Regardless, the exterior looks more similar to the real structure than other sections of the model.
FIG. 5.51: 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. The model is based on a combination of the Museo Colosseo reconstruction and the 1725 print, *L’Anfiteatro Flavio* (Quennell 1971:38-39), modified by the author to fit the dimensions of the existing arena and exterior walls in the model.
The disparities shown in the previous pages suggest that depicting the construction process may be even more taxing than depicting the model itself. This extends to comparison with models for more modern works of civil engineering: modern simulations can be built from the ground-up, meaning that the design keeps the processes and limitations in mind from square one. It is more difficult to determine the construction processes of ancient monuments such as the Colosseum, particularly following their deterioration. And anyway, 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 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.

Likewise, it is worth considering the viability of digitally recreating the Colosseum compared to other monuments, particularly ones that have better withstood similar periods of wear. The best example of the latter category would be the Pantheon, also in Rome. About nine-tenths of the structure of the intermediate block and rotunda of the Pantheon is concrete, which takes on the shape determined by the surrounding forms. In this case, the Pantheon rotunda walls were built by pouring concrete into low, wide trenches formed by the inner/outer brick walls, the trenches rising precisely upon one another until the
terrace level was reached. The dome was poured over an immense hemispherical wooden form supported by a forest of timbers and struts, upon which the negatives for the coffers were fixed (MacDonald 1976:38). The Colosseum, by contrast, was constructed from blocks of stone connected with iron brackets, and situated on the less stable bed of the former Domus lake, and indeed it was subjected to a series of earthquakes that eventually caused its exterior walls to partially collapse (Claridge 1998:277-8). The generalized explanation is that both material and structural aspects play an important role in determining how long a structure is expected to last and how quickly it deteriorates. However, destructive incidents that may occur throughout the building’s history, such as the earthquakes that damaged the Colosseum, often prevent the state of the monument over various time periods from providing a more specific idea of the monument’s in-use appearance given the current materials and circumstances.

5.4.2. Modern Applications

In the midst of this discussion, one question remains unanswered. Where and how would simulating a model of an ancient Roman monument such as the Colosseum apply to modern situations? The most important aspect to consider is that this simulation is related to a structure that was built thousands of years ago, with techniques that relied on both methodologies and concepts that could still be applied today and methods that have become outdated with the advent of the Industrial Revolution and, more importantly, that of modern green and
sustainable engineering. To understand the uses this study has regarding these fields of research, an explanation regarding them would be necessary. Green engineering is the design and construction of structures that have a minimal impact on the local environment. Sustainable engineering, however, expands its territory by also taking into account the benefit the structure poses towards human society. Though the territories of these two do overlap, the concepts themselves are not entirely identical, and specifically green engineering can be considered as being more specific than sustainable engineering.

As a case in point, an analysis of the Colosseum can be cited regarding both greenness and sustainability. Firstly, the environment presumably provided the appropriate conditions such that environmental stress posed by the Colosseum was kept to a minimum. The warm Mediterranean climate of ancient Rome would have provided a smaller degree of temperature fluctuation than in the more temperate climates to the north. This would mean less energy was devoted to heating and cooling of the Colosseum through seasonal fluctuations. Likewise, while the Colosseum did presumably use water in the form of fountains and, in its early years, flooding the arena for mock naval battles, the water came from aqueducts that channeled it in and out of the stadium and recycled it regularly. Additionally, because of the amphitheater’s open-air construction and the specialized velarium (roof awning), neither air circulation/ventilation nor issues with shading would have provided much of a problem for the spectators who often visited the building.
Secondly, the design of the Colosseum structure should be environmentally and societally tolerable. The passages or vomitoria which funneled visitors into the seating optimized the entry and exit of those who attended the tournaments held inside. During construction, most of the building materials were locally obtained, meaning they were reusable, renewable, and recyclable (and in fact, the stone facing of the Colosseum was often pilfered for other functions when the monument fell into disuse). Suitable stone was available within the Roman locale, and materials for concrete could be taken from on-site debris, such as the demolished remains of Nero’s Domus. Likewise, wood for the arena, attic and velarium could be obtained from local forests that once covered the area, and canvas for the latter was easily accessible via hemp grown specifically for this purpose.

So the Colosseum was green in that it presented a minimal impact towards the local environment. This is not to say, however, that it was sustainable. It has been previously mentioned that compared to greenness, sustainability is a broader but related concept. By factoring in the impact on the empire from the social perspective, sustainability becomes a broader notion with more criteria that the structure in question must fulfill. As will be explained later, the Colosseum, despite qualifying as a green monument, does not meet all the criteria for sustainability, which provides some highly important implications about the generic impact of Roman monuments as a whole.
With all this in mind, it is important to take into account the methodologies and concepts applied to the creation of the monument, because aspects that helped form the Colosseum, such as planning and measurement, labor organization, and the application of physics, mathematics, and engineering, provide a viable base for the planning and construction of modern structures worldwide. It may even be useful for current engineers and architects to consider the ancient techniques that may have been applied to similar structures to structures built today, and put these techniques to use accordingly.

The example of the Colosseum in particular can be compared to modern sports stadiums, which are the closest structures to ancient amphitheaters both functionally and structurally. The difference between historical and modern construction is particularly notable in that the construction techniques are less known and with less certainty with respect to the ancient structure. An example comparison can be made between the Colosseum and the Beijing National Stadium, also known as the Bird's Nest, in Beijing, China. Prior to its selection for the 2008 Beijing Olympics, the city held a bidding process for the best arena design. Multiple requirements included the ability for post-Olympics use, a retractable roof, and low maintenance costs. The "nest" design that was selected shared some similarities to the Colosseum in that it completely enclosed its stadium and initially had a retractable roof, although the latter was later eliminated for safety and budget purposes (Lubow 2006). This and other revisions during the construction process exemplify the notion that in modern
simulations used for works in progress, the design is not truly finalized and can be altered and/or improved depending on the circumstances, and the construction stages can be determined with relative certainty starting from the incipient of the process. As such, the knowledge of the construction process would be somewhat limited at best, and the historical façade and details would be primarily speculation on the part of simulated restorations.

This same point can also be applied to the construction of the Colosseum in comparison to modern structures. Materials are one of the key factors for consideration: the Colosseum was primarily built from travertine, concrete, and brick - the most common construction materials locally available at the time. Stone and concrete are heavy, solid materials that would pose at least some size limits due to the total mass used in construction at the minimum; this is in contrast with stronger but more lightweight materials of modern times, such as steel and plastics, which enable modern construction projects to achieve a larger scale in terms of both height and foundation area/span. With ideas touting the state of the environment and those supporting the expansion of human civilization in an increasing state of conflict, simulations such as the one described may provide further assistance in achieving stable mediums that support both. The objective of such solutions is to promote feasibility and economic value while minimizing harm towards the environment or humanity, the basis for green engineering. The construction processes discussed provide clues towards the sustainability issue, but the most important aspect to consider
FIG. 5.52: This diagram lists the three constituent parts of sustainability. The Colosseum fulfilled environmental and societal needs, but not economical needs, meaning it succeeded in vitality but not in sustainability as a whole.

is that the complexity the model demonstrates means that such a monument is more similar to modern structures than its appearance would suggest, meaning the principles regarding it, including sustainability, would have followed the same pattern.

As shown in Figure 5.52, sustainability satisfies requirements based on environmental, societal, and economical needs. Ideally, a structure is sustainable if it satisfies all three sets of criteria. But while it is true that, based on historical records, ancient structures such as the Colosseum may have complied with at
least one of the three major conditions as was intended, it appears that, as stated earlier, many of these would not have complied with all three conditions. The Colosseum, for example, fulfilled its social purposes and, being constructed mostly from local materials, presumably made a minimal impact on the surrounding environment. However, the claims of standard fulfillment cannot be said for the third major requirement, concerning the presumed economic impact it might have had not just on the capital, but also on the Empire as a whole.

The Colosseum employed vast amounts of man-labor due to its scale alone. Man-labor, often though not necessarily slavery, was common in ancient civilizations such as the Roman Empire, but obtaining new labor forces and expanding old ones often required annexation of nations beyond the Empire’s borders. Based on Homer-Dixon's calculations (2008), constructing the Colosseum by itself, even without the interior utilities, would have required over 44 billion kilocalories of energy; a sizable portion of that amount, over 34 billion kilocalories, was allotted to feeding the oxen that transported the materials, and the other ten billion or so was taken up by the work force. Most importantly, however, the translation to agricultural effort revealed that the Colosseum construction required a total of over 55 square kilometers of land, close to the area of Manhattan, to be used full-time to grow the necessary sustenance for ox and man alike, for at least five years. Creating and installing the keystone alone would have required only 1300 square meters of land used similarly.
Effort may be one factor, but another important consideration is the sheer funding that may also have been involved, and for such a large structure, the expenses involved would have been almost as titanic as the monument itself. Apparently, according to one school of thought, Emperor Vespasian, who began the Colosseum project, and his son Titus succeeded in this respect primarily through sheer good fortune. According to Hopkins and Beard (2011:26-28), Vespasian suppressed the Jewish uprising in AD 66. Jerusalem was eventually subdued by Titus in AD 70. Upon returning to Rome they brought back large amounts of treasure, including a seven-branched Menorah whose image still shines on the Arch of Titus (Figure 5.53). As most of this wealth was donated to the renewal of the Empire, it was natural that Nero’s building schemes would have to be overturned, particularly the previously mentioned Domus Aurea site where the Flavian Amphitheater now stands. So overall, the question to be answered is where did the money come from – and according to Hopkins and Beard, one of the inscribed stones from the arena indicated that the answer was, in fact, the spoils from the suppression of the Jewish rebellion (Hopkins & Beard 2011:32). This is not to say that the Romans would have been unable to fund the Colosseum had they not taken it upon themselves to subjugate the Jewish rebellion, and anyway the evidence is not yet clear enough to determine the validity of this theory, but in hindsight, it makes sense. The Romans always were lavish in terms of construction funds and processes, but not all the resources they had at their disposal could be obtained within the immediate vicinity of the
FIG. 5.53: The Arch of Titus, located near the Colosseum, features the Menorah, as indicated by the red arrow in (a), among the treasures the Romans gained from subjugating the Jewish rebellion, which are shown in close-up in (b). Some have theorized that the wealth obtained from the subjugation of this rebellion may have been donated to constructing the amphitheater, among other things.
cities in question. It is likely that some of these were obtained from sources elsewhere, and as such, a significant amount of the conquered spoils would have been used for purchasing and shipping the imported resources. And in any case, regardless of how much wealth the Empire would have been reputed to have at any point in its history, it would have always had to come from somewhere else, namely the recently subjugated nations, tribes, and communities that once dwelled outside of its borders.

So considering the astronomical flow of energy and funds dedicated to constructing such a complex monument, the sheer amount of assets that would have been required to construct any number of monuments such as this one, let alone entire cities, would call for an astounding supply of labor, materials, land, and funding, all of which the Roman Empire was fortunate to have. As discussed above, when applied to a large number of structures such as this one, throughout the Empire and even within Rome itself, this plethora would not have translated to just the collective effort of a single capital city, regardless of size, but rather to that of a constantly ravenous, ever-expanding colossus on a wholly different scale. Indeed, it is likely that this very enlargement process for the sake of new monuments and metropolises ultimately proved detrimental to the Roman economy and possibly society as well, since it has already been stated that the Empire outgrew the upper limit for economic stability and collapsed due to internal corruption and general failure to sustain its ever-expanding territory.
Modern structures, on the other hand, face problems that affect other aspects of sustainability. As humankind expands, the environment is increasingly compromised as structures are built with society and economy in mind. This parallels the Roman Empire’s expansion in that collapse may be imminent if new models and designs that fulfill sustainability are not developed. Simulations such as the Colosseum model that focus on construction can be used to uncover valuable new insights, which would be useful in developing models for modern construction which can provide for the benefit of the environment as well as the civilization in question. The Romans used local resources, for example, and avoided wasting fuel on imports; their organization of labor also made work more efficient, avoiding wasted effort. Additionally, the sturdy double-layered foundation provided for a building that could remain standing for long periods and be used over a longer period. Finally, the model created for this study provides a demonstration of the sound construction processes that helped the Colosseum remain standing, and also of the similarities of concepts between this monument and modern construction. So while simulations of ancient monuments may be thought of as primarily an archaeological development, it is possible and indeed highly likely to apply the concepts and theories demonstrated to modern works – a veritable case of looking to the past in order to build the future.
6.1. Summary

Throughout the course of this study, effort has been dedicated towards the analysis not only of the simulated model but the history of the architecture and construction leading up to the model. As a starting point, an overview of Roman architecture was discussed, starting with the ancestral styles that factored into its creation. Discussion was also made of the materials, techniques, and concepts that were used in Roman construction. Following this, a timeline was made of the development of Greek and Roman theaters, the half-encircling precursor to the amphitheater, and then of the amphitheater itself, with the differences between Greek and Roman theaters along with the standard theater and amphitheater being highlighted along the way. This provided a basis for the Colosseum model and an appropriate background for the historical aspects of the study.

The focus then turned to the background of the simulation. The complexity of the creation process required a user-friendly interface which narrowed down the selection of choices; Autodesk Inventor was chosen because of its flexibility and functionality with regards to graphics. Afterward, the literature search on this prospect noted that there detailed models of the Colosseum have been produced before, but the simulations tended to focus on the monument, leaving an opening for how it was constructed. Finally, a structural analysis was discussed: the planning of the structure provided the basic dimensions and specifications, and the substructure and superstructure set the
key features to look for in an ideal simulation model. The construction of each stage was described accordingly, and techniques that could apply to Roman construction in general were also included in the discussion appropriately.

With this in mind, the creation of the model was the next priority. Using Autodesk Inventor and its various functions, a model of the Colosseum was created, starting from the foundation up towards the superstructure and building it in the manner that was most optimized with regards to the software. This provided an idea of the digital construction process. Following this was a discussion of the historical construction as a comparison, explaining, in advanced detail and with literary precedent, the construction of the foundation, substructure, and the levels of the monument. Once both of these aspects of the analysis were completed, the obligatory comparison was made between them to determine the model's viability as an analytical tool. This is also accompanied by a discussion relating the structure and its background to the green engineering and sustainability of the structure. Comparisons were also made between the monument and other monuments, and between the monument and similar modern buildings, so as to judge the potential value this simulation has in various aspects of graphics, civil engineering, and historical study.

6.2. 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 capabilities and functionalities of modern graphics software enable monuments to be simulated with an increasing
degree of accuracy, based on data that has been gathered from both historical literature and on-site measurement. Understanding a simulation of the Colosseum, and the implications thereof, requires knowledge of history of the Colosseum where civil engineering and construction are concerned. Fortunately, this monument has significance with regards to construction and architecture, and a number of sources provide historically accurate dimensions which can be used as a starting point for the pictured simulation. Equally important is its historical significance, which has its grounds in the history of Roman architecture; the Romans took multiple sources into account in their construction, such as the Etruscans and other native tribes and also the ancient Greeks. The Colosseum and other monuments show that 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. Using Autodesk Inventor, the model demonstrated provides a relatively authentic simulation of the Colosseum which can be constructed using a large number of relatively simple procedures, and can additionally be modified as new developments are made. This simulation uses the original, historical plans and dimensions, but builds upon them using methods that sometimes differ from how the monument was actually built, but produce a markedly similar result. 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. Moderately advanced techniques such as patterns along curves, user-generated work planes, and three-dimensional sketches help define the more complex features of the model with a reasonable degree of authenticity while expediting the modeling process.

In a similar vein, the historical construction processes of the monument are also analyzed. In the ten years it took to construct the Colosseum, Roman architecture, construction, and civil engineering were all put to the test in many ways. A solid-concrete foundation, in two layers, provided a sturdy base for the superstructure, and was later furnished with the hypogaeum directly under the arena. Above this, the floors and seating were mounted with travertine and tuff, brick and concrete; organization of labor, exploitation of equipment, and choice of materials allowed the work to be performed relatively quickly. The result was a sturdy, long-lasting amphitheater, the biggest of its kind. Along the way, exposition is given regarding the Roman arch, one of the hallmarks of Roman civil works such as this one, as well as its derivation, the vault. Though strong and stable upon completion, the arch was constructed with care, using precise techniques that ensured the structure's integrity.

With all this in mind, the potential viability of this simulation is speculated, both in regards to the techniques behind it and in comparison with ancient and modern structures. The simulation is capable of producing a relatively realistic model, but it takes a large amount of data to do so, and the complexity may also cause the rendering to lapse. The differences between the digital construction and historical construction may also decrease the viability of the simulation as a demonstration of construction
techniques, but the construction stages can be recreated from the finished model to counteract this. A comparison with other monuments also shows that the Colosseum, while significantly sturdier than other monuments, has not survived as long as other monuments which used different construction methods, especially in the case of natural disruptions such as the earthquake that destroyed part of the amphitheater exterior.

Finally, an appropriate modern use for this type of simulation in the construction industry would be as a supplemental guide for modern civil works. The concepts that were used also apply to current construction, in this case arenas and stadiums that serve the same purpose and also employ similar features. It is also worth noting relations to green engineering and sustainability; the Colosseum was not sustainable because of the intensive labor force and expenses that went into its construction, but it was derived from local resources. So the simulation is best applied to construction in theory, and not on the field directly.

Based on all this information, it can be inferred, in a general sense, that simulating the construction of ancient monuments is indeed viable as an engineering resource, but not entirely so. There are multiple facets to the engineering of structures as a whole, such as construction, maintenance, and integrity; both archaeology and computer graphics can be similarly treated as such. The simulation works with respect to the final appearance of the monument and the graphics capabilities, in that the procedure could produce an accurate rendering with enough time and resources. With enough research, evidence, and practice, this procedure can be potentially repeated with monuments of
other shapes, sizes, locales, eras, and even civilizations, although the process obviously must be repeated for each monument analyzed.

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, and it has already been stated that graphics-wise, the most notable of these is the increase in render time relative to complexity, which can cause the program to stall if too many features are included. But the extent of the problem is not limited to the visuals, and in practice the baseline concept has shortcomings of its own. To wit, this approach could work in theory, if enough is known with respect to the construction processes related to the monument that such processes could be feasibly and accurately recreated. In practice, however, reverse-engineering the procedures in this way could provide an entirely new set of problems, such as subdivision of the structure into smaller units, recreation of individual features, and possible scaling of equipment and other utilities.

Conclusions can also be drawn from the historical construction process of the Colosseum. Labor, materials, and the actual construction process have all been analyzed thoroughly. The deduction is that it was a combination of factors – namely the complexity, materials, organization, and environment – that allowed the Colosseum to remain standing for as long as it has. Travertine is both attractive and durable, and can be used as a facing without the need for applied concrete as a form of weatherproofing. As a mixture of stone at the base for stability and concrete at higher elevations to reduce weight, the Colosseum could therefore remain intact for a longer period than if it
were entirely constructed from concrete. It is therefore likely that the main reasons it
degraded was due to human intervention and a natural disaster, and though a lack of
maintenance may have played a role to some degree, the direct theft of some of the
travertine would have been more detrimental than the decay of the material itself.

Material choice also mattered, apparently, with regards to economic concerns. The
travertine used for the exterior and skeleton was within the Roman locale, and
therefore would not have required as much expense to obtain and transport to the
work site as, for instance, if it were obtained in another province or overseas. It is
important to note that conveyance of materials will take time and expenses, especially
over long distances such as in the crossing of sea straits or overland barriers. Obtaining
materials locally would save on the energy cost of obtaining the material in the first
place, much less constructing it on-site. The same principle applies to the concrete,
which was presumably mixed and laid on site with the same benefit; the clay for the
brick facing could likewise be obtained, baked, and transported entirely within the city
locale. Relatively speaking, the only large-scale effort that would have to be expended
would likely be the 300 tons of iron that bound the stones together, and obviously the
labor force that would have been involved. Iron was not available within the Roman city
or immediate territory during this period and was normally traded from other countries
throughout the rest of Roman Europe. This meant there would be at least some
transportation costs involved in hauling the necessary iron to Rome. As for the labor
force, the sheer effort that would have been placed on a monument this large would
induce a high energy demand that the workers would have needed to counterbalance
with the devotion of more land space to agriculture than to the city itself – never mind
the prospect of the additional land that would have to be annexed should new laborers
be brought in from conquered areas elsewhere.

So the remaining question is where the simulation fits in with regards to
sustainability and analysis of the monument. The intersection of these two parts of the
study is not only crucial to the significance of the simulation, but also provides some
important implications about how it could apply to modern construction as well. In
terms of modern construction, it should be relatively facile to replicate the complexity
of the process and, in fact, many modern structures such as stadiums take a shorter
time to construct than ancient ones such as the Colosseum, because the more advanced
techniques and materials save time and effort. But these techniques and materials may
also cost more to produce and import. The construction stages presented show that the
organization processes of the Colosseum, while taking a longer period of time, could
produce a similar result to buildings today. In truth, it could be said that whether the
principles it showcases should be taken to heart and to what degree depends on
perception. Local materials as the ancients would have used would reduce the effort
required to transport resources, while modern construction techniques would have
reduced the time and effort to construct the structure. Either way, the simulation shows
that true to historical precedent, the building process of monuments such as the
Colosseum was likely as detailed and sophisticated as in modern construction, and that
the construction of many of these ancient structures, at least in the case of the Romans,
was actually very similar in concept to that of modern stadiums, skyscrapers, and other 20th/21st century construction achievements.

6.3. Recommendations

Given the conclusions above, it can be said that accurately simulating the construction process of many ancient monuments appears to be a daunting task, primarily because of the lack of information that is known to begin with. Most ancient historical literature placed precedence on the monument, its historical significance, the way it appears in the public light, and its use upon completion. In the case of impressive monuments such as the Colosseum, the sheer grandeur of the monument often overshadows the grandeur of its construction and the processes that went into creating it. On this note, it suffices to state that more information related to the construction of the structure in question, and to ancient construction in general, is required for this simulation to be viable. Continuing on this line of reasoning, it is thus imperative that historians and engineers consider broadening the field of study with regards to ancient structures. On a similar note, the construction processes should be examined in more detail instead of, for example, purely focusing on the completed monument, because a greater understanding of the monument in general could be potentially obtained in the comprehension of how the monument was built. Historians should therefore search for additional evidence on this subject, not only for the sake of recreating the building stages more accurately but also to decipher the history of the structures that the simulation intends to focus on, along with Roman architecture as a whole.
Compared to this setback, the technical issues may not seem as significant because they are more easily remedied, but this does not mean they are not significant in general. The complexity of many ancient monuments and especially their construction processes is a problem that should be addressed in the future. While the hardware hopefully improves enough to handle the relevant software functionalities, improvements to graphics engines should meanwhile be the primary priority; specifically, improvements must be made with regards to data capacity, degrees of computation, and the ability to handle complex geometry, as would be prevalent in models of an ancient monuments. The ideal program to handle this type of simulation must handle both of these issues, and additionally provide functions for assembling a structure from constituent units. The program should also allow for active scaling, positioning, and dynamic interaction with components such as the materials used or the equipment involved. Such advancements would undoubtedly qualify as the subject of future research in the field of graphics, so that the modeling process can be applied more readily to other monuments of similar complexity.

The final proposal regards how this simulation should be used in the current field of civil engineering. As mentioned near the end of Section 5.1, the simulation should be employed primarily as a method of principle, as practices become outdated over time while engineering concepts are gradually improved and retooled. Because of this, recreations of ancient methods would obviously be unreliable with respect to modern construction, and have greater potential as an analytical method to be employed by historians and the rare "historical engineer." That being said, this very analytical method
should be cited as the main reason that such a simulation would be employed to begin with. By studying the way ancient buildings were constructed and in some cases withstood the elements for much longer than most modern structures, engineers have the potential to use the methods involved as a template and update these methods with more modern and sustainable materials, so as to create greener and more resilient structures.

6.4. Closing Remarks

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.
APPENDIX A: GLOSSARY

**amphitheater** A theater that entirely encloses its arena. The Colosseum is one example.

**arena** The stage of a theater, where the performance takes place.

**cavea** The seating area in an ancient Greek/Roman theater.

**cella** The inner chambers of a temple, dedicated to the deity in question.

**Comitium** The location of the original founding of the city in question.

**cryptoporticus** A covered corridor or passageway.

**frons scaenae** The elaborately decorated background of a Roman theatre stage.

**hypogeum** An underground structure which divides a chamber into smaller chambers.

**immum** The lowest tier of a cavea, reserved for the Roman elite.

**lapis tiburtinus/travertine** A form of limestone deposited by mineral springs, often used as building material.

**ligneis** The wooden attic of the Colosseum. Derives from Latin *ligneus*, wood.

**ludus** A training academy for gladiators.

**maenianum secundum** The seating of the Colosseum reserved for ordinary citizens.

**media** The middle tier of a cavea. Reserved for middle-class male spectators.

**opus caementicium** Roman concrete, which contains no water and is mixed dry.

**opus incertum** Roman concrete faced with small irregular stones.

**opus reticulatum** Roman concrete faced with small diamond-patterned stone blocks.

**opus testaceum** Roman concrete faced with thick horizontal brick work.

**orchestra** The area in front of an ancient Greek stage reserved for the Greek chorus.
<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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<tbody>
<tr>
<td>parascaenia</td>
<td>The backdrop on a Roman theatre stage. Often used to support the skena.</td>
</tr>
<tr>
<td>pozzolana</td>
<td>A siliceous or siliceous/aluminous material, usually volcanic glass, which reacts with calcium hydroxide in water to form a cement-like substance.</td>
</tr>
<tr>
<td>quadriporticus</td>
<td>A nearly square atrium surrounded by colonnaded porticoes.</td>
</tr>
<tr>
<td>skena</td>
<td>The backdrop or scenic wall of a Greek theatre, behind the orchestra. Also served as an area where actors could change their costumes.</td>
</tr>
<tr>
<td>summum</td>
<td>The highest tier of a cavea. Reserved for lower-class spectators such as women and slaves.</td>
</tr>
<tr>
<td>tuff</td>
<td>A type of stone formed from compressed, consolidated volcanic ash.</td>
</tr>
<tr>
<td>velarium</td>
<td>A type of awning used in Roman times, which stretched over the cavea of a theater to protect spectators from the elements.</td>
</tr>
<tr>
<td>vomitoria</td>
<td>A passage situated below or behind a tier of seats in an amphitheatre or stadium, through which big crowds can enter and exit rapidly.</td>
</tr>
<tr>
<td>voussior</td>
<td>A wedge-shaped piece of the curve of an arch.</td>
</tr>
</tbody>
</table>
APPENDIX B: REFERENCES


17) Fea, Carlo. 1813. *Nuove osservazioni di Carlo Fea intorno all’arena dell’Anfiteatro Flavio*.


