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THE DEPICTION OF STRUCTURAL AND CIVIL ENGINEERING IN VITRUVIUS'S TEN BOOKS ON ARCHITECTURE — A STATE-OF-THE-ART REVIEW

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Abstract
Introduction: Ten Books on Architecture (De Architectura) is a treatise by Vitruvius that describes construction work, as taught and practiced in the 1st century. In it, the functions and duties performed in the built environment by architects, construction workers, civil engineers, surveyors, sculptors, decorators, etc., are all lumped together into either architecture or civil engineering. However, for civil engineers, who operate both in built and unbuilt environments, the scope and depth of subjects covered by this work could serve as useful resources as they develop their competences in core practical aspects of civil engineering. **Materials and Methods:** This paper explores Ten Books on Architecture in relation to civil engineering in the 21st century. The materials used for this work were obtained from internet sources, university libraries, textbooks, write-ups and commentaries that were purchased from open markets and bookshops. **Results:** The review shows that: (i) the profession of the architect, used in the times of Vitruvius interchangeably with the civil engineer and town planner, as well as the very concept of architecture or civil engineering, in terms of social standing, differs significantly from the present times; (ii) most of the projects discussed in the book form the core of what is classified in the 21st century as civil engineering; (iii) civil engineers ought to be versatile in the art solving of problems that may arise during the course of construction, both in the built and unbuilt environments; and (iv) the buildability issues of civil engineering make knowledge of how to assemble simple construction equipment a necessity. **Conclusion:** Though not recommended in the curriculum, a working knowledge of either Latin or Greek will help to make the book an indispensable companion for structural and civil engineering practitioners and also enhance their performance capacity.

Keywords: architecture, built environment, civil engineering, structural materials.

Introduction

The title that Vitruvius gave his treatise, Ten Books on Architecture (Vitruvius, 1914) may be misleading on the surface, as one can easily conclude that its subject is the modern-day concept of architecture. But a closer look at the book's table of contents will reveal a curious discovery. Apart from the fact that Vitruvius's perception of construction as such is very broad in scope and includes all major projects classified today as civil engineering, other topics covered are medicine, astrology, philosophy, and construction of military machines. Putting these together, one may conclude that Vitruvius's interpretation of architecture, representing how architecture was seen during his time, was quite different from the architecture of today. His concept of architecture and civil engineering reflects the work of many different 21st century professionals in the modern built environment, specifically civil engineers, structural materials engineers, surveyors, mechanical engineers, etc. But one may ask: who was Vitruvius as an individual? According to biographical overviews given in De Architectura (Wikipedia, 2011) and Cigola and Ceccarelli (2014), Marcus Vitruvius was a Roman military engineer and architect under both Julius Caesar and his son Augustus Caesar between 46 B. C. and 14 A. D. This is further confirmed in the preface to this book by Vitruvius himself, as he dedicates his work to Augustus Caesar as follows:

> "...for in the first place, it was this subject which made me to be known to your father to whom I was devoted on account of his great qualities. After the council of Heaven gave him a place in the dwellings of immortal life and transferred your father's power to your hand, my devotion continues unchanged as I remember him, inclined me to support you..."

He can thus be described as the architect and engineer of Caesar's Roman Empire, responsible not only for building utilitarian public infrastructure, but also for supplying and maintaining military structures like those he referred to as ballistae, scorpions and artillery. Given that in the times of Julius and Augustus Caesar, multiple wars were fought on land and sea, covering extensive territories

over the course of many years, it is understandable that Vitruvius's brand of architecture was shaped by its military undertones and subjects. Furthermore, the book was based on the average Roman's world-view at the time, hence the inclusion of subjects like astronomy and philosophy, as well as the choice of certain building and construction models, adopted exclusively to please the divine being. According to Barrow (1955), Romans of the time believed that there was a power, in form of divine beings that ruled the world, that was superior to humans and had to be submitted to in order to ensure human wellbeing. This submission to divine beings was also what allowed the ruler to dominate over the human race. Thus, Ten Books on Architecture also contains copious amounts of religious notions and thinking habits of the first-century Romans. Next, environmental and health issues cannot be divorced from construction activities, since construction workers must be healthy and able to overcome the environmental challenges at their place of work in order to proceed. This may justify the inclusion of climate and medicine concerns.

Thus, the book seems to rest on the following underlying substructures: Vitruvius's imperial military background, subjection to divinity, and environmental and health issues. It also must be noted that, in the language of that period, architects and civil engineers were considered to be the same thing as city planners and builders, and the word for them was derived from the word for kings and emperors (Barrow, 1955). No one could pursue any of those professions without previously having being a successful farmer and soldier, for a typical Roman was essentially both a farmer and military man (Barrow, 1955). According to Barrow (1955),

> "The Roman mind is the mind of the farmer and soldier, not farmer, not soldier, but farmer-soldier. Unremitting work is the lot of the farmer, for the seasons wait for no Man. Yet his own work by itself will achieve nothing, he may plan and prepare, till and sow, in patience he must await the aid of forces which he cannot understand, still less control. If he can make them favourable, he will, but more often, he can only cooperate and he places himself in line with them that they may take him as their instrument and so he may achieve his end. Accidents of weather and pest may frustrate him, he must be patient. Routine is the order of his life; seed-time, growth and harvest follow in appointed times. The life of the field is his life. If as citizen he is moved to political action at last, it will be for the defence of his land or markets or the labour of his sons. To him the knowledge born of experience is worth more than speculative theory. His virtues are honesty and thrift, forethought and patience, work, endurance and courage, self-reliance, simplicity, and humility in the face of what is greater than himself. Such are the virtues of a soldier. He too will know the value of routine, which is part of discipline, for he must respond as by instinct to a sudden call. He must be self-reliant. The strength and endurance of the farmer serve the soldier; his practical skill help him to become what Roman soldier must be, *a builder and digger of ditches, and maker of roads and ramparts. He lays out a camp or a fortification as well as he lays out a plot or a system of drains"*

The above statement is echoed in De Architectura (Wikipedia, 2011). This work notes that Roman architects were skilled in engineering, art, and craftsmanship combined. The present-day understanding of architecture, especially in the developing world, which is linked to houses, had no place in architectural practice during the times of Vitruvius, as we will see later in Table 4. The Romans' understanding of the word architecture, as per the classical studies of the time, can be described through Eq. 1:

$$\text{architecture} = \text{arche (prince/state/government)} + \text{teknon (to build)} \quad (1)$$

"To build" had the implication of "to construct" or "to assemble together" (Seward, 2007), i.e., form a resilient whole, a concept derived from the militaristic Roman mindset of the time. That is why Roman architecture encompassed not only houses, but also bridges, waterways, roads, urban drainage systems, machines, ships, and more. That Vitruvius was first and foremost a military engineer who tried to put the knowledge acquired in military campaigns to peacetime use, becomes evident in the preface to Book 1 of the Ten Books of Architecture.

In the preface, he mentions enjoying the patronage of Julius Caesar as he built war machines and engines for his military operations. This continued under Augustus Caesar, both in his wars and in the reconstruction work that followed his victory, ushering in a reign of peace. Vitruvius covers a wide variety of subjects he saw as relevant to first-century architecture or civil engineering. This includes many aspects that may seem irrelevant to modern eyes, ranging from mathematics to astronomy, meteorology, and medicine. In the Roman mindset, architecture or civil engineering needed to take into account everything touching on the physical and intellectual life of man and his surroundings. Thus, the Ten Books on Architecture treatise was the work of a Roman man with the characteristic farmer-soldier outlook.

This work has been reviewed by multiple authors and researchers. For example, Cartwright (2015) reviewed the book by summarizing each chapter and bringing out salient points. In a review by Erismis and Gezerman (2013), an attempt was made to critique the treatise, by asking questions such as: how can the time of Vitruvius be interpreted? How did Vitruvius conceptualize architecture? What did Vitruvius emphasize the most in his study? Are there any surviving buildings from the time of Vitruvius, and if there are, how exactly do they fit Vitruvius's explanations? What insights can this study offer our peers? Did Vitruvius, in fact, ever live and is there really a book called *De Architectura*? Their conclusions were that neither such a book nor the author ever existed. These conclusions were apparently drawn without knowledge of the Roman

mind, the Roman society and the political system of the time when Ten Books on Architecture was written. Some authors focused on specific aspects of the book: for example, Thiemann et al. (2010) and Small (2019) examined its plaster and painting aspects, Bosman (2015) looked at architectural theory and practice, as applied to proportions and building materials. Others like Ghazvini et al. (2020), Grúňová and Holešová (2018), Heath (1989), Newman and Vassigh (2014), Patterson (2004), Schulzová and Bošová (2019), and Wozniak-Szpakiewicz and Zhao (2018), treated the book exclusively within a present-day architectural framework. The book's examination by civil engineers, either in practice or in academia, is very scarce. Apparently, the title of the book gives the first impression that it is dedicated only to present-day architectural practices. That is, the book is perceived to contain nothing of interest to civil engineering training and practice. This paper intends to change this mindset by attempting to give insight into the civil engineering aspect of the book, which is very deep and wide in scope. This will demonstrate that civil engineers can avail themselves of the plentiful resources contained in the book for robust professional practice and academic research, especially the principles governing the design of civil works and selection of construction materials.

Thus, the aim of this study is to review the Ten Books of Architecture treatise by Vitruvius (1914), by adapting the training and practices from what was called architecture or civil engineering in the 1st century into 21st century civil engineering. The paper will focus on bringing out insights that can provide useful resources for civil engineering training and practice. This review focuses on civil engineer training, buildings, construction economy, and construction materials.

Methodology

The method employed in this review was to search the archives for materials covering the time when the Ten Books on Architecture treatise was written. These materials were obtained from internet sources and university libraries, as well as from textbooks, write-ups and commentaries that were purchased from open markets and bookshops. They were studied in an attempt to understand the society and the practices at the time when Vitruvius wrote his book.

Review

As stated in the Introduction, the concepts of architect, engineer, and town planner were used interchangeably in the times of Vitruvius because of similar professional training (Wikipedia, 2011). It is, however, obvious that in the present times, the education paths for each of these professions are different, though they do occasionally intersect, and may finally converge into a single genius architect or civil engineer as described by Vitruvius, through continuous training and practice. Bearing this in mind, the authors, being civil engineers, have decided to give insight into the book within the context of civil engineering, and have tried to situate 1st century architecture, or civil engineering, exclusively in the 21st century civil engineering framework.

Education and Training in Civil Engineering

There is no doubt that Vitruvius drew up his curriculum with his own prior education in mind. He expected civil engineers to be well-versed in many varied fields, putting all the work done by others to test through his professional judgement. Table 1 provides a summary of Vitruvius's civil engineer's curriculum.

Vitruvius's curriculum requires instruction in 9 (nine) branches of learning, which, during his time, served as the foundation for nurturing and training a potential architect, civil engineer, or urban planner. He also provided reasons for the branches' relevance, which are briefly summarized in the table. Tables 2 and 3 outline a typical curriculum of BSc. (or BEng.) degree in civil engineering, as approved by the Accrediting Agency of Nigerian Universities (NUC, 2022). The comparison between this curriculum and the contents of Table 1 reveals an inherent weakness in training a person to become Vitruvius's idea of a civil engineer.

Some elements of Vitruvius's curriculum are particularly strange to the present-day civil engineering students and professionals, but in the long run, they prove necessary for robust practices. For instance, his inclusion of political history as part of the curriculum was informed by the reasoning that a building or any form of civil infrastructure, either in part or as a whole, likely has some historical events associated with it.

He cited some structures from his time, pointing to features were meant to serve as a reminder of certain historical, cultural, and political events that had shaped the life of the nation. This is shown in Fig. 1 (Vitruvius, 1914).

Similar examples of modern-day structures conveying a political message include the Statue of Liberty and the Empire State Building, both located in the United States of America. These are shown in Fig. 2 (Maguth et al., 2013).

Analysis of Borucińska-Bieńkowska (2020) showed that cultural factors and past historical events not only influence civil infrastructure, but also provide inspiration for new art directions. Vitruvius includes philosophical knowledge in the training of civil engineers to help develop their moral character and professional ethics. He lists concepts like honesty, courtesy, righteousness, and incorruptibility. Vitruvius believes that a civil engineer cannot function without being honest and resisting corruption. According to him, these qualities can

Table 1. **Breakdown of Vitruvius's civil engineer curriculum (Vitruvius, 1914)**

	Knowledge required	Relevance to the profession
1	Pencil drawing skill	a) Required for sketching the proposed design
2	Knowledge of geometry	a) Knowing to use a ruler and a compass is required for planning buildings on the ground b) Teaches the right application of the square, the level and the plummet c) The optical aspect of geometry shows how natural light enters the building d) The arithmetical aspect of geometry allows for calculating construction costs and computing measurements e) Geometrical theories and methods help to solve symmetrical issues
3	Knowledge of (political) history	a) Allows the civil engineer to explain the underlying ideas and stories behind the ornamental elements (see Figure 1 for illustrations)
4	Knowledge of philosophy	a) Teaches the civil engineer to be not self-assuming and avaricious, but courteous, just, and honest b) Honesty and incorruptibility are essential qualities for the civil engineer c) The fundamentals of physics, which were also taught under philosophy at the time, allow for handling numerous construction tasks
5	Knowledge of music	a) Provides knowledge of canonical and mathematical theory b) Allows for properly attuning ballistae, catapults and scorpions c) Allows for building water organs and objects resembling them
6	Knowledge of medicine	a) Required for addressing issues with climate, air, healthiness and other site properties, and using different water sources to ensure that the dwelling is healthy to live in
7	Knowledge of the law	a) Required for safeguarding the interests of both the employer and the contractor while drawing up contracts b) The civil engineer must understand laws applicable to specific building elements, for example, drains, windows, water supply, etc.
8	Knowledge of astronomy	a) Required for locating the cardinal directions: East, West, South, and North
9	Theory of Heavens	a) Theory of Heavens includes knowledge of the equinox, solstice, and course of the stars b) The civil engineer must be able to comprehend the Theory of Heavens

only be obtained through philosophical studies. In the present day, when corruption is rampant in the construction industry, taking the form of extortion, contract inflation, working for officials who steal public money, abandoning professional integrity for pecuniary gains, bribery, nepotism, and so on (Chan and Owusu, 2017; Locatelli et al., 2016), this curriculum recommendation is most apt. Vitruvius's

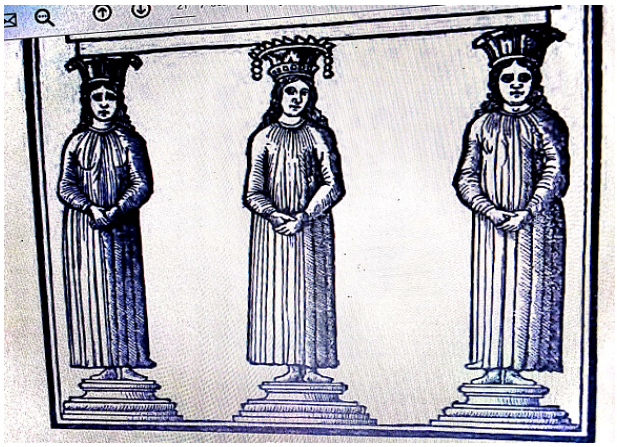
Table 2. **Breakdown of a typical curriculum for BSc/BEng. Degree in Civil Engineering**

Level	General Studies	Basic Sciences	Basic Engineering	Core Courses	Electives	SIWES	Total
100	10	30	4	0	0	0	44
200	6	0	34	2	0	0	42
300	0	0	6	38	0	0	44
400	0	0	2	21	0	6	29
500	0	0	3	28	6	6	43
TOTAL	16	30	49	89	6	12	202
Percent of Total	7.92%	14.85%	24.26%	44.06%	2.97%%	5.94	100%

Table 3. **Divisions in the Curriculum for BSc/BEng. Degree in Civil Engineering**

Curriculum	Contents
General Studies	English Language, History
Basic Sciences	Mathematics, Physics, Chemistry, Computer Skills, Drawing
Basic Engineering	Computer Skills, Introduction to Computer Programming. Drawing, Mechanics, Strength of Materials, Engineering Materials, Surveying
Core Courses	Highways, Transportation, Geotechnics, Structures, Water Resources, Hydraulics, Environmental Engineering
Electives	At the student's discretion. Usually departmental electives
SIWES	Students Industrial Work Experience Scheme

a) Single column b) Double column



c) Triple column

Fig. 1. Columns with decorations depicting historical events (Vitruvius, 1914)

a) Statue of Liberty b) Empire State Building

Fig. 2. Statue of Liberty and American Empire State Building (Maguth et al., 2013)

recommendation to include medicine on the civil engineering curriculum will not come as a surprise to a civil engineer involved in road construction or civil projects in unbuilt areas. In fact, most civil engineering construction is performed in the open field under harsh environmental conditions. It is thus necessary that civil engineers approach the issues of health and environmental resilience as pivotal to their professional excellence. In addition, there is a growing concern regarding the environmental impact of construction and the concomitant sustainability issues. The recent COVID-19 pandemic has underscored the importance of some medical training and knowledge, not because a civil engineer might want to become a medical doctor, but because they need to take the necessary precautions for preventing health hazards and fatalities in an environment where there are no medical facilities. Thus, training and acquisition of knowledge on how to adapt to different climate conditions and air quality, improve unhealthy site properties, and treat unpotable water becomes a necessity. Vitruvius appears to imply that it takes being a sound and rational person, not necessarily academic brilliance, to practice civil engineering.

The practice of civil engineering involves two or more parties, either as individuals, or as institutions and even governments; therefore, knowledge of legal principles and opinions of lawyers is necessary. Thus, Vitruvius included legal training as part of his curriculum in civil engineering. However, by law and lawyers, Vitruvius meant the civil law and lawyers from Rome, which he saw as a force that had established peace over the known world, and which his client, Emperor Augustus Caesar, personified at the time of writing his book. This was briefly stated in the Introduction. It should also be noted here that, in the Roman mindset of the time, peace meant "settled order and security of life and property" (Barrow, 1955). This is the environment that gave birth to civil engineering (Merdinger, 1949; Watson, 2020). Thus, without peace, there can be no civil engineering. Furthermore, it is through the Roman law that the established peace was administered. According to Justinian (The Ames Foundation, 2020), the precepts of Roman law are to live honestly, injure none, and give every man his due. This applies to persons, actions, and objects. Thus, in drawing up civil engineering contracts at the time, the interests of both the customer and the contractor were safeguarded under the prevailing Roman peace and law.

In our modern times, we will do well to learn the prevailing law of peaceful corporate existence, as established by the constituted authority, while practicing the civil engineer's profession. This will be a continuous process, because human society is dynamic, and law changes with the government. Nonetheless, the civil engineer's intent is to remain (The Ames Foundation, 2020), regardless of whether the government was overthrown, established where it is non-existent, or continues to operate; and that intent is: to conduct oneself honestly, injure none

(either individuals or society as a whole) and give everyone their due while practicing one's profession, at all times. According to Bonenberg (2015), basing construction planning documents on peace-driven and civilization-driven principles facilitates subsequent modernization, especially for complex metropolitan projects.

The knowledge of music, astronomy and "Theory of Heavens" may not seem relevant to many of us in the present day. This is because only few people now have the same background and experience as Vitruvius, which warranted his recommendations for the curriculum. The experience of military service and having a reigning Emperor as client is not particularly relevant to many of us. No doubt, Vitruvius's exposure to challenges in a nation of wayfaring men from a law-based republic seemed to be the bedrock of professional competence that broadened his horizons. It must be said at this point that Vitruvius's treatment of astrology and Theory of Heavens (i.e., a discussion of such things as the universe, the power of nature, etc.), though outside the scope of this paper, does not contradict the definition of civil engineering according to the Institution of Civil Engineers (ICE, 2018) of the United Kingdom. In the charter granted to the Institution of Civil Engineers (ICE, 2018) in 1828, to incorporate the profession into the body politic and corporate, civil engineering was defined as:

> "... the art of directing the great sources of power in Nature for the use and convenience of man, as the means of production and of traffic in states both for external and internal trade, as applied in the construction of roads, bridges, aqueducts, canals, river navigation and docks, for internal intercourse and exchange, and in the construction of ports, harbours, moles, breakwaters and lighthouses, and in the art of navigation by artificial power for the purposes of commerce, and in the construction and adaptation of machinery, and in the drainage of cities and towns..."

Similarly, the phrase "forces of nature" is also included in the definition of civil engineering by the American Society of Civil Engineers (ASCE, 2008). In order words, in order to fit the ICE (2018) and ASCE (2008) definition of civil engineering, a person must complete the curriculum designed by Vitruvius. All things considered, it becomes clear that continuous learning is "desiderata" to reach the peak of being recognized as authority in the profession. It is not possible to acquire all the skills recommended for a civil engineer by Vitruvius at any Civil Engineering Department in any University at any level, from undergraduate to PhD. Thus, as their duty demands, a civil engineer will have to seek further tutelage in other areas and at other departments that are not part of present-day curriculum offered by conventional civil engineering departments at universities worldwide. It is obvious that Vitruvius was an erudite scholar and voracious reader.

Practice of Civil Engineering

Knowing the nature of civil engineering in the 1st century and understanding its scope is necessary if one is to situate it within the 21st century practice. First, Vitruvius divides the civil engineering of his era into three sections, namely (i) the practice of building, (ii) construction of time pieces, and (iii) fabrication and construction of machinery. The breakdown of the building practice is presented in Table 4. Although items 1 and 2 in Table 4 were originally grouped together into one, it has been broken down into two parts for the purpose of this work.

Most of the construction projects described in Table 4 are civil engineering projects in nature from the standpoint of the 21st century practice, though some would have to be completed in collaboration with other professionals like 21st century architects. Thus, we should not lose sight of the immense overall civil engineering aspects of Table 4. Considering item 1, for example, the execution of such a project will involve nearly all the 21st century branches of civil engineering, like survey, soil and foundation engineering, structural engineering, construction materials, and provision of water and sanitation. Correspondingly, in Book 2 of De Architectura, Vitruvius deals with construction materials, while in Book 8, he sets out principles to be employed when searching for potable water in different locations, for use in homes, towns and cities. All other aspects are also addressed in different chapters of the book. Building defensive structures is purely civil engineering work. While we may not be considering military attacks in this case, structural loads on buildings can be modeled in a similar manner to resist other threats, such as erosion, winds, hurricanes, seismic effects, etc., which also bring about destruction from the civilian perspective. Such

Table 4. **Types of built structures according to Vitruvius**

	Type	Description	Example
1	Fortified towns	Fortified towns	Site planning for towns and cities
2	Public works	Defensive	Walls, towers, gates, devices against hostile attacks
		Religious	Shrines and temples to the gods
		Utilitarian	Harbors, markets, colonnades, baths, forums, circuses, emporiums, theaters, promenades, aqueducts, etc.
3	Dwellings of private individuals	Dwellings of high-status Roman citizens	Houses for different classes of people, farm houses, houses in cities and towns.

situations call for suitable, robust, strong and stable construction in form of retaining walls, shear walls, etc. Vitruvius's work gives us insight into how to create these. Religious buildings in Vitruvius's time were similar in nature to the churches, mosques and synagogues of the 21st century. But unlike the 21st century, the construction of religious edifices in the 1st century was the duty and function of the state, which was personified by the Emperor, hence Vitruvius grouping such buildings together with public projects. All these contained a substantial civil engineering element. In the same vein, the examples of construction projects Vitruvius grouped under utilities are relevant to civil engineering. The same is true for building houses for private individuals with different status and means. These are described in the respective chapters of the book. A brief analysis of Table 4 demonstrates that the projects that Vitruvius described as construction in his 1st century language, in fact, either are civil engineering projects, or contain substantial civil engineering elements. The execution of these projects requires training in the legal, philosophical and psychological aspects of human behaviors, as recommended by Vitruvius. First of all, contracts will have to be drafted for different clients, suppliers, and labor. Furthermore, daily peaceful administrative control over workers is important for maintaining an undisturbed construction process. Lastly, harmonious interactions between the construction work force and the environment where the construction is taking place cannot be neglected either, if disturbances are to be prevented. According to Arya (2009), a civil engineer should, by training amongst others, become capable of: (i) carrying out, both in concept and execution, the entire planning process for a new building structure (as seen in Table 4), (ii) studying project feasibility through mathematical calculations and drawings, and (iii) preparing the bills of quantities, specifications and contracts that will form the necessary legal and organizational framework. Civil engineering professionals should thus turn to Vitruvius's book to enrich their practices.

The second branch of civil engineering, according to Vitruvius, was the making of time pieces. What are time pieces? According to Dictionary (2020) and Merriam-Webster.com (2022), a time piece is an instrument such as a clock or watch, intended for measuring or showing progress of time. For the civil engineering practice in the 21st century, the relevance of making time piece may not make sense, since we have grown up with wrist watches and lately mobile handsets, which show time in any place and in any weather. But the 1st century Romans did not have the luxury of being able to determine the time of day regardless of location or weather conditions. Hence time piece creation, described by Vitruvius in Book 9, formed part of the civil engineering practice. Although 21st century civil engineering may not involve the construction of time pieces, there is an underlying principle to be kept in mind. Namely, that civil engineering training in any century must include elements that will allow civil engineers to be versatile in the art of solving any problems that may arise, both in the built and unbuilt environments.

Finally, the third type of civil engineering in Vitruvius's work is the construction of machinery, that is, machines and engines. In the 21st century, it is normal to expect this function from mechanical engineering, but this was not the case in the 1st century. It is to be noted, however, that general knowledge of mechanical science and engineering does form an integral part of civil engineering practice, even in the 21st century. This is because the sentence leading to the definition of civil engineering by the Institution of Civil Engineers (ICE, 2018), contains the following wording:

> "...advancement of mechanical science...".

Thus, we can deduce that this requirement is still expected in civil engineering practice in the 21st century, just as it was in the 1st century. According to Vitruvius, machines and engines are, in principle, practical necessities in civil engineering. Many constructs that fall under these terms are discussed by Vitruvius in Book 10. The machines covered in Book 10, in terms of operation principles and structures, range from military to non-military equipment. The non-military machines described by Vitruvius and relevant to this paper include, but are not limited to: (i) climbing machine — for the construction workers to view the construction site, (ii) hoisting machines of various types — for lifting materials and workers, (iii) water raising engines like water wheels on rivers, water screws, water mills, and water pumps, (iv) odometers — for measuring mileage on roads and sea, (v) balances — for testing weight, (vi) utilities like ladders, cranes, and so on. The civil engineer is expected to be conscious of the equipment requirements and include them in their designs, especially at the conception and development stage. The civil engineer either procures the necessary equipment or has the ability to construct it, or at least, was expected to do that in the 1st century practices. This is also important in the 21st century practice. Availability of construction equipment relates to the 21st century concept of buildability in civil engineering. This cannot be overemphasized (Arya, 2009). In developing countries, where resources for equipment procurement are scarce, it is imperative for civil engineers to be familiar with the principles of constructing simple essential tools like cranes, balances, etc., as described by Vitruvius, to keep their work going.

Economical Civil Engineering

One of the fundamental principles of civil engineering design projects is that the structure must

be economical in cost and maintenance (ASCE, 2008; Fapohunda, 2019).

That said, a substantial percentage of construction costs, over 40%, accounts for materials alone (Adedeji, 2012; Deepa et al., 2019). As a way to make civil construction more economical, Vitruvius noted that, firstly, the civil engineer should not recommend materials or items that cannot be obtained or assembled without great expense. Additionally, it ought to be noted that, apart from procuring the materials themselves, their transportation to the site also increases the materials cost component of the total construction costs (Ahmadian et al., 2014; Shakantu et al., 2003). Here, we ought to explore the importance of using any unconventional construction materials available in the site's vicinity, as a way to make the process more economical (Fapohunda and Daramola, 2019). To be able to do this, the civil engineer must be able to not only experiment, but also assemble, if required, the equipment and machines for such experiments. Engineering practice founded on a curriculum is as diverse, broad and deep as what was recommended by Vitruvius is essential for accomplishing this.

Construction Materials in Civil Engineering

The materials that were used for civil engineering in the 1st century should also interest the 21st century civil engineering practitioners. While these materials did not include steel and aluminum, what they did include was brick, sand, lime, stone, timber, and pozzolans. Vitruvius describes them from what can be considered a 21st century structural engineering perspective, with emphasis on strength and durability. For each of them, he extensively covers issues like material types and sources, time spent on making the material, how long it ought to be left to dry before use, how best to apply the material, simple tests to determine suitability, possible combinations with other materials, how and when the material is to be applied, and more. In this discussion, he highlights the natural, "primordial" state of each of the materials, which he considers to be a fundamental part of learning more about their nature and application. According to Vitruvius, all materials, including civil engineering construction materials, are composed of four fundamental elements, namely, heat, water, earth, and air. He believed that all things consisted of these elements or were produced by the elements coming together, resulting in infinite combinations. Thus, his book does not discuss concrete, which is a product of combining other materials, though it does mention it. Today, the world is gradually becoming aware of the negative environmental impact of using non-renewable resources, perceiving it as a portent of danger to future generations (Kau, 2007; RILEM, 2019). The construction industry is also facing some challenges due to the materials used. Concrete in particular is associated with such issues as CO_2 emissions, depletion of natural resources, and landfills, which are becoming major concerns (Savija, 2020). The fear that the construction industry will be unable to sustain the current use of materials, especially structural concrete, is driving innovation and academic research, aimed at finding alternative sources of construction materials. Researchers are looking into obtaining structural materials from industrial and agricultural wastes, as well as non-traditional materials. Familiarity with, or even in-depth knowledge of, Vitruvius's principles of the four primordial elements, which he believed all materials consisted of, would help researchers in no small measure, either to innovate new materials, or enhance suitability of previously unsuitable materials.

Final Comments About Vitruvius's Ten Books on Architecture

This exploration of Vitruvius's Ten Books on Architecture from the civil engineering perspective is not meant to be exhaustive, and neither was it a detailed discussion of every matter relevant to civil engineering that was contained in the book. The paper's main intent is to encourage civil engineers to look past the title of the book and study its contents. It appears that the word "architecture" as used in the 1st century was different from the usage in the 21st century. Architecture, as in Eq. 1, is a combination of two Greek words: "arche", meaning the state or its ruler, such as an emperor or prince, and "tekton", meaning to build or to construct. When these two words are combined to form the term "architecture", it can be understood in two ways. The first meaning it conveyed in the times of Vitruvius was a reference to a person who built an Empire, or a State. This could be Emperors, Kings, Princes, etc. The second meaning referred to a person who built for the Emperor, the King, or the State. That is, such a person had a King, an Emperor, a Prince, etc. as their client. Throughout the book, Vitruvius uses the word "architect" in the second sense, that is, a builder for the ruling Emperor, King, or Prince. This was because Vitruvius himself was the builder for two Emperors, Julius Caesar and Augustus Caesar, the two men who personified the state in their time. In addition, his work mentions others in this profession who built for rulers, namely: Dinocrates, who built the city of Alexandria for Emperor Alexander, along with Myron, Polycleitus, Phidias, and Lysippus. Furthermore, Vitruvius speaks of builders who constructed machines and engines in Book 10, for instance Diognetus (Rhodes architect), Callias (Aradus architect), Epimachus (Athenian architect under King Demetrius) and Trypho (Alexandrine architect), which clearly demonstrates a scope that no professional group in the 21st century construction industry can capture in its training. At the same time, if we place the word "architecture" within the context

of its 1st century use, we will discover that the projects discussed in Vitruvius's book actually form the core of 21st century civil engineering. Thus, the book is relevant to civil engineering training and practice. It can also serve as a guideline for the modern civil engineer in the process of skill building and in the pursuit of continuous professional training.

Conclusions

From the exposition above, it can be concluded that (i) most of the activities classified by Vitruvius as construction are, in fact, civil engineering activities in nature, if we look at them from the 21st century perspective, thus the content of his treatise ought to appeal to civil engineering professionals; (ii) civil engineers need to be versatile in the art of solving problems that may arise during the course of construction, both in the built and unbuilt environments; and (iii) the buildability issues associated with civil engineering make the knowledge of construction equipment a necessity. It should also be noted that in the 1st century, the language of communication was Latin and Greek, which everyone understood; and thus, it was not part of the curriculum designed by Vitruvius. His treatise uses copious amounts of Latin and Greek terminology, which may make the book unreadable for 21st century civil engineers. Though it is not required for the curriculum, a working knowledge of either Latin or Greek will help make the book an indispensable companion for the civil engineering practitioner.

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