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Architecture, Engineering and Building Science: The Contemporary Relevance of Vitruvius's De Architectura

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Abstract: Conferences worldwide focus on a range of disciplines relating to the construction of the built environment. They tend to emphasize either the art or the science of building, the former focusing on architectural theory and design while the latter targets a range of topics from civil and/or building engineering to building physics. Vitruvius's *De Architectura Libri Decem* is a seminal treatise more than two millennia old which addresses these themes in a holistic manner. This text remains valid today for students and professionals engaged in architecture and building engineering. Translated as *Ten Books on Architecture*, it not only presents an overall view of the disciplines of town planning, architecture and civil engineering, along with the qualifications required to practice them, but also addresses building materials, civil-engineering structures and the science influencing buildings. Although grounded in the practice and technology of Ancient Rome, the principles put forward in this treatise are still valid nowadays for effective, sustainable architectural-engineering design based on rigorous education and good knowledge of building materials and construction. Vitruvius's definition of architecture—the one still customarily used—is an inclusive philosophical statement on the essence of building for humanity to house humanity. It recalls the symbiotic relation between architecture and building engineering that is often forgotten in the contemporary emphasis on specialization.

Keywords: Vitruvius; *De Architectura*; architecture; civil engineering; structural engineering; building materials; building science; Roman architecture; Roman antiquity

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1. Introduction

De Architectura Libri Decem is the seminal comprehensive work revealing the architectural engineering history and theories in Classical Roman antiquity that has survived to the present day. It outlines the knowledge on the art and science of the architecture of Marcus Vitruvius Pollio (c. 75–15 BCE), hereafter referred to as Vitruvius. It contains a working definition for the criteria for sound architectural design—firmitas, utilitas and venustas—which has been freely translated by Henry Wotton (1568–1639) as firmness, commodity and delight [1]. Collins argued that Wotton's sequence followed Leon Battista Alberti's (1404–1472 CE) *De Re Aedificatoria Libri Decem* [2]—the next major text on architecture—and Andrea Palladio's (1508–1580) *I Quattro Libri dell'Architettura* [3], whereby the order of the first two is transposed [4]. *De Architectura Libri Decem*, translated into English as *Ten Books on Architecture*, is hereafter referred to as *De Architectura*.

De Architectura is the main historical compendium on the theory of architecture, and provided the basis for the classical tradition in architecture spanning from antiquity to the Middle Ages, the Renaissance and Neoclassicism. Soon after its completion it was immediately acknowledged by Pliny the Elder (23/24–79 CE) [5]; Sextus Julius Frontinus (c. 40–103 CE), whose two-book official report on the state of the aqueducts of Rome was dedicated to Vitruvius [6]; and later by Marcus Cetius Faventinus (fl. late 3rd/4th century CE) [7]. Its influence was still being felt in the 5th century [8]. It was known to exist

prior to 1416, when Poggio Bracciolini (1380–1459) and Cencio de Rustici (1380/90–1445) discovered it in the library of the monastery of St Gall [9]. Over 80 medieval manuscripts survived. Contrary to Kidson, who argued that this fact does not mean that they were neither read nor that any readers at the time were in a position to influence the practice of architecture [10], Martin claims that *De Architectura* was "well known in monasteries of the Middle Ages and even then was the sole literary source of knowledge of ancient architecture. It was only with the Renaissance that Vitruvius was really 'discovered'" ([8], 809–810). The influence of *De Architectura* can be traced through the work of a number of architects, artists, engineers and scholars other than Alberti and Palladio: in the 14th century through Mariano di Jacopo (1381–c. 1443), known as Taccola; in the 15th century through Donato Bramante (1444–1514), Michelangelo Buonarroti (1475–1564), the less well-known Antonio di Pietro Averlino (c. 1400–c. 1469), Robertus Valturius (c. 1405–1475), Francesco Colonna (1433–1527), Francesco di Giorgio Martini (1439–1501) and Luca Bartolomeo de Pacioli (c. 1445–1517); and in the 16th century through the significant work of Iacomo Barozzi da Vignola (1507–1573). Following the publication of Vignola's *Regola delli cinque Ordini d'Architettura* [11] and Palladio's *I Quattro Libri dell'Architettura*, the importance of *De Archiectura* diminished, and it was relegated to an introductory text on architectural theory [12]. Pagliara notes that interest in Vitruvius was revived in all periods where classicism re-emerged, notably in the 18th century with the translation of Bernardo Galiani (1724–1774) [13]; *De Architectura* was then read as interpreted by Renaissance architects and scholars [12].

In recent decades there has been renewed interest in Vitruvius's work, with several colloquia held during the 1980s [14]. Notable authors of this period include Pierre Gros [15]—who authored books on architecture and society in the Italian peninsula during the last centuries of the Roman Republic [16], a two-volume treatise on Roman-building typologies [17,18] and the history of urbanization in ancient Rome [19]—and Pier Nicola Pagliara [20]. Recent research covers *De Architectura*'s standing both in the humanities and in the sciences. Further to a publication on Vitruvius as an author [21], related studies cover a contemporary reading of the opening chapter of *De Architectura* [22], the literary significance of the treatise [23–30] and its raced–gendered narrative [31], the use of building materials and construction methods as media forming the identity of the Roman Empire [32], and Vitruvius's geographical system [33] and design (e.g., linear perspective [34], Roman temples [35], the Basilica at Fano [36,37] and acoustic vessels [38]). Studies related to the last of these themes include the geological analysis of tuff and travertine in stone masonry [39–41], mortar [42–44] and concrete technology [45–47], notably seawater concrete [48–52].

The entry on Vitruvius in the authoritative and voluminous *Encyclopedia of World Art*, concludes that "with the discovery of ancient documents, the commentaries on Vitruvius's treatise have become more definitive and the characteristics of ancient architecture have emerged with greater clarity. Interest in *De Architectura* has not declined with the advancement of archaeological exploration. Although the limits of its scope and value have been ascertained, it remains a work of fundamental importance" ([8], p. 810). The objective of this article is to critically read this treatise mainly from a pragmatic perspective. Two main research questions are addressed:

(i) What is the contemporary relevance of *De Architectura* to architecture, engineering and building science?
(ii) In which specific spheres of expertise is *De Architectura* applicable to the present-day built environment?

2. Materials and Methods

Vitruvius's *De Architectura* provided the primary source of this article. The 1914 Harvard University Press edition, translated by the Professor of Classical Philology at Harvard University, Morris Hicky Morgan (1859–1910), was used [53]. Morgan held that "a translation should not merely reproduce the substance of a book, but should also give as

clear a picture as possible of the original, of its author, and of the working of his mind. . . . [He had] the utmost confidence in the sincerity of Vitruvius and in the serious purpose of his treatise on architecture" ([54], v). The last four chapters of Book X were translated by Albert Andrew Howard (1858–1925) ([54], iii).

When citing from *De Architectura*, the book, chapter and paragraph numbers are stated in this order, with the book in uppercase Roman numerals, the chapter in lowercase Roman numerals, and the paragraph number in Arabic numerals. In the case of a preface or an introduction to a given book, the paragraph number is stated after the book number, as 'para. n'. The drawings included in *De Architectura* are not Vitruvius's; although he pledged ten diagrams and drawings and may have included others, the post-Carolingian period inherited only a few from antiquity ([9], p. 41).

Following a critical overview of the treatise focusing on (i) the context and its author, (ii) its aims and objectives, and (iii) sources, this article addresses the practice of architecture in Ancient Rome. The following themes, which were deemed relevant to contemporary architectural/engineering practice, are tackled:

1. The unity of virtues, a key to reading Vitruvius's influential definition which is still pivotal to architecture, engineering and building science;
2. Architectural design education, which converges on the formation of the contemporary architect/engineer and essential design elements;
3. Roman-built heritage, notably: building stone and mortars, and the construction of theatres, and technology—all significant characteristics which are relevant to the conservation and preservation of this legacy for humanity;
4. The scientific relevance of empirical observations contained in Latin texts.

It concludes by listing a number of themes which are relevant to present-day professionals engaged in architecture, engineering and building science.

3. Vitruvius's Treatise on Architecture

3.1. Dating De Architectura

Various periods have been proposed for when Vitruvius flourished, ranging from the time of Augustus to the early centuries of the Common Era [54]. Howard came across evidence dating him to the end of the reign of Nero—Vitruvius refers to the kingdom of Cottius ([53], VIII, iii, p. 17), a Roman province established by Nero—but did not explore this further, and instead brushed it aside with the opinion that it "is inconceivable that any Roman writer subsequently referred to it as a kingdom" ([54], iv). Morgan's position—in line with studies by Sontheimer [55] and others [8]—is that *De Architectura* was written at the time of Augustus, when the boundaries of the Roman Empire spanned from Britain to Crimea (Figure 1). Although no mention is made of the date of the text and to whom it was dedicated, the preface to Book I states that it was addressed to "Imperator Caesar" ([53], I, para. 1)—a claim supported by the first chapter of Book I ([53], I, i, p. 17), the introduction of Book II ([53], II, para. 4), Book III ([53], III, para. 4), Book IV ([53], IV, para. 1), Book V ([53], V, para. 1,5), Book VI ([53], VI, para. 5), Book IX ([53], IX, para. 18), and Book X ([53], X, para. 4)—which reads "I need have no fear of want to the end of my life, and being thus laid under obligation I began to write this work for you, because I saw that you have built and are now building extensively, and that in future also you will take care that our public and private buildings shall be worthy to go down to posterity by the side of your other splendid achievements. I have drawn up definite rules to enable you, by observing them, to have personal knowledge of the quality both of existing buildings and of those which are yet to be constructed. For in the following books I have disclosed all the principles of the art" ([53], I, para. 3).

Given that Vitruvius thought that he "ought to take the first opportunity" to present his writings on architecture to Caesar ([53], I, para. 2) we can presume that it was formulated after 27 BCE, the first years of the Pax Romana. Hence, by Imperator Caesar, Vitruvius referred to Caesar Augustus (63 BCE–14 CE), known as Octavian, who founded the Roman Principate, the earliest stage of the Roman Empire [56]. Octavian reigned from 27 BCE

until his demise. At the time of writing *De Architectura* Vitruvius was not young, and thus it is a logical assumption that he was a siege engineer during the reign of Julius Caesar (100–44 BCE). Vitruvius was therefore a contemporary of Marcus Terentius Varro (116–27 BCE), Marcus Tulius Cicero (106–43 BCE), Publius Vergilius Maro (70–19 BCE) and Publius Terentius Varro Atacinus (82–35 BCE). Just as Terentius Varro, through the *Disciplinarum libri IX*, aimed to place architecture on a par with the liberal arts, through *De Architectura* Vitruvius's objective was to upgrade the status of the profession [14,26], writing that "men have no right to profess themselves architects hastily, without having climbed from boyhood the steps of these studies and thus, nursed by the knowledge of many arts and sciences, having reached the heights of the holy ground of architecture" ([53], I, i, p. 11)).

3.2. The Context: The Man and His Work

Vitruvius comes across as a little-known architect/engineer. Citing Gros [15,24], D'Ambrosio et al. argue that "he was more likely a member of the apparitores, a professional order formed by advisors of the Roman Magisters, who acted as intermediaries and referents in the realization of public works and for their administrative management, in which he covered the specific role of scriba armamentarii (secretary of arsenals)" ([44], p. 186). Vitruvius preferred a good reputation to wealth and dishonor ([53], VI, para. 5). The ancients entrusted their projects to properly educated architects of good family, so an architect's honor was more important than his air of confidence ([53], VI, para. 6). Unlike other architects/engineers, he charged professional fees after being asked rather than asking for payment: "It is in fact those who can grant favors that are courted, not those who receive them. What are we to think must be the suspicions of a man who is asked to allow his private means to be expended in order to please a petitioner? Must he not believe that the thing is to be done for the profit and advantage of that individual?" ([53], VI, para. 5). He hoped that, through *De Architectura*, his name would be known in posterity ([53], VI, para. 5). Vitruvius's self-portrayal as less successful in the profession than his peers cannot be correct. Given that he was officially rewarded for constructing and repairing war machines, he must "have been an engineer of some brilliance, as a record of his work has been preserved in the traditional literature" ([8], p. 807).

Vitruvius comes across as ambitious and with a dose of arrogance, even if diplomatically or in a pompous manner, thanks to his use of the collective pronoun (see, for example ([53], V, para. 1) and ([53], III, para. 3). He notes that "good judges are flattered by the charm of social entertainments into an approbation which is a mere pretence" and that while "men who had reached the height of knowledge by means of correct and definite courses of study [should] be given commissions without any effort on their part, . . . the uneducated rather than the educated are in higher favour," ([53], III, para. 3). Vitruvius explicitly claimed that, rather than engaging with "the uneducated in the struggle for honour, I prefer to show the excellence of our department of knowledge by the publication of this treatise" ([53], III, para. 3). He also, arguably, expresses false humility. In one instance he compares himself unfavorably to Dinocrates, the Macedonian architect of "very lofty stature and pleasing countenance, finely formed, and extremely dignified" to whom Alexander the Great entrusted the urban design of Alexandria. He notes that "nature has not given me stature, age has marred my face, and my strength is impaired by ill health. Therefore, since these advantages fail me, I shall win your approval, as I hope, by the help of my knowledge and my writings" ([53], II, para. 1, p. 4).

Endorsing the opinion of the reputed German classical archaeologist Erich Pernice (1864–1945), Martin notes that "Vitruvius was born in humble circumstances but raised himself above his background through his work and pursuit of culture. In his treatise he expressed pride in this achievement" ([8], p. 806). Although Howard argues that the introductions to Vitruvius's books displays "turgid and pompous rhetoric"—using Dwyer's language, Vitruvius's literary style "ranged from the laconic to the bombastic, often without full control of either" ([14], pp. 632–633)—they provide an insight to his reading of the professional ethics of an architect [54].

Vitruvius directed the design and supervised the execution of a basilica at Fano ([53], V, i, p. 6), the only work which he cited as his own (Figure 2). Although nothing is left of the basilica, which was considered a turning point in the design of that type of building, it was the subject of research at the Department of Architecture, Surveying, Design, Urban Planning and History (DARDUS) at the Polytechnic University of Marche, Ancona. DARDUS's research focused on the basilica in order "to understand and recreate this building and protect its precarious and ephemeral memory", a project which led to its virtual reconstruction ([36], p. 121).

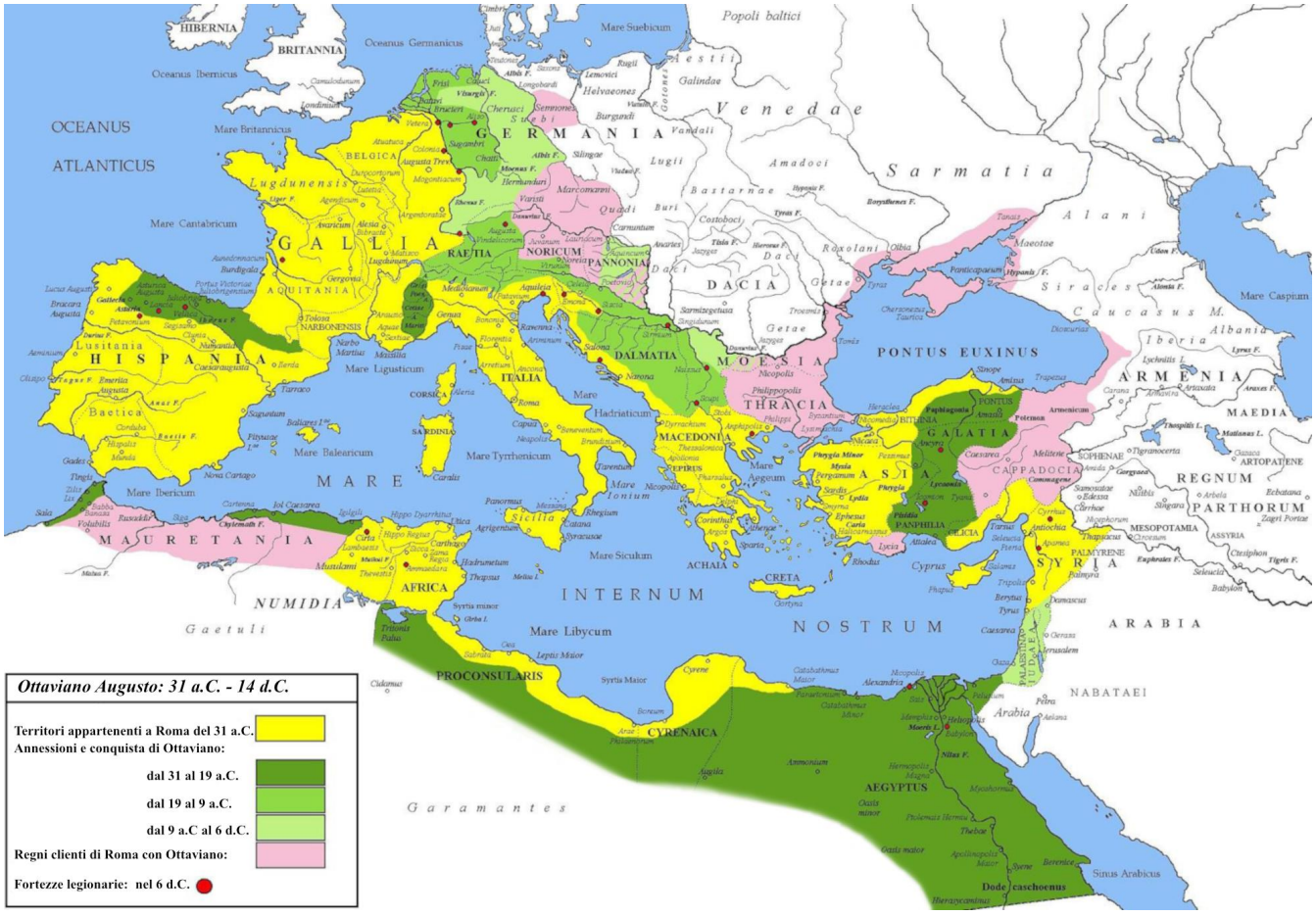
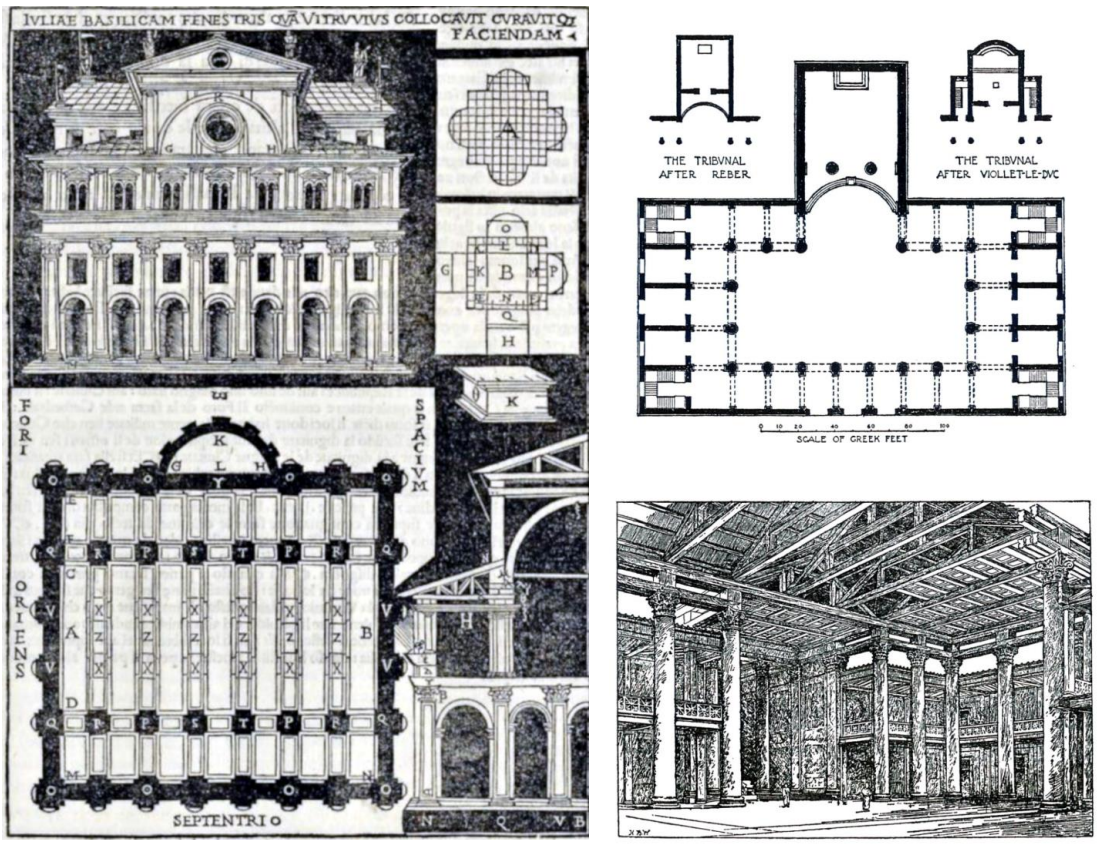


Figure 1. Roman Empire under Octavian (31 BCE–CE 14): yellow, territories before 31 BCE; dark green, territories annexed over the period 31–19 BCE; light green, territories annexed over the period 19–9 BCE; and pale green, territories annexed over the period 9 BCE–CE 6; mauve: client states (© Cristiano64/CC BY-SA 3.0) [57].



(**a**) (**b**)

Figure 2. Reconstruction of Vitruvius's Basilica at Fano by: (**a**) Cesare Cesariano (1475–1543), the translator and illustrator of the first Italian edition of Vitruvius's *De Architectura* [58]; (**b**) Morgan ([53], p. 135).

3.3. Aims and Objectives

De Architectura was aimed both at the craftsman and at expert audiences: "I promise and expect that in these volumes I shall undoubtedly show myself of very considerable importance not only to builders but also to all scholars" ([53], I, i, p. 17). Its objective was to "reduce the whole of this great art [of architecture] to a complete and orderly form of presentation, and then in different books to lay down and explain the required characteristics of different departments" ([53], IV, para. 1). One should not exclude elite potential patrons [27]. Lefas remarks that, "like any treatise meant for Augustus—who was fond of precepts and not unlikely to use such a work—or at least for the inner cycle of his sister Octavia, his was not an erratic accumulation of facts, thoughts, and guidelines" ([22], p. 1). Vitruvius could have belonged to the sort of academy set up by Octavia [59]. Later he reiterated his position and conviction that *De Architectura* would be a "gift to all the world" ([53], VI, para. 7); he indeed conceived of it as the first thorough Roman treatise on architecture ([53], IV, para. 1; VII, para. 18).

De Architectura is a prescriptive handbook, essentially a manual: "I have drawn up definite rules to enable you, by observing them, to have personal knowledge of the quality both of existing buildings and of those which are yet to be constructed". ([53], I, para. 3). Howard held that it was not of literary significance, and noted that Vitruvius experienced difficulties in communicating his thoughts: "In his hand the measuring-rod was a far mightier implement than the pen" ([54], iv). On occasion, he used a technical language akin to building specifications and contracts—a style with which he was acquainted through his profession—fraught with linguistic difficulties [54]. Vitruvius was aware of his limitations when it came to grammar—"I request, Caesar, both of you and of those who may read

the said books, that if anything is set forth with too little regard for grammatical rule, it may be pardoned. For it is not as a very great philosopher, nor as an eloquent rhetorician, nor as a grammarian trained in the highest principles of his art, that I have striven to write this work, but as an architect who has had only a dip into those studies" ([53], I, i, p. 17). But, as Morgan notes, "Latin was not transmitted to Romance lands by the polished works of Cicero, but by the every day writings and the colloquial speech of people like Vitruvius—professional men, 'publicani', business men, and soldiers" ([60], p. 501).

In the first paragraph of *De Architectura*, Vitruvius states that "I hardly dared . . . to publish my writings and long considered ideas on architecture, for fear of subjecting myself to your displeasure by an unseasonable interruption" ([53], I, para. 1). In addition, the words "under obligation" ([53], I, para. 3) may be read as either suggesting the publication was penned under his own steam under a moral obligation or as a commission that he accepted once he felt comfortable to write his work after Imperator Caesar had made his "first bestowal of [rewards for the construction and repair of ballistae, scorpions, and other war machines] upon me, [and] continued to renew them on the recommendation of your sister" ([53], I, para. 2). In either case, it is a complete essay on architecture, as claimed by Vitruvius on a number of occasions ([53], II, i, p. 8; VI, para. 7; VII, para. 14).

3.4. Structure

De Architectura is grounded in Vituvius's practice and study of Ionian architects such as Arcesius (who flourished in the 3rd century BCE), Pytheos (4th century BCE) and Hermogenes (late 3rd–early 2nd century BCE) ([53], V, iii, p. 1). It is divided into ten books; Book I has a preface, whilst the rest have introductions. Each book is short, and arranged in themes (Table 1); their contents are given in Table 2. The arrangement of the books, which, at face value, falls into two categories—architecture (Books I–VII) and engineering (Books VIII–X)—reflects his division of architecture into (i) the science of building (aedificatio), (ii) the art of making sundials and clocks (gnomonice), and (iii) mechanics (machinatio), which are covered in Books I–VIII, IX and X, respectively [14].

Table 1. Themes addressed in *De Architectura*.

Classification [1]	Book	Themes
aedificatio	I	General principles of architecture and urban planning
	II	Building materials
	III	Temple design
	IV	Temple design (continuation of Book III)
	V	Design of civil buildings
	VI	Design of domestic buildings
	VII	Floors and stucco decorations
	VIII	Hydraulics
gnomonice	IX	Astronomy and the design of clocks
machinatio	X	Civil- and military-engineering techniques

[1] See Dwyer ([14], p. 633).

A book review of a recent publication by Reitz-Joosse [61] states that "architecture is a language. Buildings are 'put together'; they can be 'read' as texts. Texts in turn are 'structured' or 'put together' like buildings. Long embedded in everyday speech, such metaphors have endowed the reciprocal relation of texts and buildings with self-evidence that is close to axiomatic" ([62], p. 5). This publication builds on an earlier article by the same author, who argued that Vitruvius produced his ideas in the order in which a city is erected on a virgin site [29]. Citing Fritz ([63], pp. 132–133), Reitz-Joosse notes that "as we read the *De Architectura* book by book, the matrix of a city comes into being, adaptable according to local conditions or the size of the community" ([29], p. 185). After discussing the education of an architect ([53], I, i, pp. 1–3), Vitruvius moves on to discuss the selection of the optimal site for a city ([53], I, i, p. 4), its walls ([53], I, i, p. 5), its basic layout of

primary and secondary streets ([53], I, i, p. 6) and the locations of main temples and the forum ([53], I, i, p. 7).

Table 2. Contents of *De Architectura* after Morgan's edition [53].

Book	Chapter Title [1]
I	i: The education of the architect; ii: The fundamental principles of architecture; iii: The departments of architecture; iv: The site of a city; v: The city walls; vi: The directions of the streets; with remarks on the winds; and vii: The sites for public buildings.
II	i: The origin of the dwelling house; ii: On the primordial substance according to the physicists; iii: Brick; iv: Sand; v: Lime; vi: Pozzolana; vii: Stone; viii: Methods of buildings walls; ix: Timber; and x: Highland and lowland fir.
III	i: On symmetry: in temples and in the human body; ii: Classification of temples; iii: The proportions of intercolumniations and of columns; iv: The foundations and substructures of temples; and v: Proportions of the base, capitals, and entablature in the Ionic Order.
IV	i: The origins of the three orders, and the proportions of the Corinthian capital; ii: The ornaments of the orders; iii: Proportions of Doric temples; iv: The cella and pranaos; v: How the temple should face; vi: The doorways of temples; vii: Tuscan temples; viii: Circular temples and other varieties; and ix: Altars.
V	i: The forum and basilica; ii: The treasury, prison, and senate house; iii: The theatre: its site, foundations, and acoustics; iv: Harmonics; v: Sounding vessels in the theatre; vi: Plan of the theatre; vii: Greek theatres; viii: Acoustics of the site of a theatre; ix: Colonnades and walks; x: Baths; xi: The palaestra; and xii: Harbors, breakwaters and shipyards.
VI	i: On climate as determining the style of the house; ii: Symmetry and modifications to it to suit the site; iii: Proportions of the principal rooms; iv: The proper exposures of the different rooms; v: How the rooms should be suited to the station of the owner; vi: The farmhouse; vii: The Greek house; and viii: On foundations and substructures.
VII	i: Floors; ii: The slaking of lime for stucco; iii: Vaultings and stucco work; iv: On stucco work in damp places, and on the decoration of dining rooms; v: The decadence of fresco painting; vi: Marble for use in stucco; vii: Natural colors; viii: Cinnabar and quicksilver; ix: Cinnabar (continued); x: Artificial colours: black; xi: Blue, burnt ochre; xii: White lead, verdigris and artificial sandarach; xiii: Purple; and xiv: Substitutes for purple, yellow ochre, malachite green and indigo.
VIII	i: How to find water; ii: Rainwater; iii: Various properties of different waters; iv: Tests of good water; v: Levelling and levelling instruments; and vi: Aqueducts, wells and cisterns.
IX	i: The zodiac and the planets; ii: The phases of the moon; iii: The course of the sun through the twelve signs; iv: The northern constellations; v: The southern constellations; vi: Astrology and weather prognostics; vii: The analemma and its applications; and viii: Sundials and water clocks.
X	i: Machines and implements; ii: Housing machines; iii: The elements of motion; iv: Engines for raising water; v: Water wheels and water mills; vi: The water screw; vii: The pump of Ctesibius; viii: The water organ; ix: The hodometer; x: Catapults or scorpiones; xi: Ballistae; xii: The stringing and tuning of catapults; xiii: Siege machines; xiv: The tortoise; xv: Hegetor's tortoise; and xvi: Measures of defence.

[1] Reference to chapter number is written before the title.

After addressing the selection of building materials in terms of availability ([53], II], he commences with the erection of public (religious ([53], III, IV] and civic ([53], V]) buildings. Reitz-Joosse notes that towards the end of Book V, Vitruvius sums up his first five books—"I have now described all that seemed necessary for the proper arrangement of things within the city walls" ([53], V, xi, p. 4)—and observes that, in his account, "[t]he bare bones of a city, those features which make a city a city, are now in place" ([29], 184). After tackling private buildings ([53], VI] Vitruvius addresses how buildings are decorated ([53], VII] and the future development of the city though the supply of water ([53], VIII, iii, p. 27), effectively completing the aedificatio and moving to practical use of gnomonice ([53], IX, viii, xv] and machination for the city in times of peace ([53], X, i–ix] and war ([53], X, x–xvi]. Reitz-Joosse argues that this macrostructure generates "an implicit parallel between the creation of a city and the creation of the text itself" ([29], pp. 185–186]; as the treatise unfolds, the ideal city comes into being. She notes that "on the lexical level, the dominant metaphor Vitruvius uses to describe his own text is neither the city nor any other type of architecture but the body (corpus)" ([29], p.186). To support her claim, she cites a number of instances from *De Architectura* ([53], I, i, 8; II, i, 8; V, para. 5; VI, para. 7; VII, para. 10; VII, para. 14; IX, viii, 15; X, para. 4; X, xvi, 12) and acknowledges Callebat [23], McEwen [26] and Oksanish [28].

3.5. Sources

De Architectura is neither plagiarized nor aimed at winning esteem by finding flaws in the works of others; on the contrary, it is grounded in the works of other authors ([53], VII, para. 10). Prior to formally acknowledging his sources, Vitruvius hails his parents and his teachers, who were responsible for his wide range of knowledge and his passion for literary and artistic disciplines ([53], VI, para. 4). With respect to certain themes addressed in his work, Vitruvius unequivocally credits the works of various authors in the introduction to Book VII. He notes that although a number of books on architecture had been published by the Greeks, no similar inclusive treatise had been published by the Romans: "many . . . have not presented the subject with well-ordered completeness, but have merely made a beginning and left, as it were, only desultory fragments. I have therefore thought that it would be a worthy and very useful thing to reduce the whole of this great art to a complete and orderly form of presentation, and then in different books to lay down and explain the required characteristics of different departments" ([53], IV, para. 1). Dwyer [14] notes that Vitruvius, in his own defense, after providing the list of earlier authors used as sources, states: "From their commentaries I have gathered what I saw was useful for the present subject, and formed it into one complete treatise, and this principally, because I saw that many books in this field had been published by the Greeks, but very few indeed by our countrymen" ([53], VII, para. 14). He acknowledged the three Romans: Fuficius, who published a book on architecture; Terentius Varro, who wrote a book on the subject in his work, *Nine Books of Disciplines* (the others being grammar, rhetoric, logic, arithmetic, geometry, astronomy, musical theory and medicine); and Publius Septimius, who wrote two books on the discipline ([53], VII, para. 14).

3.6. The Practice of Architecture in Ancient Rome

3.6.1. General

One may argue that Vitruvius's view of architectural practice at the time of writing *De Architectura* is pessimistic, the position held by Hoffmann [56], or that he was a realist about the state of the profession: "when I [Vitruvius] see that this grand art is boldly professed by the uneducated and the unskillful, and by men who, far from being acquainted with architecture, have no knowledge even of the carpenter's trade, I can find nothing but praise for those householders who, in the confidence of learning, are emboldened to build for themselves. Their judgment is that, if they must trust to inexperienced persons, it is more becoming to them to use up a good round sum at their own pleasure than at that of a stranger" ([53], VI, para. 6). Vitruvius claimed that "nobody, therefore, attempts to practise any other art in his own home . . . but only architecture, and this is because the professionals do not possess the genuine art but term themselves architects falsely" ([53], VI, para. 7).

3.6.2. A Problem of Definition

Given what was expected from an architect in Roman antiquity when compared today's professions associated with the discipline of architecture, *De Architectura* qualifies as an architectural-engineering handbook. It not only covered the design and construction of cities and buildings, including military ones, but also addressed existing practices which nowadays are considered engineering disciplines in their own right. His books covered materials science (the manufacture of building materials and dyes), chemical engineering (machines for heating water for public baths), acoustics (of amphitheaters), civil engineering (the design of roads and bridges) and mechanical engineering (water wheels and force pumps) [64].

3.6.3. Cost Estimates of Projects

On exceeding the budget for public projects, a case equally applicable to private buildings, Vitruvius cited an ancient ancestral law of the Greek city of Ephesus, whereby if the cost of a given municipal project exceeded 25% of the estimated cost, the difference

was forfeited from the architect's property, which he pledged as a security prior to the commencement of works. If less, the difference was paid for by the treasury at no penalty; if the project was completed within budget, the architect "is complimented by decrees and marks of honor" ([53], X, para. 1). Such a law ensured that "the ignorant would no longer run riot with impunity" and only competent architects, able to accurately compute the estimates for the execution of an assigned work, were engaged in the profession ([53], X, para. 2). As Vitruvius points out, exceeding the estimate by 50% or more leads to bankruptcy "in fortune and in spirit" ([53], X, para. 2). The same applied to delays in the completion of any given assignment ([53], X, para. 3).

3.6.4. On Plagiarism and Slandering of a Deceased Author

While an author should thankfully acknowledge the works of others, it is correct to admonish and punish those who plagiarize writings and ideas of others ([53], VII, para. 3) and honor those who expose them. Vitruvius cites a public poetry contest involving a jury of seven men of letters, among whom all except Aristophanes (c. 257–180 BCE) agreed on the awards to be granted to the poets. Aristophanes thought that the poet who scored the lowest according to the rest of the jury should be the winner ([53], VII, para. 6), arguing that his chosen individual "was a poet, and that the rest had recited things not their own; furthermore, that judges ought to give their approval, not to thefts, but to original compositions [and he] obliged the thieves themselves to make confession. So, the king gave orders that they should be accused of theft, and after condemnation sent them off in disgrace; he honored Aristophanes . . . and put him in charge of the library [of Alexandria]" ([53], VII, para. 7).

Known for his bitterness towards Homer—"the father of poets and captain of all literature abused in his absence, and his works, to which all the world looked up in admiration" ([53], VII, para. 8)—Zoilus (c. 400–320 BCE) fell into poverty and was punished by death (crucified, stoned or thrown alive on a funeral pyre). According to Vitruvius, "whichever of these forms of death befell him, it was a fitting punishment and his just due; for one who accuses men that cannot answer and show, face to face, what was the meaning of their writings, obviously deserves no other treatment" ([53], VII, para. 9). Although the chronology is erroneous—Ptolemy II Philadelphus (309–246 BCE) was the king from 284 to 246 BCE but Aristophanes was the chief librarian of Alexandria in c. 195 BCE and Zoilus lived much earlier—Vitruvius was staunchly against plagiarism and slandering a deceased author, believing that the culprits should be severely punished, and, in the case of the latter, even by death.

4. Contemporary Relevance of *De Architectura*

4.1. The Unity of the Virtues

It has been acknowledged that Vitruvius called for the ultimate synthesis of firmitas, utilitas and venustas, which Collins translates as structural stability, appropriate spatial accommodation and attractive appearance. "It has been generally assumed that a complete theory of architecture is always concerned essentially in some way or another with these three interrelated terms" [4]. Collins notes that this triad has been challenged in various ways since 1750: (i) different weighting was given to its components (e.g., Jean-Nicolas-Louis Durand's (1760–1834) assertion that function is the essence of beauty), (ii) ethical values were added (e.g., John Ruskin's (1819–1900) "sacrifice" and "obedience"), and (iii) new concepts were introduced (e.g., Sigfried Giedion's (1888–1968) "space-time"). It has been argued that Vitruvius's three components had no real value post-1800, when "engineers began creating structures that seemed so ostentatiously to defy the stonemasons' laws of gravity, [and] when scientific studies were creating more and more doubts as to the economical, sociological, psychological, acoustical, thermal, or optical determinants of appropriate spatial accommodation and when beauty was 'altogether in the eye of the beholder'" [4].

Was Vitruvius advocating for a synthesis of all the attributes making up the triad or for a balance in the weighting of each? The latter possibility solicits the question of whether the sequence is relevant. As pointed out earlier, both Alberti and Palladio placed utilitas before firmatas; venustas comes last, implying that "firmitas and utilitas are to be regarded as essential logical prerequisites of architectural beauty" [4]. A concise description of the evolution of the use of these terms in the history and theory or architecture is given by Collins, who notes that "since the 1960s the predominant methods of teaching architectural theory have ranged from a return to the synthesis of structural, spatial, and formal values espoused by Robert Venturi to the exploration of the architectural implications of general theories of linguistics advanced by Christian Norberg-Schulz" [4].

Through *De Architectura*, Vitruvius's position is Hellenistic; not only was he critical of his contemporaries, he recalled Greek scholars, including Socrates. This may provide a response to Lefas's query as to why Vitruvius focused on "how architecture-related knowledge is acquired, instead of giving a definition of architecture itself. . . . Plato approaches the concept of virtue by considering how it is acquired. Whether deliberately or not, Vitruvius apparently followed his example. This is not, however, made abundantly clear" ([22], p. 2). Undeniably, his definition of architecture is an attempt to answer the characteristic Socratic question 'what is *x*'? Also, reading Vitruvius's triad through Socrates's argument for the unity of virtue provides another interpretation of his definition: whilst on occasion he submits that all virtues are one and the same, elsewhere he implies that they are part of a particular whole. In Ancient Greek, arete (translated as virtue) was a term associated with ethics; the principal virtues included dikaiosune (justice), andreia (courage), sophrosune (temperance), hosia (piety), and sophia (wisdom). Each virtue is a definite distinct attribute: justice is related to treating others fairly, whereas courage manifests itself in behavior in situations that typically trigger fear in people. As Socrates argued in the *Protagoras* [65], all virtues are one: one cannot possess a virtue without having all the rest, a theme addressed in [66]. Vlastos identified three distinct formulae employed by Socrates: (i) the unity thesis, (ii) the similarity thesis and (iii) the biconditionality thesis ([67], pp. 221–265]. Although he argued that Socrates's main concern related to the third thesis—what activates any one of the virtues must activate all of them—scholars consistently argued for the first formula. The second formula relates to whether a particular virtue is similar to each of the others; since all virtues are similar but not identical, the second formula is superior to the biconditionality thesis [68]. The formula for the biconditionality thesis reads "Necessarily, for all *x*, if and only if (iff) *x* is courageous then *x* is just, iff *x* is just then *x* is pious, iff *x* is pious then *x* is temperate, iff *x* is temperate then *x* is wise" ([67], 232, fn. 26).

With respect to architecture (*x*), the virtues are firmness, commodity and delight. Each has a definite and distinct characteristic: firmness is related to structural stability, commodity to spatial accommodation, and delight to beautiful appearance. Thus, the third formula does not apply; nor does the second. With respect to the unity thesis, Socrates placed two options before the lead sophist Protagoras (490–420 BCE c.): "[A] virtue is one thing, and justice, temperance, etc. are parts of it; [B] 'virtue', 'justice', 'temperance', etc. are all names of the same thing" ([67], p. 225). Option A fits the Vitruvian virtues of architecture: architecture is one thing, and firmness, commodity and delight are parts of it.

Regarding the question 'what is *x*?' Clark argues that it "gives rise to two distinct kinds of investigations into virtue, a conceptual investigation into the ousia and a psychological investigation into the dunamis" ([69], p. 445). Plato acknowledged the difference between definitional accounts of the former and psychological accounts of the later. Clark further claims that virtues are "'one and the same' psychologically, while they are 'parts of a single whole' conceptually" ([69], p. 445). Thus, applying this reasoning, Vitruvius's definition can be formulated thus: necessarily, for all *x*, *x* must be firm, functional and beautiful. His position is not a nominal but a real definition of *x*. It is an account of the actual elements of character—ethically valid—to which the term *x* applies: architecture must stand, function and be beautiful; these are the attributes which all buildings should possess in order to be considered architecture. Some 20th and 21st century architects

fall into Socrates's blunder mentioned in *Protagoras* (349d–351b) [65], that is, confusing x being a function of y with x being y. Thus, instead of stating that structure, function or delight is a condition for 'architecture', one claims that architecture is structure, function or delight. Furthermore, the Vitruvian definition makes use of the juncture 'and', not 'or'. Applying Reitz-Joosse's language on the body metaphor with respect to the arrangement of the books of *De Architectura*—"the different limbs and parts of a human body are all equally important and mutually interdependent: the whole corpus is neither complete nor harmonious without all of them" ([29], p. 186)—one may read the attributes of structure, function and delight as different members and segments of architecture that are all equally vital and symbiotically dependent. Architecture is neither attained nor congruent without all the three members.

The definition of what constitutes architecture, according to Vitruvius,—stated over 2000 years ago—is still the most distinct and concise. With respect to contemporary architecture, we still assess it in terms of whether it is structurally sound (firmitas), functional (utilitas) and delightful (venustas). Vitruvius's definition underlines current research on the operational use of the term architecture as the synergistic expression of aesthetics and function [70]. While architects emphasize the former, non-architects stress the latter dimension; they discard the rhetorical talk of architects for an architecture which is "pragmatic, utilitarian, and based on sense perception" [71].

4.2. Architectural-Design Education

4.2.1. On the Formation of an Architect/Engineer

For Vitruvius, education was a main pillar in the formation of a citizen. He recalled Theophrastus who, in his defense of acquiring learning rather than money, argued that "he who thinks himself entrenched in defenses not of learning but of luck, moves in slippery paths, struggling through life unsteadily and insecurely" ([53], VI, para. 2). He adds that "all the gifts which fortune bestows she can easily take away; but education, when combined with intelligence, never fails, but abides steadily on to the very end of life" ([53], VI, para. 3). Thus, it is understandable that the opening paragraph of the first chapter of Book I of *De Architectura* addresses education: "The architect should be equipped with knowledge of many branches of study and varied kinds of learning, for it is by his judgement that all work done by the other arts is put to test. This knowledge is the child of practice and theory" ([53], I, i, p. 1). The education of an architect, effectively an architect/engineer in today's terms, should include knowledge of drawing, geometry, history, philosophy, music, medicine, law and astronomy ([53], I, i, p. 3). Drawing is useful for sketching, geometry brings the ability to solve issues related to symmetry ([53], I, i, p. 4) and history is important for understanding the contextual narrative ([53], I, i, p. 5). Philosophy "makes an architect high-minded and not self-assuming" ([53], I, i, p. 7). Also, given that at the time physics was read as natural philosophy, Vitruvius points out that "nobody who has not learned the fundamental principles of physics from philosophy will be able to provide against the damage which [water and air currents] do" ([53], I, i, p. 7). Music is important for understanding canonical and mathematical theory ([53], I, i, p. 8); without this knowledge, the architect will not be able to study theatres, water organs or other instruments ([53], I, i, p. 9). Medicine is required, to assess the healthiness of building, and law is important in order "not to leave disputed points for the householders to settle after the works are finished" ([53], I, i, p. 10).

Is Vitruvius calling for an encyclopedic education for architects/engineers? That was how Alberti read it, and he subsequently disapproved of such an approach [12]. Yet Vitruvius was not calling for an encyclopedic, but for a holistic, education. Although one may argue that the disciplines he lists are not nowadays required, they are definitely relevant and their lack is evident in the practice of this and other professions. One may contest the significance of studying philosophy, medicine or law, but the arguments Vitruvius raises are valid and often addressed through various study units offered at undergraduate level in architecture and civil-engineering courses, for example, professional ethics, sanitary

legislation and law for architects/civil engineers. Vitruvius further argues that philosophy renders a professional "just, and honest without avariciousness. This is very important, for no work can be rightly done without honesty and incorruptibility" ([53], I, i, p. 7). This is nowadays termed professional conduct, an important dimension enshrined in national legislations and endorsed worldwide by professional chambers. The notion that buildings render their occupants unwell if badly designed is a known fact. Standpoints Vitruvius addressed under medicine are tackled through the contemporary sanitary laws and regulations to which a given development project must conform, as, to use Vitruvius's words, "without these considerations, the healthiness of a dwelling cannot be assured" ([53], I, i, p. 10). Similarly, with respect to principles of law, an architect/engineer "should know those which are necessary in the case of buildings having party walls, with regard to water dripping from the eaves, and also the laws about drains, windows, and water supply" ([53], I, i, p. 10). These remain recurring issues arising in present-day developments. Given that Roman law is still the basis of several national legislations, disputes often have to be resolved around whether such considerations were taken into account on a given building site.

4.2.2. Essential Design Elements

The second chapter of Book I introduces the general principles of architectural design: "architecture depends on order, arrangement, eurythmy, symmetry, propriety, and economy" ([53], I, ii, p. 1). The main attributes which establish a design, the theme of the next chapter, are given in the following premise: "All [buildings] must be built with due reference to durability, convenience, and beauty" ([53], I, iii, p. 2). These attributes are defined thus: "durability will be assured when foundations are carried down to the solid ground and materials wisely . . . selected; convenience, when the arrangement of the apartments is faultless and presents no hindrance to use, and when each class of building is assigned to its suitable and appropriate exposure; and beauty, when the appearance of the work is pleasing and in good taste, and when its members are in due proportion according to correct principles of symmetry" ([53], I, iii, p. 2). These elements have governed the history and theory of architecture since then. The concept of symmetry as comprehended by Vitruvius differs from the contemporary notion associated with this term. Hon and Goldstein point out that "the meaning of the term in an aesthetic sense gradually shifted in the context of architecture before the image of the balance was attached to the term in the middle of the 18th century and well before the first modern scientific usage by [Adrien-Marie] Legendre in 1794" ([72], p. 1). The characteristics listed by Vitruvius are still tackled today in the theory and practice of architecture. The premise regulating these attributes is the definition of architecture, which is still, over a broad spectrum, widely accepted.

Furthermore, Vitruvius puts forth the theory that buildings should reproduce human proportions: "in the human body there is a kind of symmetrical harmony between forearm, foot, palm, finger, and other small parts; and so it is with perfect buildings" ([53], I, ii, p. 4). He defines proportion as "a correspondence among the measures of the members of an entire work, and of the whole to a certain part selected as standard" ([53], III, i, I). Aesthetic principles are outlined in Book III; these were eventually translated in the drawing Homo Vitruvianus, the Vitruvian Man, drawn by Leonardo da Vinci (1452–1519) in c. 1490, one of the "all-time iconic images of Western civilization" ([73], p. 224). This theory was ignored in mainstream architecture following Charles-Édouard Jeanneret-Gris (1887–1965), who in 1920 adopted the pseudonym Le Corbusier. He devised the Modulor [74]—the concept of using a module in the design process, dated to *De Architectura* [75]—although he did not acknowledge Vitruvius. This anthropometric scale of proportions is proof of Le Corbusier's lack of knowledge of actual human proportions [76]. When registering its patent, he admitted that he did not know how to explain it ([74], p. 42), a point noted by Lorenzo-Palomera et al. when arguing that his idea is an anthropometric myth ([77], p. 113).

In his introduction to urban planning, Vitruvius puts forward the criteria for selecting the site, adopting a layout, and deciding on the distribution of buildings ([53], I, iv–vii). These criteria are influenced by the miasma theory advanced by Hippocrates, a medical theory which was replaced in 1880 by germ theory, which stipulated that germs, not miasma (the ancient Greek term for pollution), are the cause of specific diseases. According to Vitruvius, "for fortified towns the following general principles are to be observed. First comes the choice of a very healthy site. Such a site will be high, neither misty nor frosty, and in a climate neither hot nor cold, but temperate; further, without marshes in the neighbourhood. For when the morning breezes blow toward the town at sunrise, if they bring with them mists from marshes and, mingled with the mist, the poisonous breath of the creatures of the marshes to be wafted into the bodies of the inhabitants, they will make the site unhealthy. Again, if the town is on the coast with a southern or western exposure, it will not be healthy, because in summer the southern sky grows hot at sunrise and is fiery at noon, while a western exposure grows warm after sunrise, is hot at noon, and at evening all aglow" ([53], I, iv, p. 1). Vitruvius tackled the theme of climate when discussing the design of private dwellings. During the Hellenistic era, geography developed into a "specialized science whose purpose essentially consisted in measuring the earth and drafting a map of the oikoumene [literally meaning the inhabited word]. . . . Vitruvius conveys a geographical system which associates climatic, somatic, and psychic features" ([33], p. 58). Recalling Aristotle's *Oeconomica* I.1345a [78], he admired domestic architecture without architects and wrote about xenia, a long-esteemed Greek ethical principle freely translated as hospitality to strangers ([53], VI, vii); "the Greek xenia referred to both a set of ritualised practices and a socio-political disposition" [79].

4.3. Roman Built Heritage

4.3.1. Stone Masonry and Mortars

Extensive analytical studies of Roman stone masonry were undertaken by Jackson et al. [39] and Jackson and Marra [40]. Both are based on geological field observations, petrological data and analysis of Latin texts, including *De Architectura* ([53], II, vii, pp. 1–5), incorporating updated geological maps. These studies provide a scientific understanding of the characteristics of the stone used in Roman buildings, and address its careful selection and preservation. The maps not only provide information on its occurrence but also a basis on which to study transportation routes from quarries to building sites, and the economy of urban construction. Field observations are used alongside *De Architectura* to establish that, by the time this treatise was written, Roman builders (i) had good knowledge of the material properties of the different volcanic tuffs, and (ii) applied such knowledge to the erection of specific structural elements within large public monuments dated to the 1st century BCE and the 1st century CE: "Tufo di Tuscolo, a hard, lithic–crystal tuff, provided blocks for piers and weight-bearing walls; Lapis Gabinus, a well-cemented predominantly lithic–vitric tuff, served as ashlar masonry in foundations and as voussoirs in flat arches; Tufo Giallo della Via Tiberina, a pumice-bearing vitric tuff, furnished 'caementa' for concrete work in vaults" [39]. The Romans utilized the durable travertine for keystones in arches, in pavements at the base of weight-bearing tuff columns, and as structural reinforcement of the soft tuff masonry through decorative cladding. To protect tuff building stone from the elements, marble cladding or stucco coatings were also used.

The study by Jackson and Marra also contains an appendix which provides geological descriptions of each geological fabric and a gazetteer of existing Roman buildings that make use of it. The data is thorough, and useful not only in tracing the provenance of volcanic rocks—tuffs, pozzolana, and lavas—but also in appreciating the empirical understanding of their properties as provided by Vitruvius [40]. They note that "The Roman invention of robust concretes composed primarily of volcanic rock freed builders from the limitations of working with inconsistent and less durable cut-stone tuff masonry, eventually leading them to a truly innovative architecture of complex, molded interior spaces" ([40], p. 430). A case-study dating to the time of Vitruvius which illustrates the careful selection of building

materials in Roman antiquity is the Theater of Marcellus (44–11 BCE), the theme of another study by Jackson et al. [80] (Figure 3).

Figure 3. The Theater of Marcellus, Rome; view from Via Montanara showing later redevelopment (© Jensens [81]).

A study to trace the provenance of Roman mortar aggregates was undertaken by D'Ambrosio et al. [44]. The mortar technology used by the Romans was consistent. A study by Pavía and Caro concluded that all mortars are of good quality, irrespective of whether they are used in monuments or modest rural dwellings; indeed, some of the oldest mortars are the best preserved [42]. Following petrographic analysis of Roman mortars dating from between 1500 and 2000 years ago—the majority manufactured using non-hydraulic lime, their hydraulicity being due to pozzolanic additions (ceramics)—new facts emerged from their study regarding the calcination and slaking of lime. Their findings on the binder cohesion reveal high reactivity and water-retention capacity and low shrinkage for the lime. This is indicative of long lime slaking and the soft burning of limestone for lime-making, as advised by Roman authors ([42], p. 1811). Vitruvius advised the former, to ensure a homogeneous consistency and avoid cracks appearing in plasters ([53], VII, ii, 7, pp. 42,81).

4.3.2. Theatres

It is widely acknowledged that ancient Greek and Roman theatres have impeccable acoustics. Vitruvius dedicated a significant part of his discussion on the design of civil buildings to theatres ([53], V, iii-vi). "The Roman Empire included an enormous geographic extension. It is evident that geographic distances between cities produced great morphologic differences between buildings of the same architectonic typology. Many peculiar characteristics personalized each Roman theatre in agreement with their space-temporary situation. In addition, with the uninterrupted use of the theatres during several centuries, successive architectonic interventions were carried out in order to adapt the theatre to the requirements of every society" ([38], p. 5).

Several ancient Roman theatres are still in a good state of repair and some include later interventions to adapt them to more recent needs. The theatre of Philippopolis, dating to the 1st century CE, located at the center of Plovdiv, Bulgaria, is one of the world's best-preserved theatres still in use (Figure 4a). The theatre in Amman, Jordan, dates to

the 2nd century CE, when the settlement was known as the Roman city of Philadelphia (Figure 4b). The theatre in Mérida, Spain, originally constructed in 16 to 15 BCE, underwent renovations at the end of the 1st century/early 2nd century CE and between 330 and 340 CE (Figure 4c). The theatre in Lyon, France, was erected in two phases, the most recent commencing at the beginning of the 2nd century CE (Figure 4d). Although the theatres in Spain and in France have been designated UNESCO World Heritage sites, those in Bulgaria and in Jordan are not protected. The theatre in Spain was inscribed in 1993 as part of the Archaeological Ensemble of Mérida under criteria (iii) and (iv) [82]. The theatre in France was inscribed in 1998 as part of the historic center of Lyon, according to criteria (ii) and (iv) [83]. UNESCO's selection criteria state that it is necessary for a site: "(ii) to exhibit an important interchange of human values, over a span of time or within a cultural area of the world, on developments in architecture or technology, monumental arts, town-planning or landscape design; (iii) to bear a unique or at least exceptional testimony to a cultural tradition or to a civilization which is living or which has disappeared; (iv) to be an outstanding example of a type of building, architectural or technological ensemble or landscape which illustrates (a) significant stage(s) in human history" [84]. The theatres in Bulgaria and Jordan are impressive structures and outstanding examples of ancient Roman antiquity.

Figure 4. Roman Theatre: (**a**) Plovdiv, Bulgaria (© Dennis Jarvis/CC BY-SA 2.0) [85]; (**b**) Amman, Jordan (© Bernard Gagnon/CC BY-SA 4.0) [86]; (**c**) Mérida, Spain (© Benjamín Núñez González/CC BY-SA 4.0) [87]; (**d**) Lyon, France (© Vincent Bloch) [88].

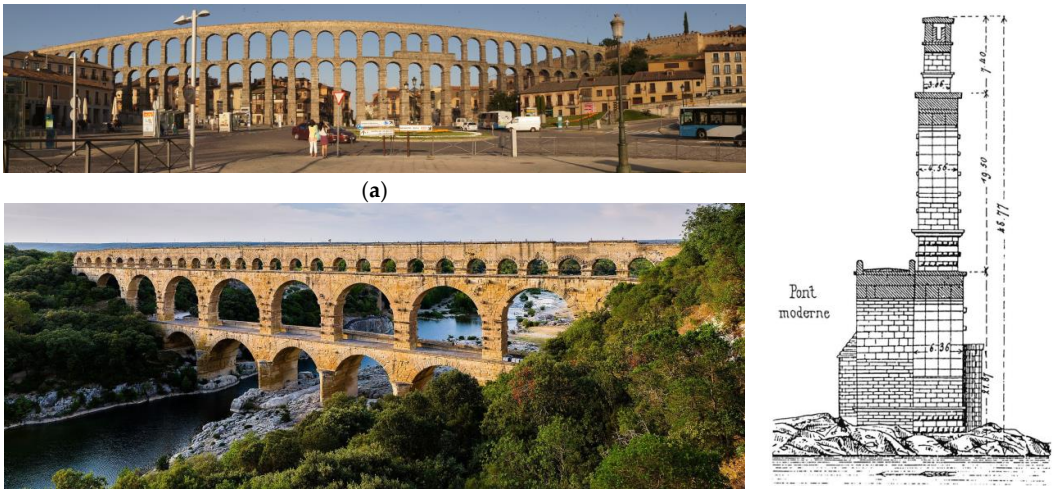
Vitruvius was interested in theatres which function well. He was "a practical man, not a theorist. His interest in the voice is in constructing spaces that are serviceable to the requirements of oratory and the theatre, to ensure that the voice can be distinctly heard: both by the speaker, for self-assurance, as well as by the audience" ([89], p. 78). Thus, beyond the architectural-engineering dimensions, these theatres had acoustic mechanisms—sounding bronze vessels ([53], I, i, p. 9; V, v, pp. 1–7)—to improve the audibility of the voices of actors,

through resonance. Given that none of these vases survive today, the only information on them is found in *De Architectura*. Certainly, in Vitruvius's time, if "it is asked in what theatre these vessels have been employed, we cannot point to any in Rome itself, but only to those in the districts of Italy and in a good many Greek states" ([53], V, v, viii). Recent research on these vases undertaken by Barba at al. acknowledges that Jose Ortiz y Sanz (1739–1822) doubted their effectiveness, and George Charles Izenour (1912–2007) believed their effect would have been very poor [38]. The former translated *De Architectura* into Spanish [90]; the latter was a leading innovator in theatre design and technology and taught at Yale University from 1940 to 1977 [91].

4.3.3. Technology

Books VIII to X are the main sources on Roman technology. Although some chapters are short (for example, the one on the construction of aqueducts, wells and cisterns ([53], VIII, vi) they are still useful for understanding Roman engineering. Further to the design of sundials and water clocks—both significant instruments for measuring time that were an important dimension in the development of civilization ([53], IX, viii)—Vitruvius tackles engineering machinery such as hoists, cranes and pulleys ([53], X). Renaissance designs and drawings reproducing Vitruvius's machines are included in a recent collection of essays on the history of mechanical engineering [92].

Given the numerous surviving Roman aqueducts, wells and cisterns, the chapter on their construction is useful in understanding the manner in which they were surveyed and the appropriateness of the building materials utilized for their erection. The surviving aqueducts in Segovia (Spain) (Figure 5a) and Pont du Gard (France) (Figure 5b), probably erected in the middle of the 1st century CE, date from the decades following the completion of *De Architectura*. Its contents offer important insights for any restoration and/or conservation intervention involving these engineering structures. Both were included on the UNESCO World Heritage List in 1985 in terms of criteria (i), (iii) and (iv) [93,94]. The two sites offer unique testimony regarding a civilization which has disappeared, and represent outstanding exemplars of human development; additionally, in terms of criterion (i), they "represent a masterpiece of human creative genius" [84]. There are other less impressive structures which nevertheless recall the creative genius of this bygone civilization; they are still outstanding examples of technological innovation in human history representative of high culture.



(**a**) (b) (c)

Figure 5. Roman Aqueducts: (**a**) panoramic view of Aqueduct of Segovia, Spain (© Z3144228/CC BY-SA 4.0) [95]; (**b**) Pont du Gard Aqueduct, France (© Benh Lieu Song/CC BY-SA 3.0 [96]); (**c**) Cross section of the Pont du Gard by Alfred Léger (1840–?) [97].

Equally important are movable Roman hydrodynamic-lifting machines such as the water wheel ([53], X, v), water screw ([53], X, vi)—better known as the Archimedes screw—and Ctesibius force pump ([53], X, vii). Parts of a wooden water wheel for draining a mine, found at the Rio Tinto Copper Mines (Spain), and an oak board from the box-rim of a dewatering device at the Dolaucothi mine (Wales) are now housed in the British Museum [98] and National Museum of Wales [99], respectively. Five fragments of a bronze double-action water pump, including a nail, Bolsena (Italy) is kept at the British Museum [100].

4.3.4. Scientific Relevance of Empirical Observations

The survival to this day of Roman structures is proof of their resilience and an indicator of the craftmanship and durability of the building materials used. Although, as far as we know, scientific experimentation was rudimentary at the time, empirical observations were relevant. Roman concrete has stood the test of time, as colossal structures such as the Pantheon (Figure 6) and the Colosseum (Figure 7), dating from approximately two millennia ago, testify. Vitruvius advised using clay pipes instead of lead for potable water ([53], VIII, vi, p. 10); laborers in lead foundries at the time suffered "day and day burn out and [loss of] all the virtues of the blood from their limbs" ([53], VIII, vi, p. 11).

(**a**) (**b**)

Figure 6. The Pantheon, Rome: (**a**) elevation overlooking the Fontana del Pantheon (© Rabax63/CC BY-SA 4.0) [101]; (**b**) interior (© Macrons/CC BY-SA 4.0) [102].

(**a**) (**b**)

Figure 7. The Colosseum, Rome: (**a**) exterior (© AlexanderVanLoon/CC BY-SA 3.0) [103]; (**b**) aerial view (© Kasa Fue/CC BY-SA 4.0) [104].

On the relevance of empirical observations for contemporary scientific research, it is worth mentioning a recent study which validated the observations of Pliny the Elder [105].

Recalling his encyclopedic *Naturalis Historia* 35.166—his sources on Roman construction techniques and wall painting included *De Architectura*—he notes that "the most inferior portion of the earth's substance, which is in consequence designated dust [volcanic ash or earth, now called pozzolana], on the hills of Pozzuoli, encounters the waves of the sea and as soon as it is submerged turns into a single mass of stone that withstands the attacks of the waves and becomes stronger every day" [5]. Vitruvius has noticed the significance of volcanic ash with respect to marine concrete [46,51], "There is also a kind of powder which from natural causes produces astonishing results. It is found in the neighbourhood of Baiae and in the country belonging to the towns round about Mt. Vesuvius. This substance, when mixed with lime and rubble, not only lends strength to buildings of other kinds, but even when piers of it are constructed in the sea, they set hard under water. . . . .When the three substances . . . are mixed together, the water suddenly taken in makes them cohere, and the moisture quickly hardens them so that they set into a mass which neither the waves nor the force of the water can dissolve" ([53], II, vi, p. 1).

Jackson et al. [105] further reinforced earlier findings [50,51] that, unlike conventional concrete, Roman concrete is durable, due the presence of the rare hydrothermal mineral aluminous tobermorite (Al-tobermorite). Their study, covered by the media (e.g., [106–108]), noted that this mineral "forms crack-stopping fibers and [crystal] plates within voids in the cement." This research "revealed that the Romans didn't initially put Al-tobermorite in their concrete—instead, the mineral formed over a slow and evolving timeline of chemical reactions with the seawater itself" [108]. Given that this mineral evolves slowly at ambient temperatures, the island of Surtsey—a UNESCO World Heritage site located off the southern coast of Iceland which was formed by volcanic eruptions in 1963–1967 [109]—is being studied, to better understand the formation of Al-tobermorite at low temperatures. "By examining samples from [this site], scientists can probe small-scale reactions within isolated geologic microenvironments to decipher the chronology of mineral growth" [108].

4.3.5. Final Comments

Vitruvius's wish that, through *De Architectura* he would be renowned for posterity, was fulfilled. His accounts on urban, civil and domestic architecture, as well as building materials, formed the basis of the systemic excavations at Herculaneum (Figure 8) and Pompeii (Figure 9) which commenced in 1738 and 1748, respectively [110]. Both archaeological settlements, together with Torre Annunziata, were, as a single entity, designated a UNESCO World Heritage Site in 1997, under criteria (iii), (iv) and (v) [111]; criterion (v) states that the site is an "outstanding example of a traditional human settlement, land-use, or sea-use which is representative of a culture (or cultures), or human interaction with the environment especially when it has become vulnerable under the impact of irreversible change" [84]. These Roman towns, which were largely preserved under volcanic ash following the violent eruption of Mount Vesuvius in 79 CE, were frozen in time, and thus provide a unique snapshot of Roman life then; "a unique opportunity . . . to use . . . as an urban laboratory" ([112], 630). Today, Vitruvius's text has been augmented by further archaeological research on these and other Roman remains. His version of the logeum of Greek theatres ([53], V, vii, p. 2), the theme of a research paper published by the American scholar Louis Dyer (1851–1908) [113], squarely fits the archaeological findings [8]. In particular, Martin notes that Vitruvius's description tallies with the archeological discovery of the Theater of Priene, which was studied by von Gerkan [114].

Figure 8. Herculaneum: panorama of the excavation (© Xtreambar/CC BY-SA 3.0) [115].

(**a**)

(**b**)

(**c**)

Figure 9. Pompei: (**a**) panoramic view of the Forum of Pompeii, with Vesuvius at the rear (© Heinz-Josef Lücking/CC BY-SA 3.0) [116]; (**b**) Via dell'Abbondanza (© Lord Pheasant) [117]; (**c**) Thermopolium of Vetutius Placidus opening directly onto the south side of the Via dell'Abbondanza (© Carole Raddato/CC BY-SA 2.0) [118].

5. Conclusions

The integrated design principles and solutions advocated by Vitruvius still form part of the education of an architect/engineer today. Roman architecture, engineering, building materials and construction techniques, all addressed in *De Architectura*, formed the uniqueness of the empire. Given that this comprehensive essay has significant "lessons

for the theory of types and for the construction of design heuristics", Heath argued for a reading of Vitruvius's work in terms of design method ([119], p. 246). The following sections reflect on areas of further contemporary relevance of this comprehensive, didactic and technical handbook.

1. Comprehension of the context of Roman architecture

Most Roman sites originally formed part of an urban context. They transformed the original landscape and the environs geomorphologically and architecturally over the centuries. This context can be assessed with respect to the parameters regulating the location of the city ([53], I, iv) and public buildings ([53], I, vii). Preserving such sites for posterity ensures that Roman remains are read in the original context. This is of overriding importance in building typologies dictated, and thus conditioned, by the location of the site, as in theatres, for example. Where parts of such a context is missing, the use of software to recreate accurately virtual reality will prove useful.

2. Protection of Roman cultural heritage

A significant portion of the cultural patrimony—in the form of architectural buildings and other structures—across a considerable part of Europe, North Africa and the Middle East is represented by tangible heritage dating to Roman antiquity. Roman architecture and the building science of the time, both themes covered in Vitruvius's treatise, are an integral part of today's heritage. This Roman handbook is a collection of valuable knowledge, some of which is unique, such as his discussion of the techniques of fresco painting ([53], VII, v) which, as Martin notes [8], formed the basis of the classification of the Pompeian styles drawn up by Mau [120].

3. Consolidation and restoration of Roman remains

For scientific restoration, knowledge of the architectural language used in built structures—be they temples ([53], III; IV); public ([53], V) or private ([53], VI) buildings; or aqueducts, wells and cisterns ([53], VIII, vi)—and the construction techniques ([53], II, viii) and materials ([53], II, iii–vii, ix–x) used to build them, are crucial when it comes to comprehending their anatomy. Empirical observations included in historical texts are of scientific relevance; they are often based on oral tradition and are therefore much older than the texts in which they were first documented, as is the case with *De Architectura*. Rome's most precious cultural heritage is erected in tuff building stones that are rapidly deteriorating due to the past removal of cladding for recycling into other use/s or exposure initiated by archaeological excavations. "To prevent further deterioration and eventual corrosion of the monuments, the tuffs should be placed under protective cover, as Vitruvius recommended more than 2000 years ago" ([39], p. 508).

4. Knowledge of Roman Building Materials

De Architectura is a written statement which records the building materials used at the time. As reported by Marie Jackson, the lead researcher on Al-tobermorite, the Romans "had excellent capabilities for empirical observations—they were using a method based on science and knowledge, and it's this careful observation and experimentation that led to these remarkably durable materials" [108]. Deciphering the nature of durable Roman building materials such as concrete may help improve the characteristics of modern counterparts, by introducing similar components. Durability impacts not only on the age and strength of the material but also on its depreciation and related issues such as serviceability and insurance.

5. Assessment of Roman building materials

An inclusive approach to assess the material properties of the geology of building stones is a mineralogical, geochemical, textural and physical analysis. Citing Jackson and Marra, "ultimately, integration of petrographic and rock testing data with systemic observations of the structural elements of volcanic stone construction in the Roman monuments gives us new insights about Roman builders' empirical understanding of stone material

properties and the evolution of their architecture" ([40], p. 431). Tuff lithologies abundant in "lava and crystal fragments have the greatest compressive strengths and durability. Pumice, clay and/or significant percentages of altered vitric matrix decrease [the] compressive strength as well as the adherence of zeolite cements to vitric and lithic fragments" ([39], p. 508). The mineralogy of the tuff used by the Romans enhanced the durability of their concrete; "it augmented the reactivity of Roman pozzolane with lime and increased the bonding strength of coarse tuff aggregate with robust pozzolanic mortar" ([40], p. 431).

6. Research on contemporary-building construction materials

Studying Roman structures provides insight to the durability of the building materials. For example, as noted by April when reporting on research which vindicated the observations of Pliny the Elder [108], this discovery provides an opportunity to develop a formula for the manufacture of more durable concrete; indeed, Jackson's research is partially focused on establishing the concrete mixture used by the Romans [45,48–52,107]. The latest research following this reasoning was published in *Science Advances* in the first week of 2023. Inspired by their findings on Roman concrete, Seymour et al. propose a mixture with self-healing potential, with a view to developing more durable concrete [47].

7. Architectural Education

Architectural education is a relevant topic of contemporary research. Papers are regularly published in a number of highly ranked journals, and there is even a specialized publication on this topic, *The Journal of Architectural Education*. In Vitruvian terms, architecture affects all aspects of human life, from the physical to the mental. It has profound effects on our surroundings. The education Vitruvius advocated was not academic, but pragmatic. He called for architects/engineers to receive a holistic education in order that they could address the well-being of all in their work. Architectural issues must be comprehended through interdisciplinary education: "Those . . . who from tender years receive instruction in the various forms of learning recognize the same stamp on all the arts and an intercourse between all studies and so they more readily comprehend them all" ([53], I, i, p. 12).

8. Acknowledging sources

Plagiarism is the act of adopting others' creative work and passing it off as one's own. It may involve copying directly from a source without the author's permission or presenting others' ideas as if they were one's own. Unlike the humanities, the practice of architecture/engineering/building science does not involve copying text, but it involves design elements and/or ideas. In design studios, students of any of these disciplines are encouraged in the early phases of a design project to find case studies in order to study the assigned task. If the assessment criteria are thorough, there will be a percentage mark allocated for this phase. Besides analyzing these case studies, they are effectively referenced as relevant to the design project. While it is imperative that students cite any case studies they have used—and they may be significantly penalized if they fail to do so—likewise, practitioners should also cite their sources for projects, as everyone stands on the shoulders of those who went before.

9. Physical and psychological well-being

Vitruvius addressed both the well-being of society and of the users of a given place. When addressing the location of cities, he argued that "we cannot but believe that we must take great care to select a very temperate climate for the site of our city, since healthfulness is, as we have said, the first requisite" ([53], I, iv, p. 8). Furthermore, climate is intrinsically linked with health, notably with respect to domestic architecture ([53], VI, i). He outlined design solutions to improve the quality of living conditions for users of both public (e.g., baths ([53], X, x, pp. 1–5) and private buildings ([53], VI, i, pp. 2–4; VI, iv, pp. 1–2; VI, v, pp. 1–2; VI, vi, pp. 1–3, 6–7).

10. Budget for a given development

It is a common occurrence, notably in public works, that completion costs for a given project significantly exceed budget estimates. This may be due to underestimating the cost (due to negligence or incompetence), unforeseen events (supply-chain issues, personnel problems such as sickness, encountering archaeological remains, etc.), or even corruption (overcharging for materials, adding unnecessary extras, etc.). While it may not be necessary to introduce such draconian legislation as the 25% rule cited by Vitruvius, "plans should be worked out carefully, and with the greatest attention, before the structures are begun" ([53], X, para. 4).

Although grounded in the practice and technology of ancient Rome, the principles put forward in *De Architectura* remain valid today for effective, sustainable architectural-engineering design based on rigorous education and a good knowledge of building materials and construction. Citing published literature [121,122], D'Ambrosio et al. noted that the "criteria of selection of the materials and the methodology to produce mortar [as described by Vitruvius] have remained substantially unchanged until the introduction of the Portland cement in the XIXth century" ([44], p. 186). Also, Vitruvius's definition of architecture—the one still customarily used—is an inclusive philosophical statement on the essence of building for humanity to house humanity. It recalls the symbiotic relation between architecture and building engineering that is often forgotten in the contemporary emphasis on specialization.

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