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Research

Geometry, the Measure of the World

Abstract. This study considers the relationship between the approach to urban planning in Portugal up to the eighteenth century, and the effective process of urbanisation, from both a theoretical and practical perspective. Portuguese urban layout does not develop as a set of random shapes but rather arises from structured thinking by “urban makers” who are firmly grounded in the subject of geometry. Being able to measure the universe and codify it in drawings was one of the major scientific accomplishments of the age of Portuguese discoveries in the sixteenth century and the acquisition of such knowledge demanded a unique ability for abstraction which could not have simply emerged out of nothing. Portugal’s investment in the training of skilled professionals is made evident in treatises, manuals, dissertations, and cartography and iconography works. The interpretation of the ideas of Order and Space in urban design evolved through history in parallel with the evolution of philosophical and scientific thought. In fact, urban space is associated the search of the laws of the nature and the intelligibility of the cosmos.

There is no doubt that the journeys of this realm in these last hundred years are the greatest, the most marvellous, of most high and distinguished intentions, of any people in the world. The Portuguese dared to discover the great ocean seas. They set forth fearlessly. They discovered new islands, new lands, new seas, new peoples and more, a new sky and new stars. (...) Indeed it is clear that these discoveries, of coasts, islands and land masses, would not have been made or recorded had our mariners not set out well-educated and equipped with the instruments and rules of astronomy and geometry, which are the things with which cosmographers concern themselves (...) [Nunes 1544].

(...) Vitruvius stated that one could not be called a perfect architect without being an expert in (...) the following: Knowing the art of accounting in order to declare the expenses incurred by the building; it is necessary to be an expert in Geometry. Who is curious about this art should study Euclid and there will find many things of use; it is necessary for the architect to know how to sketch for through this he shows his designs and how to build them, as well as each of the other things that understanding has declared (...) [Rodrigues 1576].

Introduction

Throughout history, the interpretation of the ideas of order and space in urban planning has evolved in parallel with the evolution of philosophical and scientific thought, which examined these concepts in intimately association with the search for geometrical and numerical laws in nature and intelligibility in the cosmos (the general laws governing the universe and its constitution).

This tendency to see the world as geometrical on all its different scales, from celestial and planetary systems (macrocosmos) to the human body (microcosmos), became the origin of the Portuguese urban planner's framework of thought and informed the logic of urban designs during the period of the Discoveries in the sixteenth century. This is revealed in the treatises that directly influenced the formation of the Portuguese *Uomo Universalis*.

The first steps in the teaching of geometry in Portugal were made in relation to astronomy (cosmology and cosmography), navigation, commerce and military architecture, as a response to the enormous challenge of expanding an empire across the world. This led to progress in science and geometry, in both theory and practice, and the training of a body of qualified professionals to support the policy of urban settlement in Africa, India and Brazil.

The needs of commerce, as well as of fortification and settlement, demanded study of the outside world, exactly as it revealed itself to be, with its properties and processes of transformation. The problems of navigation led to an increasingly careful investigation of the movements of celestial bodies and demanded a more rigorous study of movement in general, a quantitative study that enabled one to measure and predict [Caraça 2003: 187].

Seeing the cosmos as geometrical

The theoretical and rational discourse on cosmic order and unity finds in geometry one of its most solid foundations, not only for the construction of mental models, but also in verbal discourse, through the well-defined concept of space regulated by Pythagorean number and by the relationships between Euclidean geometrical figures. The Greeks submitted the image of the cosmos to pure scientific operations sustained by geometry, [Dilthey 1992: 79-84], which allowed them to establish a permanent, uniform, abstract order for what was observed.

Throughout the development of philosophical and scientific knowledge, Man has researched and studied geometrical models in nature, the human body, the universe and in aesthetics, searching for a universal logic, a harmonic law and a metric law to explain them. Various geometrical archetypes and numerical ratios were established in the search for logical relationships that could satisfy both reason and the eye.

The Pythagoreans were the first to apply themselves to mathematics, and they not only advanced its study, but also ... decided that its principles were the principles of all things. As, from such principles, numbers are by nature primary, and they seemed to see in numbers many similarities with things that are and come to be ...; just as, on the other hand, they saw that the modifications and ratios of the musical scale could be expressed in numbers; and as, in short, the integral nature of all other things appeared modelled by numbers, and numbers are judged to be the primary elements in nature as a whole, they made the supposition that the elements of numbers were the elements of all things, and that the entire heavens were a musical scale and a number [Aristotle, *Metaphysics*, I.5.985b].

In his dialogue *Timaeus*, Plato looks to the fundamental content of Pythagorean philosophy to express his admiration for numbers, proportions and geometry. In the *Republic*, he describes his idea of geometry as “a faculty whose preservation outweighs ten thousand eyes, for by it only is reality beheld” [Plato, *Republic* VII, 527e]. In this way,

Plato and the Pythagoreans built their theories of the cosmos, fundamental constituents of nature associated with regular solids.

Admiration for the cosmos, defined by a mathematical order, is also expressed by the Greek mathematician Euclid (third century B.C.). His *Elements*, the first systematic discussion of the geometry of ruler and compass and the first text to talk about the theory of numbers, is the point of reference in the classical tradition and was taught as a compulsory subject for the investigation of the laws of the cosmos and the development of geometrical models of urban planning.

Effectively, Euclidean geometry is one of the foundations of philosophical and scientific thought, appearing in the treatises and compendia of the major schools of Europe in the sixteenth century. This approach emerges as a way of conceptualising and systematising knowledge, allowing us to identify today the structure of the geometrical thought of the practitioners of urban planning and to decode the origins of the logic of urban design.

Pedro Nunes and António Rodrigues on the training of urban planners in Portugal

The different approaches that led to the adoption of various urban planning solutions were conditioned by the theoretical and practical training of Portuguese urban planners (who were also architects, engineers, geographers, geometers, priests, military men, noblemen, etc).

Science and pragmatism became incorporated into the spirit of scholars and the brave captains of the seas, building a new understanding of ancient Mediterranean practices, a tradition which these men inherited and continued. They gathered information in Italy and from Arab scholarship, where they found the fundamentals of geometry needed to discern the secrets of astronomy, and these they put to use in making navigational charts and colonising new lands [Tavares 2007: 16] (fig. 1).

Fig. 1. *Mundi Sphaera Coelesti ac quomodo sic architectatus est.* From Cesariano's 1521 edition of Vitruvius

The history of navigation in Portugal began with Prince Henry the Navigator (1394 - 1460), whose aim was to prepare navigators to head out across the ocean to discover new lands for their King, and to conquer souls for their God. In order to navigate the high seas, it was necessary to measure the stars at regular intervals through the science of astronomy, so as to determine position. Thus Prince Henry wanted to create a place where astronomy could be taught, along with the principles of arithmetic and geometry, on which this science depended. The astronomical and geographical works of Claudius Ptolemy (87-151) were studied, and the help of the Catalan Jácome de Malhorca (1350?-1427?) was enlisted. According to the famous chronicler João de Barros (c.1496-1570), he "... was very expert at making compasses and drawing navigational charts, and would direct the preparation of expeditions which would leave under his orders to explore the secrets of the seas" [Pedrosa 1997: 34].

The fifteenth century saw the beginning of the development of mathematics in Portugal. The first work on astronomy published in Portugal, *Almanach Perpetuum* (1496) by Abraão Zacuto (1450-1510), King D. João II's astronomer and cosmographer, as well as the migration of young Portuguese men to foreign universities, reveal the growing importance of mathematical and geometric education [Henriques 2005: 181-198].

With the development of navigation, commercial activity gave impulse to the study of arithmetic. Already in the first quarter of the sixteenth century, an edition of the *Tractado da Pratica Darysmetica* (1519) by Gaspar Nycolas appeared. This would become one of the most important books in the field of scientific culture and education in Portugal. It can be regarded as an official description of a new science that became the theoretical basis for the framework of the mental models of modern man [Carita 1999: 139-146].

One of the examples of the importance granted to scientific knowledge, and of the Portuguese Crown's investment in the training of specialists, is the internationally renowned mathematician Pedro Nunes (1502-1578), Chief Cosmographer of the Realm and professor of mathematics in the *Paço* School or the *Paço da Ribeira* School for Young Gentlemen. One can find references to him, or evidence of his influence, in works of all the great mathematicians, astronomers and cosmographers of the second half of the sixteenth century and the seventeenth century. The Jesuit mathematician Christopher Clavius referred to Pedro Nunes as a famous mathematician, a penetrating intellect and inferior to none in mathematics in their age. Some of Clavius's important scientific contributions – for example, in relation to the nonius or the problem of Crepusculus – originate in and essentially depend on the works and theories of Pedro Nunes [Leitão 2002: 15-28].

Among the various works of this distinguished cosmographer – which include the *Tratado da Sphera* (1537) (fig. 2); a translation of the work of Sacrobosco, *De Crepusculis* (1542); *De erratis Orontii Finaei* (1546); the *Libro de Álgebra en Aritmética y Geometria* (1567) inspired by the work of Euclid; and a translation of the work of Vitruvius (1541), as well as original works that enriched science and the art of navigation – are the *Tratado sobre certas dúvidas da navegação* and the *Tratado em defensam da carta de marear* (1566).

It was the requirements of navigation that imposed the study of astronomy, and made the study of the principles of geometry essential.

Fig. 2. *Astronomici Introductorii de Sphaera* in Nunes, *Tratado da Sphaera* (1537)

The fundamental sciences for navigation (geometry, arithmetic and cosmography), which led to the domination of the seas and the conquest of markets and territories, were also the essential disciplines for the scientific, philosophical spirit of the sixteenth century. These found direct expression in the conception and practice of Portuguese urban planning across the world [Teixeira & Valla 1999: 121-137]. In the sixteenth century, the training of architects involved a combination of generic studies in military architecture, Euclidean geometry and cosmography [Xavier 2006: 27].

The mentors for these studies lectured outside the University, in two technical training institutes in Lisbon. The famous *Aula da Sphaera* (Class of the Sphere) was taught at the Jesuit College of *Santo Antão* and involved an in-depth study of the cosmography and cosmology of the age. A large number of treatises are known to have been composed by its professors, in the fields of cosmography, astronomy, navigation and military architecture.

From the beginning, architectural issues were of relevance to the college's curriculum and among its masters and students were various architects, according to Rafael Moreira [1982: ch. 2].

The other institute was the *Paço da Ribeira* School for Young Gentlemen, geared towards the instruction of seafarers and urban planners. Here the pedagogical approach was in agreement with Vitruvius, tailored to a method of teaching that could not conceive of any training without a strong scientific foundation in the *Quadrivium*, Euclidean geometry, arithmetic, astronomy and music, in addition to the subjects of the *Trivium*. The programme included the principles of cartography and the use of the main navigational and architectural instruments. It was aimed at noblemen who wished to serve Portugal in war and in the settlement and fortification of new territories.

A class in military architecture was also taught here from 1562 onwards, articulated with the teaching of geometry and cosmography, and was introduced to form part of the training of the young King D. Sebastião (1554-1578). This programme was strengthened with the employment of Pedro Nunes to teach the *Lições de Matemática e Cosmografia* (Lessons of Mathematics and Cosmography), in which the humanist João Baptista Lavanha (15??-1624) also collaborated. The school would serve as a model for the Academy of

Mathematics and Architecture in Madrid, founded by King Phillip II and directed by the architect, mathematician and geometer Juan de Herrera (1530-1597) [Xavier 2006: 38].

In 1573, António Rodrigues (c. 1525-1590), the Master of works and fortifications of the Realm, assumed the teaching of applied geometry for architectural design and perspective to the young noblemen destined for careers at arms and in government. As professor of military architecture and related sciences at the *Aula do Paço*, he taught the main theories of architecture and fortification, as well as the methods and instruments of good building fit for the King. His *Tratado de Arquitectura* [1576] bears witness to his activity as a teacher, providing an exposition of the subject in both theory and practice. The text possesses a didactic tone appropriate to the context of scientific instruction at the *Paço* School. The treatise is composed of two books, the first of which deals with military architecture, geometry, trigonometry and basically uses as references the treatises of Vitruvius, Alberti, Pietro Cataneo and Serlio. The second “explains what is [Euclidean] Geometry” and is a book on perspective.

As heir to the Italian school of architecture and the scientific tradition of the geometrical-mathematical and astronomical variety, the thought of António Rodrigues reveals the mark of Pedro Nunes, whom he imitates even in his choice of language, according to Moreira. He lists the fundamental aspects of cosmography as presented in Nunes’s *Tratado da Sphera*, and states that “it is useful for the fortifier and architect to understand the sphere, in order to know how to arrange his instruments according to the graduation of degrees into which the said sphere is divided” [Rodrigues 1576] (fig. 3). Such scientific knowledge was essential to the invention and use of accurate instruments for measurement in architecture. These were inspired by the instruments and methodology used in navigation (astrolabe, quadrant, *Balestilha* or Pedro Nunes’s nonius) (fig. 4), which measured space by sight in ways similar to the procedures that had already been described by Alberti in his *Ludi Matematici* (c. 1451), and others (fig. 5).

Fig. 3. Practical Geometry instruments, propositions 26, 27, 29. From António Rodrigues *Tratado de Arquitectura*, 1576

Fig. 4. Pedro Nunes's nonius (Museu da Marinha, Lisbon)

Fig. 5. With simple instruments, astronomers and surveyors in the sixteenth century could determine to useful accuracy the angular separation on the moon and a star and the heights of towers.
From the frontispiece of Johannes Werner, *Introductio geographica Petri Apiani* (Ingolstadt, 1533)

The treatise of António Rodrigues is a compilation of knowledge focussed on the solution of practical problems using the principles of Euclidean geometry, which are essential to practical geometry (longimetry, planimetry, stereometry, trigonometry), to arithmetic and to design. Longimetry would teach how to measure and represent accessible distances, heights and depths; planimetry, how to measure and represent the area of surfaces; stereometry, how to calculate and represent the volume of solid objects; trigonometry, how to measure and represent inaccessible distances by triangulation. Arithmetic would teach, in broad terms, “counting” and “calculating” [Bueno 2003: ch. 3]; design, how to represent an “idea” to be realised on the ground.

The genesis of Portuguese urban design as cosmo-geometric logic

Geometry assumes the role of a preparatory science, a mental discipline and a rigorous ordering rationale for the composition and configuration of space, a kind of support that seems to disappear once the building is complete, but which can be brought out at any moment if one knows the rules [Murtinho 2000: 1].

In Europe, from the fifteenth century onwards, these rules would support aesthetic theories and the principles of urban planning, where the main desire for order stems from the geometrical logic of the mental and the real. In treatises, plans, projects and construction, the configuration and composition of urban space are subject to Euclidean and Vitruvian unity and rationality. For Alberti, the city should be constructed as an expression of the austere pleasure of geometry. The radio-concentric design realises this geometric perfection, the perfection of the cosmos where man is to live, as proposed by Filarete (1400-1465). Numerous sixteenth century theories adopted this design to plan the “ideal city”.

In the same manner as Plato, the urban planner was fascinated by the correspondence of the macrocosm to the world created by man. Through the use of geometry and Pythagorean ratios, he defined a new universal concept of a “cosmos in the measure of man” and an “anthropomorphic microcosmos”, represented in various anthropomorphic diagrams (*Homo ad Circulum* and *Homo ad Quadratum*). Both converge in the theory of a space that can be defined in terms of a series of logical measurements, ordered according to precise laws of arithmetic and geometry [Muratore 1975: 30-31]. Based on the Platonic concept of a unified cosmos and a centralised vision of the *Orbe Circolare*, ideal cities were conceived as microscopic organisms, dominated by the desire to define through their design the objective laws that regulate beauty and coincide with the structure of the cosmos, representing a mental ideal rationalised by the laws of proportion, symmetry, centrality and perspective.

Geometry was adopted as a conceptual support for the idea of urban space and the investigation of the laws of the cosmos. It had a profound influence on the Western world through its construction of formal regulatory models that employed the most basic Euclidean shapes (the circle, the triangle and the square), drawn with straightedge (ruler without marked divisions) and compass.

Fig. 6. Euclidean geometry based on António Rodrigues, *Tratado de Arquitectura* (1576)
(drawing by the author)

In Portugal these relationships, fundamental to the urban planners' framework of thought and to the genesis of the logic of urban models used in the colonisation of new territories, are revealed in the treatises of the cosmographer Pedro Nunes and the architect António Rodrigues. For Pedro Nunes,

The sphere according to Euclid is a body that is caused by the movement of its circumference... . For the sky being rounded there are three reasons. Similitude, utility and necessity. By similitude it can be proved that the sky is rounded because this tangible world is made in the likeness of the archetypal world: in which there is no beginning and no end. And for that reason the tangible world has a rounded shape: in which there is no beginning and no end. Utility because of all the bodies and perimeters the sphere is the greatest; and of all the shapes, the rounded is the most capable. ... Necessity is because if the world had another shape ... some place would be empty... [Nunes 2002: vol. 1, 7-10].

For António Rodrigues, being an expert in geometry is an essential condition for the urban planner, for

Geometry is none other than shapes, which cannot be made without lines, angles and points. The principle of this art has been explained, and we shall

review it here by explaining its elements, and we shall deal with the shapes that for this treatise are necessary with an explanation of each one and what they serve for. As for this Geometry, it will be seen that nothing can be done without it, nor can the art of mathematics be properly understood by one who takes pleasure in it, without being an expert in Geometry. Therefore, in this treatise we shall not deal further with those shapes that are necessary, with their explanations and how they operate. Who is curious about this art should study Euclid ... [Rodrigues 1576].

Based on definitions of “what is geometry”, the Portuguese architect presents a series of fundamental “propositions” for practical geometry in order to “sketch” and “proportion” fortifications, settlements and buildings (fig. 6).

António Rodrigues, who studied in Italy (1560-1564), was a critical reader of concepts formulated from the understanding of classical language and expressed as a theory compatible with neo-Platonic humanism. He organised the principles of an erudite, classical discourse, submitting them to composition controlled by reason and geometrical precision [Tavares 2007: 34]. He dedicated his life to the exercise of his profession, between practical planning and mathematical reflection. From his Italian apprenticeship he inherited theoretical knowledge of classical and military architecture and, from Pedro Nunes, tradition and love for science, raising architecture to the category of an exact science.

The role of the “architect” and of “Italian-inspired civilian and military architecture” became firmly established in Portugal in the sixteenth century [Bueno 2003: ch. 3]. The treatise of António Rodrigues is one of the examples of this, and of the spread of the theories of Vitruvius and Cataneo, which the Portuguese architect copied in order to form his own personal doctrine, in the style of those who copied each other successively in the effort to construct a logical and collective discourse. It was in this way that the Portuguese treatise used certain arguments common to the texts that were used as a model for the training of urban planners. These included the employment of regular methods in the composition of form, or rather, of proportion, symmetry and harmony, achieved by controlling the compositional phases of the “plan”, which was understood to be a pure exercise in geometry.

The Portuguese treatise reveals a strong classical component of Vitruvian origins. In other words, geometry is applied to the *Compositio* (composition) of buildings and cities and, as Vitruvius wrote,

rests on *Symmetria* (commensurability), a principle that architects should submit to with great care. Commensurability is born of *Proportio* (proportion)... . Proportion consists of the *Commodulatio* (modular) ratio of a certain *Rata pars* (part) of the elements in each section or the whole of the design, on which basis the system of commensurabilities is defined [Vitruvius, I. 2. 2] (fig. 7).

In relation to Pietro Cataneo (15??-1569), if it is unlikely that António Rodrigues was influenced by his *Quattro Libri dell'Architettura* (1554) during the initial period of his professional activity in Portugal, this influence became clearer later on, in the organisation of his manuscripts for lessons at the Paço School. Of particular importance is the consideration of the quality and hygiene of sites chosen for building cities and houses, as

well as the quality of materials and the conditions necessary for the good *fábrica* of houses and forts [Tavares 2007: 95]. This influence strengthened the ability of the *Paço* School to train specialists in the construction of fortifications. Indeed, Pietro Cataneo describes the construction and fortification of cities even before dealing with orders of columns and other architectural topics. Fortified cities are ideal solutions based on geometrical shapes and the precise organisation of roads for circulation (figs. 8, 9). They recall the ideas of Filarete and the schematic city designs of Francesco di Giorgio.

Fig. 7. Sphere of solar quadrant, from Vitruvius, *Architettura con il suo commento...raportato per M. Giambattista Caporali di Perugia* (1536)

Fig. 8. Ideal city by Pietro Cataneo From Pietro Cataneo, *Quattro Libri del Architettura* (1554)

Fig. 9. Plan of Damão, a Portuguese settlement in India. Arquivo Histórico Ultramarino, Lisbon

Fig. 10. Geometrical design and composition in a Portuguese approach to urban layout (drawing by the author)

The treatise of António Rodrigues proves that there was a clear investment by the realm in the training of noblemen destined to spearhead the designs of expansion, as well as professionals to plan and adapt geometrical models to various contexts (fig. 10). Although we cannot be certain that this Portuguese architect designed any particular urban space, his formal repertoires are recognisable in the cities of the Portuguese colonies, as the genesis of the logic of urban planning. Examples include the cities of Damão (fig. 9) and Baçaim in 1589.

The fortifications of these cities are regular, with bulwarks and a grid-like plan, based around a central square. Other cities started to show more regular grids with wider streets, such as Cochim, designed by Júlio Simão (Chief Engineer of India from 1598), Chaul, Nepatão, S. Tomé de Meliapor and Solor, among many other Portuguese cities. During a fifty-year period all the fortresses were remodeled, which indicates a policy not only of commerce, but also of territorial conquest [Teixeira & Valla 1999: 133].

Conclusion

We can conclude that in the sixteenth century the Portuguese Crown, like its European counterparts, set about creating the conditions for the training of specialised professionals, with the aim of dominating their territories according to pre-defined objectives. This training was based on knowledge of cosmography, practical geometry, astronomy and arithmetic, both theoretical and practical, articulated with the construction of models based

on Euclid and Vitruvius, which were fundamental to the Portuguese urban planners' framework of thought.

It would be this framework that would establish geometrical matrices for structuring space, in the act of thinking, planning and building in new lands, demonstrating how geometry brought together the various fields of knowledge that formed the basis of Portuguese urban planning.

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