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The Design Process and the Building Site: Leonardo da Vinci at Milan Cathedral as a Case Study

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The involvement of Leonardo da Vinci (1452–1519) in the competition for the design of the dome (*tiburio*) of Milan Cathedral in 1487 offers a window onto many aspects of architectural practice and management in the early modern period. It allows us to investigate several features of the building-site administration, the design process, and the complex decision-making processes of several large Italian building projects. Many written sources document the construction of the dome of Milan Cathedral, primarily administrative notes and book accounts. Only through a detailed aggregation and analysis of those data, given the long history of the building, can those aspects be philologically reconstructed. Up to now, the sources related to Leonardo's involvement with the Milan dome have been analysed mainly for his ideas on architecture and to exalt his exceptionality, which has isolated the artist from his own time and his project from its background. This article re-reads this case study of the 1487 competition for the dome in the context of the cathedral's entire building history, to point out different aspects of architectural and management habits of early modern building projects, together with aspects of Leonardo's design process.

Keywords: architectural competitions; architectural drawings; building site; design process; Leonardo da Vinci; Milan Cathedral

Introduction

Many aspects of architectural practice and management in the early modern period can be inferred from an evaluation of the involvement of Leonardo da Vinci (1452–1519) in the competition, in 1487, for the design of the *tiburio*, the specific type of dome at the crossing of Milan Cathedral (**Figures** 1 and **2**). This episode allows us to focus on features of the building-site administration, the design process, and the complex decision-making process of many great Italian projects of the early modern period, but with a long tradition since the Middle Ages.[1] This article will also examine aspects of the design process, such as Leonardo's knowledge of the cathedral's building site; its prolonged construction over centuries, from 1386 until the 19th century; the drawing techniques (*spolvero*, scale unit, calculation); the wood modelling employed by the architect; and his knowledge of materials and construction techniques.

The erection of the dome of Milan Cathedral is documented in many written sources, most of which have been published, especially in the nine volumes of the *Annali della Fabbrica del Duomo di Milano dall'origine fino al presente*, printed between 1877 and 1885 and then enriched, and in some cases revised, in several publications produced over the next century and a half. These written sources consist mainly of administrative notes and book accounts, both containing lists of data with very synthetic explanations. With a detailed aggregation and analysis of these data, which also consider the long history of the building, its design and decision-making processes can be reconstructed. Moreover, sources about Leonardo's involvement in this episode have been mainly used until now for exploring the author's ideas on architecture and exalting his outstanding skills, finally detaching him from his own time and his project from the context. Leonardo, in fact, is often considered an artist apart, a *unicum* isolated in his greatness from his contemporaries (Borgo, Maffeis and Nova 2019).

A re-reading of the competition for the dome of the Milan Cathedral in the context of the cathedral's entire building history is presented here as a case study to illustrate different aspects of architectural practice and management of large building projects of the early modern period, together with some operative elements of Leonardo's architectural activity. The intent is not to illustrate all the previous interpretations of Leonardo's project for the lantern nor to analyse the extensive existing bibliography on these reconstructive hypotheses, elsewhere presented by the author. Rather, in addition to presenting a new hypothesis, it investigates the architect's involvement in this project to better understand features and practices of the architectural (and building-site) world of his time, drawing attention to the building 'process'.

Figure 1: Giacomo Brogi (1822–1881), *Milano. La cattedrale* [Milan. The cathedral], ca. 1870. Catalogue no. 3818. View of the façade and right side of the cathedral.

Figure 2: Giacomo Brogi (1822–1881), *Milano. Panorama dal campanile della Chiesa di San Carlo* [Milan. View from the belltower of the church of San Carlo], ca. 1870. Catalogue no. 5903. The highest point is the cathedral's *tiburio*.

The Competition

From the beginning of the cathedral's construction in 1386, the deputies of the Veneranda Fabbrica del Duomo di Milano (Veneranda Fabbrica), the administrative body that oversaw the building's construction and subsequent maintenance, called upon the very best designers for such an ambitious project. Over the years, this body appointed numerous architects from all over Europe, formed many commissions, and launched several competitions for the design and the construction of both the entire cathedral and its different parts and details, such as the elevation of the building and the design of the large capitals of the nave at the end of fourteenth century, or the dome at the end of fifteenth century. This consolidated system, which included numerous meetings and consultations with experts and took place almost continuously throughout the history of the building, undoubtedly slowed down the decision-making process. However, this system was a widely used *modus operandi* for the control of such complex enterprises, not at all improvised (Ceriani Sebregondi and Schofield 2016: 82–84).

The competition of 1487 for the design of the *tiburio*, the dome at the crossing of the cathedral, was no exception. It was here that Leonardo's involvement in the project began, taking part in the competition with Donato Bramante, Luca Fancelli, Francesco di Giorgio Martini, and many Lombard architects, such as Giovanni Antonio Amadeo, Giovanni Battagio, Gian Giacomo Dolcebuono, Pietro da Gorgonzola, Marco Leguterio, Giovanni da Molteno, the priest-architect Simone Sirtori, and Antonio da Pandino, and also a German, Giovanni Mayer (Hans Mayer, from Graz). Leonardo was thus one of the many consulted architects on the project; he never had a permanent position on the Cathedral's building site.

In Leonardo's famous letter of 1485–1486 to Ludovico Sforza, called il Moro, the regent of the duchy of Milan, Leonardo celebrates his own expertise as a (military) engineer and architect.[2] However, the competition for the *tiburio*, which took place five years after his arrival in Milan in 1482, was actually Leonardo's first direct experience as an architect. In fact, he is never called 'ingeniarius' (architect) in the documents about the *tiburio*; Leonardo differs from Bramante, whose experience and prestige were recognised in the architectural field.

First, Study

What were Leonardo's preliminary steps in approaching the design of the *tiburio*?

We have some evidence that demonstrates how, armed with curiosity, Leonardo collected information to become familiar with the building site, its previous history, and the proposals of other masters involved in the competition. His use of sheets from old accounting books shows that he had close contacts with the administrative body of the cathedral in those years. There are many examples of his reuse of sheets from old accounting books of the Veneranda Fabbrica, such as the fragments Windsor 12476v with a drawing of an old man, dated about 1487, which was part of *Codex Atlanticus*, f. 37v.[3]

We have also the initial paragraph of a Leonardo's letter about the *tiburio*. This was intended to accompany his own wooden model, begun in July 1487 and probably completed in January 1488, and thus can be dated to January 1488.[4] The letter testifies to his knowledge of the first project of Milan Cathedral, elaborated a hundred years earlier by Gabriele Stornaloco in 1391. In this document, in fact, he refers to the 'invention by the first architect of the cathedral' and 'what his intention was'. Unfortunately, the text is rather vague and does not allow us to understand how his project may have 'corresponded' and 'conformed' to the 'building already initiated'.[5]

Leonardo's presence on or around the building site is also testified by several drawings in his manuscripts. On folio 10v of the Paris *Manuscript B* (**Figure 3**), Leonardo famously sketches eight schemata for vaults (Marinoni 1990: 16). In reality, these are drawings of ceilings with lowered vaults for *rooms* ('the reason [ratio] of a vault, that is, one third of the diameter of the room'),[6] which probably were conceived as being made of timber. They are accompanied by a second annotation that reads 'del Tedesco in Domo' ('of the German in the Cathedral'). The sheet has been discussed by scholars, who generally understand this last annotation to be a reference to drawings intended for the cathedral's design by a German person,[7] but I speculate that it could simply refer to someone merely *working* at the cathedral. In other words, a German — perhaps Mayer[8] — may have shown some of his drawings to Leonardo, which he then copied or re-elaborated in his notebook. Other contacts with architects involved in the competition are suggested by Leonardo's schemes for the *tiburio* in folios 12r (**Figure 4**) and 27v of *Codex Trivulzianus*. These drawings illustrate an octagonal dome with eight radial flying buttresses over the roof of the church, the same solution adopted by Amadeo. It is very possible that Leonardo was taking note of this interesting solution, which was also praised by Bramante in his *Opinio* as particularly suitable for the stability of the dome (Ceriani Sebregondi 2019b: 141–142). When Leonardo later became interested in hydraulics, in the early 1490s, he undertook a similar process, studying first the solutions of local masters (Galluzzi 1987: 72). Other evidence of Leonardo's eagerness to learn from more expert masters may be found in the well-known episode when Francesco di Giorgio Martini was asked to consult about the Pavia Cathedral design in 1490. *Leonardo* asked to accompany him, a request that indicates they were not equals.[9] The fact that Leonardo was allowed to study the proposals of other masters involved in the Milan competition, already presented to the Veneranda Fabbrica and probably kept at the building site, again suggests that he was in close contact with the administrative body of the cathedral.

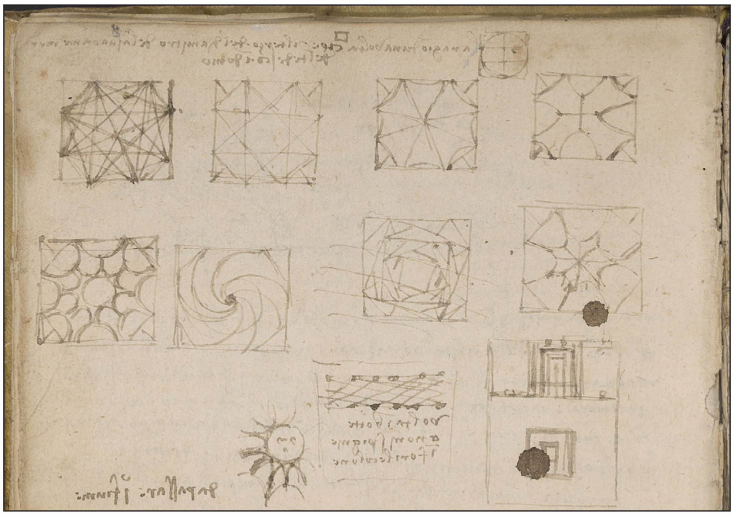

Figure 3: Paris, Institut de France, Leonardo da Vinci, *Manuscript B*, f. 10v (MS 2173), detail. © RMN-Grand Palais-Institut de France.

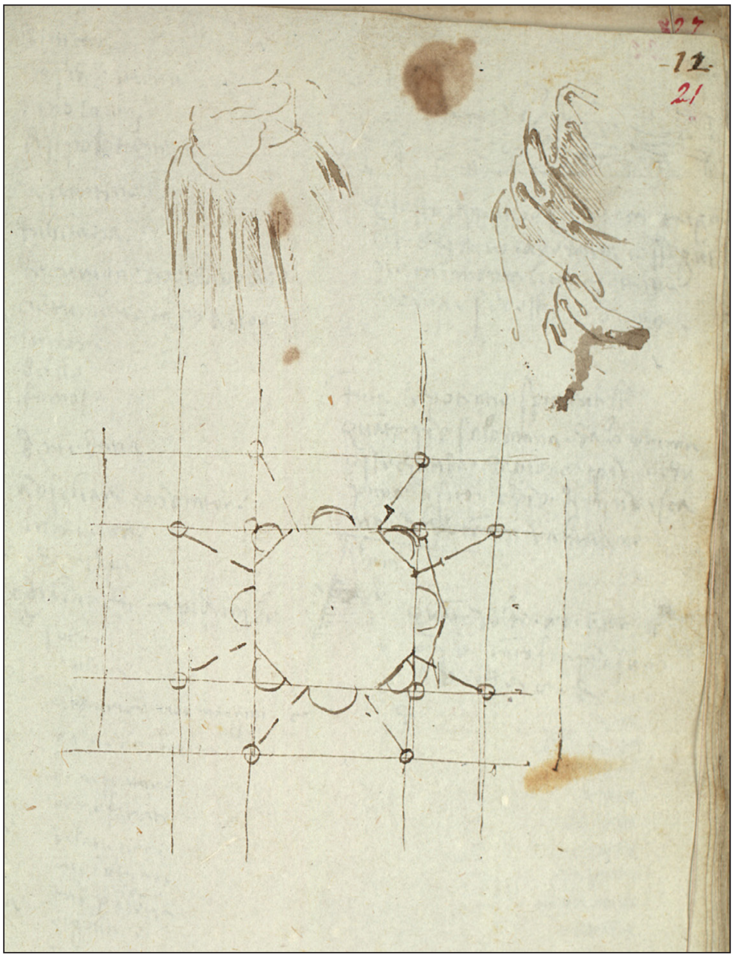

Figure 4: Milan, Archivio Storico civico di Milano, Biblioteca Trivulziana, Leonardo da Vinci, *Codex Trivulzianus*, f. 12r (p. 21) (codice Trivulziano 2162), detail. © Comune di Milano – all rights reserved.

First Sketches

By carefully studying Leonardo’s drawings, we can also understand how he began the design process. Several of his manuscript codices contain quickly traced drawings for numerous possible design solutions for the *tiburio*. They include circular domes, Brunelleschian double shell domes, octagonal domes with and without niches or with and without buttresses, with a square base, and so on. His design ideas can be found in *Codex Trivulzianus*, folios 8r (**Figure 5**) and 27v; *Codex Atlanticus*, folios 719r and 818r; and Paris *Manuscript B*, folios 3r and 27r. It is likely that other drawings for the project, perhaps on loose sheets and larger than those on the mentioned notebooks, have been lost; by the time he built his wooden model in July 1487, Leonardo would certainly have prepared several detailed drawings.

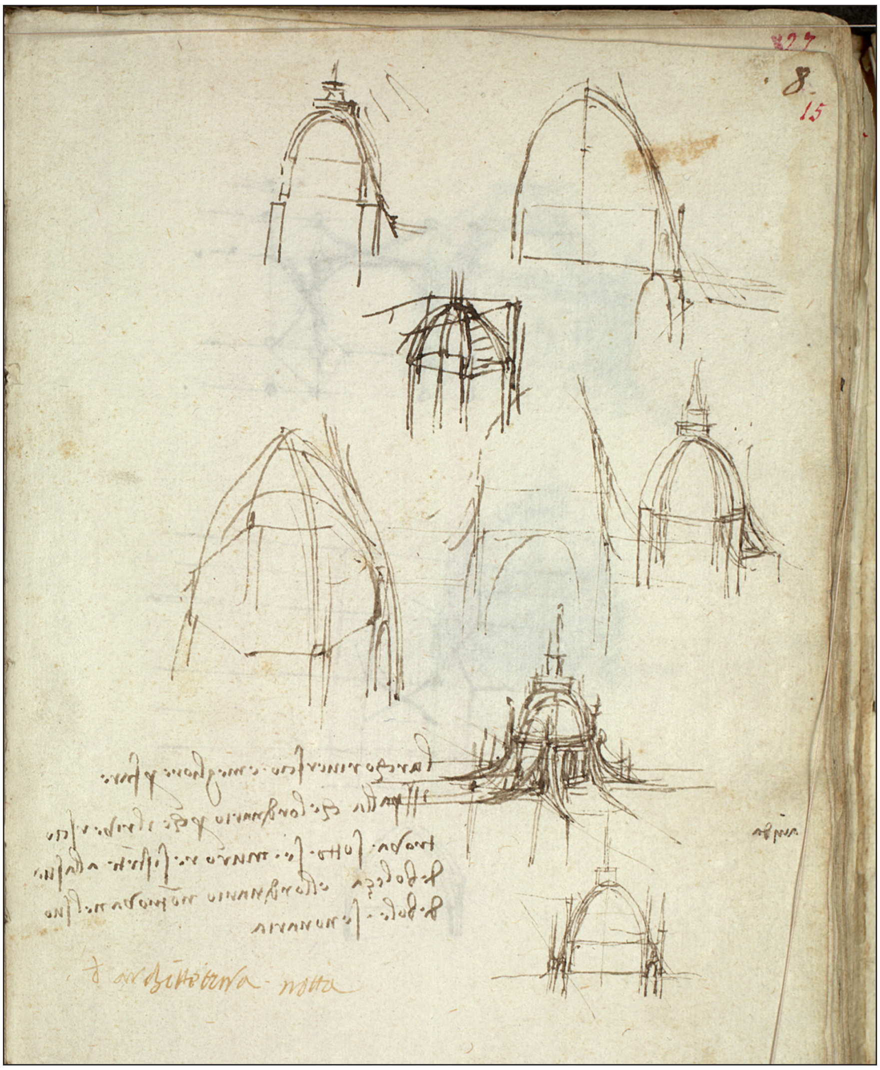

Figure 5: Milan, Archivio Storico civico di Milano, Biblioteca Trivulziana, Leonardo da Vinci, *Codex Trivulzianus*, f. 8r (p. 15) (codice Trivulziano 2162), detail. © Comune di Milano – all rights reserved.

Scrolling through the pages of Leonardo's very small format notebooks, one can discover many extremely tiny and schematic plans of the dome, executed quickly with single strokes to represent walls and buttresses. Their variety suggests that the artist was experimenting simultaneously with very different types of solutions, probably still at the beginning of the design process. It is even possible that they date to before he entered the competition, perhaps late 1486, when the German chief architect Giovanni Nexemperger (Hans Nexemperger, from Graz) left both the building site and Milan (see Repishti and Schofield 2019b: 106–24), leaving open the problem of the *tiburio*.

Wooden Models

Once the Veneranda Fabbrica had entrusted the project to the several architects involved in the competition, it funded the creation of wooden models of their different proposals. This was a standard procedure in the great Italian building projects of the early modern period, part of a long tradition that goes back to the Middle Ages. As in a two-stage design competition of today, the committee would have chosen the definitive models from among the many proposals. These would have then been compared, analysed, discussed, and reviewed. This process was also followed at the cathedral, for instance, with Stornaloco and Giovannino de Grassi at the end of fifteenth century, with Filarete in the 1450s, and Nexemperger in the 1480s.[10] Wooden models were also made for the *tiburio* competition and are recorded in the administrative papers of the cathedral, along with the expenses they entailed. Models are also mentioned in Bramante's *Opinio*, which can be dated to the first half of 1487 (Ceriani Sebregondi 2019b: 137–138). In total, we have mentions of models for the *tiburio* by Leonardo (30 July 1487–11 January 1488); Bramante (begun 1 September 1487, and carried out by Daniele Visconti and Santo Ambrogio da Lonate); Pietro da Gorgonzola (1487–May 1488), Mayer (14 May 1488–11 April 1489); and Amadeo, Sirtori, Pandino and Giovanni da Molteno (without dates). Fancelli, too, presumably made a model, but at his own expense (between 7 March and 22 December 1487).

Leonardo's model was carried out by the *magister a lignamine* (carpenter) Bernardino da Abbiate, also called de Madiis, and his associate, and it cost about 138 *lire* in total, paid from 30 July 1487 to 11 January 1488.[11] This was a substantial sum if one considers that Nexemperger was paid 288 *lire* (180 golden florins) per year as head engineer of the cathedral in 1483,[12] and Fancelli was paid 330 *lire* for a stay in Milan of almost ten months in 1487.[13] Unfortunately, we do not know anything about this model's appearance. However, it is clear that none of the quick and small sketches in Leonardo's above-mentioned notebooks could have provided a carpenter with sufficient information to make a model.

Two Detailed Drawings

The well-known and enigmatic drawing in folio 850r of *Codex Atlanticus*, and its precedent f. 851r, are the only detailed iconographic documents related to this commission that survive (**Figures 6** and **7**).[14] They show the dome in an almost orthogonal cross-section, albeit with distortions and inaccuracies of projection, as also noted by other scholars.[15] Until now, the drawings have been related to the construction of the wooden model and dated to the beginning of the design process.[16] However, I argue that they can hardly have been completed before or in connection with the construction of the model, because they represent details and joints between stone blocks that are concealed in the walls and would not make sense as instructions for fabricating a wooden model. In my view, the execution of the two drawings most likely post-dates the model, and they are presumably linked to static and structural engineering considerations conducted after or parallel to the construction of the model, as we will see.

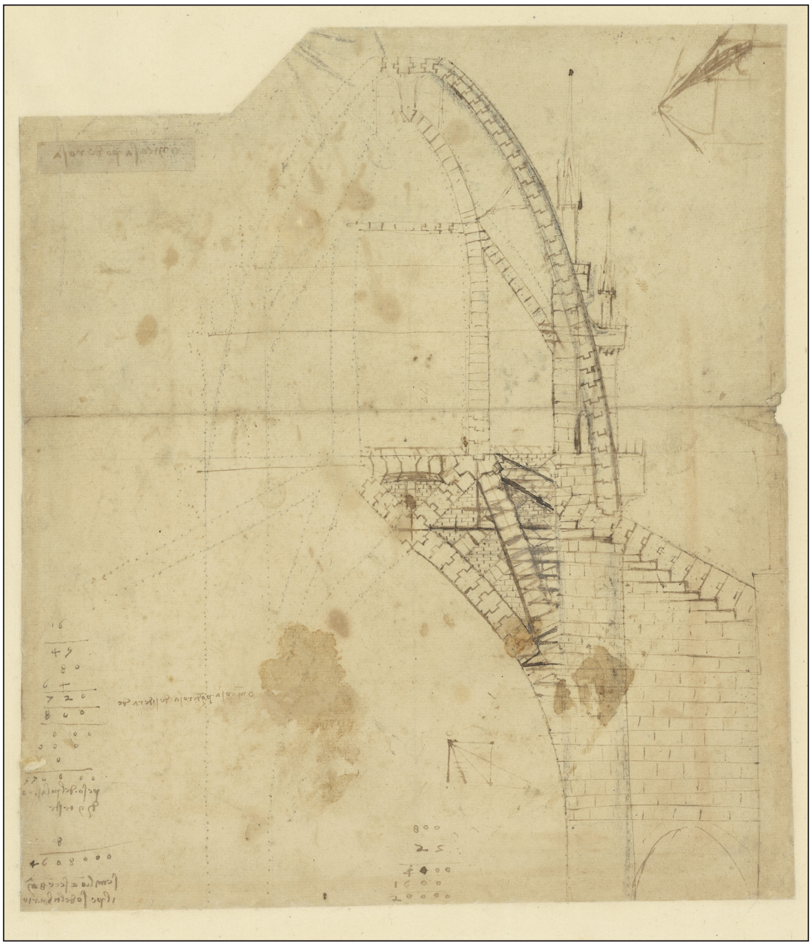

Figure 6: Milan, Biblioteca Ambrosiana, Leonardo da Vinci, *Codex Atlanticus*, f. 850r (CA f. 850r). ©Veneranda Biblioteca Ambrosiana/Metis e Mida.

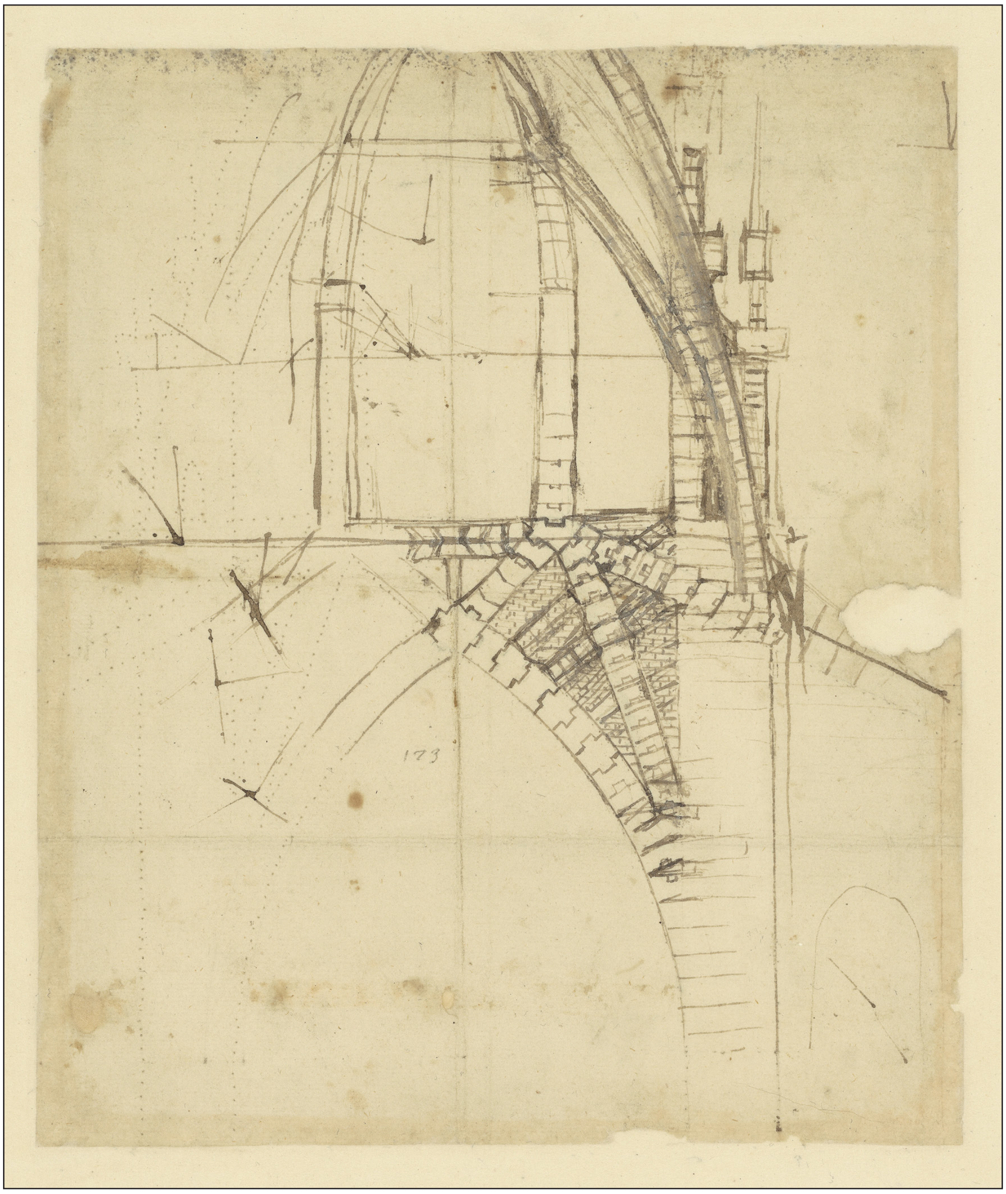

Figure 7: Milan, Biblioteca Ambrosiana, Leonardo da Vinci, *Codex Atlanticus*, f. 851r (CA f. 851r). ©Veneranda Biblioteca Ambrosiana/Metis e Mida.

Leonardo's mastery in drawing and representational systems is well known. In addition to the impeccable perspective of his paintings, he developed conventions for scientific drawings that are still in use today, such as the 'exploded' view for machine illustrations, working on a 'progressive definition of a specific method of representation technique' that he would master by the early 1490s (Galluzzi 1987: 95).

Scholars have often stressed that Leonardo's studies of statics and architecture should be evaluated in conjunction with his astonishing anatomical studies.[17] Therefore, it seems curious that a vertical section in orthogonal projection — incidentally, the only orthogonal section in the whole of Leonardo's architectural drawing *corpus* (Schofield 1991: 132)[18] — seems to have created so many issues about representation for him.[19] At the same time, we must not forget that an orthogonal representation in architectural drawings, in particular for elevations and sections, which Raphael would eventually define in his letter to Pope Leo X, dated to 1519, was not yet common.[20] Indeed, this problem of representation has raised some doubts about the authorship of the drawing. In 1915, commenting on the *Codex Atlanticus*, f. 851r (but this also applies to the *Codex Atlanticus*, f. 850r), just Francesco Malaguzzi Valeri admitted that, 'to tell the truth, it does not seem to speak in favour of Leonardo architect', that it reveals 'a lack of spontaneity to almost leave suspect that the drawing is not his' (Malaguzzi Valeri 1915: 434).

The two drawings, 851r and 850r, successive copies made using the *spolvero* technique,[21] have the same scale, which has a precise relationship to the existing building.[22] Taking the width of the great arch of the crossing under the *tiburio* as a reference — the only element represented in the drawing existing at the time comparable with the actual building — the scale corresponds to the ratio of 1:144. Although this proportion may appear abstruse in decimal terms, according to the Milanese duodecimal unit system, it corresponds to a precise and practical ratio of 1 *punto* (point) = 1 *braccio* (arm), where the *punto* is 1/12 of an *oncia* (ounce), which is 1/12 of the *braccio*.

Given the characteristics of the drawings, it is possible that a collaborator executed both of them and these were then modified, corrected, and annotated by Leonardo. Unfortunately, even in this case information about possible collaborators is scarce. Apart from the carpenter Bernardino da Abbiate, who made the wooden model, we know nothing about Leonardo's pupils or collaborators at the cathedral or in his workshop during the period of the dome commission.[23] In addition, only a couple of cases have been identified in which Leonardo intervened in the work of possible pupils: for instance, in the *Codex Atlanticus*, folio 399v, his writing is adjacent to a female head in profile by another unsure hand, while folios 692r–v contain arithmetic operations, namely divisions, not all by Leonardo's hand, and only two of the nine are correct.

Since the late 1970s, most scholarship has maintained that these drawings represent a project consisting of a double shell with a squared dome on the outside (*a padiglione*) and an octagonal inner dome.[24] This hypothesis could be read as a combination of two earlier proposals: a square-shaped *tiburio*, similar to that conceived in the 1390s, and an octagonal dome, like the one built by Guiniforte Solari in the 1470s, subsequently demolished (**Figures 8** and **9**).[25] This interpretation of the two drawings, however, is by no means certain. In fact, the drawings' distortions and inaccuracies in the representation of a three-dimensional architectural organism do not allow us to understand the structure that Leonardo had in mind. Building on the available data, we can, however, make some suppositions and propose a different hypothesis.

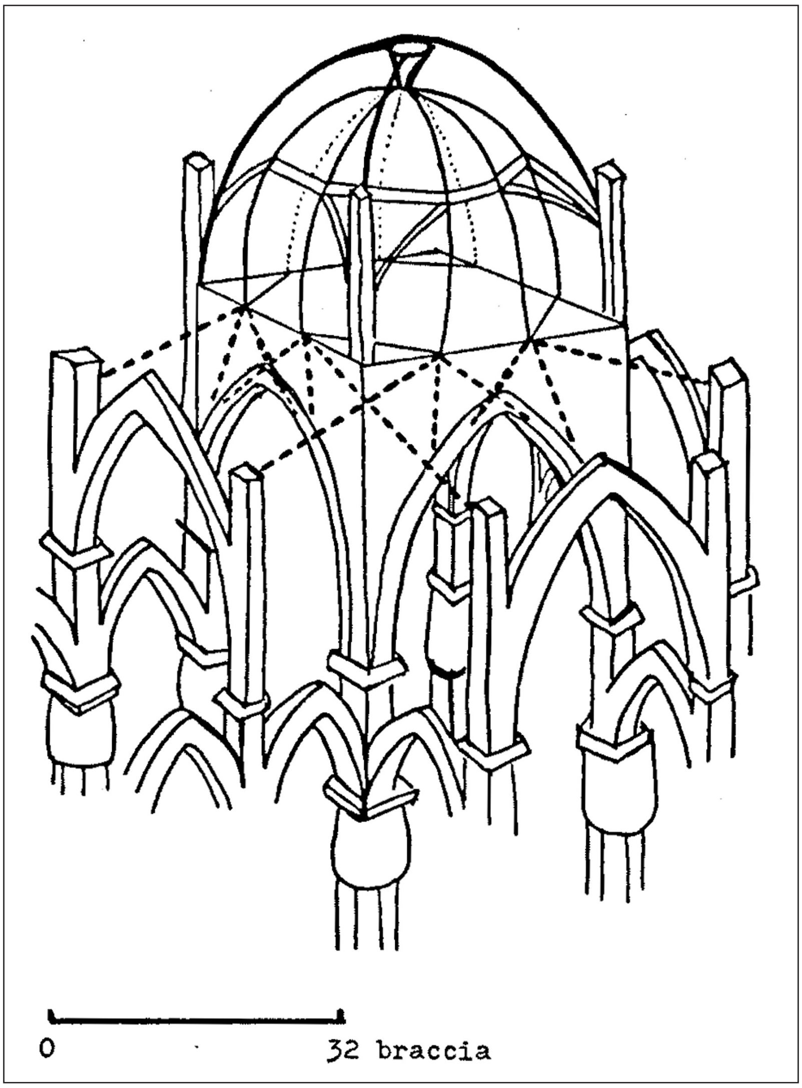

Figure 8: Reconstructive hypothesis of Leonardo da Vinci's project for the dome of Milan Cathedral according to Frances Fergusson (Fergusson 1977: 188).

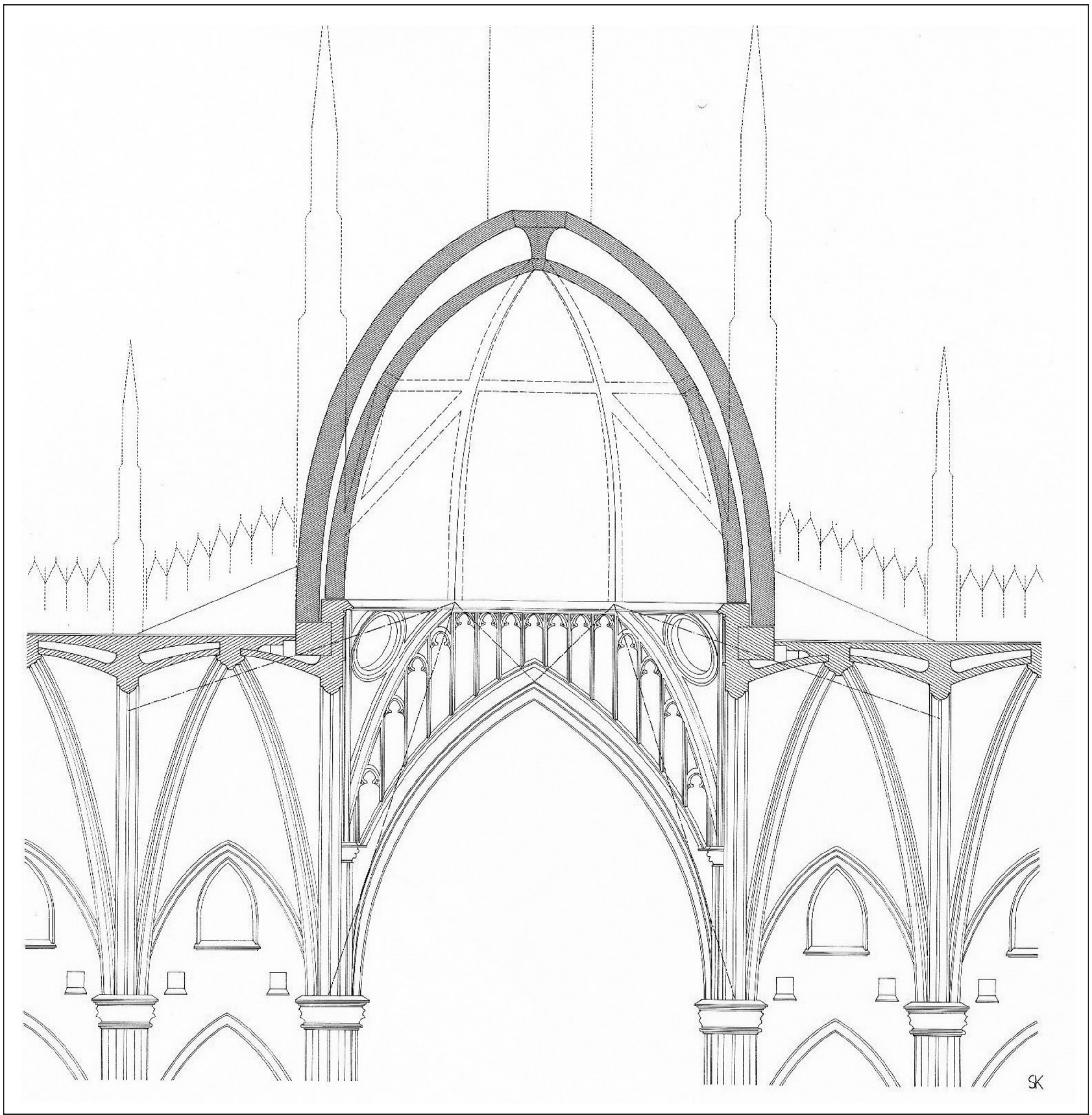

Figure 9: Reconstructive hypothesis of Leonardo da Vinci's project for the dome of Milan Cathedral according to Jean Guillaume (Guillaume 1987: 218).

The solution on which Leonardo dwells the most and reproposes many times in his sketches is a dome with a shape similar to Brunelleschi's structure for Santa Maria del Fiore in Florence: a raised, ribbed dome with a double shell on an octagonal plan.[26] Other elements point in the same direction. We know that Brunelleschi's influence on Leonardo's technical and mechanical training was fundamental.[27] The same was likely true in his architectural and engineering beginnings.[28]

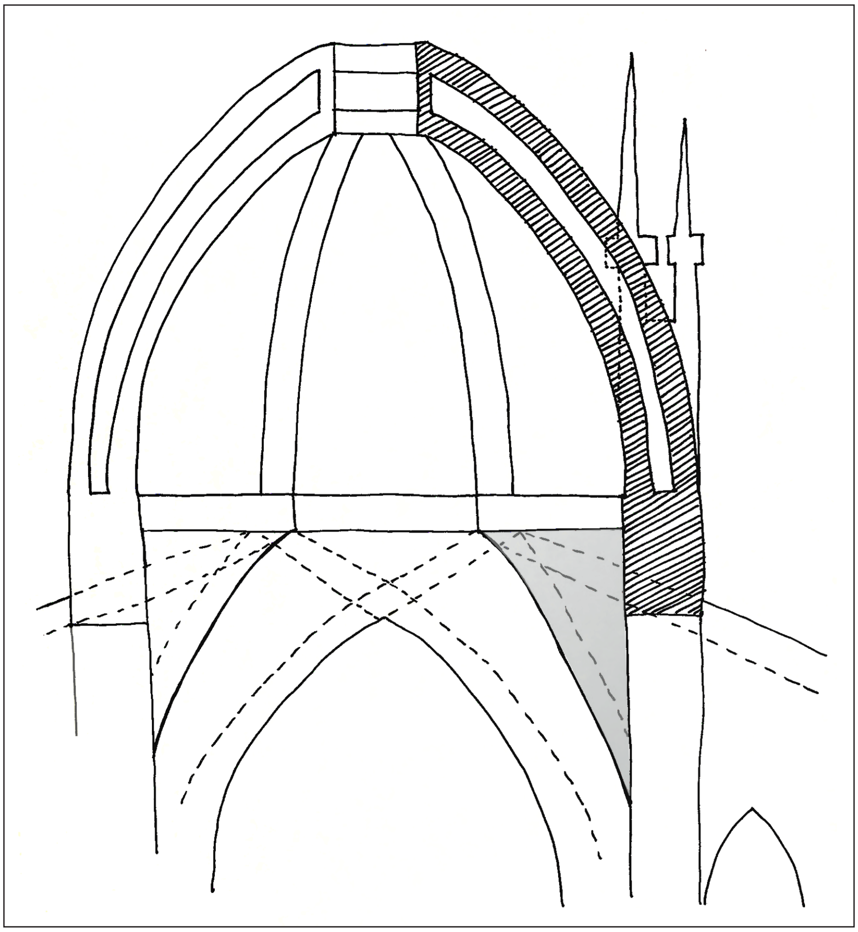

Figure 10: Reconstructive hypothesis of Leonardo da Vinci's project for the dome of Milan Cathedral according to the author.

The history of the Milan Cathedral, too, suggests this interpretation of Leonardo's proposal. The Veneranda Fabbrica had determined that the cathedral should have an octagonal dome structure as early as the 1460s, under the oversight of Guiniforte Solari, and it is unlikely that this goal changed; only proposals engaging octagonal solutions appear to have been considered. After initially celebrating the idea of a squared *tiburio* for this cathedral, Bramante changed course as well. In his *Opinio*, he decided in the end to follow the Lombard tradition by proposing an octagonal dome, stabilised by radial external flying buttresses (Ceriani Sebregondi 2019c: 153–55). The configuration of a dome of this type (octagonal double shell) is, in my view, more likely if compared to Leonardo's training and to the history of the Duomo (**Figure 10**).

Moving to the final stages of the competition, we know that several dignitaries took part at the great plenary meeting of 27 June 1490, when the final project was approved in the official final report on the *tiburio*: Ludovico Sforza, the deputies of the Veneranda Fabbrica, members of the duke's council, the architects involved, as well as an external expert architect (who remains unknown). The authorities ultimately rejected Leonardo's proposal, together with those of many other participants, Bramante and Fancelli included. Only Amadeo (this time alongside Dolcebuono), Sirtori, Battagio (a new competitor), and Francesco di Giorgio (who entered the competition directly now, as an expert) passed to the second stage of the competition. The winners of the commission were eventually Amadeo and Dolcebuono, two architects deeply familiar with the cathedral and its history. They were familiar with the building site and entirely capable of constructing a traditional Lombard octagonal *tiburio*, as was the intention of the Veneranda Fabbrica, at least since the 1460s.

Then, Theorising

Although Leonardo did not pass even the first round of the competition, the experience was galvanising for him, on both practical and intellectual grounds. The collaboration with other experts and the focus on technical aspects related to architecture prompted his continuing and abiding interest over the following years in the principles of statics. This curiosity about theorising general statics and engineering assumptions was already evident in the aforementioned letter that was intended to accompany his wooden model for the Milan Cathedral. In this note, Leonardo did not describe the project but rather wrote that it was necessary for the architect to know 'the rules from which a correct building derives and where those rules came from' and 'the reasons that make the building endure, and the nature of the weight, and the will of the force, and the way in which they have to be woven and connected together'.[29] Armed with these principles, his intention was to 'demonstrate first the load, and the many reasons for which and how buildings fall, and the means of their stability and durability'.[30] As Arnaldo Bruschi has argued, the dome competition provided Leonardo with the opportunity to develop a 'theory on statics' and general principles of structural mechanics, based on weights and forces, as well as to identify how which forces act on a structure (Bruschi 1978: 335–37, 343).

Stimulated by this experience, he continued to reflect on the issues raised by the *tiburio* competition even after the project had been entrusted to Amadeo and Dolcebuono. After 1490, in fact, Leonardo began to concentrate his research on mechanics, identifying four 'powers' through which to read the phenomena of nature: movement, weight, strength, and percussion (Galluzzi 1987: 45, 74, 94–95).[31] A drawing in the *Codex Forster II*, f. 93r, for example, is likely related to the reflections prompted by the construction of the dome of Milan Cathedral (**Figure 11**). He annotates it with these words: 'Principle. Here is shown how the arches made on the sides of the octagon push the pillars in the corners outwards, as it is demonstrated in the line HC and in the line TD, which push the pillar M outwards. That is, they strive to drive it away from the centre of the octagon'.[32] Meanwhile, in the Madrid *Codex I*, folio 139r, is another attempt to generalise the problem of the load on crossed, pointed arches (**Figure 12**).

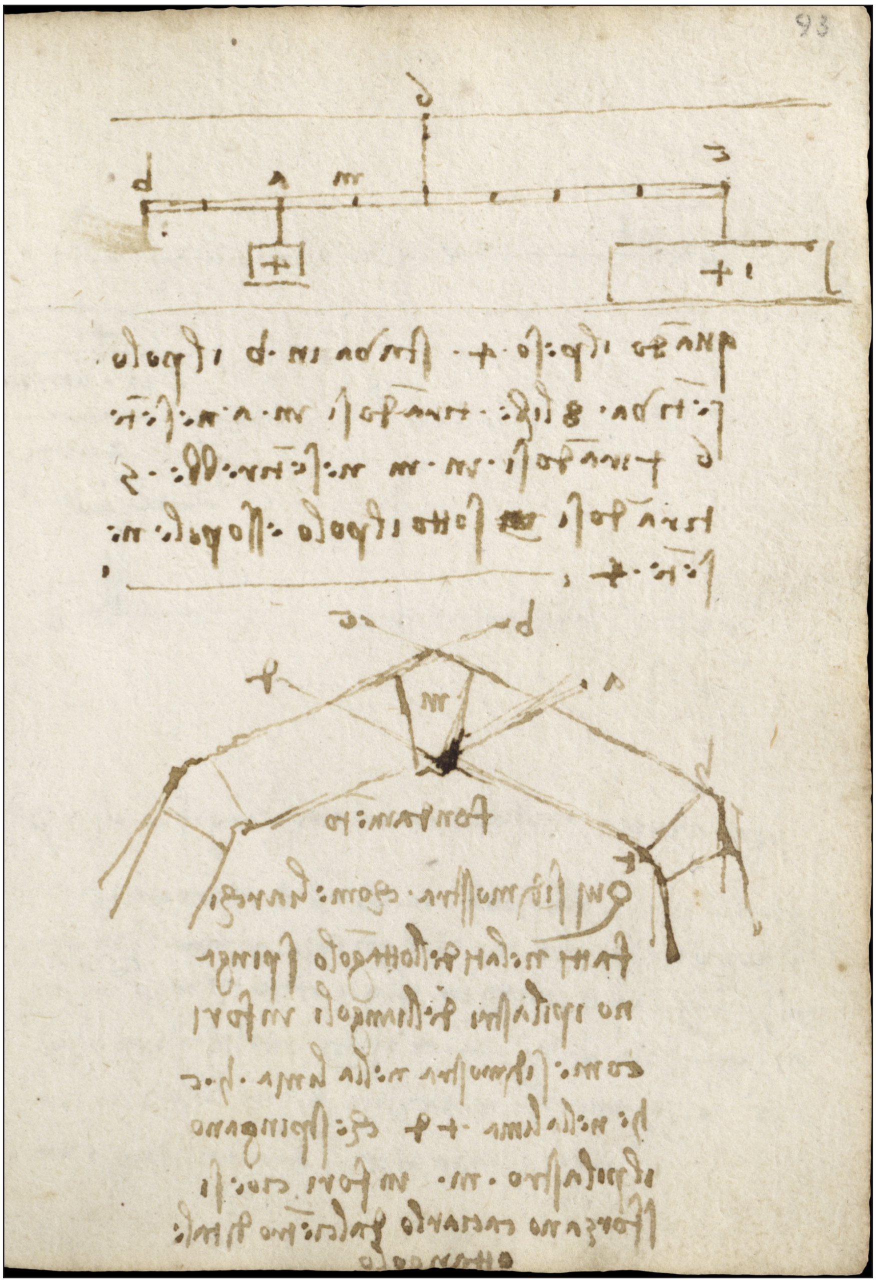

Figure 11: London, Victoria and Albert Museum, Leonardo da Vinci, *Codex Forster II*, f. 93r. (MSL/1876/Forster/141/II). © Victoria and Albert Museum, London.

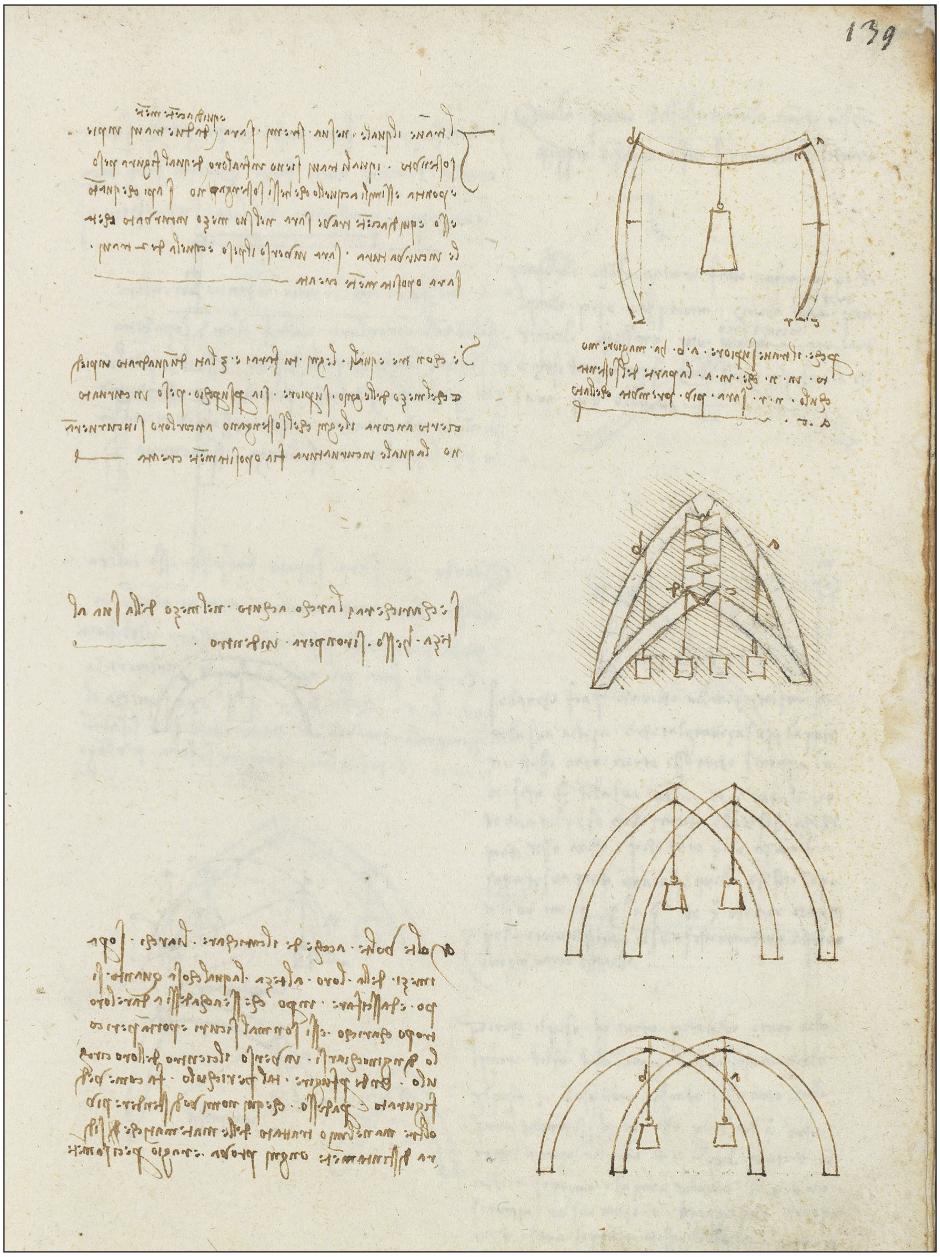

Figure 12: Madrid, Biblioteca Nacional de España, Leonardo da Vinci, *Madrid Codex I*, f. 139r (MSS/8937). © Biblioteca Nacional de España.

For Leonardo, however, 'wisdom is the daughter of the experience' ('la sapienzia è figliola dela sperienzia', from *Codex Forster III*, f. 14r) — knowledge derives from an actual case study and direct experience. Returning to *Codex Atlanticus*, f. 850r (**Figure 6**), thus, at the bottom centre and bottom left of the drawing are some calculations and short texts by Leonardo. On the left, he estimates the weight of the individual ribs of the vault and then, multiplying the result by eight, he deduces the weight of the entire dome. Leonardo tries, first, to calculate the volume, in cubic *braccia*, of the ribs of the vault, indicated as 'pilastri'. He then multiplies the volume by the weight in *libbre* (pounds) of a cubic *braccio*. While he does not specify the material, this would presumably be made of stone.[33] However, even though he expressly states that the result refers to the weight of the 'pilastri', it is not clear what the measures 16 and 45 mean, making it impossible to identify the elements for which Leonardo is trying to determine their weights.[34] Therefore, it is not clear how Leonardo arrived at his conclusions for the weight of the dome.

He also conceived stone 'chains' and tenon-and-mortise masonry joints to increase the rigidity of the structure while involving other parts of the building to support the dome in addition to the four piers of the crossing. He repeatedly illustrated those techniques of tenon-and-mortise and tooth joints of stone blocks in the *Codex Atlanticus.*[35] The use of *lapides cum caudis* (stones with dovetail cut), similar in principle to those illustrated in folio 850r of the codex, had already been discussed in the 21 January 1409 meeting at the cathedral building site (Veneranda Fabbrica 1877: 289; Di Teodoro 2012: 189–90).[36] Leonardo's attempt to involve other parts of the building in support of the dome, too, was an approach that he considered in many other sketches.[37] The resistance of the piers to the eccentric loads of the future dome had always been one of the main concerns of the Veneranda Fabbrica and led to countless consultations and debates from the beginning of the project a century earlier. This static and structural theme was, in fact, a chief concern as early as the 1400s. It manifested in the clash between Jean Mignot and the Lombard architects, and then in the 1460s, with the structure built by Guiniforte Solari, which was subsequently demolished.[38]

Conclusion

Evaluating the competition for the design of the dome of Milan Cathedral enables us to retrace the different phases of the building-site administration, the design process, and the decision-making process of one of the largest Italian building projects of the early modern period. This research also reveals how for Leonardo the competition was his first opportunity to both engage in architectural design and study problems of statics and mechanics in depth. He observed the work of his colleagues as well as local building traditions and then reflected on these topics in graphic form in his notebooks. Drawing was a tool of understanding, reasoning, and conceiving while he actively searched for ideas and solutions in every facet of the world around him.

Notes

[1] For the cathedrals of Siena and Florence, see for instance Giorgi and Moscadelli 2005; Grote 2009.

I would like to thank Janna Israel for having revised my English with great generosity.

[2] *Codex Atlanticus*, f. 1082r; Richter 1883, vol. 2: 395–98; Calvi 1982: 69–75; Marinoni 1980b: 181–84. For the dating the reference is Schofield 1991: 113–15.

[3] Other examples can be found in Windsor 12632v; 12634v (Clark and Pedretti 1968–69, vol. 1: 79, 132–33); or *Codex Atlanticus*, ff. 265r, 301v, 675v, 852r (see also Calvi 1982: 73–75).

[4] *Codex Atlanticus*, f. 730r; Beltrami 1919: 23–25; Calvi 1982: 98–102; Brizio 1952: 633–34; Firpo 1963: 22; Bruschi 1978: 349–53; Pedretti 1978: 35; Marinoni 1979, vol. 9: 40–42; Pedretti 1978–79, vol. 2: 90; Vecce 1998: 90–91; Villata 1999: 40–42; Repishti and Schofield 2019c: 369–70. The letter is normally roughly dated to between 1487 and 1490.

The text is the following: 'Signori padri diputati, sì come ai medici, tutori, curatori de li ammalati bisogna intendere che cosa è omo, che cosa è vita, che cosa è sanità e in che modo una parità, una concordanza d'elementi la mantiene e così una discordanza di quelli la ruina e disfà, e conosciuto ben le sopra dette nature, potrà meglio riparare che chi n'è privato. Voi sapete le medicine, essendo bene adoperate, rendon sanità ai malati. Queste bene adoperate sara[n], quando il medico con lo intendere la lor natura intenderà che cosa è omo, che cosa è vita, che cosa è complessione e così sanità. Conosciute ben queste, ben conoscerà il suo contrario. Essendo così, ben vi saperà riparare. Voi sapete le medicine, essendo bene adoperate, rendon sanità ai malati e quello che bene le conosce, ben l'adopererà, quando ancora lui conoscerà che cosa è omo, che cosa è vita e complessione, che cosa è sanità. Conoscendo queste, bene conoscerà i sua contrari. Essendo così, pi[ù] visino sarà al riparo ch'alcun altro. Questo medesimo bisogna al malato domo, cioè uno medico architetto, che 'ntenda bene che cosa è edifizio e da che regole il retto edificare diriva e donde dette regole sono tratte e 'n quante parte sieno divise e quale sieno le cagione che tengano lo edifizio insieme e che lo fanno premanente, e che natura sia quella del peso, e quale sia il disiderio de la forza, e in che modo si debbono contessere e collegare insieme e, congiunte, che effetto partorisc[h]ino. Chi di queste sopra dette cose arà vera cognizione, vi lascerà di sua rason e opera sadisfatto. Onde per questo io m'ingegnerò non ditraendo, non infamando alcuno, di saddisfare in parte con ragioni e in parte coll'opere, alcuna volta dimostrando li effetti per le cagioni, alcuna vol[t]a affermando le ragioni colle sperienze, con queste accomodando alcuna alturità de li architetti antichi, le pruove de li edifizi fatti e quali sieno le cagioni di lor ruina e di loro premanenzia eccetera. E con quelle dimonstrare prima del carico e quale e quante sieno le cagioni che danno ruina a li edifizi e quale è il modo della loro stabilità e premanenza. Ma per non essere plorisso a vostr'eccellenze dirò prima la invenzione del primo architetto del domo e chiaramente vi dimostrerò qual fussi sua intenzione, affermando quella collo principiato edifizio e facendovi questo intendere, chiaramente potrete conoscere il modello da me fatto avere in sé quella simmetria, quella corrispondenzia, quella conformità, quale s'appartiene al principiato edifizio. Che cosa è edifizio e donde le regole del retto edificare hanno dirivazione, e quante e quali sieno le parte appartenente a quelle. O io o altri che lo dimostri me' di me, pigliatelo. Mettete da canto ogni passione'.

For the affirmed analogy between medicine and architecture (which was already used by Leon Battista Alberti and Filarete) and the reference to the 2nd-century Greek physician Galeno, see Gukovskij 1964.

[5] All translations provided in the text are mine.

[6] 'la ragion d'una volta, cioè il terzo del diametro de la sua camera'.

[7] For the discussion of previous literature, see Repishti and Schofield 2019b: 115–21. A hypothesis on connections with Northern operative geometry is in Burioni 2019: 169–72. On this latter subject, see also Ceriani Sebregondi and Schofield 2016: 69–72.

[8] For this proposal and the resulting dating of the drawings at 1488–1489, see Repishti and Schofield 2019B: 120.

[9] ASMi, *Autografi*, 102, f. 34, 8 June 1490: 'Postscripta: rechedendo ancora magistro Leonardo fiorentino et magistro Iohanne Antonio Amadeo, operarete che vengano ancora loro'; ASMi, *Comuni*, 48, 10 June 1490: 'Magistro Leonardo fiorentino me ha dicto sarà sempre aparechiato omne volta sii rechiesto, siché, como se invii el senese, venerà anchora luy' (Malaguzzi Valeri 1901: 95; Beltrami 1919: 30–31; Maiocchi 1937: vol. 1, doc. 1492; Beltrami 1964c: 371; Brizio 1974: 9–10, 25–26, with a different interpretation; Solmi 1976: 17–19; *Ludovico il Moro* 1983: 98; Schofield, Shell and Sironi 1989: 183–84; Sciolla 1996: 6–7; Vecce 1998: 127–28; Villata 1 999: 66–68; Repishti and Schofield 2019c: 379–80).

Later, he learned from Bramante about a drawbridge: Marinoni 1986: 54–55, fol. 53v, ca 1499, 'Modo del ponte levatoio che mi mostrò Donnino' ('The structure of the drawbridge that was shown to me by Donnino'). As recently highlighted by Jill Pederson, 'ideas did not flow unilaterally from Leonardo, but were part of a more nuanced dynamic that values exchange, conflict, camaraderie, and above all the social ties' (Pederson 2019: 164).

[10] For the models carried out for Milan Cathedral, see Benati 2009: 77n1; Benati and Repishti 2017. On three-dimensional models more generally, see Saalman 1959: 102–5; Goldthwaite 1982: 369–81; Pacciani 1987; Millon 1994.

[11] AVFDMi, *Registri*, 263, f. 81v, 30 July 1487; 667, f. 35r, 30 July 1487; 667, f. 37r, 8 August 1487; 277, f. 36v, 8 August 1487; 667, f. 39v, 18 August 1487; 667, f. 41v, 27 August 1487; 667, f. 49r, 28 September 1487; 667, f. 49v, 30 September 1487; 277, ff. 43v, 62v, 30 September 1487; 263, f. 81v, 30 September 1487; 669, f. 3r, 11 January 1488; 277, f. 62v, 11 January 1488; 263, f. 81v, 11 January 1488; Calvi 1869: 90–91; Veneranda Fabbrica 1880: 38, 41; Boito 1889: 227–28; Uzielli 1896: 95–97; Muntz 1899: 224n1; Seidlitz 1909: vol. 1, 118; Beltrami 1919: 20–23; Beltrami 1964a: 80; Beltrami 1964c: 365–66, 378–79; Heydenreich 1963: 7; Mezzanotte 1968: 24; Heydenreich 1971: 29–30; Pedretti 1978: 34; Patetta 1987: 46n51; Schofield 1991: 118; Boucheron 1998: 257; Vecce 1998: 88–90; Villata 1999: 35–40; Patetta 2001; Repishti and Schofield 2019c: 365–67, 370.

[12] ASMi, *Notarile*, 1558, Bertola Pecchi, 16 May 1483; AVFDMi, *Registri*, 878, ff. 36v–37v, 16 May 1483; AVFDMi, *Archivio Storico*, 150, 1, 16 May 1483; Franchetti 1821: 15n; Veneranda Fabbrica 1880: 16–18; Beltrami 1964a: 79; Beltrami 1964b: 348; Beltrami 1964c: 362; Patetta 1987: 46n45,46; Repishti and Schofield 2019c: 339–41.

[13] AVFDMi, *Registri*, 667, f. 12v, 24 March 1487; 667, f. 29r, 26 June 1487; 667, f. 33r, 17 July 1487; 271, f. 18r, 14 August 1487; 667, f. 55v, 3 November 1487; 667, f. 56r, 3 November 1487; 667, f. 65v, 12 December 1487; 667, f. 67r, 17 December 1487; Veneranda Fabbrica 1880: 35, 38–40; Beltrami 1964a: 80; Vasić Vatovec 1979: 415–16; Repishti and Schofield 2019c: 366, 368.

[14] *Codex Atlanticus*, f. 850r: 332 x 293 mm, black chalk, pen, brown ink, on paper, *verso* plain; f. 851r: same paper, 282 x 237 mm, black chalk, stylus, compasses, pen, brown ink, on paper, *verso* plain. We surmise that *Codex Atlanticus*, f. 851r, was traced before *Codex Atlanticus*, f. 850r, because on the *verso* there are only small holes for the *spolvero* without traces of ink: this means that the drawing was done first and then the perforation. In addition, this drawing was certainly made from scratch as there are traces of stylus and compasses for the construction lines (these are absent on *Codex Atlanticus*, f. 850r). This was then copied by means of the *spolvero* on *Codex Atlanticus*, f. 850r. Here, the drawing was traced after perforation, since on the *verso* the ink pierced by the already-made holes is visible. The two drawings are therefore at the same scale. See note 22.

On these two drawings, see Richter 1883, vol. 2: 61–62 and pl. C; Boito 1889: 227; Malaguzzi Valeri 1901: 94; Malaguzzi Valeri 1915: 433–35; Beltrami 1964c: 367–70; Heydenreich 1963: 7; Heydenreich 1971: 19, 30–32; Fergusson 1977: 187–88; Bruschi 1978: 339n, 344–45; Marinoni 1980a: 49–50; Marani 1982: 88–89; Guillaume 1987: 217–22 (resumed in Guillaume 2019: 32–33); Bambach 1988, vol. 2.1: 196–200; Schofield 1989: 81; Schofield 1991: 132–33; Marani 1998: 31–33; Patetta 2001: 119–20; Marani 2004, vol. 2: 569–71; Bambach 2019, vol. 2: 179; Ceriani Sebregondi 2019a; Ceriani Sebregondi 2019d.

[15] Bruschi 1978: 344; Pedretti 1978: 34; Marani 1998: 31; Marani 2004: 571.

[16] Boito 1889: 227, tentatively; Bruschi 1978: 344, tentatively; Pedretti 1978–79, vol. 2: 145; Schofield 1989: 80; Schofield 1991: 118; Bambach 2019, vol. 2: 179.

[17] Among others, Bruschi 1978: 345; Guillaume 1987: 223; Kemp 2006: 88, 93; Ackerman 2002: x, 58, 153. See for instance the skull in profile and section, dated around 1489, Windsor 19057r, which in particular presents in the lower drawing a very clear and effective vertical section in orthogonal projection.

[18] Elevations in orthogonal projection too are virtually absent in Leonardo's repertory (Ackerman 2002: 70).

[19] In the drawing the sectioned parts are not graphically distinguished from those in projection, and the different planes in which the elements are located are not easily recognisable, in particular the spatial direction of the lower arches. Here are some of the major doubts raised by the drawing: Are the pendentives present or any other transitional system connecting the dome to the four pillars of the crossing? Shouldn't the turrets in the four corners be visible only on the outside of the dome shell, if this truly were a section in orthogonal projection? Where is the inclined element at the top right — generally interpreted as a flying buttress — positioned in space? Are the different stone chains in the lower part all positioned on the same plane? If, instead of a cross-section, there was a section made along one of the walls of the crossing (which is rather bizarre for a section anyway), as proposed by Fergusson (and then followed by Guillaume and Schofield), wouldn't the shell be interrupted horizontally, as it is curved towards the observer out of the plane of section? Otherwise, one must suppose that the shell was flattened on the section plane. The elements that have been interpreted as inclined arches connecting the dome to the turrets shouldn't be visible; and also, the indications about the turrets would result very inaccurate.

[20] On the fixing of architectural representation system and orthogonal projection drawings in the early 16th century, see the seminal Lotz 1956 and Thoenes 1993. The Northern 'Gothic' culture of representation in orthogonal projection, very present in the Milan Cathedral building site, could have influenced Leonardo in his attempts to realise a vertical section in orthogonal projection for the *tiburio*. See note 7 and Lotz 1956: 209.

[21] To copy a drawing from another through the *spolvero* technique, one must fix the drawing to be copied onto a white sheet, then thickly punch the contours of the drawing with a needle and pass a canvas bag filled with chalk powder over the holes. On the sheet below, a dotted trace will appear that can then be traced by joining the points or used as a guide to create a new drawing with further developments or alternative solutions to the first drawing, as in this case. According to Bambach 1988, vol. 1: 224–226 and Bambach 1990: 129, this technique for copies *on paper* only began in the 1480s, and Leonardo and Perugino were the first artists to adopt it. Bambach thinks there must have been an intermediate drawing between the two 851r and 850r, as she believes that some perforations do not match (Bambach 1988, vol. 2.1: 199 and Bambach 1991: 79). Finally, both drawings were made only for the right half, then folded vertically and copied by means of the *spolvero* technique on the left half (see also Bambach 1988, vol. 2.1: 196–200).

[22] Since the two drawings are of the same size and proportions, Fergusson (1977: 187)'s suggestion cannot be accepted — that the *Codex Atlanticus*, f. 851r, was intended to be a preparatory sketch, with wrong proportions, while the *Codex Atlanticus*, f. 850r, would have had the right proportions.

[23] On Leonardo's assistants in Milan, see Bambach 2019, vol. 1: 320–21.

[24] Fergusson 1977: 187–88; Guillaume 1987: 217–222 (resumed in Guillaume 2019: 32–33); Schofield 1989: 80–81. Both Frommel, Apollonio, Gaiani and Bertacchi 2020 and Diotallevi 2020 consider Guillaume's hypothesis as a starting point for their 3D models.

[25] Guiniforte Solari became architect of the Veneranda Fabbrica in 1459. His project for the dome was probably an octagonal structure resting on a system of decreasing arches in the corners instead of pendentives, in line with the dome of the Certosa di Pavia, built by Guiniforte himself, and with the Lombard traditions. After his death in 1481, the dome was demolished because of structural problems and other undefined defects. On this important episode, for which the archival records are extremely scarce, see Repishti and Schofield 2019a; on Guiniforte Solari, Gritti 2018.

[26] For the frequency in Leonardo's sketches of this scheme, see Beltrami 1964c: 368; Verga 1980: 10; Chastel 1987: 203. Many examples can be found in *Codex Trivulzianus*, ff. 9r, 12r, 20v, 21r, 27v; *Codex Atlanticus*, ff. 719r, 1010v; *Paris Manuscript B*, ff. 3r, 4v, even though not all these drawings are necessarily linked to the project for the Duomo, and it could also be that these are general architectural reflections on the theme of the dome, stimulated by the Milan Cathedral occasion.

[27] Galluzzi 1987: 63.

[28] Reference to Brunelleschi as primary stimulus for Leonardo's churches is present also in Ackerman 2002: 72–90.

[29] *Codex Atlanticus*, f. 730r: 'da che regole il retto edificare diriva e donde dette regole sono tratte' and 'quale sieno le cagione che tengano lo edifizio insieme e che lo fanno premanente, e che natura sia quella del peso, e quale sia il disiderio de la forza, e in che modo si debbono contessere e collegare insieme'.

[30] *Codex Atlanticus*, f. 730r: 'dimonstrare prima del carico e quale e quante sieno le cagioni che danno ruina a li edifizi e quale è il modo della loro stabilità e premanenza'.

[31] General reflections on loading and breaking schemes of pointed and round arches can be also found in *Madrid Codex I*, ff. 139r–140r, 142v–143r; *Paris Manuscript A*, ff. 47v, 49v–51r, 53r.

[32] 'Fondamento. Qui si dimosstra come li archi fatti ne' lati dell'ottangolo spingano i pilastri delli angoli in fori, come si dimostra nella linia h c e nella linia t d, che sspingano il pilastro m in fori, cioè si sforzano caciarlo dal cientro di tale ottangolo'.

[33] Even though the arithmetic result of 4,608,000 is correct, he instead writes in letters 'se' mjlion' e secen' 8 mila il peso del tiburio' ('six million and six hundreds 8 thousand the weight of the dome'): it may be an oversight, or it can be assumed that he has added the weight of the masonry panels between the stone ribs at a flat rate to the total. The arithmetic operations performed, which prove that Leonardo mastered two- and three-digit multiplication in column, are: 16 × 45 = 720; 720 × 800 = 576,000 (*libbre grosse*?); × 8 (ribs) = 4,608,000. On the side, close to 720 × 800, we find: 'ognj cosa ponderosa desidera de...' ('everything with a weight wants ...'; Richter 1883, vol. 2: 62, interprets 'de' as 'descendere' = going down); under the result 576,000: 'peso del pilastro de 9 teste' ('weight of the pillar of 9 headers'); under the result 4,608,000: 'se' mjlion' e secen' 8 mila il peso del tiburio' ('six millions and six hundreds 8 thousand the weight of the dome'). At the bottom centre is the operation: 800 × 25 = 20,000. If we rely on Cesariano 1521: XXIVr, according to whom 'ciascuno brazo cubale di marmore pexa libre 800' ('each cubic *braccio* of marble weights 800 *libbre*'), then Leonardo would have calculated

the stone cubic *braccia* of the ribs of the dome and then multiplied them by the weight in *libbre grosse* (0.7625 kg) of a cubic *braccio* (0.21 cubic metres).

[34] Because if it were *braccia* we would have a huge panel of 16 × 45 *braccia* and a depth of 9 headers (about 9.4 × 26.5 × 1.1 m), while if it were *once* we would have a block of about 0.8 × 2.2 × 1.1 m, and in neither of the two cases is it possible to identify similar elements in the *tiburio*; secondly, from the measurements given by Cesariano, the Candoglia marble would weigh as much as 2,904 kg per cubic metre, while it is currently estimated that it weighs 2,710 kg per cubic metre.

[35] *Codex Atlanticus*, ff. 50r, 76r, 91v, 301r, 1074r, all datable to the late 1480s; see also Bruschi 1978: 345.

[36] Veneranda Fabbrica 1877: 289. See also Di Teodoro 2012: 189–90.

[37] *Codex Trivulzianus*, ff. 8v, 12r, 21r, 27r, 27v; *Paris Manuscript B*, ff. 27r, 78v; *Windsor*, f. 19134v; *Codex Atlanticus*, ff. 400r, 1060r. The hypothesis that the long metal tie-rods described in the 1490 final report on the *tiburio* may be variants or they derive from the stone chains proposed by Leonardo (Fergusson 1977: 182; Schofield 1989: 79–80) does not seem acceptable because, besides the fact that they belong to distinct productive and constructive worlds, they respond to two opposite static principles: traction in the former, compression in the latter.

[38] Ceriani Sebregondi and Schofield 2016: 84–86; Ceriani Sebregondi 2019e; Repishti and Schofield 2019b.

Competing Interests

The author has no competing interests to declare.

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