History Research, March 2026, Vol. 8, No. 3, 142-156
doi: 10.17265/2159-550X/2026.03.002

Paddle-Wheel Ships in the Engineering Imagination of Francesco di Giorgio Martini Technology, Power Transmission, and the Limits of Renaissance Naval Innovation

Plinio Innocenzi
University of Sassari, Sassari, Italy

Among the numerous mechanical and military devices conceived by Francesco di Giorgio Martini (1439-1501), his projects for paddle-wheel ships occupy a distinctive position. These designs reveal an ambitious attempt to overcome the constraints of wind-dependent navigation through mechanically driven propulsion. This article examines Francesco di Giorgio paddle-wheel ship concepts within their technical, historical, and epistemological context. By analysing their mechanical architecture, power transmission logic, and operational assumptions, the study highlights both the originality of these designs and the structural limitations that prevented their practical realization. The analysis situates Francesco di Giorgio projects within the broader Renaissance issue of artificial motion, prefiguring later developments in steam-powered navigation while remaining firmly rooted in human and animal energy regimes.

Keywords: Francesco di Giorgio, Renaissance, engineering, paddle ships

Introduction: Artificial Motion at Sea in the Renaissance

Renaissance engineers developed a particular fascination with *moto artificiale (artificial motion)*, i.e. motion generated independently of natural forces such as wind, gravity, or animal and human power. In naval contexts, this aspiration translated into some attempts to supplement or replace sails and oars with mechanical propulsion systems. Francesco di Giorgio Martini (FdGM)[1], one of the most outstanding polymaths of Italian Renaissance, in his treatises, devoted himself not only to architectural studies but also to mechanical and naval engineering, following in the tradition of his fellow citizen Mariano di Jacopo, known as Il Taccola (c. 1382-c. 1453) (Galluzzi, 1991)[2].

Plinio Innocenzi, Ph.D., Professor, Laboratory of Materials Science and Nanotechnology, Department of Engineering, CR-INSTM, University of Sassari, Sassari, Italy.

[1] Francesco di Giorgio Martini (FdGM) was born in Siena in September 1439. His father, Giorgio Martini del Viva, served as a city official in the Biccherna office (the financial magistracies) and owned modest properties both in Siena and the surrounding countryside. FdGM likely began his artistic journey as an apprentice to Lorenzo di Pietro, known as "il Vecchietta" (1410-1480), a prominent artist active in Siena. Accompanying il Vecchietta to Rome, he had the chance to study classical architecture firsthand. FdGM received a broad education, encompassing painting, sculpture, and architecture. He rose to become one of the Renaissance most esteemed and in-demand Italian military architects. In 1475, he relocated to the court of Duke Federico da Montefeltro, where he contributed to the completion of the Ducal Palace. In addition to his achievements as an artist-engineer, FdGM was recognized for his wide-ranging humanistic learning. His command of Latin allowed him to translate Vitruvius *De Architectura* into vernacular Italian. The architectural and engineering expertise he amassed formed the foundation of his Treatise on Architecture, in which he also adapted concepts and designs from Taccola's earlier works.

[2] Mariano di Jacopo (il Taccola) (c. 1382-c. 1453) was a Sienese engineer, architect, and early theorist of machines, active in the first half of the 15th century. Trained within the civic and military engineering tradition of Siena, he authored illustrated treatises such as *De ingeneis* and *De machinis*, devoted to hydraulic works, lifting devices, and war machines. The drawings from Taccola combine practical engineering knowledge with schematic experimentation, anticipating later Renaissance machine books. Although his work circulated mainly in manuscript form, it exerted a significant influence on later engineers, including Francesco di Giorgio Martini. He is today regarded as a key transitional figure between medieval technical practice and Renaissance engineering thought.

The treatises of FdGM, together with those of Taccola, were widely circulated thanks to the diffusion of several manuscript copies, including one owned by Leonardo da Vinci himself (Guess, 1998). Although FdGM machines drew on previous traditions, they marked an important transition in their representation, moving away from approximate and semi-fantastic graphics to become true engineering designs. Not all machines and designs achieve the same graphic quality. However, the final versions of his treatises show the development of an advanced technique with orthogonal and perspective projections of the machines. The machines of FdGM can be grouped into several main categories: instruments for warfare, construction machines, hydraulic machines and systems, civil and military ships, and machines for both land and sea mobility. The latter are particularly interesting because they denote a capacity for innovation beyond the knowledge of the time. In particular, the development of mechanics for the transmission of motion. FdGM designs self-propelled carts whose mechanics would allow control of movement and direction, even if the traction force is still human, to be exerted through a system of cranks (Innocenzi, 2014). His codices are also rich in ship designs for different uses, including war, transport, and civilian uses, such as pile-driving ships. Many of these designs still refer to Taccola's previous tradition, but some, such as those for paddle ships, are original and innovative. He anticipated and inspired later work on the subject by Leonardo da Vinci, and his ideas lie between the early projects of the German school and those of Leonardo (Innocenzi, 2019).

Unlike earlier ad hoc sketches of mechanical ships, FdGM embedded paddle-wheel propulsion within a coherent theoretical framework of his knowledge of mechanics. Several ideas have been translated into articulated projects, even if scattered in his manuscripts. His ship projects must be considered not as isolated attempts but as integral parts of a broader investigation into power transmission, rotational motion, and the development of advanced mechanical devices well beyond the knowledge of the time.

The present article is dedicated to analysing FdGM paddle-wheel ship projects within their technical, historical, and epistemological context. Rather than asking whether these machines could have functioned effectively in practice, a question often answered retrospectively through modern engineering criteria, this study aims to reconstruct the internal logic governing their conception. By observing the mechanical architecture of the drawings, their potential power sources, and the assumptions embedded in their interaction with water, the article treats these ships as *epistemic machines*: devices through which Renaissance engineers, such as FdGM, explored what artificial motion could plausibly achieve under the energetic and material conditions of their time.

To situate the work of FdGM historically, the article first reviews earlier wheel-driven boats developed within the German and Italian traditions of the late Middle Ages, as found in the Anonymous of the Hussite Wars, Konrad Kyeser *Bellifortis*, and Roberto Valturio. These precedents demonstrate that the basic idea of paddle-wheel propulsion was already circulating well before Francesco di Giorgio Martini, though typically in fragmented or schematic form. Against this background, FdGM contribution lies not in the invention of the concept itself, but in its systematic rearticulation within a coherent mechanical framework. His designs integrate paddle wheels into articulated transmission systems and explore multiple modes of actuation, revealing both an ambition to mechanize navigation and an acute awareness of its difficulties. Finally, the article positions FdGM paddle-wheel ships as a critical precursor to Leonardo da Vinci later investigations. Leonardo did not merely inherit these ideas; he intensified their mechanical scrutiny, pushing them to the point where their limitations became unavoidable. Seen in this light, FdGM wheel ships mark a moment when artificial naval propulsion became fully thinkable as a mechanical problem, even as its practical realization remained beyond reach. The failure of these designs is, therefore, not incidental, but historically productive, illuminating the boundary between mechanical imagination and energetic feasibility in the pre-industrial world.

Wheel-Driven Boats Before Francesco di Giorgio

The general idea of wheel-driven boats appeared already before the projects depicted by FdGM. During the late Middle Ages Italian and German "engineers" developed some very basic concepts of paddle-wheel boats powered by men. The idea was to mechanise rowing so a vessel could move without relying on oars or wind. Sketches from ca. 1400-1470 reveal some notable designs that pre-date the boats drawn later by FdGM. These early prototypes illustrate how military engineers adapted the crank and connecting-rod to transfer human power to rotating paddle wheels, and they help explain the technical background familiar to FdGM.

The German School

A mid-15th-century manuscript attributed to an Anonymous author of the Hussite Wars (*Codex Latin Monacensis 197*) includes a drawing of a small river boat with four paddle wheels (Figure 1). Two operators sit facing opposite directions and turn hand-cranks that are linked to the wheels by simple connecting rods. Each crank rotates a vertical axle carrying double sets of paddles, so that one person powers the wheels at each end of the boat. The operator arms act as the connecting rods, converting reciprocating motion into continuous rotation. Clearly, the rotation of the cranks by the two men requires a careful synchronization.

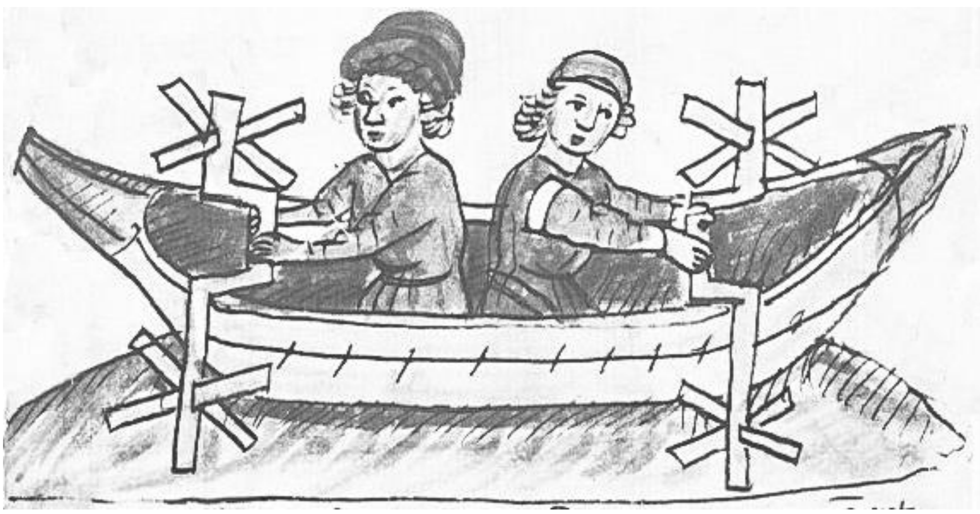

Figure 1. Wheel boat. Anonymus of the Hussite Wars. 1475 +/- 3. Bayerische Staatsbibliothek München (Detail).

The concept and the design appear quite rudimentary, but the drawing demonstrates early understanding of how to link several paddle wheels to human power. The accompanying text in the manuscript says that: "This is a ship that travels on quiet waters. It has four pinions and requires four men, two aft and two fore. It could easily carry twenty armed men as well as the four who drive it. The pinions (gearwheels) go in the water and inside the ship each one has a crank which is turned from within the ship. In this way, one can travel back and forth on the water. The ship should be covered over so that the people inside might not be seen. It should have a steeled point on its bow and secondary points on each side and also a cannon. It is called a warship; the people of Catalonia use this type to prevail over all other ships".[3] The description does not exactly correspond to the drawing but

---

[3] Original text: "Daz ist ein schiff daz get auff stillen wasseren, und hat 4 vettig. Da gehoren 4 man czw, czwen hinten und czwen foren, und daz mag wol xx wappen tragen, und dy vier man dy daz schiff czychen. Und dy vettigch gen in daz wasser und inwendig hat ydlich vettich ein wendl den man umbtrybt inwendig in dem schiff. So mag man faren auff dem wasser ab und czw. Und daz schiff sol verdeckt sein, daz man dy leyt nicht geschen müg, und sol fornen ein sthachln spicz haben, und an yedlicher sytten ein nebenn spicz und ain puchsen. Daz hayst ein streytt schyff doman dye von Katalon all andern schiffen oblige".

expresses more complex ideas, such as the construction of a stealth boat. The simple design in the *Manuscript of the Hussite Wars* can be considered as a starting point for more sophisticated crankshaft-driven paddle boats.

The German military engineer Konrad Kyeser (1366-1405) compiled *Bellifortis* around 1405. *Bellifortis* survives in multiple medieval manuscript copies, produced between the early 15th and early 16th century. There is no single authoritative autograph, but rather a tradition of illustrated copies, some close to the authorial redaction, others adapted to local military interests. Scholarly consensus generally recognizes about 12-15 manuscript versions, of which 8-10 are considered complete or near-complete and authoritative for textual and iconographic study. The treatise contains illustrations of siege machines, dredges, and paddle-wheel ships. The different versions of the manuscripts show some variations in the paddle ship design. In the copy at the Universitätsbibliothek Göttingen a drawing shows a robust war-boat fitted with large paddle wheels driven by a central crankshaft (Figure 2). A cage-like frame in the vessel centre encloses a vertical axis and a spiral or worm gear that transmits rotation to the side paddle. Kyeser wrote a small description of the boat in Latin: “This ship runs very quickly through the water. Through large tracts, they are moving above the wheels. They are also well-wheeled, as you clearly see (English translation)”[4]. His manuscript also includes fantastical schemes for ships mounted on wheels to traverse land, hinting at his fascination with applying rotary motion to transport.

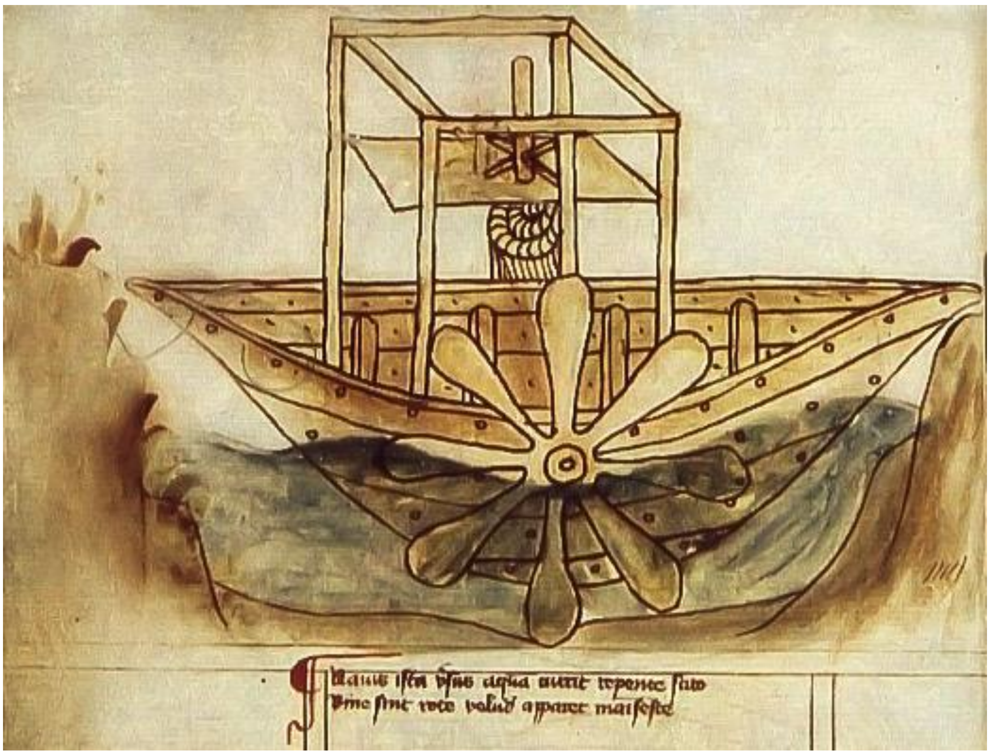

Figure 2. Conrad Keyser. Bellifortis. 1405 +/- 3. Universitätsbibliothek Göttingen. 2° Cod. Ms. philos. 64 (Detail).

The use of a mechanised transmission distinguishes the boat of Keyser from the simple crank-handles seen in the Hussite drawing. By placing a crankshaft mid-ship, he anticipated later designs where multiple paddles are linked by a single rotating shaft. This arrangement reduces the labour required from the crew and hints at how engineers began to imagine mechanical power, whether human or animal, driving marine propulsion. It should

[4] Original text: “Navis ista aquam citissime currit Per tractus grandes sint supra rotas moventes Sint etiam rote bine prout vides aperte”.

be noted, however, that the gearing cannot be clearly discerned, making the feasibility of the system quite problematic.

A later copy at the Universitätsbibliothek Frankfurt am Main shows a much more advanced design of the paddle wheel (Figure 3). The Frankfurt copy of *Bellifortis* marks a decisive conceptual shift within the manuscript tradition, transforming the paddle wheel from a hydraulic or emblematic element into a genuinely propulsive device. The wheel is structurally integrated into the hull and explicitly driven by human power through a crank-and-gear transmission. This arrangement implies an elementary but non-trivial understanding of torque generation, speed reduction, and mechanical continuity between operator and water. While the design suffers from evident limitations, single-wheel asymmetry, unresolved steering, and low energetic efficiency, it nonetheless constitutes a true mechanical hypothesis rather than a purely imaginative construction. In this respect, the Frankfurt *Bellifortis* occupies an intermediate position between medieval mill technology and Renaissance naval engineering: Propulsion is conceived in principle, though not yet optimized as a system. The drawing thus provides an essential missing link between the iconographic experimentation of earlier *Bellifortis* manuscript copies and the mechanically integrated paddle-ship designs of FdGM, in whom rotary motion is finally embedded within a fully articulated naval architecture.

Figure 3. Human-powered paddle-wheel vessel as depicted in the Frankfurt manuscript of *Bellifortis* by Konrad Kyeser[5]. 1460. Universitätsbibliothek Frankfurt am Main. Ms. germ. qu. 15 (Detail).

The wheel-driven boats documented in the Anonymous of the Hussite Wars and in Kyeser's *Bellifortis* mark a transitional stage between rowing and mechanically powered vessels. They demonstrate how German scholars developed the basic concept of *crank mechanisms* much earlier than the spread of steam engines. The sketches lack the drawing skills of Italian engineers such as FdGM and Leonardo da Vinci and look quite naïve, but the basic idea is already there.

[5] Available on line at: https://sammlungen.ub.uni-frankfurt.de/download/pdf/3657168.pdf.

Earlier Italian Treatises

Italian scholars and engineers were already experimenting with paddle-wheel boats when FdGM was young. In 1335, Guido da Vigevano sketched a vessel moved by paddle wheels using double-elbow cranks, one of the earliest applications of the crank in Europe. Later, Roberto Valturio produced the lavishly illustrated *De re militari* (completed 1463, printed 1472). Book XI includes ships with paddle wheels joined by a single connecting rod and a rudder. Valturio, who was at the service of the Lord of Rimini, Sigismondo Pandolfo Malatesta (1417-1468), also proposed boats made of detachable blocks for ease of transport (Figure 4).

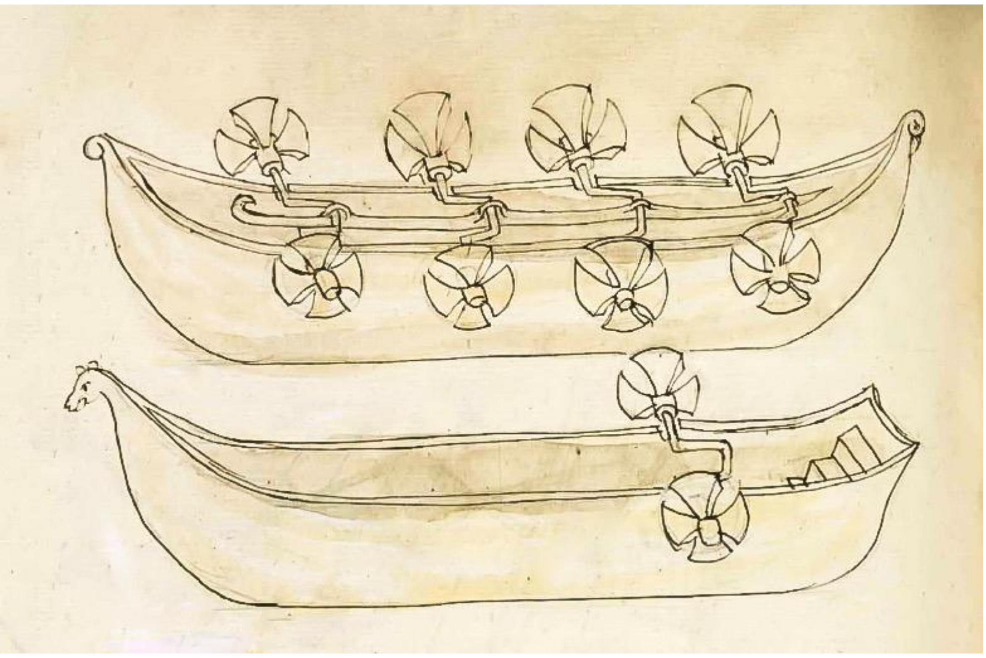

Figure 4. Multiple-wheel paddle vessel as illustrated in De re militari by Roberto Valturio. c. 1472 (Valturio, Lessing J. Rosenwald Collection, & Franck, n.d.) (Detail).

The paddle-wheel vessel depicted in Roberto Valturio's *De re militari* represents a mature reconfiguration of earlier medieval concepts of rotary motion applied to navigation. Unlike the heterogeneous models of the German manuscript tradition, where paddle wheels oscillate between hydraulic analogy, symbolic motion, and isolated human-powered experiments, the design of Valturio treats propulsion as an integrated system. The repetition of multiple wheels along the hull, mechanically synchronized through articulated shafts, reveals a conscious effort to address fundamental engineering problems already implicit in earlier German models: asymmetric thrust, limited power output, and poor directional control. Here, propulsion is no longer a localized mechanical curiosity, but a distributed function embedded in the architecture of the vessel itself. In contrast to the Frankfurt *Bellifortis* paddle ship, which demonstrates feasibility through a single human-driven wheel, Valturio advances toward scalability by multiplying actuators and enforcing symmetry. This shift reflects a broader Italian Renaissance tendency to rationalize inherited technical imagery into coherent mechanical systems. Valturio does not merely transmit the visual language of the German school; he restructures it, transforming the paddle wheel from an experimental appendage into a repeatable, modular element of naval design.

Italian courts collected foreign military treatises, and the influence of Kyeser *Bellifortis* on Italian engineers, even if not directly documented, is quite likely. The crank-and-paddle concept described in the

Anonymous of the Hussite Wars was known in German manuscripts, and it appears again in Kyeser work. The concept of linking multiple paddles with compound cranks, first seen in the Hussite drawing, was later improved by Valturio and adopted by FdGM. Although direct evidence that FdGM saw Kyeser manuscript is lacking, the diffusion of such works through copyists and the shared iconography of military devices suggest he could have been aware of the central crankshaft concept. *De Re Militari* of Valturio enjoyed wide circulation and was deeply influential so that even Leonardo da Vinci largely used his ideas. Given FdGM profession and his contact with the Renaissance courts, it is very likely he knew and studied the military treatise of Valturio.

The Paddle-Wheel Concept in Francesco di Giorgio

The core idea behind FdGM wheel ships consists of one or more large lateral paddle wheels mounted on the hull, partially submerged, and driven by an internal mechanical system. The wheels are typically depicted as radial structures with flat paddles, closely resembling later 18th-19th century side-wheel steamships in principle, though not in execution. The hulls themselves are conventional for the period, indicating that the innovation lies entirely in propulsion rather than naval architecture. This choice suggests a pragmatic approach: FdGM sought to modify existing ship typologies rather than invent entirely new ships.

The most critical aspect of these designs is the proposed power source. Francesco di Giorgio envisaged paddle wheels driven by human operators turning capstans or cranks, or animal power transmitted through treadmills. The power is transmitted through complex gear trains, converting reciprocating motion into continuous rotation. These mechanisms reflect Renaissance mastery of static machines, such as winches, mills, and hoists, adapted for continuous dynamic operation. The gear systems, often involving lantern gears and spur wheels, demonstrate a sophisticated understanding of torque multiplication and rotational kinematics. However, the designs implicitly assume sustained mechanical output far exceeding what human or animal power could realistically provide in a maritime environment.

The Sources

The designs for paddle boats are scattered throughout his various manuscripts and are represented with different degrees of graphic quality, which changes greatly depending on the manuscript itself. The starting point for studying FdGM projects is the *Codicetto Vaticano* (or *Taccuino* (Notebook)) (*Codex Urb. Lat.* 1757) (Merrill, 2020). The *Taccuino* is exactly what can be expected by its name, a very small notebook filled of observations, sketches, and annotations. It was compiled within a decade from 1465 until at least 1476. The initial part of the notebook, consisting of 191 sheets, is mostly a reorganized compilation of drawings and projects taken from *De Ingeneis* by Mariano di Jacopo (il Taccola) (Prager & Scaglia, 1972) (1381-1453) and the *Re Militari* of Roberto Valturio (1405-1475). The *Taccuino* will be the used for preparing the *Trattato di Architettura Civile e Militare* (*Treatise of Civil and Military Architecture*) and the *Opusculum de Architectura*. The *Taccuino* contains five different sketches of paddle-wheel ships. This group of drawings, even if they are just roughly sketched, contains all the concept of the paddle boats projects.

Codicetto Vaticano, Fol. 13r

Figure 5 shows a drawing by FdGM found in the *Taccuino* Folio 13r. The illustration is accompanied by an interesting technical note: “F[a]ciendo andar la r[u]ota per forza de h[u]omini che dara moto al na[v]iglio senza vento dove non e vento ne si puo usare vela questa inuentione potra giouare ma conuiene molta forza et continuo affaticare [del] h[u]omo [?] (By turning the wheel with human power, which will propel the ship without wind where there is no wind and sails cannot be used, this invention may be useful, but it requires a great deal of strength and continuous effort on the part of man)".

While the drawing admits a paddle-wheel interpretation, the accompanying text is fully compatible, and arguably more naturally so, with a traction-based system in which a human-powered rotating wheel winds or tensions a rope that pulls the small boat through the water. The emphasis on *forza de huomini* (strength of men), *molta forza* (a lot of strength), and *continuo affaticare* (continuos effort), coupled with the absence of explicit reference to water interaction, suggests that Francesco di Giorgio may here be exploring an on-board hauling mechanism rather than a true paddle propulsor. The FdG design, although very simple and schematic, would represent a system for pulling a boat, for example from the sea to a pier, using a paddle wheel submerged in water. This would make it much easier to pull the vessel.

Figure 5. Human-powered system for imparting to pull a vessel in water. *Opusculum de architectura*. Francesco di Giorgio (Detail). Biblioteca Apostolica Vaticana. Rome. Italy.

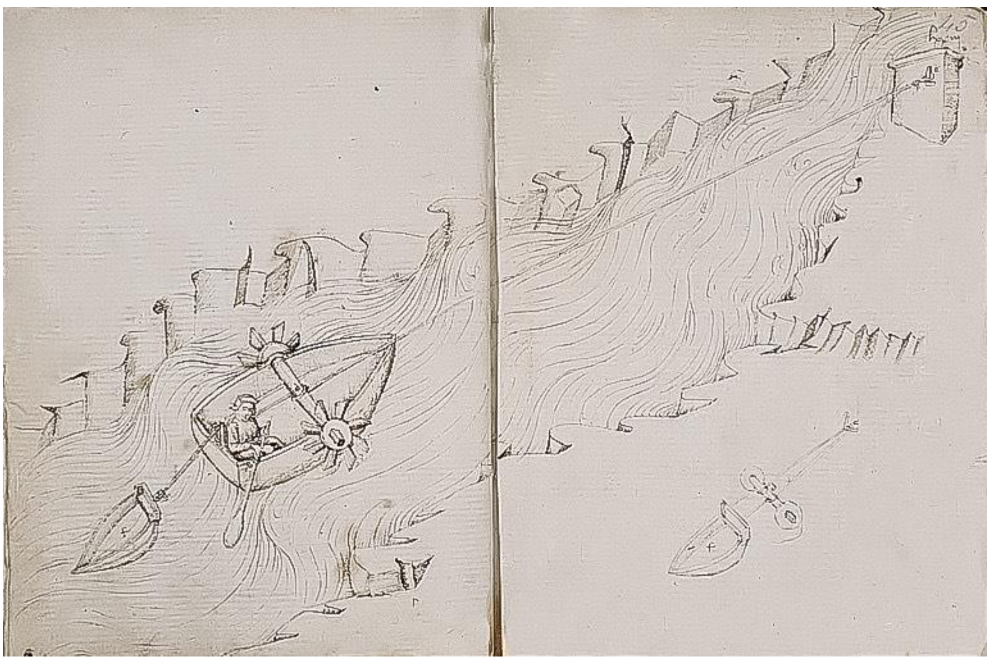

Figure 6. De Ingeneis. Ms. Palatino 766. Biblioteca Nazionale di Firenze.

This drawing has another interesting aspect, its connection with one of Taccola sketches (Figure 6). In fact, a very similar drawing can be found in the treatise *De Machinis* (1449), which illustrates a close mechanism but for moving upstream in a river. The drawing attributed to Taccola depicts a fluvial vessel advancing upstream by means of a tensioned rope anchored ahead, combined with rotating wheels mounted on the boat. The wheels do not act directly on the water for propulsion; instead, they serve as traction and transmission elements, transforming human or mechanical effort into controlled motion along the rope. This places the device within the technological family of tow-assisted navigation (alzaia), while introducing a significant mechanical refinement: the integration of rotary elements to reduce friction, regulate force, and allow intermittent or continuous upstream advance. The river current is explicitly acknowledged in the drawing, not as a source of energy but as an opposing force to be mechanically overcome. Francesco di Giorgio borrowed this concept and generalized it to the possibility of pulling a small vessel by means of a rope connected to wheels immersed in water.

Small Paddle Boats

The other four projects found in the *Taccuino* can be divided into two groups: one involving small boats and the other dedicated to large boats, which, in fact, use treadwheels as a means of propulsion.

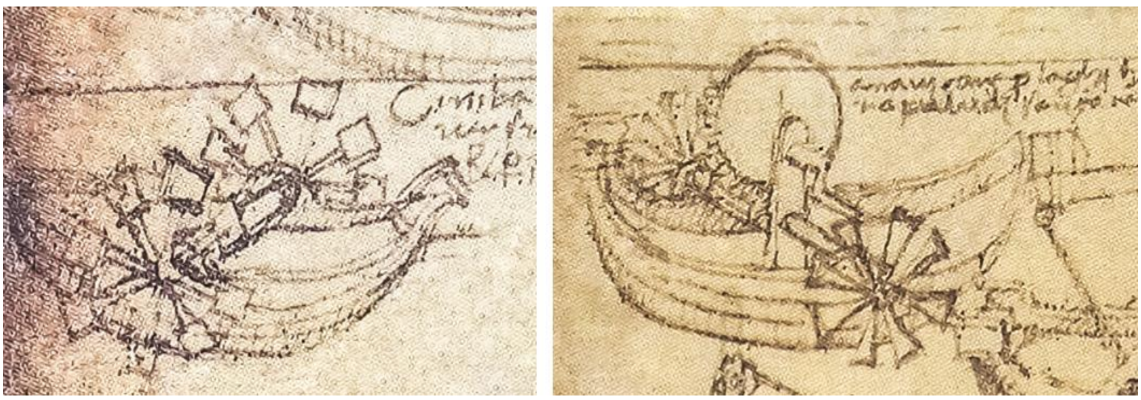

Figure 7. Projects of small wheel boats from the Taccuino of Francesco di Giorgio. Left, Folio 18r; right Folio 19v (Details). Biblioteca Apostolica Vaticana. Rome. Italy.

Figure 7 shows two drawings from the *Taccuino* of FdGM. Both sketches depict small vessels with lateral paddle wheels, but at a reduced scale, shifting the focus from naval architecture to mechanical feasibility. The two sketches document an early and exploratory phase of his thinking on artificial naval propulsion. The first drawing reduces the vessel to a minimal support for a lateral paddle wheel, treating the wheel almost as an abstract tool for motion and leaving issues of transmission, power, and structural integration entirely implicit. The second sketch, while still schematic, introduces a more articulated hull and a clearer spatial accommodation of the wheel, suggesting an initial awareness of load transfer and structural constraints. This drawing is quite similar to that one in Figure 3 from *Bellifortis*. Read together, the two images trace a conceptual progression from mechanical analogy to nascent system thinking, in which the mill-derived paddle wheel is gradually forced to confront the practical requirements of installation within a vessel, even as the problems of actuation and energetic sustainability remain unresolved.

More in detail, the first boat (left image in Figure 7) is powered by two eight-spoke paddle wheels connected by a rotating axle. In the drawing, the mechanism for transmitting motion to the paddle wheels is not explicitly represented. The axle supporting the wheels is clearly visible, as are the wheels themselves and their interaction with the water, but there is no clear representation of the driving force (men, animals, cranks, auxiliary wheels) or the kinematic connection that would cause the axle to rotate.

In the other drawing (right image in Figure 7), the device is radial in structure, consisting of a clearly defined central hub mounted on a horizontal shaft (*asse*), from which a series of straight spokes extend toward the periphery. Attached to the outer ends of these spokes are broad, flat paddle boards (*battenti*), rectangular or slightly trapezoidal in form, without curvature or angular profiling. The wheel is shown as partially immersed in the water, with only its lower sector engaged during rotation. Propulsion is generated through direct impact: As the wheel turns, the paddles enter the water on the downward stroke and displace it backward, producing forward motion of the vessel by reaction. The upper paddles emerge fully from the water, limiting resistive drag on the return stroke. This configuration confirms that the intended mode of action is impulsive rather than lift-based, consistent with the author's repeated use of the verb *battere* in the accompanying text.

Mechanically, the paddle wheel is rigidly coupled to the driving shaft, with no evidence of intermediate gearing, belts, or regulating mechanisms. This choice implies low rotational speed and high torque, which are appropriate for human-powered operation and for overcoming water's inertia, but at the cost of efficiency. The wheel is mounted laterally outside the hull, fully exposed to the water, and lacks any form of casing or hydrodynamic fairing. Such exposure underscores the primacy of mechanical clarity over performance refinement and reflects a design philosophy in which robustness and conceptual transparency outweigh energetic considerations.

The absence of curved blades, feathering devices, or variable immersion depth further confirms that the paddle wheel is not an experimental hydrodynamic invention, but a conservative adaptation of an established mechanical archetype. In this sense, the wheel functions as a "mobile mill wheel", embodying FdGM broader strategy of extending proven terrestrial machines into new domains. Its form encapsulates both the ingenuity and the limitations of Renaissance mechanical reasoning: Rotation is correctly identified as the key to artificial motion, yet the energetic and fluid-dynamic consequences of applying this form to navigation remain largely untheorized.

Large Wheel Boats Actioned by Treadmills

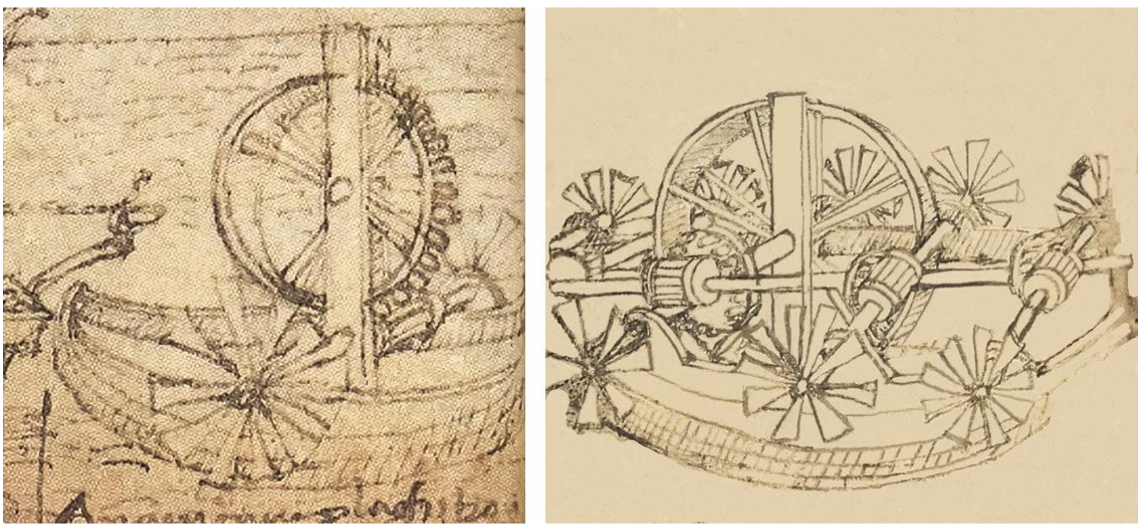

Figure 8. Projects of large wheel boats moved by treadmills from the Taccuino of Francesco di Giorgio. Left, Folio 18v; right Folio 17v (Details). Biblioteca Apostolica Vaticana. Rome. Italy.

Figure 8 (Folio 17v, *Opusculum de Architectura*) shows a real six-wheeled paddle boat. FdGM describes the ship as it follows: "Questa navicella si condurrà con ruote che battono l'acqua, quando l'uomo fa girare i ferri, o vero l'asse, con forza d'uomini, e farà andare la nave senza vento, ma con molta fatica continua (This vessel will be propelled by wheels that beat the water, when men turn the irons, or rather the axle, with human strength, and will move the ship without wind, but with much continuous effort)". The comment is quite similar to that used for Figure 5, but the reference to a wheel-powered boat is explicit in this case. The text lays out a complete mechanism with a man who turns *ferri/asse* (ironwork or shaft), a shaft that rotates the wheels beating the water. The boat moves without wind and the motion in water requires continuous fatigue (work) from the crew. This appears, therefore, a fully explicit paddle-wheel propulsion description.

The design of large wheel-boats driven by internal treadmills, marks a decisive conceptual shift with respect to the earlier sketches of small wheel boats. While the small vessels reduce the hull to a minimal support for a single or pair of lateral paddle wheels. Which serve primarily as exploratory probes into the feasibility of artificial motion, the treadmill boats represent an explicit attempt at scaling the system both mechanically and energetically. Here, propulsion is no longer entrusted to an abstract or implicit source of rotation, but to a clearly articulated human-powered engine: one or more treadmills directly coupled to a common transverse shaft driving multiple paddle wheels. This arrangement signals an important advance in thinking, as Francesco di Giorgio confronts the problem of power density by multiplying operators and coordinating their efforts through a centralized transmission. At the same time, the paddle wheels remain fundamentally mill-derived in form, radial wheels with flat paddles acting by impact, indicating continuity rather than rupture in hydrodynamic conception. Compared to the small boats, the large treadmill vessels thus embody a transition from conceptual experimentation to integrated mechanical architecture: The propulsion principle is unchanged, but it is embedded in a more coherent spatial, structural, and energetic framework. Yet the persistence of human power as the sole energy source, now made visually and mechanically explicit, also renders the system's limitation unmistakable. The treadmill boats, more clearly than the small sketches, expose the energetic limits of Renaissance artificial navigation, transforming the wheel boat from a speculative device into a diagnostic instrument that reveals the boundary between mechanical ingenuity and physiological constraint.

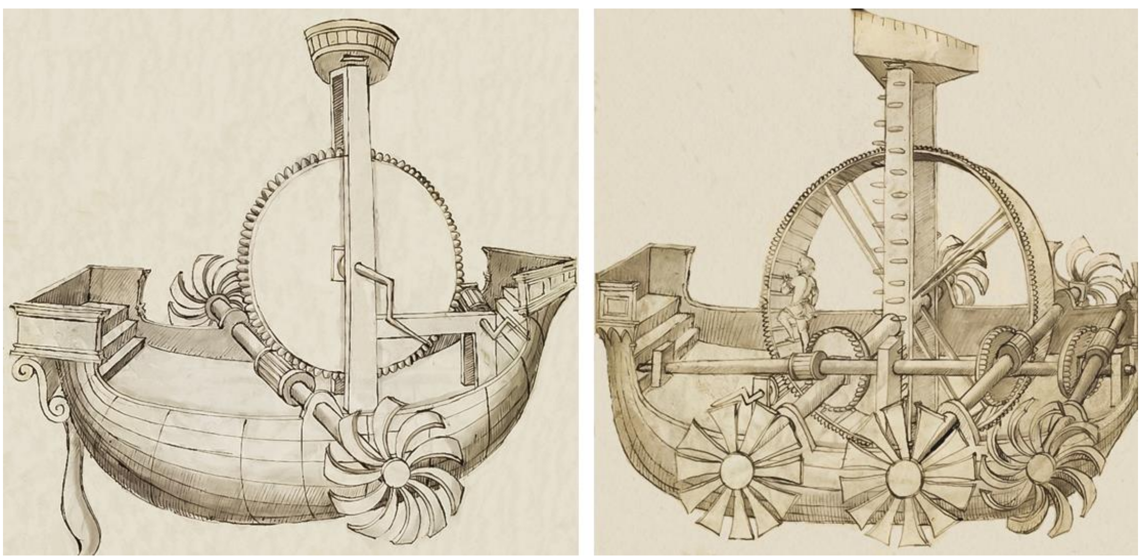

Figure 9. Ships moved by treadmills. *Opusculum de Architectura*. Ms. 197.b.21. British Museum. London.

The last two projects of boats moved by man-powered treadmills are shown in the *Opusculum de Architectura*[6] (Figure 9). The two treadmill-powered wheel-boat drawings in the *Opusculum de architectura*, without accompanying textual explanation, represent a distinctive stage in the idea of artificial naval propulsion. Their lack of commentary should not be interpreted as accidental or as a sign of incompleteness; rather, it may reflect the fact that these images function as visual syntheses of ideas already articulated elsewhere in the *Taccuino*. By the time these plates were produced, the conceptual elements of paddle-wheel propulsion, human power, rotary motion, mill-derived wheels, and continuous fatigue were sufficiently established to allow the image to operate autonomously. In contrast to the earlier small wheel-boat sketches, which explore propulsion in a tentative and exploratory manner, these drawings display a fully articulated mechanical architecture. A large central treadmill, driven by one or more operators, is rigidly coupled through gearing to a transverse shaft that synchronously drives multiple lateral paddle wheels. The system resolves several uncertainties present in earlier projects: The power source is explicit, the transmission of motion is mechanically unambiguous, and thrust is symmetrically distributed along the hull. The vessel is no longer a minimal support for an experimental wheel but a structurally integrated machine, conceived as a floating power system. These uncommented plates thus mark a form of conceptual closure within FdGM exploration of wheel boats. Having progressively moved from small, schematic experiments to large, systematized machines, the author allows the image to speak where further explanation would be redundant. The wheel boat has become a fully thinkable machine, but also a fully bound one: mechanically coherent, architecturally integrated, and yet irreducibly constrained by the limits of human power.

Codex Ashburnham 351, Folio 53r

Another project of a small wheel boat appears in the *Codex Ashburnham 351*[7], Folio 53r (Figure 10)[8]. The small sketches are accompanied by an explanatory text and a caption beneath the drawing: "*retricini portante pale* (retricini bearing paddles)". Interestingly, FdGM is using a very specific and technical term, *retricini*, which refers to a wooden wheel with projecting toothed blades or paddles, typically used in water mills, distinct from simple flat paddles. The use of the technical term such as *retricini*, rather than generic *ruote* (wheels) or *pale* (paddles), confirms that FdGM conceived the device by direct analogy with water-mill technology.

The accompanying text explains what was the purpose of such boat: "Similmente, se 'l mare o fiume le bonbarde essercitar si vorranno, faccisi el navilio alquanto longo, sopra del quale la cassa di conpossizion piena, co la sopra posta e piantata bonbarda, sopra de' suo' rulli corrire possa; e, dirietro ad essa, due anelli inne' quali un grosso e giusto fussello, che per essi volgendo girare possa; e, ne la sommità e testa d'esso, due parate retrecini

[6] The *Opusculum de Architectura* is an 80-page Codex, now kept at the British Museum in London under the catalogue number Ms. 197.b.21, containing about two hundred illustrations and drawings of machines and fortifications. It is the first complete treatise attributed to Francesco di Giorgio, even if it does not contain any accompanying text but only a dedication on the front page to the Duke of Urbino, Federico da Montefeltro (1422-1482). The *Opusculum* should have been completed between 1475 and 1477, using the notes from the Taccuino, when Francesco di Giorgio moved from Siena to Urbino. The *Opusculum* contains a collection of various machines, such as pumps, mills, vehicles, construction, and war machines, as well as numerous plans of fortresses.

[7] The earliest version of the *Trattato di Architettura* is most likely the one found in Codex Ashburnham 361 (circa 1479-1481), housed in the Biblioteca Mediceo-Laurenziana in Florence. This manuscript is not signed, and at least two contributors have been identified, likely Francesco di Giorgio Martini himself and one of his workshop collaborators. The pages are organized into two columns, each featuring illustrations alongside the text. Notably, this is the copy of the *Trattato di Architettura* that came into possession of Leonardo da Vinci and bears his annotations.

[8] The Codex Ashburnam 361 and Codex Saluzziano 148. https://engineeringhistoricalmemory.com/FGM.php?page=1&section=361.

di cinque giuste e grosse pale, le quali innell'acqua piei sei abbino stensione. E cche da ttutte due le parti e tteste del navilio due gangarate e scommesse paratelle, le quali chiavare e schiavare si possino; e, nel colpire e rretrecin dal carro cacciato, nell'acqua le pale percotendo, siccome in terra resistenzia farà, ed anco per le paratelle che non manco aiuto dà, siccome la figura manifesta X (This is a vessel designed so that the river itself, with its current, propels it forward, and by turning the side wheels, which are equipped with paddles, moves the vessel without any other effort. This is done because the current strikes the paddles, thus generating a continuous motion, useful for moving forward and keeping the boat steady against the current, as needed)".

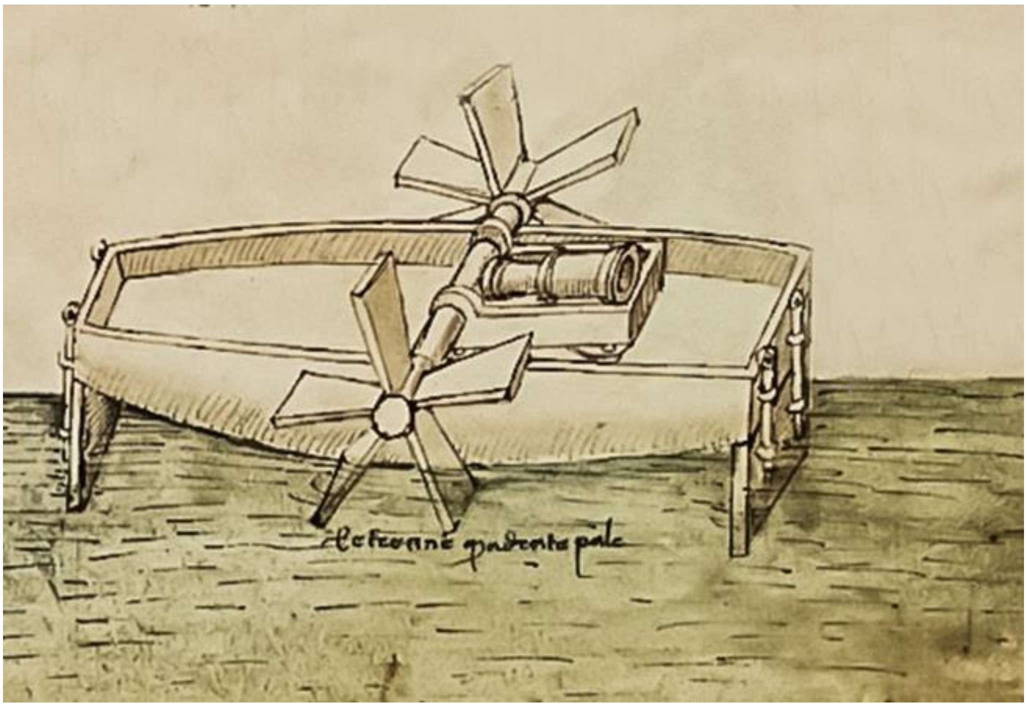

Figure 10. Sketch of a small boat. Codex Ashburhnam 351, Folio 53r (Detail). Biblioteca Mediceo-Laurenziana. Florence.

In this passage, Francesco di Giorgio is not describing a current-driven wheel boat, but a floating gunnery platform in which stern paddle assemblies (retrecini) and deployable side plates (paratelle) are conceived to generate in water the kind of reaction ("resistenza") that land provides to a wheeled vehicle, thereby stabilizing and assisting propulsion as the figure indicates. The "two panels" are not anchors; they are deployable resistance surfaces. Mechanically, they serve two coupled purposes: increasing the reaction against the water so the paddle strokes "bite" instead of just churning and stabilizing the platform during bombard operation.

After Francesco di Giorgio, Leonardo da Vinci and the Mechanical Interrogation of Wheel-Ship Propulsion

The wheel-ship projects of Leonardo da Vinci (*Codex Atlanticus*, Folio 945r; *Manuscript B*, Folio 83r) represent the most advanced designs of mechanically driven naval propulsion during Renaissance and a decisive transformation of the conceptual framework established by FdGM. While Leonardo inherits the fundamental idea of artificial motion at sea through paddle wheels, his treatment of the problem is markedly different in method, scope, and design skills. Leonardo did not invent the concept of the paddle-wheel ship *ex nihilo*. The structural similarities between his drawings and those of FdGM, most notably the lateral placement of wheels and the explicit analogy with mill technology, indicate a clear line of conceptual transmission. This dependence is historically plausible and philologically supported by the documented familiarity of Leonardo with FdGM treatises (Mussini, 1991; Innocenzi, 2022). What distinguishes Leonardo is not the originality of the concept, but the intensification of mechanical scrutiny (Innocenzi, 2020). Where FdGM proposes a typological solution, Leonardo subjects the same solution to continuous variation, refinement, and implicit critique. Leonardo wheel-ship drawings, particularly in the *Codex Atlanticus*, differ from earlier Renaissance schemes in their level of internal articulation. He consistently represented shafts, gears, and cranks with explicit spatial relations; paddle blades with differentiated geometry and operators or animals interacting with the mechanism. This shift marks a transition from the *idea* of propulsion to the idea of the ship as a mechanically integrated whole.

Leonardo paddle wheels exhibit greater sensitivity to water interaction. Variations in blade shape, immersion depth, and wheel placement suggest an intuitive engagement with hydrodynamic resistance. While still pre-theoretical, this concern represents a conceptual advance: Water is no longer a passive medium to be "beaten", but a resistant substance whose property conditions mechanical success. In this respect, Leonardo partially corrects the mill analogy. Whereas mill wheels operate in a predictable flow, Leonardo increasingly treats water as a variable and adversarial environment.

Leonardo should therefore be understood not as a parallel inventor, but as the critical inheritor of the vision of FdGM, an engineer who pushes the logic of wheel-ship propulsion far enough to demonstrate why it cannot yet succeed.

Technical Assessment: Why the Designs Were Impractical

A fundamental limitation of Renaissance paddle-wheel ships lies in power density. Human or animal muscle provides limited continuous power (on the order of 50-150 W per individual), insufficient to propel a large displacement vessel against currents or wind resistance. FdGM drawings do not explicitly address this mismatch between required and available power. The paddle wheels designed by FdGM lack hydrodynamic optimization. Paddle immersion depth, blade angle, and slip losses are not systematically treated, reflecting the absence of a quantitative theory of fluid resistance. As a result, much of the input energy would have been dissipated in turbulence rather than converted into forward thrust. Integrating large rotating wheels into wooden hulls can introduce severe structural stresses, including continuous vibration, asymmetric thrust, and water ingress through the axle housing. They would have posed significant challenges, issues not addressed in the manuscripts.

Despite their impracticality, FdGM wheel ships represent one of the earliest systematic attempts to mechanize naval propulsion and show a clear separation between the source of power and the means of propulsion. This marks a transition from empirical shipbuilding toward analytical engineering design. In this sense, these projects anticipate later breakthroughs made possible only with the advent of high-energy-density power sources, notably steam engines. The conceptual architecture of paddle-wheel propulsion in the 18th century closely mirrors the Renaissance vision, differing primarily in the availability of adequate power. When compared with 19th-century paddle steamers, the continuity is striking: lateral wheels, rotational motion, and direct mechanical coupling to propulsion elements. What FdGM lacked was not imagination or mechanical insight, but an energy technology capable of realizing his designs. This underscores a broader pattern in Renaissance engineering: conceptual anticipation outpacing material and energetic feasibility.

Conclusions

The paddle-wheel ship projects of Francesco di Giorgio Martini represent an interesting example in the history of Renaissance engineering, not because they anticipated modern steam navigation in a technical sense, but because they forced the problem of naval propulsion into the domain of mechanical reasoning. By separating the source of power from the means of propulsion and embedding rotary motion within the architecture of the vessel itself, Francesco di Giorgio transformed navigation from a largely empirical practice into a mechanical device. These designs reveal an engineer working at the boundaries of his conceptual environment. Paddle wheels, derived from mill technology and applied to waterborne motion, provided a possible mechanical interface through which artificial motion could be imagined at sea. Yet the very clarity of these constructions made their constraints visible. The manuscripts expose the capacity to conceive coherent systems of power transmission that far exceeded the energetic resources known during Renaissance. In this respect, the wheel ships do not fail incidentally; they succeed precisely in making this mismatch legible.

Seen against earlier medieval experiments and later developments in Leonardo da Vinci notebooks, the paddle-wheel vessels of Francesco di Giorgio Martini mark a moment when the problem of artificial naval propulsion becomes fully articulated, its mechanical vocabulary established, and its limitations implicitly acknowledged. What follows in Leonardo is not invention in a strict sense, but a development of the same principles that reveals why the solution must await a different energy power source.

The wheel ships of Francesco di Giorgio Martini should, therefore, be considered neither as impractical curiosities nor as premature inventions, but as conceptual constructions that expanded the known horizon of engineering. They demonstrate how Renaissance engineers used machines not only to solve problems, but to define them, mapping the boundary between mechanical possibility and physiological constraint.

References

Galluzzi, P. (1991). Prima di Leonardo. Cultura delle macchine a Siena nel Rinascimento (Before Leonardo. Machine culture in Siena during the Renaissance). Electa.

Guess, A. C. (1998). The machines of Francesco di Giorgio: Demonstrations of the world history and theory of architecture. McGill University.

Innocenzi, P. (2014). The engineering and mechanics of self-propelled vehicles from the Renaissance: The projects of Francesco di Giorgio. *Advances in Historical Studies, 13*, 73-93.

Innocenzi, P. (2019). *The innovators behind Leonardo. The true story of the scientific and technological renaissance.* New York: Springer. Retrieved from https://doi.org/10.1007/978-3-319-90449-8

Innocenzi, P. (2020). Leonardo and the design of machines. In E. Cicalò (Ed.), *Proceedings of the 2nd International and Interdisciplinary Conference on Image and Imagination. IMG 2019. Advances in Intelligent Systems and Computing* (Vol. 1140, pp. 36-46). New York: Springer. Retrieved from https://doi.org/10.1007/978-3-030-41018-6_5

Innocenzi, P. (2022). Leonardo da Vinci e le macchine di Francesco di Giorgio Martini. In E. Pellegrini (Ed.), *Leonardo e la cultura senese. Tracce di reciproche influenze. Atti delle Giornate di studio* (pp. 129-139). Siena, 29-30 Novembre 2019. Betti Editrice.

Merrill, E. (2020). Fifteenth-century sienese model books and the origins of Francesco di Giorgio's Codicetto. *Journal of the Warburg and Courtauld Institutes, LXXXIII*, 37-80. Retrieved from https://doi.org/10.1086/JWCI83010037

Mussini, M. (1991). Il trattato di Francesco di Giorgio e Leonardo: Il Codice Estense restituito (The treatise by Francesco di Giorgio and Leonardo: The Estense Codex restored). Università di Parma, Istituto di storia dell'arte.

Prager, F., & Scaglia, G. (1972). *Mariano Taccola and his book "De Ingeneis".* Cambridge: The MIT Press.

Valturio, R., Lessing J. Rosenwald Collection, & Franck, P. (n.d.). *De Re Militari.* [3d Quarter of 15th Cent] [Manuscript/Mixed Material] Library of Congress. Retrieved from https://www.loc.gov/item/2011655080/