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Blaise Pascal's Mechanical Calculator: Geometric Modelling and Virtual Reconstruction

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Abstract: This article shows the three-dimensional (3D) modelling and virtual reconstruction of the first mechanical calculating machine used for accounting purposes designed by Blaise Pascal in 1642. To obtain the 3D CAD (computer-aided design) model and the geometric documentation of said invention, CATIA V5 R20 software has been used. The starting materials for this research, mainly the plans of this arithmetic machine, are collected in the volumes *Oeuvres de Blaise Pascal* published in 1779. Sketches of said machine are found therein that lack scale, are not dimensioned and certain details are absent; that is, they were not drawn with precision in terms of their measurements and proportions, but they do provide qualitative information on the shape and mechanism of the machine. Thanks to the three-dimensional modelling carried out; it has been possible to explain in detail both its operation and the final assembly of the invention, made from the assemblies of its different subsets. In this way, the reader of the manuscript is brought closer to the perfect understanding of the workings of a machine that constituted a major milestone in the technological development of the time.

Keywords: Blaise Pascal; mechanical calculator; CATIA; geometric modelling; virtual reconstruction

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1. Introduction

Blaise Pascal was a seventeenth-century French mathematician, physicist, theologian and philosopher who made a notable contribution to mathematics and natural history. In particular, he designed and built mechanical calculators, one of which being the first mechanical calculator used for accounting purposes, called Pascaline [1,2]. Pascal developed this mechanical calculator to facilitate the laborious arithmetic calculations of his father Étienne Pascal's job as a tax inspector in Rouen (France). The purpose of the machine was to add and subtract two numbers directly and to carry out multiplication and division by repeated addition or subtraction. It is, therefore, an automatic computing system that returns the result of an arithmetic operation based on a mechanical principle [3,4].

In the seventeenth century, the currency in circulation in France was the livre, which was equivalent to the franc. The division and subdivision of this currency were the sous (sols) and the denarii (deniers), whereby one livre was equivalent to 20 sous, and the sou to 12 denarii. This monetary system came from medieval times and was adopted by the Carolingian Empire and spread throughout Western Europe. It remained in France until the 1789 revolution [5]. Therefore, Pascal designed his accounting calculator taking into account these divisions and subdivisions, and did not limit to the decimal system, although he also subsequently manufactured machines with only decimal divisions.

Pascal built more than 50 original machines of which only 9 have been preserved, most of which are on display to the public in museums. Four of them can be found in the Musée des Arts et Métiers in Paris: two eight-digit accounting calculators, a six-digit decimal calculator and a six-digit accounting calculator that was assembled in the eighteenth century from original parts; two original calculators are exhibited at the Musée d'Historie Naturelle Henri-Lecoq in Clermont-Ferrand: an eight-digit decimal and a five-digit countable, which is the smallest of all preserved machines and the only one that has a box that facilitates its transport. In the Mathematisch-Physikalischer Salon in Dresden (Germany), there is an eight-digit accounting calculator. Finally, the two remaining calculators are in private collections, IBM's and Léon Parcé's [6].

The eight-digit accounting calculator found in the Mathematisch-Physikalischer Salon in Dresden is the most important reference of the model presented in this manuscript, measuring 10 cm in height, 44.5 cm in width and 14.7 cm in depth, and the materials used are brass, wood and paper as are most of the specimens exhibited today [7].

During the attempted commercialisation of the Pascaline machine, Pascal became aware of the existence of counterfeits. To remedy this situation, all manufactured copies henceforth included his signature and the inscription "Esto probati instrumenti symbolum hoc.; Blasius Pascal; arvernus, inventor, 20 Mai 1652", which means" Let this signature be the sign of a verified machine. Blaise Pascal of Auvergne, Inventor, 20 May, 1652" [3]. Today, some of the replicas of these originals are currently exhibited in museums [8], although there are also versions made manually by artisans in modern workshops using the same techniques and materials of the time, such as brass and mahogany, which faithfully reproduce the principles of the scientific Pascaline [9].

The present investigation pursues the study of historical machines that have made a notable contribution to the technological development of computing [6], such as the Pascaline, designed by Blaise Pascal in 1642 at the tender age of 19, and the Antikythera Mechanism, an ancient analogue calculator [10].

To this end, said historical invention is analysed from the point of view of engineering graphics to obtain its three-dimensional (3D) geometric modelling and virtual reconstruction by following a methodology established in previous work by the authors [11–17]. Likewise, as a first step in the study and recovery of the technical historical heritage, the 3D model is required. To this end, CAD (computer-aided design) techniques have provided fundamental support in numerous investigations related to various machines [18–21] that follow the objectives set out in the document Principles of Seville [22] on virtual archaeology, which in turn cites the London Charter [23] regarding the computer-based visualisation of cultural heritage.

The objective pursued by this research has been to obtain a reliable 3D CAD model that allows the reader to understand the importance of this invention from an engineering point of view. Likewise, this model can help in the conservation of this example of the technical historical heritage since it will allow having a model to carry out future studies and develop applications in a virtual environment. The innovation presented in this research is due to the fact that there is no 3D CAD model with this degree of detail, which will help to fully understand the operation of said historical invention.

As future uses of this 3D CAD model, the following stand out:

- The possibility of developing user interaction applications that allow knowing the operation of the invention, detailed knowledge of each of its components or the materials from which they were manufactured.
- The possibility of incorporating its WebGL model into a website.
- The possibility of obtaining realistic virtual recreations for public display or printing said 3D CAD model using additive manufacturing techniques.

The remainder of this paper is as follows: in Section 2, the materials and methods are presented, and in Section 3, the results of the modelling process of said historical invention are presented, explaining in detail its operation and graphically showing its main subsets and how they have been assembled. Finally, in Section 4, concluding remarks are presented.

2. Materials and Methods

The initial materials for this research, mainly in the form of the plans of this arithmetic machine, are collected in the *Oeuvres de Blaise Pascal* volumes published in 1779 [24]. Sketches of said machine are found therein that lack scale, are not dimensioned and certain details are absent; that is, they were not drawn with precision in terms of their measurements and proportions, but they do provide qualitative information on the shape and mechanism of the machine.

These sketches consist of six projections (views) of the Pascaline: the first includes the top view of the machine; the second shows a perspective of the interior; in the third, the left view is shown with a transparency effect, thereby visualising the mechanism of internal gears; and the last three are front or perspective views of certain subsets of the mechanism on which the operation is based.

The methodology followed has been supported by parametric 3D CAD modelling, based on the knowledge of descriptive geometry and on empirical techniques of direct measurement. To this end, known measurements of the machines currently preserved have been taken that have enabled the graphic scale of the plans to be ascertained in order to model each of its elements. Therefore, in order to compose the 3D CAD model of Pascaline, the sketches were studied for the completion of the analysis of the form and function of all its components, together with the observation of images and descriptions of the preserved specimens. Likewise, in order to model the details absent from their plans, the necessary assumptions were adopted so that the result would be consistent with the material available and it would fulfil the required functionality.

The 3D modelling shown in the present investigation, therefore, adheres to the prototype collected in the plans of the original work, and hence to the machines preserved today that best fit these plans.

Finally, thanks to CATIA V5 R20 software, the modelling of each piece and its subsequent assembly was carried out, thereby establishing the corresponding geometric, dimensional and movement restrictions (degrees of freedom) [25]. The parts were modelled defining 2D dimensioned profiles using the Sketch tool in the Part Design module available at CATIA V5 R20. Subsequently, from the 2D sketches, 3D models were obtained using extrusion (Pad), emptying (Pocket) or revolution (Shaft) operations, among others. On the other hand, some of the parts are metal sheets, and the Sheet Metal Design module was used for their modelling, which allowed sheet metal bending operations such as Bend from Flat or Tear Drop. Once all the parts had been modelled, the assembly was carried out in an orderly manner, first in sub-sets and, from them, the complete model of the machine was formed.

Figure 1 shows the steps followed in the modelling process. Throughout the process, the dimensions, geometry, materials, as well as distribution and degrees of freedom of the parts in the model were those that appear in the plans and similar to the exposed machines, thus obtaining a reliable 3D model of the arithmetic machine designed by Pascal.

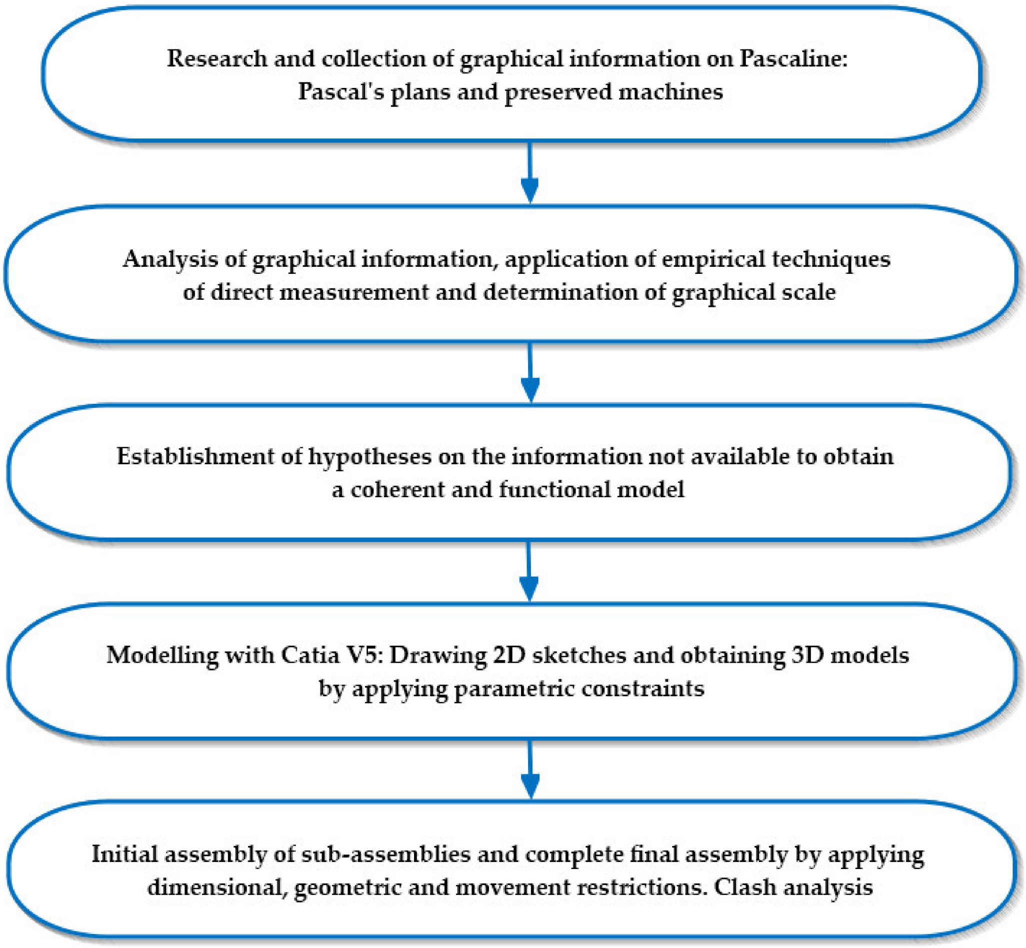


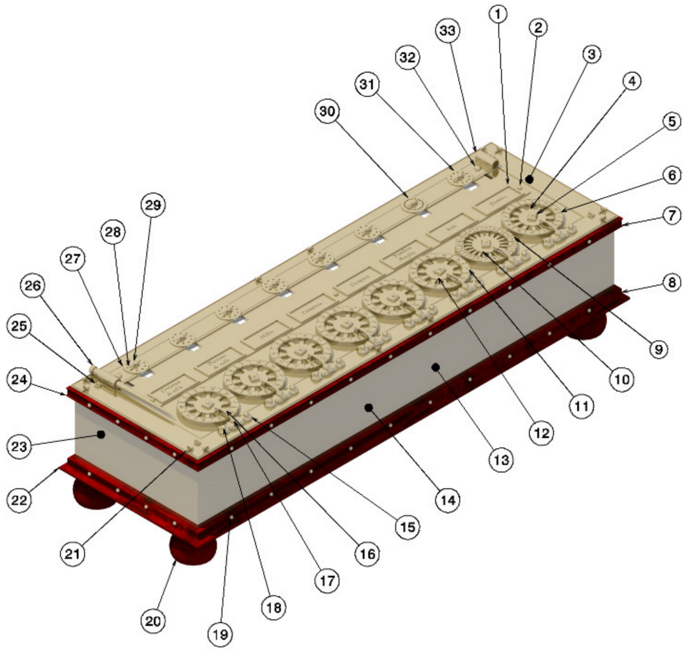
Figure 1. Flowchart in the modelling process.

3. Results and Discussion

3.1. Considerations and Operation

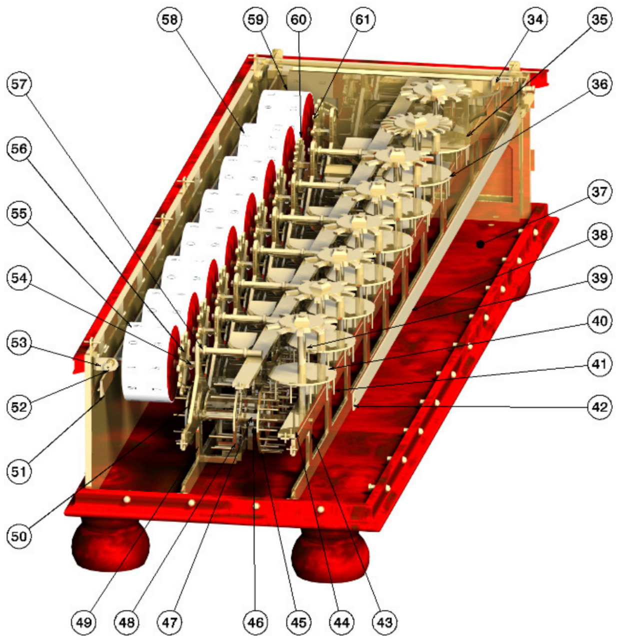
In accordance with the information collected in plans and images and after having studied the mechanism, the Pascaline was modelled using CATIA V5 R20 software, with external measurements similar to those of the surviving machines, in such a way that they were also in accordance with the proportions observed in the plans. The model presents a height of 105 mm, and its base is 135 mm deep and 445 mm wide. Once the external measurements had been established, scales were adopted from the different sketches for the congruent modelling of all the elements.

With Pascal's arithmetic machine, both additions and subtractions could be carried out automatically, thanks to its mechanical system for the carry required in this type of operation. In order to provide a detailed explanation of the operation of said machine, Figures 2–4 are used, which are three assembly plans where the model is presented with its list of elements. Figure 2 contains a perspective of the exterior of the machine. In Figure 3, the internal part is viewed through the transparency of the front panels (13) and (14), the side panel (23), the upper edges (7) and (24), the left-hand lateral structure (34) and the lid (3) with all its elements. In Figure 4, the previous transparencies are maintained, and those of other interior elements are added to render the most internal parts of the Pascaline visible, thereby defining their location in the assembly.



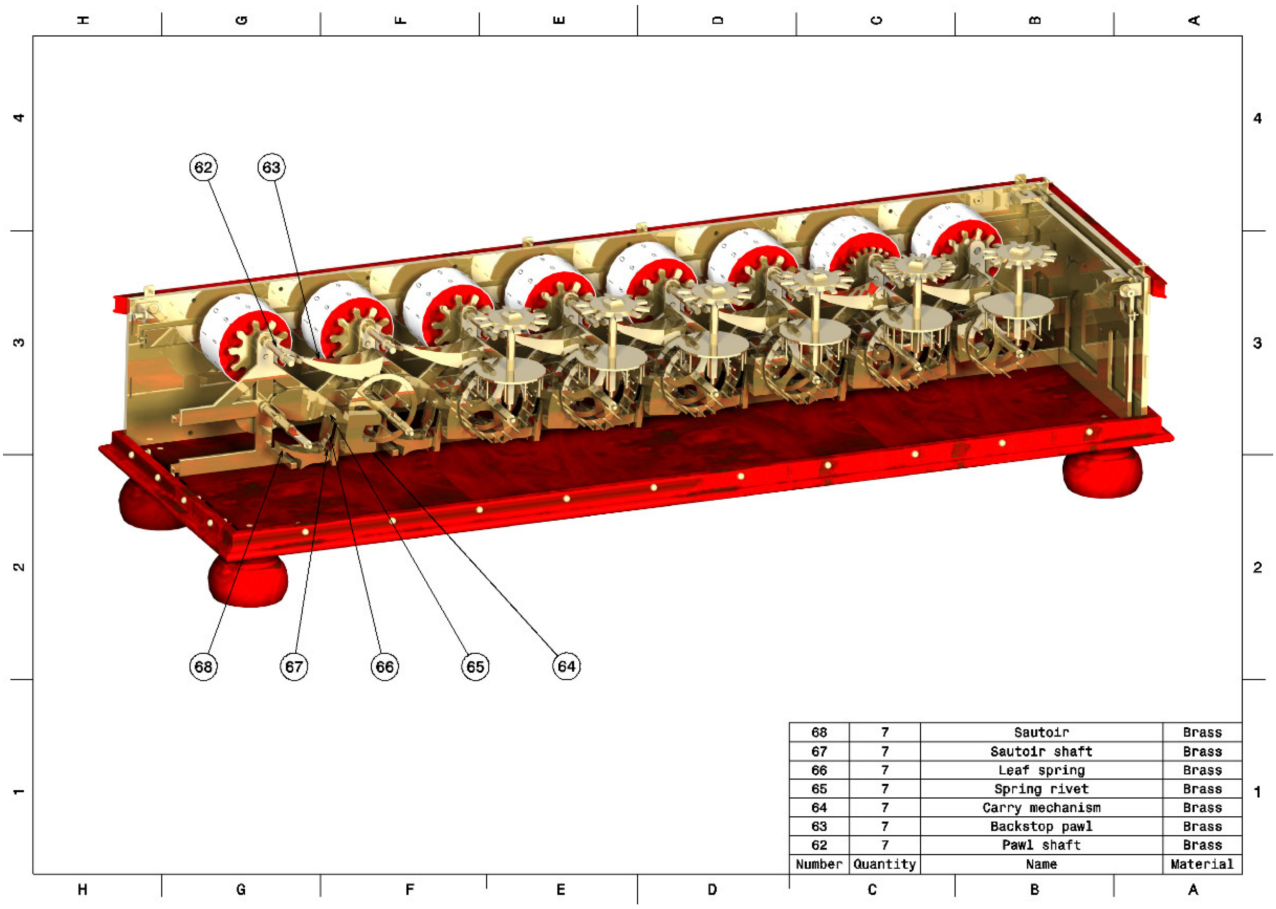
Number	Quantity	Name	Material
33	1	Sliding panel	Brass
32	2	Sliding panel shaft	Brass
31	1	12-point wheel	Brass
30	1	20-point wheel	Brass
29	8	Pointer rotating rivet	Brass
28	8	Marker/pointer cylinder	Brass
27	6	10-point wheel	Brass
26	1	Stylus	Brass
25	4	Cover-fixing screw	Brass
24	2	Upper short edge	Wood
23	2	Side panel	Brass
22	2	Lower short edge	Wood
21	12	Panel pin	Brass
20	4	Box foot	Wood
19	28	Edge rivet	Brass
18	16	Indicator lateral rivet	Brass
17	8	Indicator central rivet	Brass
16	8	Stop bar	Brass
15	8	Indicator base	Brass
14	2	Left-hand front panel	Brass
13	2	Right-hand front panel	Brass
12	6	10-point input wheel	Brass
11	6	10-point numbered crown	Brass
10	1	20-point input wheel	Brass
9	1	20-point numbered crown	Brass
8	2	Lower long edge	Wood
7	2	Upper long edge	Wood
6	1	12-point numbered crown	Brass
5	8	Wheel nut	Brass
4	1	12-point input wheel	Brass
3	1	Lid	Brass
2	2	Information panel rivet	Brass
1	1	Information panel	Brass

Figure 2. Assembly plan for the Pascaline (Elements 1–33).



Number	Quantity	Name	Material
61	1	12-point output gear	Brass
60	1	20-point output gear	Brass
59	1	12-point output drum	Wood and paper
58	1	20-point output drum	Wood and paper
57	124	Retaining washer	Brass
56	6	Output gear	Brass
55	6	10-point output drum	Wood and paper
54	8	Output drum shaft	Brass
53	4	Panel reinforcement	Brass
52	8	Reinforcement rivet	Brass
51	8	Drum support bar	Brass
50	8	Third accumulator gear	Brass
49	1	Main support structure	Brass
48	8	Intermediate accumulator gear	Brass
47	8	Accumulator shaft	Brass
46	16	Intermediate bars	Brass
45	8	First accumulator gear	Brass
44	1	Input shaft support bar	Brass
43	1	Accumulator support structure	Brass
42	16	Frame pin	Brass
41	368	Gear tooth	Brass
40	6	10-point input gear	Brass
39	8	Input shaft	Brass
38	1	Front bar of the structure	Brass
37	1	Box base	Wood
36	1	20-point input gear	Brass
35	6	12-point input gear	Brass
34	2	Lateral structure	Brass

Figure 3. Assembly plan of the interior of the Pascaline using transparencies of the lid, and side and front panels (Elements 34–61).



Number	Quantity	Name	Material
68	7	Sautoir	Brass
67	7	Sautoir shaft	Brass
66	7	Leaf spring	Brass
65	7	Spring rivet	Brass
64	7	Carry mechanism	Brass
63	7	Backstop pawl	Brass
62	7	Pawl shaft	Brass

Figure 4. Assembly plan of the interior of the Pascaline with added transparency of input wheels and accumulators of the highest levels (Elements 62–68).

As mentioned above, the Pascaline was designed for calculations for accounting purposes, and hence the machine has all the necessary elements to work with the monetary system of the time integrated into its mechanism. Its use for accounting is reflected in the information panel (1) found in the central part of the lid (3). This panel has an informative function and has eight engravings that indicate from right to left: deniers (denarii), sols (sous), nombres simples (units), dixaines (tens), centeines (hundreds), milles (thousands), dixaines de mille (tens of thousands) and centeines de mille (hundreds of thousands). These engravings divide the machine into eight strips, called levels, each dedicated to the positional value indicated on the inscription.

The lower part of the lid (3) is the input area where the user enters the addends. In this area, there are eight toothed input wheels located under the eight markings on the information panel (1) that determine, as indicated, their positional value. The first wheel (4), starting from the right, has 12 teeth, and is intended for the introduction of the number of denarii that follow a duodecimal system, whereby 12 denarii constitute a sou. The second wheel (10), with 20 teeth, corresponds to the number of sous that follow a vigesimal system, in which 20 sous constitute one livre. Finally, the next six wheels (12) are all equal to 10 teeth, and range from units to hundreds of thousands of livres, all following a decimal system.

Around each of the input wheels is a numbered circular crown: the first, starting from the right (6), has the numbers from 0 to 11 engraved for denarii; the second (9), from 0 to 19 for sous and the next six (11) from 0 to 9 for livres and their decimal multiples. An element appears under each crown, called the stop bar (16), whose function is to facilitate the incorporation of numbers into the machine.

In order to perform addition with Pascal's machine, the initial step is to enter the first addend. To this end, the input wheels (4), (10) and (12) are used, which are necessary for the inclusion of all the figures that make up the addend. Each digit must be incorporated in the pertinent place indicated on the information panel (1). To carry out its input, the number is located on the corresponding crowns (6), (9) and (11), and the stylus (26) is placed between the teeth located next to it, as indicated in Figure 5. With the help of the stylus, the wheel is rotated clockwise until it touches the stop bar (16). In this way, the teeth of the input wheel have been moved as many positions as indicated by the input number.

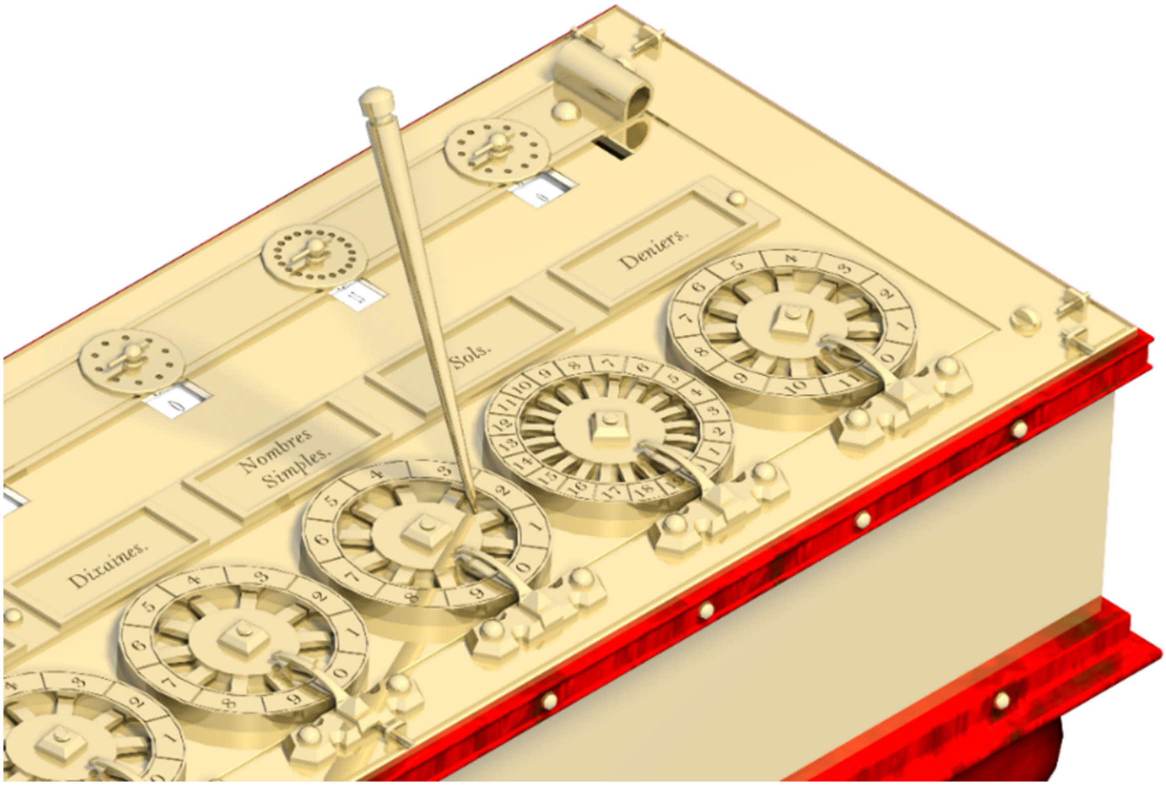


Figure 5. Addend input method.

The lid (3) has rectangular perforations, called windows, in the upper part, which reveal the output drums inside the box (55), (58) and (59); these show the result of the operation. These drums are cylindrical in shape with the numbers corresponding to the possible values of each level printed on their lateral surface; that is, the numbers from 0 to 9 are drawn on those level drums under the decimal system (55), from 0 to 19 for the drum corresponding to sous (58) and from 0 to 11 for the drum of denarii (59). Likewise, there are two rows of numbers printed on each drum: the lower row in ascending order and the upper row in descending order, either one of which can be employed depending on the operation performed (addition or subtraction, respectively). Above the perforated windows in the lid, there is a sliding panel (33) that can slide over these windows in such a way as to reveal either the ascending or descending row of numbers inscribed on the drums. Therefore, this panel is used to select the desired operation in the calculation. The operation of addition is first explained, followed by the explanation of the operation of the machine for subtraction.

By entering the first addend, it can be observed that this number is registered in the windows. The input wheels and the output drums communicate inside the machine by means of a gear train in such a way that a rotation of the input wheel of a certain level produces the same rotation of the corresponding drum.

The type of gear used by Pascal is the so-called lantern gear; its teeth (41) have a circular profile, which obtains a cylindrical shape, and are arranged in a circle so that their axes are parallel to the axle of the wheel. This type of gear was widely used in ancient times.

Figure 6 shows, in greater detail, the gear train responsible for transmitting motion from input to output on one level. Said gear train is made up of four gears. The first input gear (40) is attached to the same shaft (39) as the input wheel (12), thereby forming a rigid sub-assembly. This gear fits with another sub-assembly called the accumulator, formed of three gears, (45), (48) and (50), coupled on the accumulator shaft (47); however, the intermediate gear (48) is destined for another function, as detailed later, and hence it does not participate in the transmission of movement at the output. Finally, the gear train ends with another sub-assembly formed of an output gear (56) connected by means of a shaft (54) to the output drum (55). These three subsets link the input and output of each level, transmitting the information entered from one point to another.

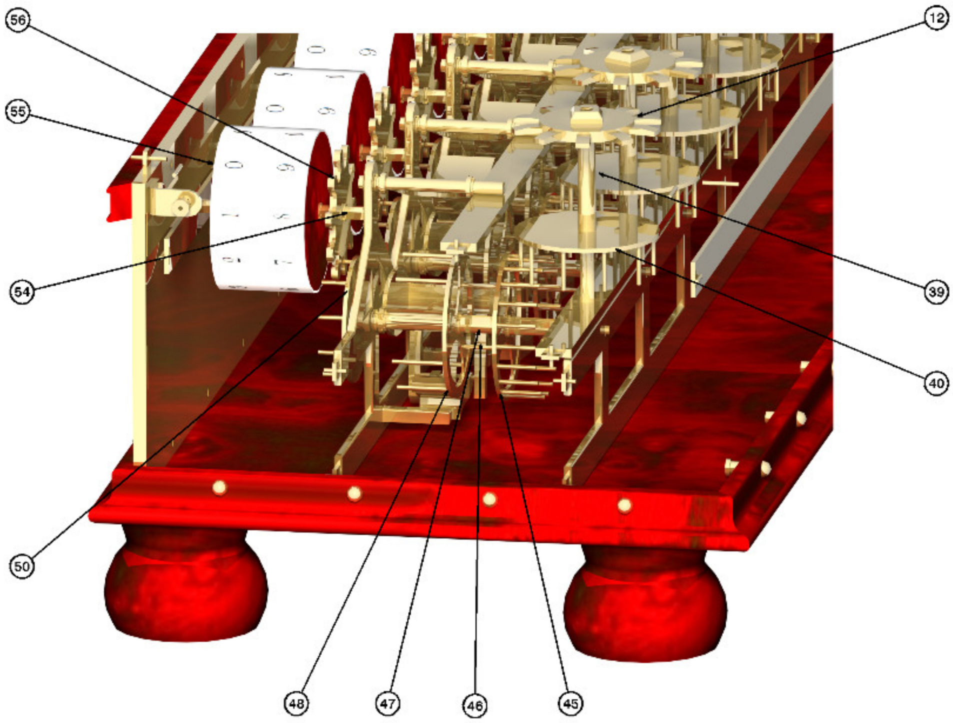


Figure 6. Zoomed representation of the mechanism showed in Figure 3.

Once the first addend has been entered, the process is repeated to add the rest of the addends in such a way that these are accumulated in the output drum, thereby providing the result of the sum. When a drum makes a complete turn, this means exceeding the largest quantity available in that position (9 for the decimal system, 11 for duodecimal and 19 for vigesimal), and therefore a unit must be added to the level above. A series of elements that communicate the gear trains of each level and their consecutive level forces the value in the upper level to increase by one unit. The coupling responsible for the carry is formed mainly by a part called the carry mechanism (64), a leaf spring (66) and a sautoir (68). The method for transmitting the movement is based on the weight of this sub-assembly, which is supported on intermediate bars (46) that join the first two gears of the level accumulator that performs the complete rotation. At the completion of one turn, the carry mechanism (64) falls, and the sautoir (68) attached to it drives the teeth of the intermediate gear of the accumulator (48) of the next level, causing its rotation and hence the gear train of the upper level advances one position. The sautoir (68) is allowed to rotate with respect to a shaft (67); that is, it has a degree of freedom of movement with respect to the carry mechanism (64). The function of the leaf spring (66) in this sub-assembly is to keep this piece (68) coupled to the teeth of the intermediate gear of the upper-level accumulator, and, thanks to this system, the sautoir remains adapted at all times to the gear. In addition to all the parts of the mechanism described above, the Pascaline also has a backstop pawl (63) at each level that is supported on the intermediate gear of the accumulator (48), which prevents its backward movement and, therefore, the backward movement of the entire mechanism.

Pascal's arithmetic machine does not have an automatic zero setting, but instead, to restart the machine, the input wheels (4), (10) and (12) has to be turned until the zero appears in each of the outlet drums (55), (58) and (59).

On the other hand, the procedure to calculate a subtraction is similar to that carried out for addition but with certain nuances. First of all, the slat that forms the sliding panel (33) has to be slid downwards over the windows of the lid (3) so that the descending numerical row of the output drums (55), (58) and (59) become visible. The direction of rotation of the drum is the same as for addition, but in this case, the numbers decrease since the row with the numbers in decreasing order is visible.

In order to ensure that the procedure of use is the same in both operations, the numbers are placed on the drum in such a way that there is a relationship between the ascending and descending rows of complements to 9 in the case of the decimal system (livres and higher levels), complements to 19 in the case of the vigesimal system (sous) and complements to 12 in the case of the duodecimal system (denarii). The entire operation is therefore based on this add-on system. At the starting point, when the machine is set to zero for the row corresponding to addition, then by sliding the panel (33) to perform a subtraction, the windows corresponding to livres and higher levels show a 9 in the drums, an 11 for the sous window, while the denarii window reveals a 19.

In order to input the minuend, the input wheels have to be rotated until this number appears on the drums. To this end, the amount to be entered is given by the complements of the figures that make up the minuend, complements to 9, 11 or 19, depending on the level. For example, in order to add 240 livres, 15 sous and 8 denarii, the input would be: $11 - 8 = 3$ for denarii, $19 - 15 = 4$ for sous, $9 - 0 = 9$ for livre units, $9 - 4 = 5$ in the tens, $9 - 2 = 7$ in the hundreds and in the remaining wheels would be marked as 9 so that 0 appears on the drums. However, these calculations are not actually necessary if the wheels are turned until the minuend is seen on the drums. For the incorporation of the subtrahend, the procedure is exactly the same as in the introduction of addends. Therefore, since the numerical row of the drum is in descending order, the amount input by turning the input wheels is automatically subtracted from the minuend.

3.2. *Modelling of Elements and Assembly of Subsets*

The Pascaline was a machine made up of a large number of small parts. The objective of this modelling is to create a representation as exact as possible of the original machine by independently producing all the parts that would have been manufactured in this way for their subsequent assembly. A total of 97 files (CATPart) have been designed, which include the modelling of all the parts that make up the complete machine. To facilitate the understanding of the model, the modelling of the elements is presented as grouped into various subsets that have been established according to their purpose.

3.2.1. Modelling the Internal Mechanism

The internal mechanism can be divided into three sub-assemblies with clearly differentiated functions: the transmission of the main movement carried out by means of a gear train, the carry performed by the carry mechanism and the locking of the backstop by means of a pawl. These three sub-assemblies are closely related by a common element: the accumulator.

The transmission of the main movement would include, in turn, an input sub-assembly, an intermediate sub-assembly and an output sub-assembly. Each of these comprises several elements assembled on the same shaft, held by retaining washers. The input sub-assembly

(Figure 7) comprises a toothed wheel and a lantern gear, the latter composed of a series of cylindrical bars that have been engaged by means of the corresponding constraints on a circular base. This sub-assembly is the user interface, that is, the element with which the user interacts with the machine by turning the upper numbered crown to input the addends.

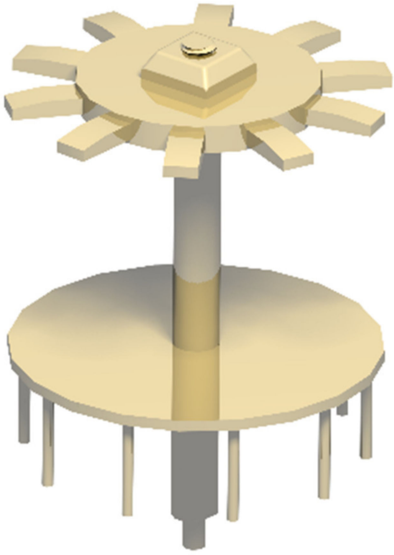


Figure 7. Input sub-assembly.

The intermediate sub-assembly or accumulator (Figure 8) is mainly responsible for transmitting the numbers entered to the output sub-assembly and is composed of several lantern gears. The extreme gears participate in the transmission of the main movement; however, the intermediate gear intervenes in the other two functions of the mechanism, namely, the carry and reverse locking. Between the first gear and the intermediate gear, there are two bars that support the carry mechanism.

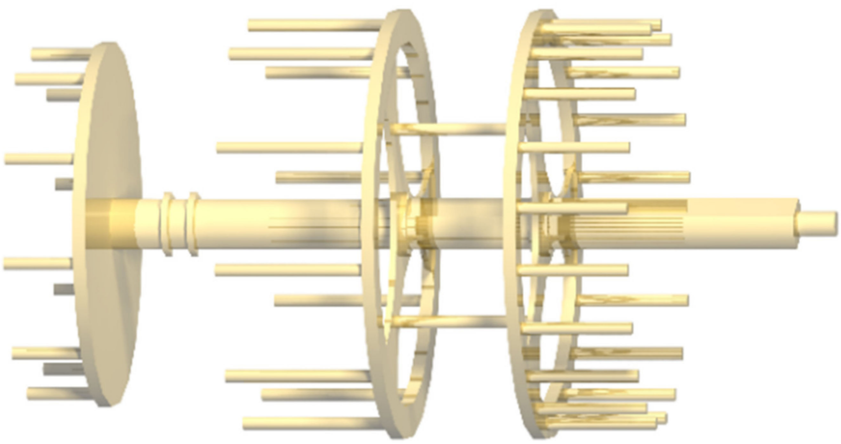


Figure 8. Intermediate sub-assembly or accumulator.

The output sub-assembly (Figure 9) comprises a toothed wheel and the drum: the latter is worthy of mention as a peculiar part in modelling. This is a cylindrical component on whose lateral surface a 3D mapping includes the rows of numbers that provide the result of the operations.

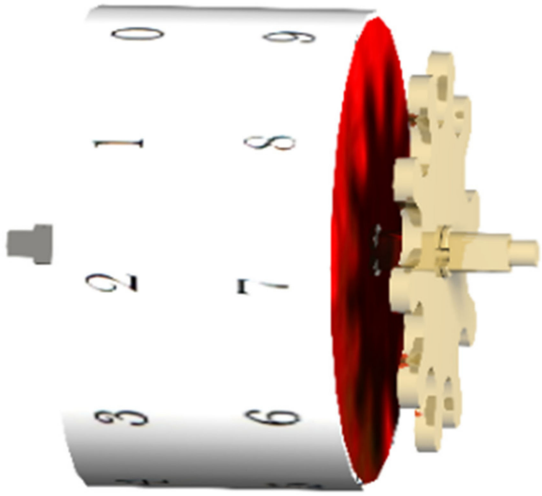


Figure 9. Output sub-assembly.

Figure 10 illustrates the directions of rotation for the transmission of motion between the input and output sub-assemblies.

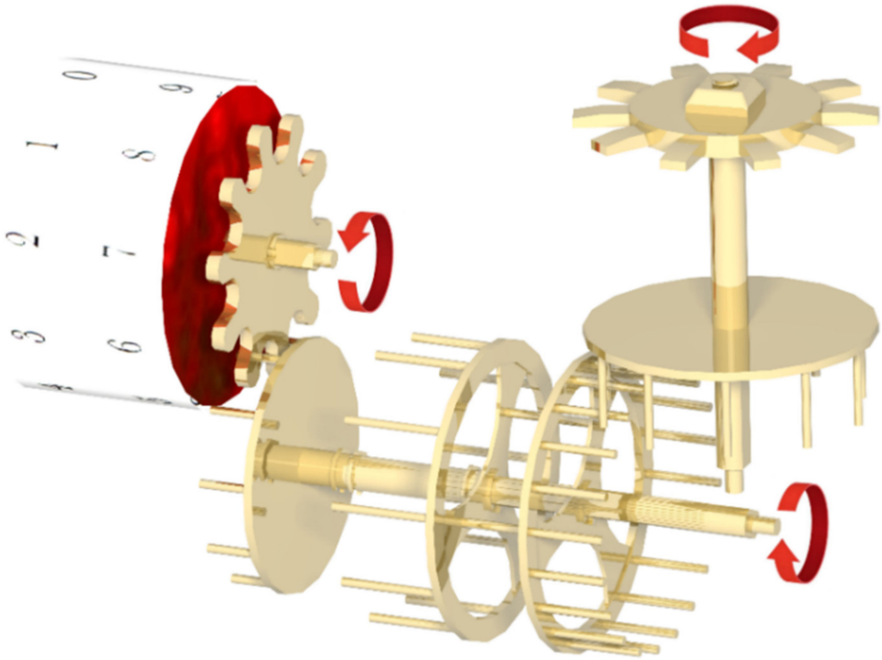


Figure 10. Transmission of the main movement.

Included in the most unique parts to be modelled is the assembly of the pieces (carry mechanism) that are responsible for performing the carry of the operations to the higher level (Figure 11). This is composed of a larger and heavier piece, which is the body of the assembly, a leaf spring, a sautoir, its shaft and the appropriate connecting elements.

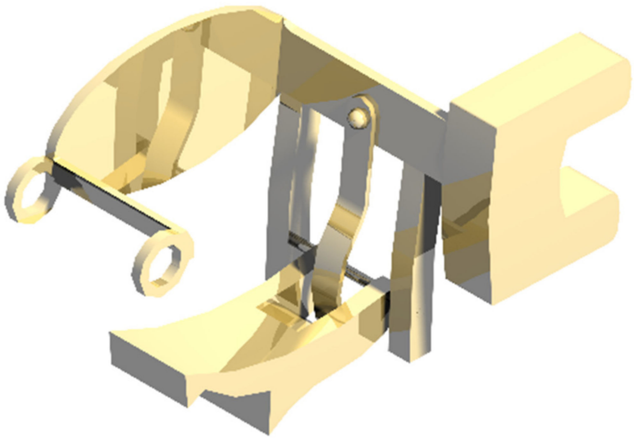


Figure 11. Carry mechanism.

The carry mechanism is assembled on the same shaft as the upper-level accumulator but is able to rotate with respect to said axle. As the numbers of the operations are entered, the accumulator in the lower level rotates. In the final stretch of its circular path, its intermediate bars meet the carry mechanism and begin to lift it. If they complete the turn, they will be at their highest point, at which point they lose contact with the carry mechanism and let it fall. This downward motion causes the sautoir to drive the intermediate gear to the next level. Therefore, the area in which the carry mechanism moves is reduced to a circular sector between its initial position and the highest point to which it is lifted before its fall. Figure 12 shows the contact points of the carry mechanism with the accumulators, with the intermediate bar on the lower level and with the intermediate gear on the upper level. For the sake of visualisation, the first gears of both accumulators have been removed from the figure.

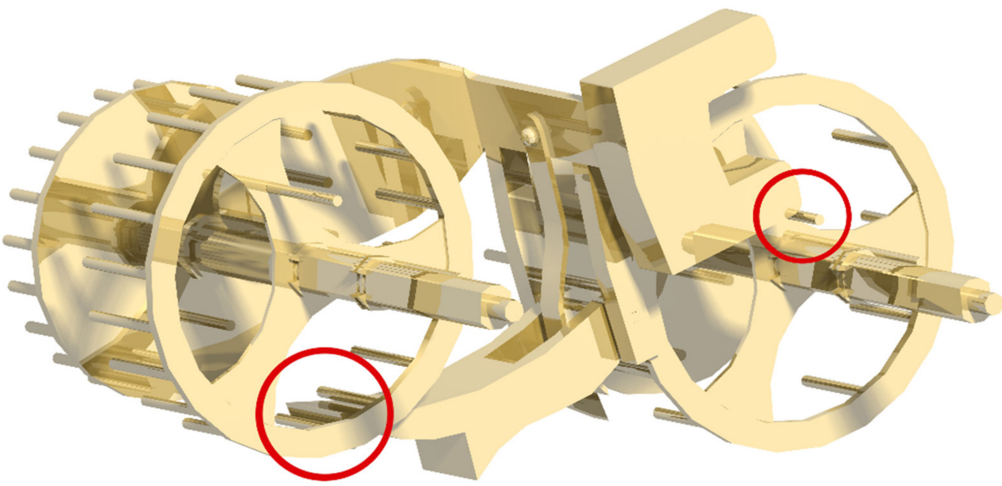


Figure 12. Points of contact of the carry mechanism with the two accumulators.

The leaf spring is a metal sheet that fulfils the function of adjusting the sautoir at all times to the teeth of the intermediate gear of the upper-level accumulator, thanks to the elasticity of the metal, so that when the carry mechanism falls, the part is in the correct position to transmit the movement.

To finish the modelling of the internal mechanism, Figure 13 shows the pawl in charge of preventing recoil at each level, since the Pascaline works in only one direction of rotation.

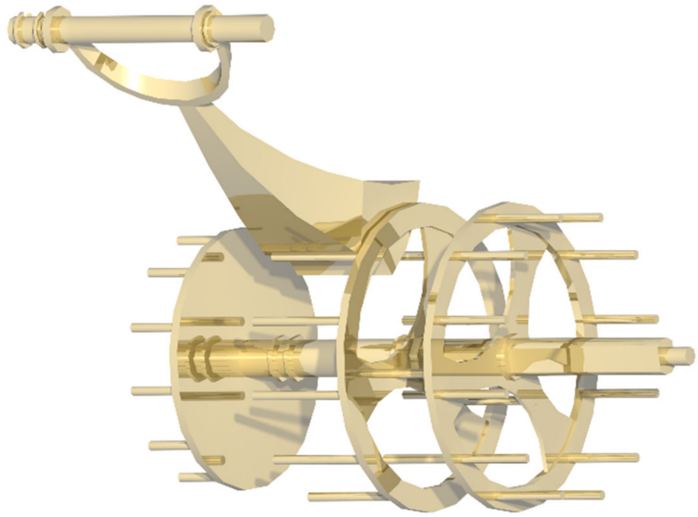


Figure 13. Backstop pawl resting on the accumulator.

Likewise, three different models of each of the sub-assemblies described in the mechanism have been designed in order to adjust their operation to the divisions of the decimal (livre and higher), vigesimal (sous) and duodecimal (denarii) systems.

3.2.2. Modelling of the Structure

The internal structure does not appear fully defined in the plans; the solution adopted herein is that of observing these plans together with the available images of the interior of the replicas shown. The designed structure consists of a series of metal panels, including two transverse panels for the sides and four longitudinal panels that contain the cavities where the axes of the internal mechanism fit in such a way that enables their rotation. The side walls have flanges where the lid is supported and fixed, and the panels of the structure are fixed by means of pins (Figure 14).

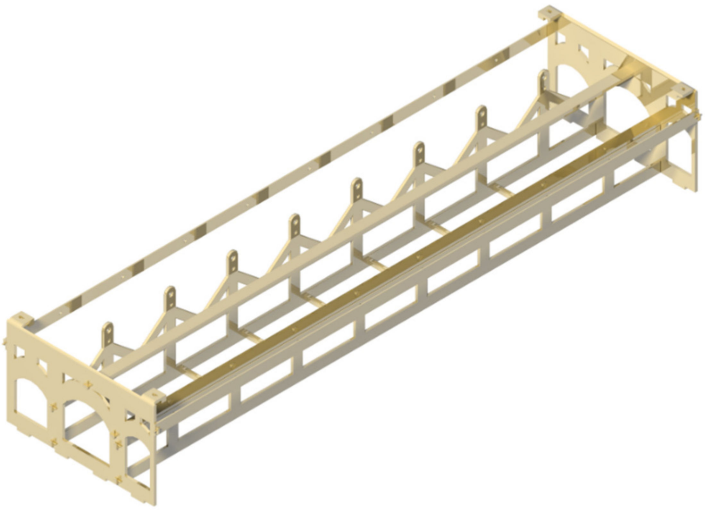


Figure 14. Structure of the assembled Pascaline.

Certain bars should be borne in mind whose function is to stop the carry mechanism when it falls during the carry (Figure 15). These bars are perpendicular to the main support panel that supports the shafts of the sub-assemblies of the backstop pawl, the output drum, the carry mechanism and the accumulator.

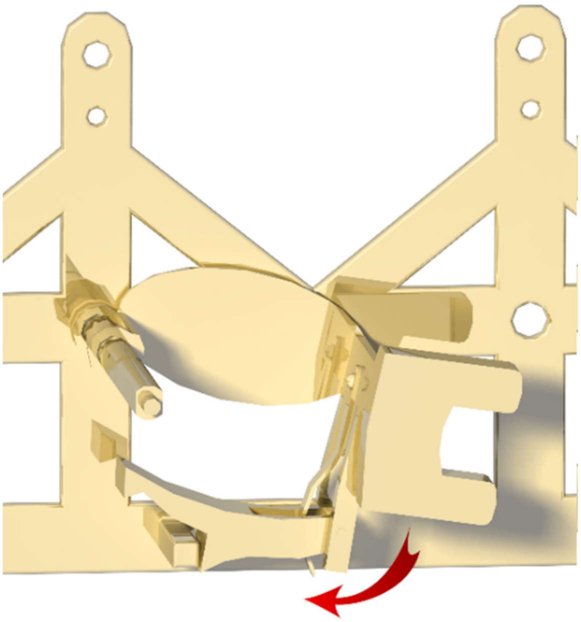


Figure 15. Falling movement of the carry mechanism in its final position with contact at the top of the structure.

In Figure 16, with the mechanism assembled in the frame, the carry mechanism is shown at its highest point when it loses contact with the lower-level bar and falls. The circular sector in which the carry mechanism moves can be observed in greater detail.

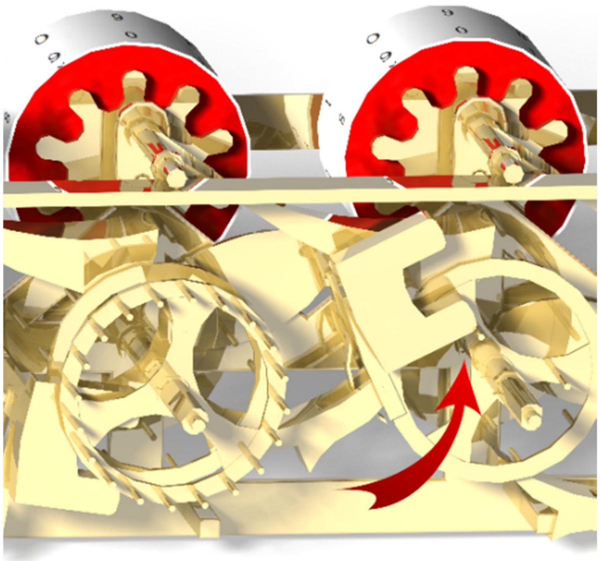


Figure 16. Highest point of upward movement of the carry mechanism.

3.2.3. Modelling of the External Part

The exterior of the Pascaline is box-shaped and consists of a base, panels, edges, feet and a lid, the latter being the most important for its use.

The panels are of sheet metal, and both the base and the feet have been modelled from wood (Figure 17). The panels are attached to the base with nails and have flanges where the lid is secured by means of pins. Likewise, reinforcements are included in the upper corners to fix the walls.

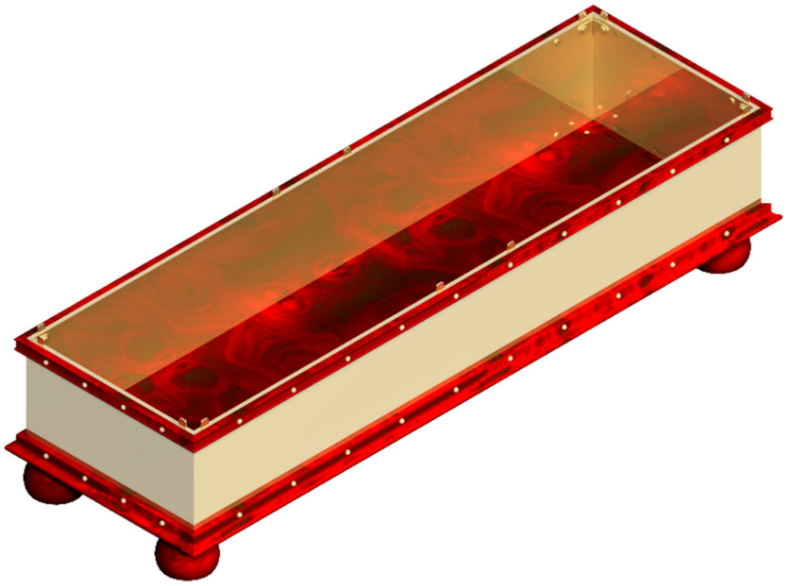


Figure 17. Assembled panels, base, edges and feet.

For the lid, a metal sheet has been modelled in which the necessary rectangular perforations have been made to visualise the two rows of numbers printed on the output drums located inside the machine. The slots and holes have also been made in order to fix the information panel, the numbered crowns, the stop bars, the screws for fastening the lid to the internal structure, the flanges for fastening the panels and the mechanism of the sliding panel with which the operation to be carried out is chosen. Figure 18 shows the sub-assembly formed by the lid and all its pre-assembled components by means of the appropriate constraints.

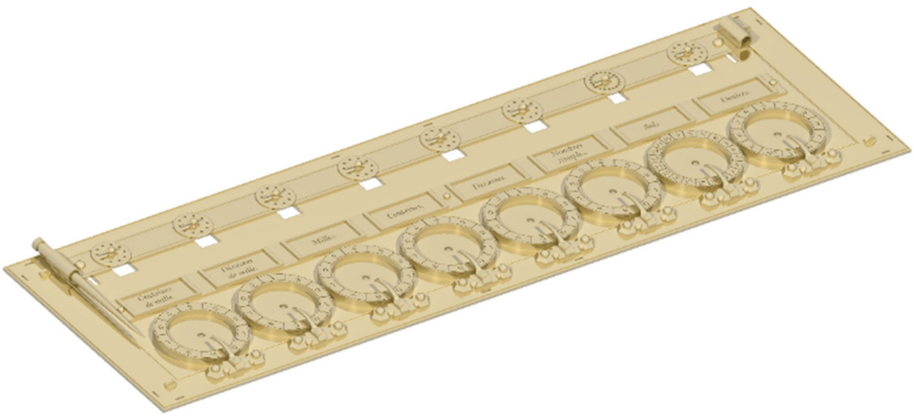


Figure 18. Lid and assembled components.

The numbered crowns and the stop bars, discussed in greater detail in Figure 19, are the elements that facilitate the input of addends. The input wheels described in the mechanism are located on the numbered crowns and connected to the interior of the machine by means of a threaded shaft.

Figure 19. Models of the numbered crowns together with the stop bars in their real relative position.

The sliding panel can slide over the windows that reveal the numbers printed on the output drums by means of shafts inserted into slots drilled in the lid.

In certain machines, the sliding panel contains dials whose purpose cannot be found in the information collected from Pascal. Although they appear on the plans, no function is indicated in the details of the mechanism, and only a few preserved machines contain said dials. In this modelling, the hypothesis has been formulated that their function is to make a type of annotation related to the operations, since not only does each dial present a series of perforations that coincide with the divisions of the level where it is located, but there is also a cylindrical-shaped part that could be rotated to mark one of the positions (Figure 20). In the model, the rotation of the disc on the panel has been prevented so that only the cylindrical part can be moved.

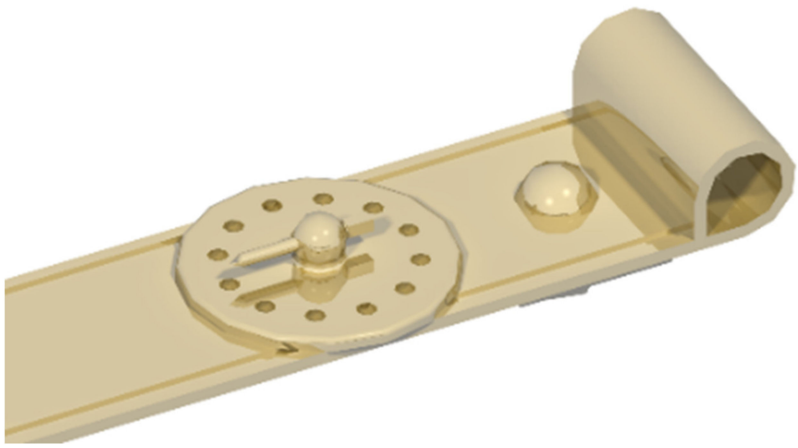


Figure 20. Dial on the sliding panel.

The last part that is included in this model is the stylus. Although this element is not visible in Pascal's plans, it is exhibited in several of the machines on display, and, furthermore, it is considered a useful element for operating the machine. The sliding panel has a cylindrical cavity, produced by bending the sheet, where the stylus is inserted when not in use (Figure 21).

Figure 21. Stylus located in the cylindrical cavity of the sliding panel.

3.3. Final Assembly

The Pascaline contains a large number of small components, and hence, during modelling, the assembly via sub-assemblies has been shown to simplify the final assembly. Figure 22 shows an exploded view of the model in which the division of these subassemblies can be observed.

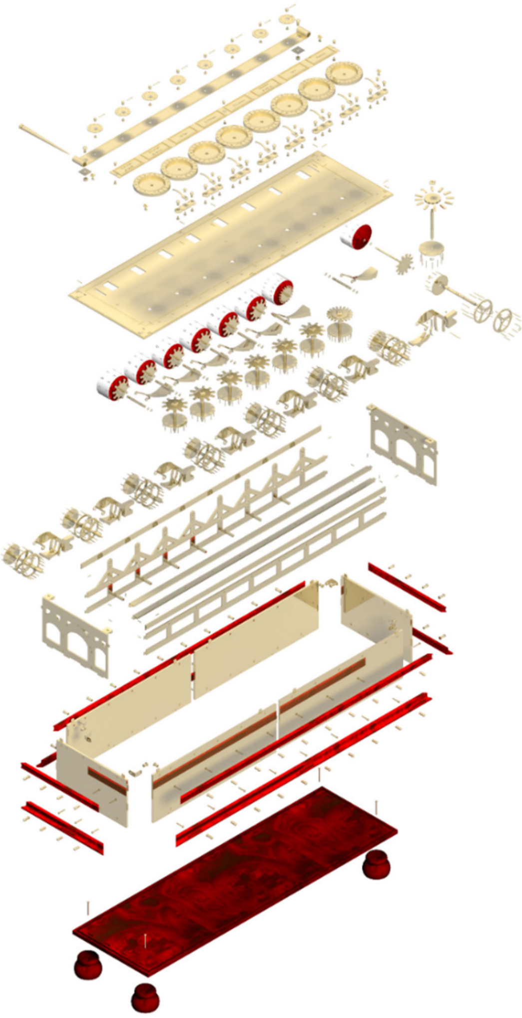


Figure 22. Exploded view of the 3D CAD model of the Pascaline.

All the modelling has been carried out in a coherent way with the location and real movement transmissions between the pieces in order to facilitate their assembly and carry out a future simulation. Certain parts, unspecified in the plans, are designed that so that they fulfil the required functions in their assembly, such as rigid sub-assemblies and sub-assemblies with relative rotations among their elements.

Constraints have been employed in the assembly of the elements, thereby matching axes and/or surfaces. The criterion applied always remains in accordance with the actual allowed and restricted movements, both of the parts that comprise the mechanisms and those of the fixed components, positioning each part in such a way that its degrees of freedom are respected.

The first step in the final assembly process is to insert the elements of the mechanism into the bars of the frame and to fix them. In Figure 23, the complete internal mechanism of the Pascaline is illustrated, with its eight numerical levels assembled in the structure.

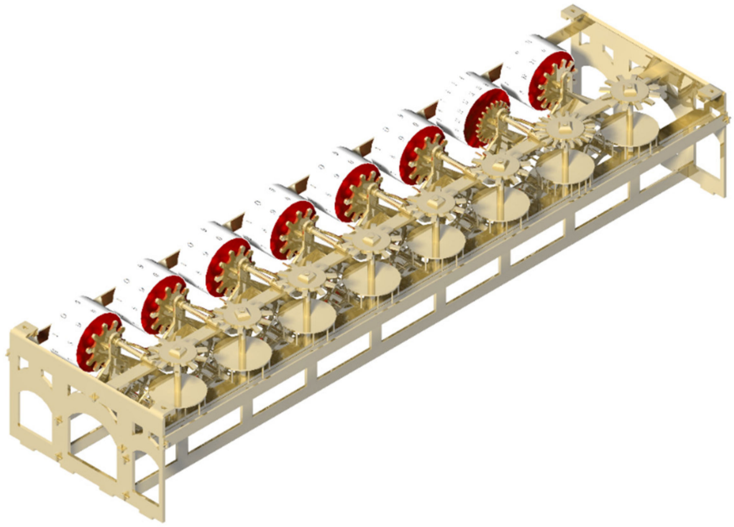


Figure 23. Complete mechanism assembled in the structure.

In Figure 24, the relative location of the lid with respect to the structure can be observed, resting on the side panels to which it will be fixed.

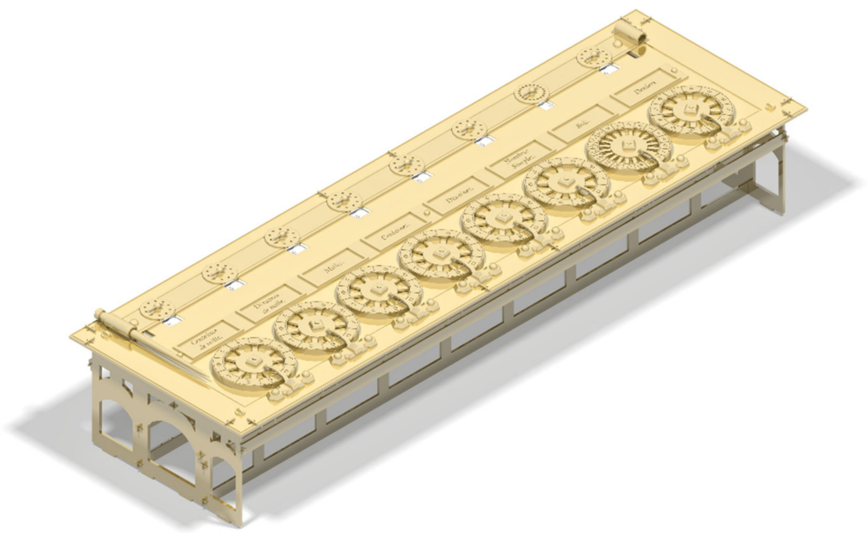


Figure 24. Location of the lid on the structure.

Before positioning the lid, the structure with the mechanism already assembled is inserted into the box (Figures 25 and 26). It must be taken into account that the input wheels actually screw on their axes after fixing the lid since these pieces form the outer part of the mechanism and are located on the crowns, although for simplicity, they are shown herein attached to the internal sub-assembly.

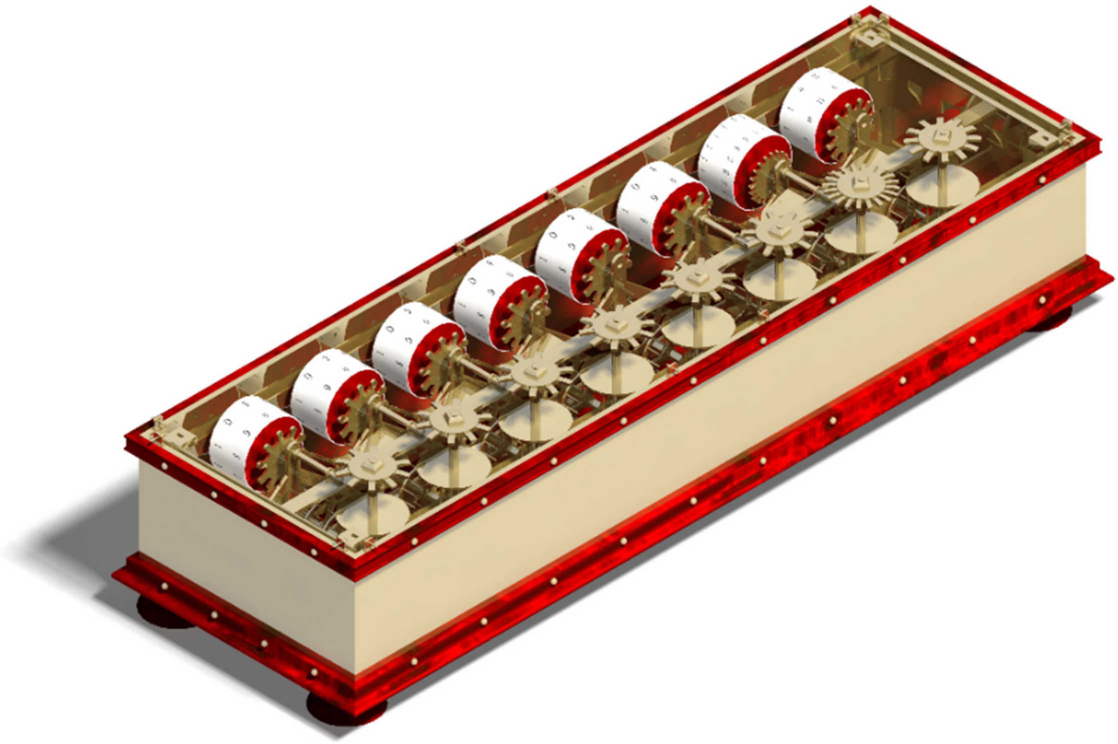


Figure 25. Axonometric view of the Pascaline without its lid.

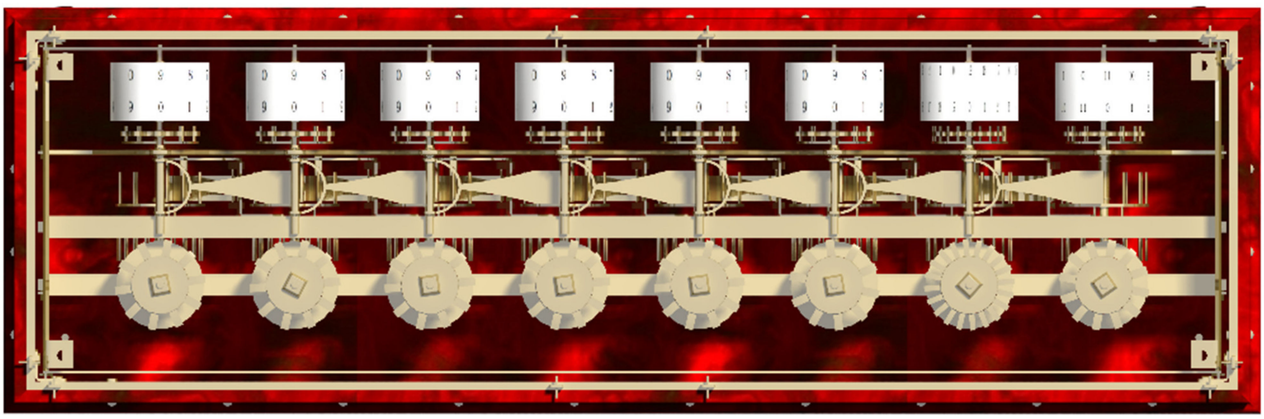


Figure 26. Top view of the Pascaline without its lid.

Figure 27 shows a perspective of the sectioned model, with the levels above the units removed, in order to show the arrangement of the elements in the bars of the structure and their distribution inside the machine in greater detail.

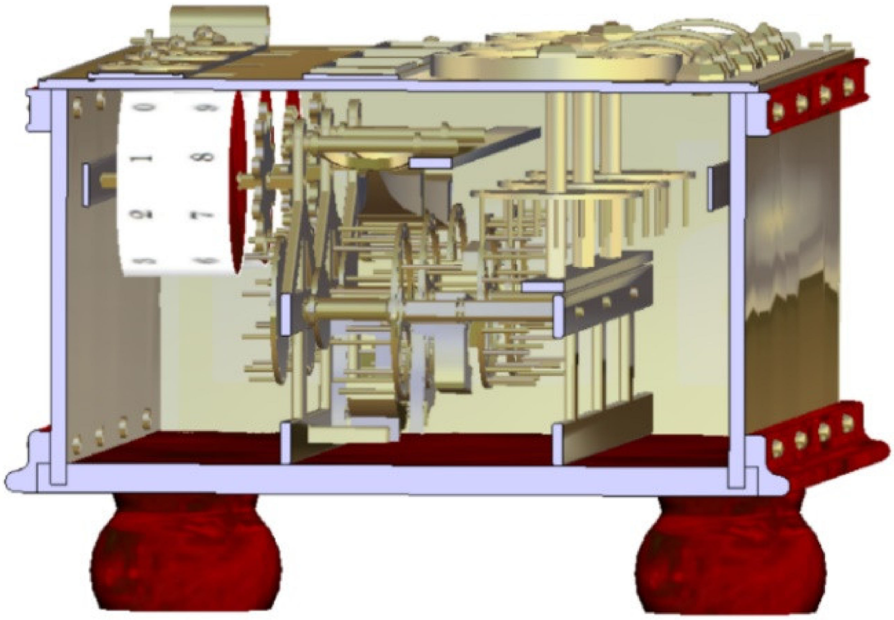


Figure 27. Perspective of the sectioned model.

Finally, an axonometric view of the complete 3D CAD model of the Pascaline can be shown (Figure 28).

Figure 28. Complete 3D CAD model of the Pascaline.

4. Conclusions

Blaise Pascal's Pascaline was the first mechanical automatic calculator in history and represented a breakthrough in the technological development of computing. Despite its flaws, the Pascaline, without doubt, constituted a major initial step on the path to today's computer technology.

The main objective of this research involves obtaining a reliable 3D model of said historical machine by means of CAD techniques using CATIA V5 R20 software from the material available from various written references. Likewise, an investigation has been carried out on the object of study, for which the necessary data is collected for its understanding and modelling. In order to complete the details omitted from the plans, the available images of the machines have also been studied as conserved in various museums.

The methodology employed in this research has involved the application of descriptive geometry and empirical measurement techniques to achieve the 3D model and consequently its virtual reconstruction.

Therefore, after having modelled each element of the assembly, it was necessary to apply various dimensional, geometric and movement restrictions in order to achieve a coherent assembly of each of the sub-assemblies and to obtain a fully functional 3D model.

From said 3D CAD model, it has been possible to obtain the assembly drawings with their indicative list of elements, which has facilitated the detailed explanation of said machine, and to achieve a perfect understanding of its operation, its properties and its capacity. Likewise, a variety of perspectives and views have been obtained that facilitate the understanding of the numerous interior details of the historical invention.

This research methodology can be applied to a multitude of historical inventions studied over the centuries, and it enables us to testify to these major contributions of technology to society by highlighting their legacy thanks to the techniques of modelling and virtual reconstruction.

Finally, and as possible future work, first, a more in-depth simulation of this model with CATIA V5 R20 software could be produced by studying the characteristics and defects of its operation. Second, the 3D models of calculators subsequent to the appearance of the Pascaline could be obtained, thereby carrying out a global project on the evolution of calculating machines throughout history.

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