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A Historical Account on Italian Mechanism Models

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Abstract

This illustration-based paper presents and account of Italian History on the collections mechanism models that were used and still can be used in design, teaching, and research activities not only on research and development of mechanical systems. A conceptual procedure is outlined for the development and use of mechanism models mainly at reduced scaled size. Main Italian collections of mechanism models are introduced with their historical values and current status. Those examples are reported also to show the value of Cultural Heritage that mechanism models and corresponding developments may have as worthful for preservation and understanding of past achievements in mechanism design and its application even in other frames.

Keywords: history of mechanisms; history of mechanical engineering; Italian history of MMS teaching; Italian collections of mechanism models; mechanism models.

Introduction

Modeling and models have been and still are used as basis for activity in acquiring knowledge and implementing results in design and operation of systems in general and more specifically in machines. The study of modeling and models from the historical point of view is generally not approached with adequate attention and in fact specific historical investigations are reported in the literature referring to their evolution but only simple comments are indicated on specific modeling and consequent design solutions only for those machines that had a significant impact on technological

and social developments. Even in the context of the history of machines referring to mechanics teaching and machine design, modeling models are not mentioned as necessary tools for the introduction and explanation of the fundamental concepts for training and for practical issues in design and operation of functional characteristics of machines and mechanisms, so much so that in historical studies models are very rarely mentioned with such a characterization and/or aim, even if only for didactic purposes.

However, sometimes, the History of Science and Technology is also explained by using short mention to models such as in encyclopedic works, like for example in Capocaccia (1973) and Singer *et al.* (2012), and in specific works in conferences and journals, like for example in papers at the HHM symposia like Zhang and Ceccarelli (2019), as well as in teaching activities with some entertainment purposes, as for example with LEGO packages (LEGO, 2019). Some specific attention is addressed to models of mechanisms when their historical values are considered for museum exhibitions and historical temporary shows as an attraction to past developments, as outlined for example in Ceccarelli (2011, 2013 and 2016).

The history of teaching in Italy referring to mechanism design can be outlined looking at the developments in academic sites where machine mechanics was/is taught, as for example in Ceccarelli (2014b). The history of this specific historical development is often attached with an attention to individual figures, who used models on personal basis and experience in each teaching academic frame and therefore, it is difficult to get an overview that the author has partially attempted in the reference Ceccarelli (2016). In the teaching of design and functionality of mechanisms but also in the analysis and definition of the mechanical structures of machines and systems, today in mechatronics domain, the use of modeling and models can be refreshed of particular importance as it can be recognized in the didactic texts where formulations and mathematical modeling as well as calculation procedures for analysis and design are based on graphical schemes that can be also of a virtual nature requiring very often to be validated by models of a physical nature, even in prototype form. In this work an attempt is presented following a previous work in Ceccarelli (2020) to combine an historical study of the teaching of machine mechanics in Italy with the history of the use of models not only for teaching but also for other related activities.

1. Mechanism models

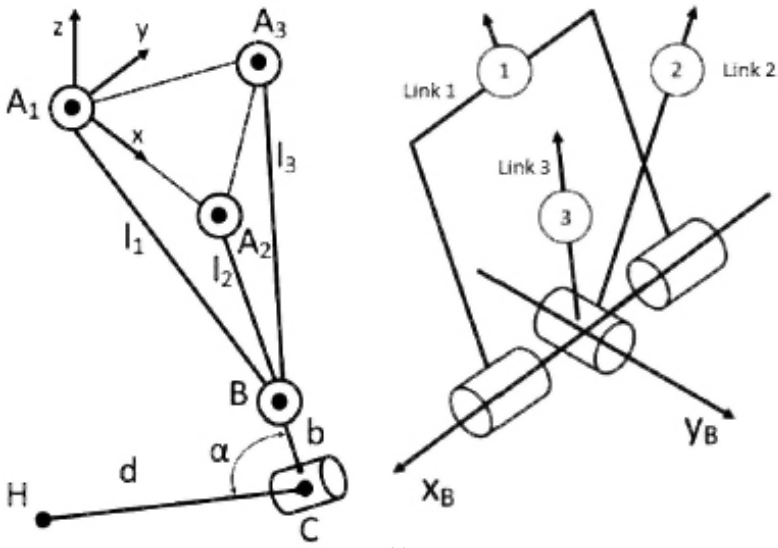
A mechanism is defined in the IFToMM terminology (IFToMM, 2003), as "Constrained system of bodies designed to convert motions of, and

forces on, one or several bodies into motions of, and forces on, the remaining bodies". From the didactic point of view in many texts, such as Lopez-Cajùn and Ceccarelli (2013), and Uicker *et al.* (2017), a mechanism is recognized as a set of rigid bodies or links connected to each other with the aim of converting the mechanical energy input at a different level on an output link. Therefore, the purpose of a mechanism is identified in motion transmission capacity and force transmission capacity with the characteristics of motion generator and action generator, respectively, using the output link according to the characteristic imposed at the input. Thus, in general a mechanism can be considered a key component in a machine design because of its function in converting mechanical energy to a proper level for machine operation as also recognized in Ceccarelli (2018).

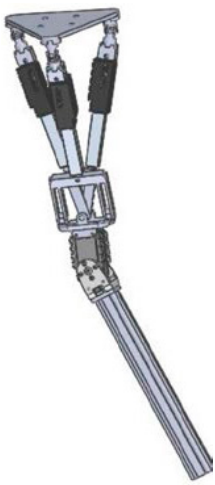
Consequently, a mechanism model is represented with a schematization of the structure and its functions with graphical representations and/or mathematical modeling that can be useful for analysis and simulation of operation and performance in carrying out the task for which the mechanism is designed and then applied. A model is understood as a simplified representation of a system and in the case of a mechanical design it is an ideal representation of the mechanism structure preserving the main mechanical characteristics, as indicated in Ceccarelli (2020).

Considering the above-mentioned understanding for a mechanism model, it is also possible to recognize the modelling of a mechanism useful not only for design purposes but also for explaining the functioning with the peculiar operation performance. Indeed, a mechanism model can be elaborated for design, simulation and exhibition purposes with representations that today span from virtual solutions in computer-oriented software packages to scaled simplified mechanical constructions up to well defined prototypes or demonstrators, even referring to the same design as an evolution of the definition of the solution.

An example of a model of a modern mechanism is illustrated in *Fig. 1* referring to a mechanical design of LARMbot arm for humanoids (Russo & Ceccarelli, 2018; Fort, Ceccarelli, & Laribi, 2022) in which the model is represented as a kinematic diagram in *Fig. 1a*, as a CAD solution in *Fig. 1b* and with a lab prototype in *Fig. 1c*. The kinematic model is aimed both to explain the design structure and basic parameters of the conceived solution, the CAD design is used to define the details of the mechanical design and to analyze the feasibility of its operation, and the prototype is used for design validation and testing the operation performance, with activity spanning from teaching to design up exhibition.



(a)



(b)

(c)

Figure 1. – Example of models for a mechanism solution of a humanoid arm (Russo & Ceccarelli, 2018; Fort, Ceccarelli, & Laribi, 2022): (a) kinematic model for design algorithms; (b) CAD model for mechanical design and simulation; (c) a lab prototype for testing.

As mentioned above, in general, mechanism models are aimed and included in a variety of activities for teaching, study, research, design, demonstrative illustrations and presentations, simulation, validation operation characterization, experimental check, and even promotion and market exhibition. They are used not only for developing mechanical systems, but even as means or part of systems in activities in other disciplines, with similar aims or complementary purposes as for example indicated in Ceccarelli (2012) referring to service applications.

Today mechanism models can be developed as sketches or drawings (by hand or by computer-graphics tools), mechanical constructions either in scaled sizes or prototype structures, and virtual computer-based designs as based on different type of software and visualization with or without human interaction. *Figure 2* outlines the evolution of mechanism models from historical viewpoints looking at technical constructions as linked to achievements and technological means (Ceccarelli, 2020).

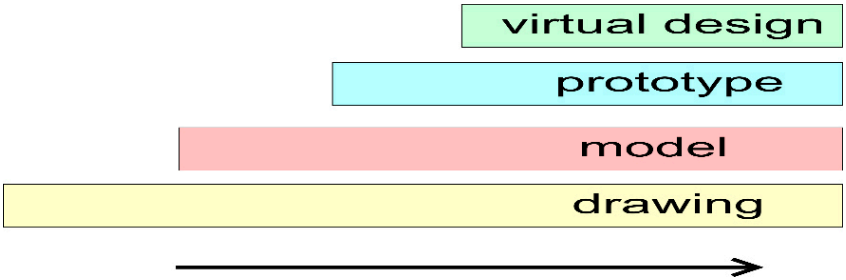


Figure 2. – A timeline of conceptual evolution of mechanism models (Ceccarelli, 2020).

In *Figure 2* the first level of a model refers to a graphical representation in the form of a drawing that since in Antiquity it has been elaborated as drawing schemes containing lot of details. Still today the first ideas are sketched with drawings (either by hand or by graphics software) that can be used as first step of an activity either in explaining or in designing mechanical systems or in developing concepts and solutions. A graphical drawing model can have different formats as well as different levels of accuracy, not only in terms of graphical representation and it is used in many disciplines other than in mechanical design. Over the time those drawing models have evolved from pure line abstraction to naturalistic representation towards technical synthetic standardized drawing languages (see for example isometric views and cross-sections with ruled color for material and lines), as for example referring to gear designs in Ceccarelli and Cigola (2012).

The second level in *Figure 2* named as "model" stresses the modelling as a mechanical model that can lead to a prototype solution for a machine design or an experiment whose phenomenon is to be investigated. Historically for long time mainly during the growing of Science and Technology, model constructions were widely used before proceeding to further activities and, after last decades of the success of Informatics today they have regained significance for a physical experience, mainly with prototypes with full features that are used before final constructions of machine products. in addition, a mechanical model can be formulated with a mathematization that can give highlight of the mechanical characteristics and can be further used both for reiteration in design and teaching explanations of parameters in design and operation issues.

A prototype as a third level model in *Figure 2*, is considered a full solution of a mechanical solution and likewise it can be developed in reduced scale yet. A protype model is understood as a tentative design for a final product and it is often the model by which the design process and the operation performance are validated without having the full products in all its details or manufacturing accuracy, before entering in the market or in approved invention.

Since constructions of mechanical models and prototypes require lot of efforts both in manufacturing and cost, the advent of Computer Science provided alternatives with the fourth level of virtual designs that are developed, operated, and tested with different level of virtuality from simple CAD solutions up to haptic-sensed 3D systems. The virtual models are today extensively used but they can be still developed after an activity which is based on previous levels of modelling, including even a first drawing model, that in last decades was somehow ignored although necessary and indeed worked out. The level of virtual modelling in *Figure 2* emphasizes not only the deepening of functionality analysis using models even for final design products but also aspects concerning with the durability and economic convenience of models including multidisciplinary and integration for different purposes in study, design, and teaching.

The today virtual models are used also to represent the other type of models as an expression of their interesting contents not only in the Science and Technology but also for the History of Mechanical Engineering with a value of Cultural Heritage when design formulation (graphical or mathematical representations) and products are worthful to be preserved, although not completely preserved in the original solutions, as means to show the historical evolution of knowledge and to stimulate inspiration for further developments.

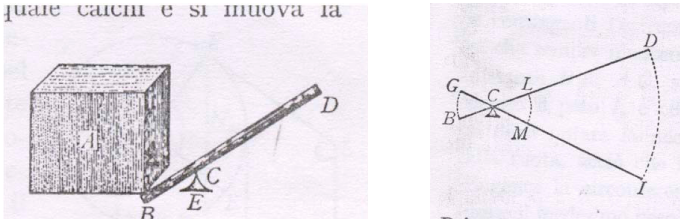
Mechanism models have been and are still developed in different formats as above indicated in *Figure 2* for different aims and frames of applications for activities in teaching, analysis, design, experimental activity and historical investigations with still a key role not only for mechanical systems, but even as means or part of systems in other disciplines. The example in *Figure 1* illustrates the still current interest in the practice of model developments in the different forms and formats, as referring to the very modern domain of Robotics.

2. Italian collections of mechanical models

Examples based on illustrations are discussed below with the aim of showing the characteristics of the models and of the modeling introduced above in the context of the Italian historical panorama with the relative peculiarities.

Since ancient times, the analysis and design of mechanisms was carried out using examples and models to define characteristics and solutions suited to required tasks. Probably also scale models with perishable materials were used, which in fact have not reached us, but which have been illustrated and discussed in treatises or even represented in artistic works. *Figure 3* shows an example from the work of Archimedes (ca. 287-212 BC) of the third century BC. relating to the schematic of the functioning of the machines with the basic conceptual principle recognized in the mechanics of the lever (Ceccarelli, 2014b). *Figure 3a* shows the graphic representation reconstructed during the Renaissance as from the work by Guidubaldo Del Monte (1577) as the re-edition/discover of the Archimedes work (Commandino, 1558) with an explanation of a text and a synthetic representation of the mechanism, whereas *Figure 3b* shows the scheme still synthetic but for a mechanical study for the purposes of a formulation for analysis and design due to Galilei in his explanations during the first academic lectures on machines of his course held in 1593-98 in Padua (Galilei, 1964; Ceccarelli, 2006). In this figure it is evident the formulation of the model in terms of graphic design coming from an ancient text that could probably have been accompanied by a graphic scheme, but enriched with the characteristics of an essentially graphic modeling for the characteristics of explanation and design of the functionality of the machine to which it refers or to the lever mechanism A. D. for a marble cutting machine with the characteristic of being illustrative in the main mechanisms and with a publicity purpose, even if it was found on the surface of a sarcophagus near the city of Hierapolis (currently in Turkey) as the tomb of

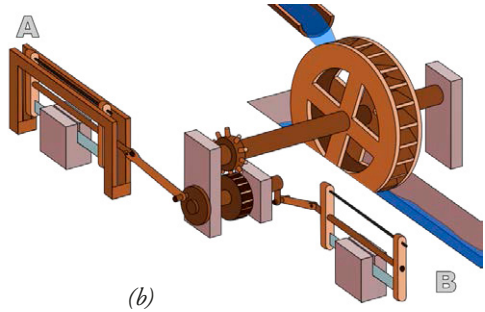
Marcus Aurelius Ammianos, a local miller. In this model of an artistic type as an archaeological finding, the informative and explanatory purposes can be noted with emphasis, although the design features are not detailed also in order not to allow readers to reproduce a machine with high technological value that can be considered of even economic value, not indifferent for the family of the person housed in the sarcophagus.



(a) *(b)*

Figure 3. – The lever model by Galilei (1964):
(a) a natural description model; (b) a kinematic diagram model.

(a)



(b)

Figure 4. – Bas-relief representing the Hierapolis saw (Rossi, Russo, & Russo, 2009):
(a) the archeological finding; (b) a mechanical model.

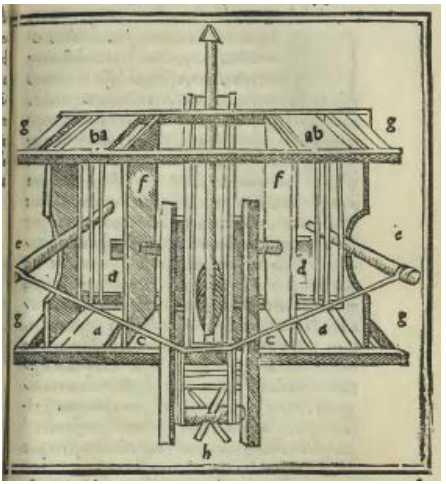
Figure 4b shows a modern mechanical model of the marble cutting machine formulated with a CAD elaboration with the clear interpretative intention not only of the archaeological bas-relief of *Figure 4a*, but also of the functionality of the machine, highlighting the main elements recognizable in the hydraulic turbine as a source of energy and in the slider-crank mechanism that guides the saw in the operation against the marble. This example highlights that already in ancient times the modeling of machines and mechanisms was used for various purposes, that is, popularization and commercial and social advertising. It should be noted that the CAD model of *Figure 4b* can be used, as indeed it with various solutions that can be found in websites and museum exhibitions, for a virtual model with animation of the operation of the entire machine, with emphasis on the kinematics and the role of the fundamental of slider-crank mechanism. *Figure 4a* (Rossi, Russo, & Russo, 2009) shows an example of a model in a marble bas-relief of the third century.

The explanatory purpose of models of mechanisms with content of cultural heritage value with today's attention can be seen in the mechanical model of *Figure 5* of the Roman catapult. *Figure 5a* shows the graphic representation reconstructed during the Renaissance in the work of Fra Giocondo (1433-1515) for the princeps re-edition (Fra' Giocondo, 1511) of the treatise *De Architettura* by Vitruvius (80-15 BC) in which the model of the war machine structure also explains how machine works as based on the mechanism consisting of two levers with elastic joints connected by the launching cable, also with a brief explanation text. *Figure 5b* shows a scale wooden model exhibited at the Museum of Roman Civilization in Rome (2010) with a clear explanatory purpose of the structure both in functional aspects referring to the mechanisms as in the constructional peculiarities with assembly of parts that the Roman legionaries could find in the field during the war campaigns.

Another significant reference referring to the modeling in Antiquity with reconstructions in the Renaissance and beyond, can be considered the work of Vitruvius (80-15 BC), whose specific studies on machines and mechanisms in liber X were then rediscovered during the Renaissance and republished also with sets of figures and graphic models resulting from interpretations of the text and the direct experience of the authors of the reproductions with machine designs that have been a reference for a long time both at a technical and historiographic level, as discussed in Cigola and Ceccarelli (2016). This last aspect of historiographical attention has recently received even greater attention with the creation of virtual models that have been elaborated and exhibited, also with scenic animations of various scenography in various occasions and occasions, such as the virtual

exhibition of Vitruvian machines linked to Leonardo da Vinci in 2019 in the Malatesta palace in Fano, the birthplace of Vitruvius.

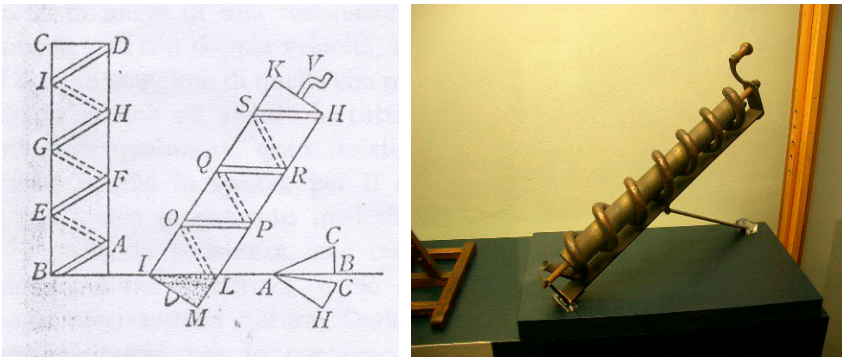
Actually todays, virtual models even with 3D views and animation are extensively used mainly in exhibitions within museums or events showing past design of machines and mechanisms with aim to show the functionality of those past machines with cultural heritage values but also with modern concepts for design and functionality.



(a)

(b)

Figure 5. – Ancient Roman repeating catapult: (a) a mechanical scheme, by Fra' Giocondo (1511); (b) a reconstruction in the Museum of Roman Culture in Rome (2010).



(a) (b)

Figure 6. – Models of the Archimedes pump: (a) graphic diagram of the structure and functioning of the screw (Galilei, 1964); (b) mechanical model of 17th century in Florence Museum (Miniati, 1991).

Figure 6, referring to the Archimedes pump for lifting water as an example of the experimental mechanics that was established since the 17th century, shows how mechanical models were used for didactic and experimental purposes. *Figure 6a* shows a graphic model again from Galilei's lessons with a graphical representations as traditional means for a long time in the study of the functioning of machines and mechanisms while *Figure 6b* (Miniati, 1991), shows the mechanical model built for research but also used in teaching for more than a century, in the form that today is preserved at the museum of the history of science in Florence having also acquired a character of historical value and cultural heritage of science and technology. In the mechanical model of *Figure 6b* it is worth noting the accuracy of the mechanical construction aimed at representing the main elements for the functionality of the mechanism with which the screw performs the function of water lifting pump according to the mechanics and the representative scheme of *Figure 6a*. This link between mechanical models and graphical models is still essentially based on the modeling of the design and functional characteristics useful not only for the analysis of the functioning but also for the design and use of the examined mechanism. Therefore, it can be recognized that one type of model completes the other and vice versa.

The use of graphic models has been persistent for a long time and of practical utility especially in the technical-scientific literature as in the didactic one with characteristics still considered necessary today both in the didactic aspects and in the design formulations. Already in the Renaissance

it can be thought that this graphic modeling was flanked by mechanical models in scale which, however, have not come down to us not only for their limited purpose in terms of use and validation of concepts at the time of design and restricted teaching practice, but also and above all for having probably been built with perishable materials such as wood.

Subsequently, this didactic-demonstrative purpose of graphic models of the machines had its success in the Theatrum Machinarum in the form of catalogs of machines in which the structures of the machines are represented with a text accompanying as a description of the functionality and construction peculiarities. This approach can be traced historically starting from the manual by Francesco di Giorgio Martini (1439-1502) (Ceccarelli & Molari, 2020), up to the first printing of a real manual of the machines by Agostino Ramelli (1588). *Figure 7* shows an example of such modeling from the Ramelli catalog (1588) with pedagogical purposes for a wide audience, also with the intention of attracting possible commitment for the design and construction of the represented and new machines. This didactic-illustrative purpose has developed since the first manuals of machines by Francesco di Giorgio of the early Renaissance up to the elaboration of complex catalogs in the form of the Theatrum Machinarum and finally also in specific chapters of the didactic texts and reports of research activities and design during the, 19th century during the developments of the Industrial Revolution.

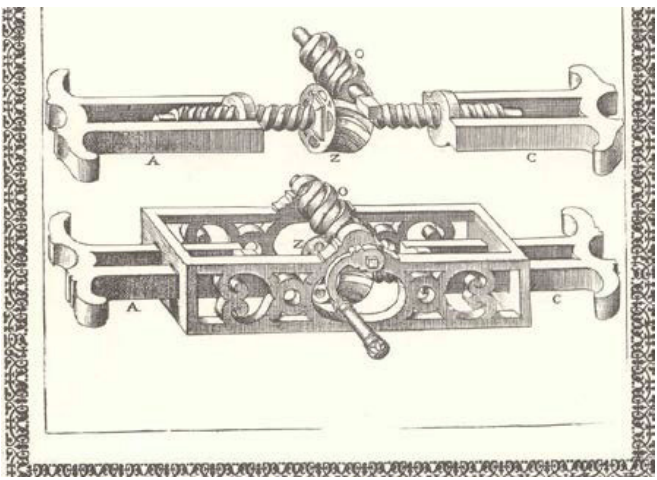


Figure 7. – Example of graphic modeling of mechanisms in machines typical of Theatrum Machinarum from the work of Agostino Ramelli in 1588.

During the development of the Industrial Revolution these catalogs specialized in the representation of graphic models of mechanisms within treatises further developed in technical manuals among which the first European (Italian) manual can be ascribed to the work of Giuseppe Antonio Borgnis (1781-1863). The example of *Figure 8* shows the modeling of the mechanisms with the aim of explaining a classification of the structural and functional possibilities of the various types of mechanisms.

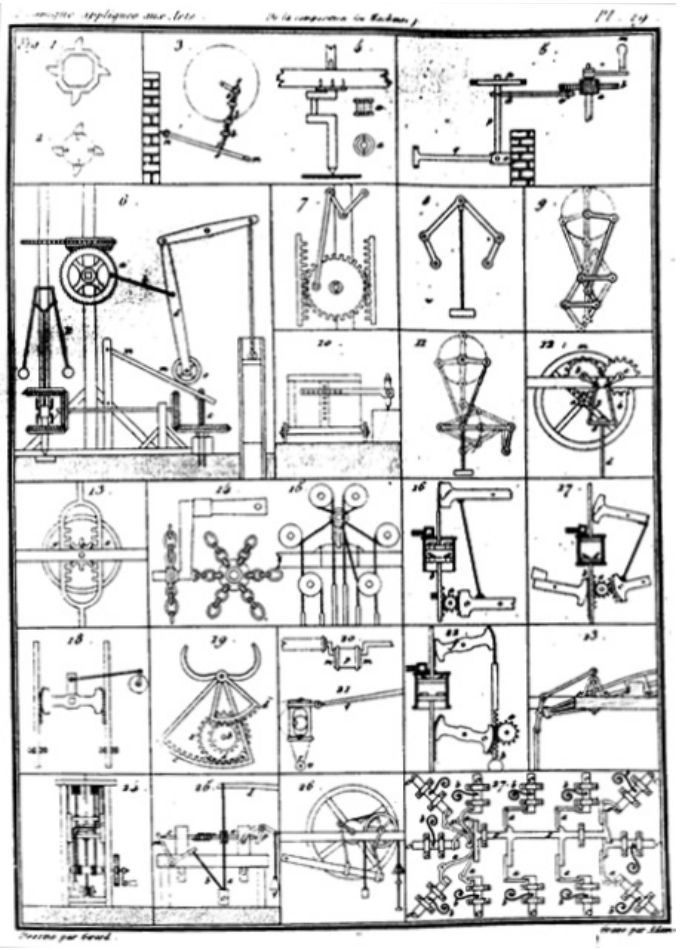


Figure 8. – Graphic modeling of mechanisms for a classification from the work of Borgnis (1823).

These aims for design and teaching activities have given rise to a specific literature and also to a research aimed at discovering unitary principles in the variety of mechanisms according to the various types also with the help of small scale models that have seen full success with the production of modeling designed by Franz Reuleaux (1829-1905) and produced by the Voigt company (following a well-established tradition in Germany, even if it also existed in other European countries, including in the states of fragmented Italy) with planetary circulation (Kerle, Mauersberger, & Ceccarelli, 2011), which in fact it has also reached the engineering schools in Italy.

In particular, in Italy this activity has seen a production of specific literature since the first courses dedicated to the training of mechanical engineers at the University of Turin which later became Polytechnic of Turin with Professor Carlo Ignazio Giulio (1803-1859) with his work that follwed didactic study by Gaspard Monge (1747-1818) further developed by Robert Willis (1800-1875) and continued throughout the nineteenth century until reaching the work of Francesco Masi (1852-1944) (Ceccarelli, 2010) at the University of Bologna with its encyclopedic treatise *The theory of mechanisms* of 1897 in which the modeling of mechanisms is treated not only on a graphic level but also on an analytical-formulistic level as represented in the example of *Figure 9*.

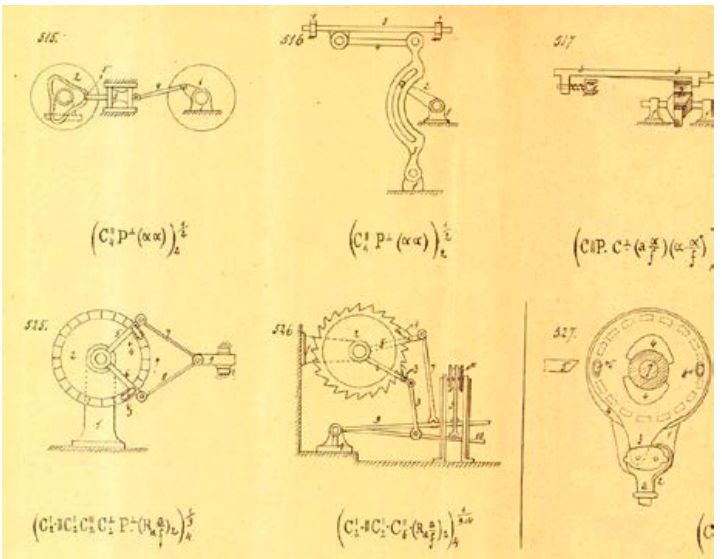


Figure 9. – Example of graphic-analytical models of mechanisms from the work of Francesco Masi in Bologna at the end of the 19th century.

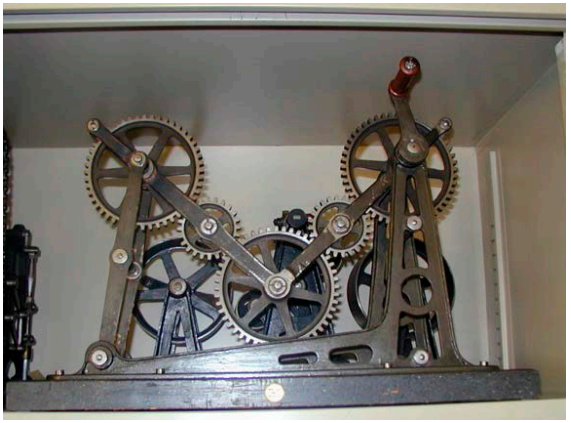
In *Figure 9* it is to note how the mechanism model with its graphic drawing is used to identify a mathematical model with a innovative formulation, that can be useful both for analysis and design purposes, as today is implemented with more advance algorithm of informatic expert systems.

This development of graphic models for analytical formulations with the purpose of analyzing and teaching the functionality of the mechanisms were also accompanied by products of various types of physical-mechanical models, both in scale with emulation of Voigt models and models specifically designed by the Italian teachers.

Figure 10 shows examples of those physical-mechanical models which were produced starting from the end of the, 19th century up to the 60s of the, 20th centuries with evident didactic purposes in courses dedicated to the study of kinematics and design of mechanisms for machines even with complex structures. *Figure 10* shows as an example of the dissemination throughout the national level models preserved in several Italian academic institutions with mechanical construction structures respectively in metal, plastic, wood, and combination of materials to represent as such modeling also for didactic purposes has been produced with a great variety of solutions.

In the, 1980-90s of the past century, the advent of computers and related computerized modeling technologies have also produced a bursting development of virtual models that are still used today in courses to explain the structures of mechanisms and their functionality with dedicated algorithms for the virtual simulation of their performance and numerical representation as a characterization of the principles and solutions proposed and further developable for even innovative designs. Such virtual models are frequently also used in other fields, such as those indicated in *Figures 4-6* for museum exhibition purposes and preservation of contents of technical-cultural heritage.

Subsequently, at the beginning of this century didactic techniques for the study of mechanisms and machines were developed that combine the various types of modeling described above, i.e. graphic, physical-mechanical, computerized virtual ones, in such a way that a student in training for not only mechanical engineering of machines with mechatronic solutions can also appreciate the structure and mechanical functionality typical of man-machine and machine-machine interaction and integration with further systems from other disciplines that are now essential in the modern mechatronic structure of a machine and a mechanism when combined with various types of drives, control systems and sensorization that are necessary for the regulation of the machines according to the applications to which they are dedicated and designed.

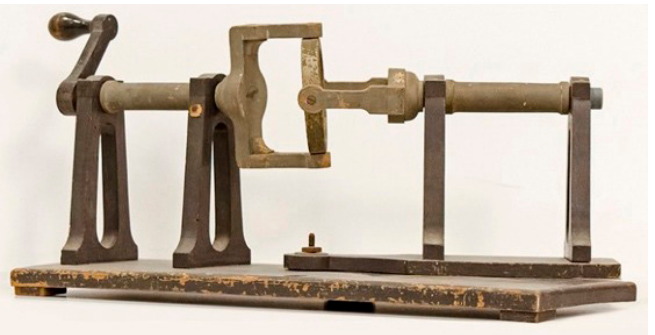


(a)

(b)

(c)

(d)



(e)

Figure 10. – Examples of physical-mechanical models of mechanisms for didactic purposes in the 20th century at: (a) Politecnico di Torino; (b) Politecnico di Milano; (c) University of Bologna; (d) University of Rome; (e) University of Palermo.

Although today the teaching and design techniques are based on computer-assisted modeling and therefore based on a mathematical and simulation modeling, the realization of physical-mechanical models is once again considered necessary and fundamental for a rational and efficient training to develop adequate knowledge and awareness of the problems of the solutions that an engineer must face for the development and management of mechanisms and machines with a mechatronic structure real designs for correct and efficient operation, as shown in the example of *Figure 1*.

Conclusions

Mechanism models have paid and still pay an important role in explaining and validating machine design concepts and operation performance in teaching, research and technological transfer, even in publicity to the public. An historical evolution is presented looking at main features of model categories in drawings, mechanical models, protypes, and virtual solutions. Italian collections are introduced as from main Italian university sites with an eye from the very past up todays solutions with the aim of recognizing an important contribution of using mechanism models in the development of machine designs and the science of mechanisms over time.

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Riassunto

Il presente contributo presenta e racconta la storia italiana sulla collezione dei modelli meccanici che sono stati utilizzati e possono ancora essere utilizzati nelle attività di progettazione, insegnamento e ricerca, non solo circoscritti alla ricerca e allo sviluppo di sistemi meccanici. Sono presentate le principali collezioni italiane, con i loro valori storici e il loro stato attuale. Questi esempi sono riportati anche e soprattutto per dimostrare il valore del Patrimonio Culturale che questi modelli e gli sviluppi corrispondenti possono avere, utili per la conservazione e la comprensione dei risultati del passato nella progettazione e la loro applicazione anche in altri contesti.

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