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Mechanism and Machine Science Educational Workshop Based on Schröder-Reuleaux Ancient Models of Politecnico di Torino

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Abstract

Around the world, there are many collections of models of mechanisms and machine components of historical value. Among these, there is an important collection kept at the Politecnico di Torino, Department of Mechanical and Aerospace Engineering-DIMEAS. It consists of about 85 Reuleaux models manufactured by the Schröder company of Darmstadt in the second half of the 19th century. It includes linkages, gears, cam-follower systems, belt drives, couplings and clutches whose history is reconstructed. Some models are still used effectively today in teaching the science of mechanisms and machine. The paper presents both the important historical collection and the didactic methodology adopted in the course “Mechanics of Automatic Machines” in which students practice the developing of virtual models of some selected mechanisms.

Keywords

History of Mechanisms and Machines, Mechanism Model, Schröder-Reuleaux Models, Engineering Education, Kinematics Education

1. Introduction

Mechanism and Machine Science (MMS) deals with the *theory* and *practice* of the geometry, kinematics, dynamics, and control of mechanisms, machine components and machines (Ceccarelli & Bragastini, 2014). One of the pioneers of MMS, Franz Reuleaux, in the introduction of his famous “The kinematics of machinery” underlines that “*Theory* and *Practice* are not antagonistic, as is so often tacitly assumed. (omissis) *Theory* is not necessarily unpractical, nor *Practice* unscientific, although both of these things may occur. Indeed in any depart-

ment thoroughly elucidated by Science the truly practical coincides with the theoretical, if the theory be right.” (Reuleaux, 1875).

An effective teaching of the MMS must therefore include both theoretical and practical activities. In order to acquire the skills necessary to carry out an accurate functional study of mechanisms and machine components, it is advisable, for a student, on the one hand to develop rigorous analytical models aimed at calculating the main kinematic quantities, on the other to visualize concretely the movements of the whole mechanism or of some of its parts. The activities are complementary: pure visualization does not allow the student to calculate the main kinematic quantities nor evaluate the effect of the system parameters on the kinematic behavior; the analytical modelling by itself, vice-versa, often provides detailed results that, however, are abstract, not immediately and intuitively associable with the real and that, sometimes, do not make it possible to clarify how the mechanism actually moves.

Today’s students have an advantage over their colleagues from previous generations by having easy-to-use calculation and simulation tools available. Once written the kinematic equations of the mechanism under study, it is easy to calculate, by numerical computing software, the trends of the main functional quantities, like positions, speeds, accelerations, centrodes, etc. There are also tools that allow to build models with a graphical interface, and to automatically calculate the kinematic quantities. In addition, 2D and 3D computer graphics and computer-aided design software are also effective, suitable for producing very realistic virtual animations (Arnay et al., 2017; Fu, 2003). All those virtual tools are extremely significant but the physical interaction with a real model provides a deeper understanding and the opportunity to implement the analysis process, which is preliminary to the ability of synthesis and design of mechanisms.

In the past, in the absence of calculation and animation tools, the teachers worked hard in the design and construction of real 2D and 3D models, to be used both to show the trend of mathematical curves (Kempe, 1877; Tedeschini Lalli, 2009; Bartolini Bussi & Maschietto, 2006), and to allow students to visualize the kinematics of the mechanisms and machine components (Ceccarelli, 2020; Moon, 2007).

Christopher Polhem, Swedish industrialist and inventor of the 17th century, felt that a technical laboratory would be an important part of future engineering education (Tekniska Museet Stockholm). For this reason, he established the *Laboratorium Mechanicum* in 1697. The collection of wooden models, called *mechanical alphabet*, was used for educational purposes, to demonstrate simple motion conversion principles and illustrate the machine components that every engineer should know.

As is clear from his publications, Robert Willis (1800-1875) of Cambridge University, one of the founders of MMS, theorist of kinematics, already in 1840 created a collection of mechanical models in wood and brass, both for demonstrations and for educational purposes (Moon, 2003). The models described in

his text “Principles of mechanism” (Willis, 1870), ten or so, included a four-bar mechanism, a slider-crank mechanism and a universal joint.

During the same period, Ferdinand Redtenbacher (1809-1863), professor at Karlsruhe Polytechnic School, developed, most likely independently, a valuable collection of at least 100 models, documenting their construction in his monograph “Motion Mechanisms” (Redtenbacher, 1857; Wauer et al., 2009).

After his death, his student Franz Reuleaux (1829-1905) at the Technical University of Berlin, Germany, designed and built the largest collection in the world of around 800 models, (Moon 2003; Moon, 2007). After his death, sixty of his models were shipped to the Deutsches Museum of Munich and have thus come to us together with a dozen preserved in Hannover. The other models were entrusted to the care of his student Wilhelm Hartmann (1853-1922), but sadly the most important part of the collection was presumably destroyed during the Second World War.

Fortunately, the designs of Reuleaux’s models have been preserved thanks to reproductions of the makers Gustav Voigt and Jacob Schröder (Bautista Paz et al., 2010).

Gustav Voigt of Berlin built, with the permission and supervision of Reuleaux, about 360 models (Moon, 2004, Voigt, 1907). Some models were to be used for didactic purposes in conjunction with Reuleaux’s book “Kinematics of Machinery”, as evidenced by the numbers and letters that refer directly to the figures in the text (Moon, 2004).

In 1837 Jacob Peter Schröder (1809-1887) of Polytechnisches Arbeits-Institut of Darmstadt, Germany, teacher of projective geometry, started the production of educational models in cast iron (Moon, 2007). As cited in his catalog (Schröder, 1884), his models are taken from the work of professors Redtenbacher, Reuleaux, Moll, Grove or from practices, based on files from the Darmstadt Polytechnic. For ease of use, the main body is made of good, solid, dry wood. The small parts, such as screws, are made of metal. In some cases, the whole models are made of metal, depending on the need. The models were produced in two different sizes: the larger ones are approximately 400 mm high, the smaller ones approximately 250 mm. Schröder’s models have been awarded in numerous exhibitions: Darmstadt (1837, 1839, 1861, 1876); Berlin (1844); Leipzig (1850); London (1851, 1863); Munich (1854); Paris (1867); Karlsruhe (1869); Wien (1873); Philadelphia (1876); Sidney (1879); Melbourne (1880); Amsterdam (honorary diploma 1889).

In general, in the 19th century, there were different model makers in Germany and France (Moon, 2007), but also in Russia and in Italy.

In the world, several original collections have been preserved in excellent condition up to date, some of which listed by Moon (Moon, 2007). Among the most important constituted by the Voigt-Reuleaux models we want to remember those of the Cornell University of Ithaca (230 pieces) and the University of Porto (130 pieces). As for Schröder’s models, we remember the collection of the Fondazione Scienza e Tecnica of Florence (100 pieces) and, not mentioned by Moon, the

collection of about 85 pieces of the Politecnico di Torino (Marchis, 2009). In Italy, in almost all the historic engineering institutions active before the Second World War one can find collections of educational mechanisms with pieces both built by international and local manufacturers. At the Museum of Engines and Mechanisms of the University of Palermo (museomotori.unipa.it) are preserved more than one hundred didactical models, in metal or wood, which illustrate elementary machines, mechanisms, transmission components, and various steam engine types (Monastero & Genchi, 2016). The pieces were built by either German or Italian manufacturers e.g., the Schröder Company of Darmstadt, other specialized companies, or even local craftsmen under direct supervision of prof. Elia Ovazza (1852-1928) (Ceccarelli et al., 2016). At the Politecnico di Milano, there is a collection of 40 pieces made by the Società di Incoraggiamento Arti e Mestieri (SIAM) in the 1920s and 1930s, and widely used by prof Ottorino Sesini and his successors (De Alberti & Rovida, 1999). These are mostly linkages, joints, and gears. **Table 1** integrates the data published in (Moon, 2007) with those relating to the collections of Politecnico di Torino, University of Palermo and Politecnico di Milano. The details of the Bauman Moscow State Technical University collection have been updated in the **Table 1**, using information deducible from Golovin & Tarabarin, 2008. The Russian collection consist of original creations of Theory of Mechanism Machines department scientists and postgraduate; original creations of Russian and Soviet engineers and scientists; models reconstructed by foremen of Bauman University according to projects of foreign scientists; copies of interesting models. Some pieces come from collections of Redtenbacher, Reuleaux and Clair.

The educational collections, besides being important from a historical point of view, still today can be valid tools for teaching kinematics. To avoid deterioration due to their use for educational purposes, some suggest making copies by 3D additive manufacturing (Vlasov & Samoylova, 2016). The original models, however, have a particular charm that encourages their reuse. In these cases, a careful restoration is necessary to preserve its deterioration (Spasskaya & Terehova, 2016).

The paper deals with the important collection of Schröder-Reuleaux models of the Politecnico di Torino (Italy), and its current use in one of the laboratory activities of the course “Mechanics of Automatic Machines”. First a history of the collection is drawn, then a brief description is given. Subsequently the selected mechanisms used in the didactic laboratory are described in detail and finally the didactic methodology adopted for the kinematic study is presented.

2. The Politecnico di Torino Schröder-Reuleaux Collection

The history of the collection of didactic models of the Department of Mechanical and Aerospace Engineering-DIMEAS—of the Politecnico di Torino intersects with the history of the Regio Museo Industriale Italiano (Royal Italian Industrial Museum) established in 1862 by Regio Decreto (Royal Decree) of Vittorio

Table 1. Model collections of kinematic mechanisms in the world (Moon, 2007 integrated with Politecnico di Torino, University of Palermo and Politecnico di Milano collections).

Location	Institution	# models	Vintage	Designer
Aachen, Germany	RWTH-Technische Hochschule	300	modern	
Berlin, Germany	Technische Universität	40	modern	
Boston, MA, USA	Boston Museum of Science	120	1940s	Clark/Brown
Cambridge, UK	Cambridge University	40	19 th - 20 th C.	
Chemnitz, Germany	Technische Universität	?	modern	
Columbia, PA, USA	Nat. Clock and Watch Museum	80	17 th - 20 th C	
Columbus, OH, USA	Ohio State University	50	1950s	Illinois Gear Co.
Denmark	Hauck Foundation	?	18 th C	
Dresden, Germany	Technische Universität	120	19 th - 20 th C.	
Florence, Italy	Fondazione Scienza e Tecnica	100	19 th C.	Schröder
Hannover, Germany	Technische Universität	20	1880	Reuleaux
Hannover, Germany	Technische Universität	200	modern	
Ithaca, NY, USA	Cornell University	230	1882	Reuleaux/Voigt
Ithaca, NY, USA	Cornell University	20	1869	Schröder
Karlsruhe, Germany	Universität Karlsruhe	100	c.1866	Redtenbacher
Kyoto, Japan	Kyoto University Museum		c. 1890	Reuleaux/Voigt
London, UK	Science Museum	20	19 th C.	Schröder
London, UK	Victoria and Albert Museum			
Milan, Italy	Science Museum		20 th C.	Leonardo copies
Milan, Italy	Politecnico di Milano	40	1920-30	SIAM
Moscow, Russia	Bauman State Tech. Univ.	600	19 th - 20 th C	Russian scientists
Munich, Germany	Deutsches Museum	100	19 th C.	Reuleaux
New York, USA	IBM	?	1950-1970	Leonardo copies
Newark, NJ, USA	Newark Museum	160	1930s	Clark/Brown
Paris, France	Musée des Arts et Métiers	?	19 th C.	Schröder
Palermo, Italy	University of Palermo	> 100	19 th C.	Schröder/Local craftsmen
Porto, Portugal	University of Porto	113	c. 1890	Reuleaux/Voigt
Prague, Czech Rep.	Technical University	23		Schröder
Riga, Latvia	Technical University	?		Schröder?
Rome, Italy	University	20		
Stockholm, Sweden	Science Museum		18 th C.	Polhem
Tainan, Taiwan	Nat. Cheng Kung Univ	c. 60		Japanese maker
Turin, Italy	Politecnico di Torino	85	end 19 th C.	Schröder
Vinci, Italy	Leonardo da Vinci Museum		20 th C	Leonardo copies
Zurich, Switzerland	ETH	10	c. 1880	Voigt/Reuleaux

Emanuele II, king of Italy. Its seat has been fixed in Torino in 1865 (**Figure 1**). The purpose of the Regio Museo Industriale Italiano was to “promoting industrial education and the progress of industries and commerce”, making use, for the first installation, of the objects and devices collected and purchased at the Great London Exposition of 1862 (Bonini, 1902; Marchis, 1986).

According to the organic regulation, in order to promote the progress of industry the Regio Museo Industriale Italiano, among the various activities, had to collect and preserve a permanent historical and progressive exhibition of objects, scientifically ordered and related to industry. The collection was financed with the contribution of 70,000 lire per year from the Municipality and the Province of Turin. In addition, the museum was an industrial higher education institute. The Regio Museo, through teaching accompanied by practical exercises, with the Scuola d'Applicazione per Ingegneri di Torino (established with the Casati Law in 1859), contributed to the training of industrial and civil engineers and provided to specialization on physics, chemistry and mechanics studies applied to industry (Regio Museo Industriale Italiano in Torino, 1891).

Among the compulsory courses for aspiring industrial engineers there were: Kinematics Applied to Machines, Machine Design and Composition, Applied

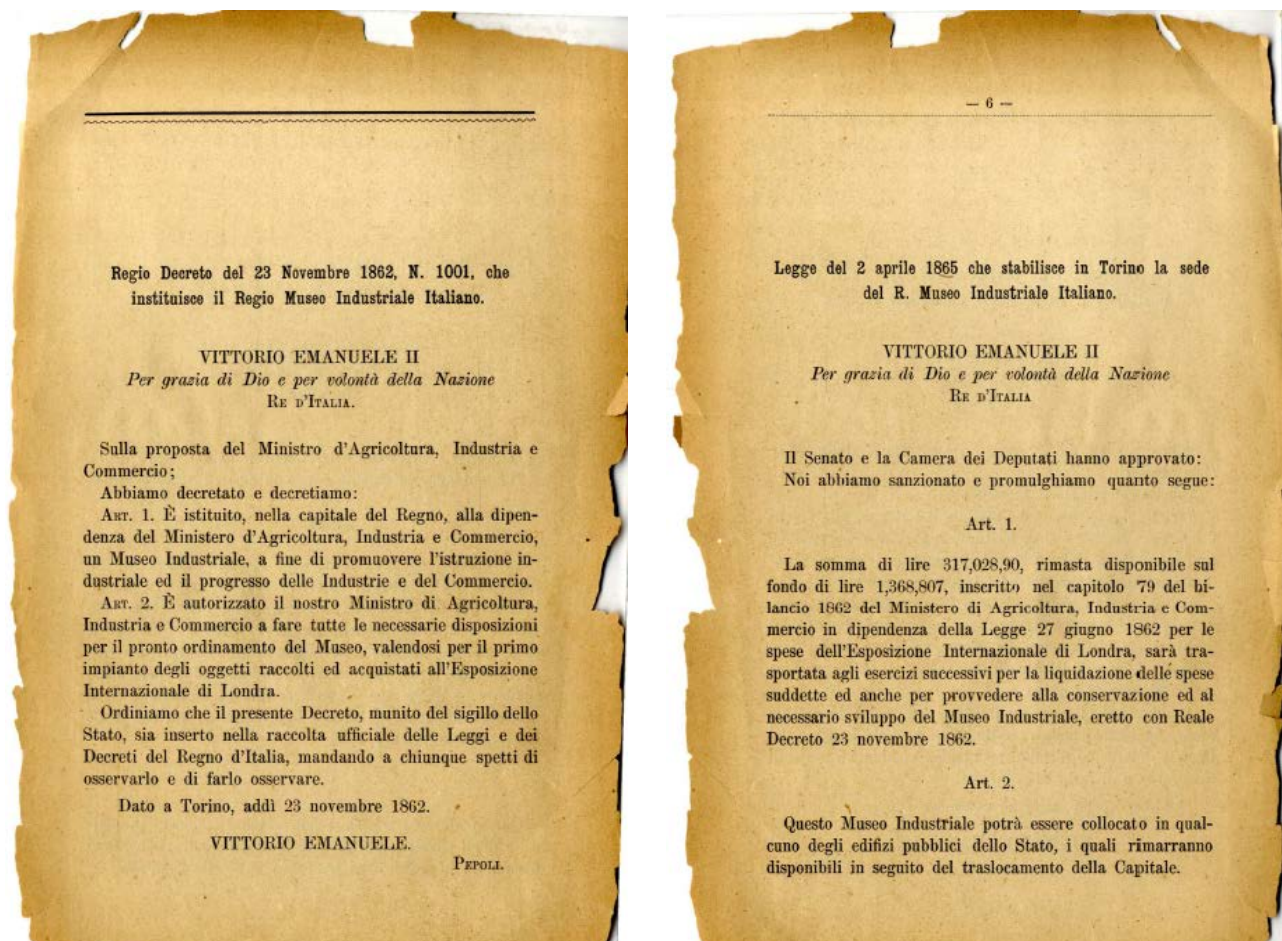


Figure 1. Royal Decree of establishment of Regio Museo Industriale Italiano.

Mechanics (Cocconcelli, 2021), Practical Hydraulics and Hydraulic Machines. The attention paid to teaching mechanics is evidenced by the presence, in the collections of the Regio Museo, of 89 “educational toys and models of machine elements” (giocattoli istruttivi e modelli di elementi di macchine), as already reported in the publication “Il Regio Museo Industriale Italiano” of 1873 (Figure 2).

At the Institute of Mechanics of the Museum there was a cabinet of Composition of Machines, “intended to make known the shape and proportions of the different parts constituting the machines” with an attached laboratory in which, among others, there were “construction models of all the components and elements of machines [omissis] partly provided by the renowned Company Schröder of Darmstadt and partly made in Italy by mechanical workshops on the basis of drawings supplied by the professor of Composition and Construction of Machines” (Bonini, 1902; Marchis, 1986). In 1906 The Museo Industriale and the Scuola di Applicazione per Ingegneri merged, forming the original nucleus of the Politecnico di Torino (Marchis, 2009).

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IV. COLLEZIONE DI OGGETTI ATTINENTI ALL'ISTRUZIONE ELEMENTARE E SECONDARIA	N° DEGLI OGGETTI
Materiale da scuola	8
Giocattoli istruttivi	67
Tabelle murali pitturate per l'istruzione elementare	48
Lettura	80
Scrittura e materiali relativi	146
Geografia ed astronomia	200
Collezioni dimostrative per l'insegnamento della storia naturale, circa	3500
Carte, diagrammi relativi alla storia naturale	65
Disegno elementare	381
Geometria e corpi solidi ad uso delle scuole elemen- tari e secondarie	441
Oggetti relativi alla fisica ad uso delle scuole ele- mentari	141
Meccanica, giocattoli istruttivi e modelli di elementi di macchine	89
Diagrammi murali	348
Libri di istruzione pubblica nazionale ed estera in tutte le lingue (1)	2348
Oggetti per l'insegnamento ed occupazione dei ciechi	71
Libri a rilievo ad uso dei ciechi	75
Libri per l'insegnamento speciale dei sordo-muti	28
Fotografie di scuole elementari e secondarie, e di altre cose attinenti all'istruzione pubblica	20
Modello topografico del Monte Cenisio	1
<i>Totale</i>	8057

(1) Vedi *Illustrazioni della didattica*, parte 1^a, Torino 1869, opera ufficiale che la Direzione del R. Museo industriale italiano fece pubblicare in occasione del VI Congresso pedagogico, tenutosi in Torino, e nella quale trovasi il Catalogo di tutte le pubblicazioni relative alla istruzione elementare e secondaria esistenti in questo Stabilimento.

Figure 2. List of objects relating to education of the Regio Museo Industriale Italiano.

In this way the collection has come almost entirely to us and is currently kept at the Department of Mechanical and Aerospace Engineering-DIMEAS—of the Politecnico di Torino. It consists of about 85 models (Figure 3), for the most part built by the company J. Schröder of Darmstadt, whose catalog is shown in Figure 4.

Each model is marked with the Schröder company logo and the corresponding catalog number (Figure 5). The collection is very varied, and includes, among others, linkages, gears, cam-follower systems, belt drives, couplings and clutches (Figure 6).



Figure 3. Some cabinets of the Politecnico di Torino collection.

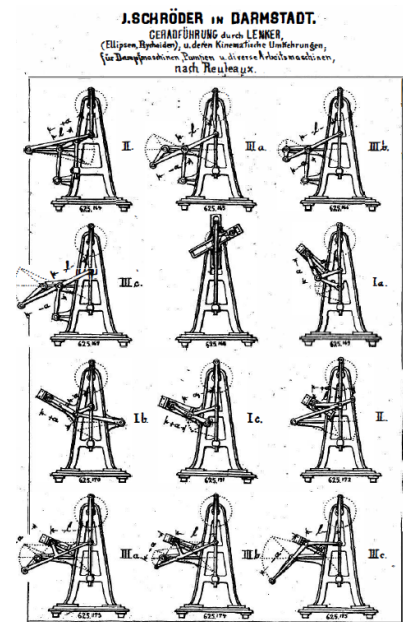
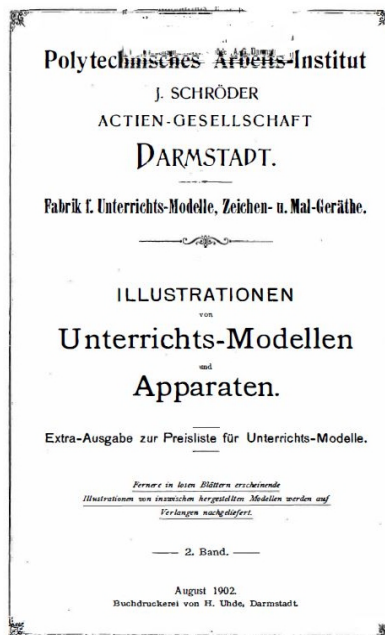


Figure 4. J. Schröder catalog (version 1902).



Figure 5. Proprietary brand (trademark) and Schröder catalogue number.

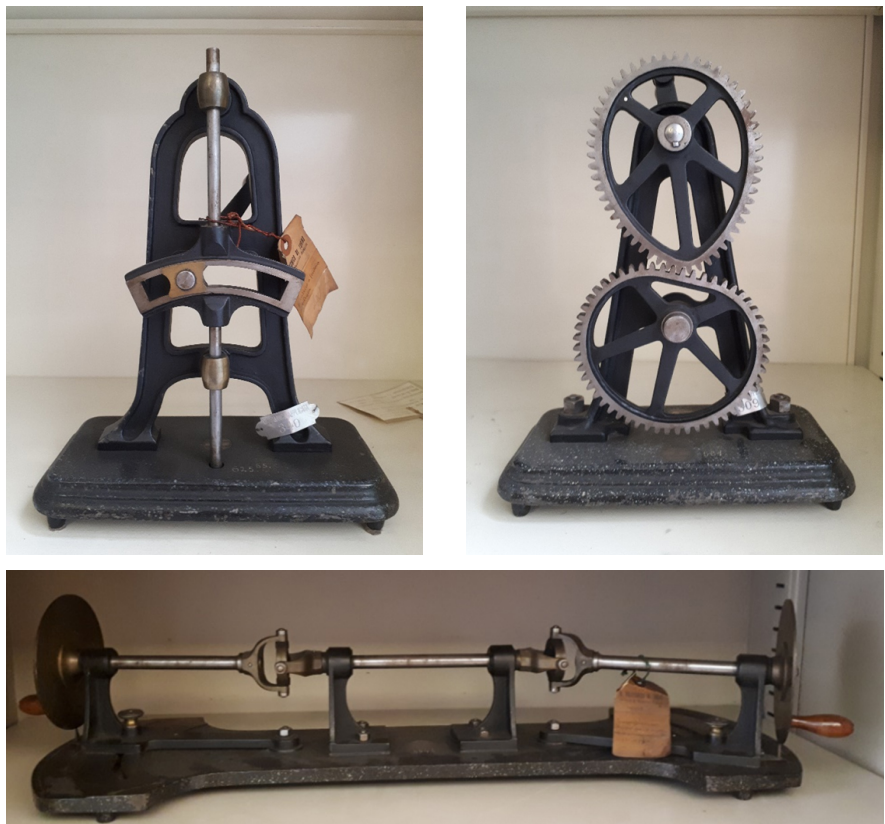


Figure 6. Some models of the collection of Politecnico di Torino-DIMEAS.

3. The Models Used in the Educational Workshop

The mechanism models used in the experimental workshop of the course “Mechanics of Automatic Machines” (Figure 7) are approximate or exact straight-line mechanisms and their inversions (Geradföhrung durch Lenker und deren kinematische Umkehrungen), originally developed for steam engines, pumps and various working machines, as reported in the J. Schröder’s catalog:

- 1) n. 625¹⁶⁴ Evans four-bar approximate straight-line mechanism (Ellipsen-Lenker II Art, angenäherter, normaler mit Schwingestütze nach Evans);

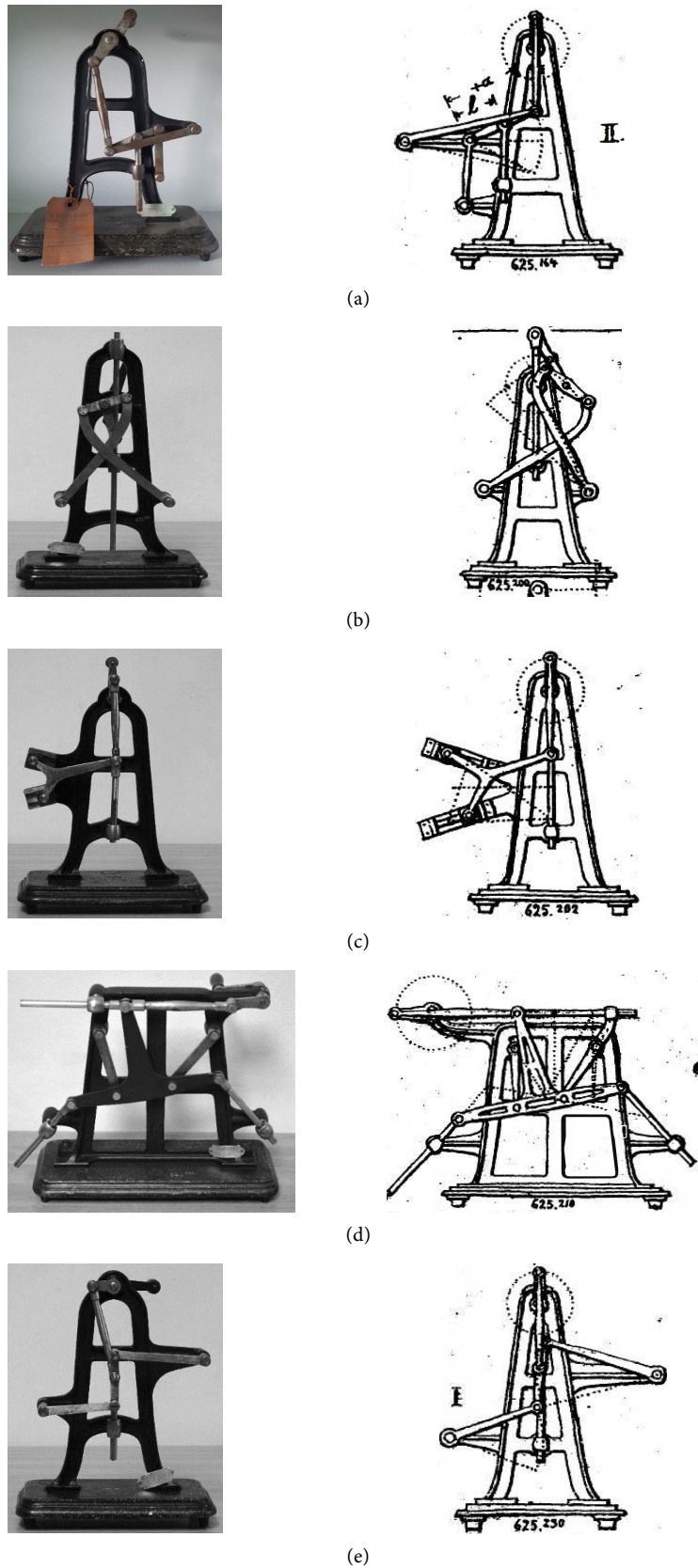


Figure 7. The mechanisms of the Politecnico di Torino collections used in the educational workshop (left) and the same models in the Schröder's catalog (right).

- 2) n. 625²⁰⁰ Chebyshev four-bar approximate straight-line mechanism (Geschränkter und Ellipsen-Lenker I. Art, a: nach Tenischew);
- 3) n. 625²⁰² Reuleaux four-bar slider-crank straight-line mechanism (Dreiecks-Lenker, normaler, gleichschenkliger mit Gleitlagern nach Reuleaux);
- 4) n. 625²¹⁰ Roberts four-bar approximate straight-line mechanism (Desgl. normaler mit Gegenlenkern an inneren Drehpunkten und drei geradgeführten Punkten nach Roberts);
- 5) n. 625²³⁰ Watt four-bar approximate straight-line mechanism (Lemniscoiden-Lenker-1. Art, die Drehpunkte auf verschiedenen Seiten, ein mittlerer Punkt des Lenkstücks gerade geführt).

4. The Educational Methodology

Although today's students have at their disposal very effective calculation and visualization tools, the analytical and virtual models alone do not allow a complete understanding of the general functioning of mechanism or machine components (Franco et al., 2021). In general, a physical didactic model enables an immediate and intuitive experimental visualization of: 1) the type of motion of the single links and of the whole mechanism; 2) the design solutions adopted to avoid geometric interference between links during operation (for example the choice between the cantilever and straddle-mounted revolute joints); 3) the dynamic physical meaning of the toggle positions; 4) the effect of the backlash within kinematic pairs.

In addition, the use of a real model allows students to practice the passage, non-obvious, between the real model and the virtual model: 1) to carry out a mechanical relief; 2) to draw a kinematic scheme starting from the real model by isolating the significant physical phenomena and neglecting the secondary ones; 3) recognizing redundant constraints.

Last but not least it is positive, fascinating and exciting for the student to handle kinematic models conceived and built more than a hundred years ago, testifying that current knowledge is however based on solid roots grown and developed over the centuries. Evidence of this fact is that the same exercise conducted with recent models, or with 3D printed copies of the original models, did not arise the same interest.

Based on these considerations, starting from 2015 we have designed a three-hours didactic laboratory which involves the use of historical models. The laboratory is part of the course of "Automatic Machine Mechanics" held at second year of the MSc in Mechanical Engineering. The course is attended by about 140 students, divided in small group of 4 - 5 people.

For each analyzed mechanism, the following activities are proposed:

Experimental functional analysis. It consists in verifying the functioning of the mechanism by observing the types of motion of the links, the role of the joints, including the reasons that determined the choice of the position of the joints and the dimension of the links. The student is asked to divide the mechanism into a

series of sub-mechanisms, identifying three different functions: the input (or motion generation) mechanism constituted by a crank and connecting rod; the main mechanism aimed at realizing the desired motion (straight-line or approximate straight line coupler curves); the visualization mechanism devoted to show the straight-line coupler curve. By way of example, **Figure 8** shows the different parts of the Evans four bar approximate straight-line mechanism. Note that the designer, to show the approximate straight-line motion of the coupler point E , used a prismatic joint, whose members are respectively connected to the point E and to the frame.

Geometric relief and schematization. Starting from the given mechanism, students must trace a coherent kinematic model, taking into account the correctness of the symbolism adopted, and taking care to respect the geometric congruence. The main dimensions of the mechanism of **Figure 8** are reported in **Table 2**.

Determination of degrees of freedom. The Grubler's equation allows to calculate the mobility M of a mechanism knowing the number of links L , the number of full joints (1 degree of freedom joints) J_1 and the number of half joints (2 degree of freedom joints) J_2 :

$$M = 3(L - 1) - 2J_1 - J_2 \quad (1)$$

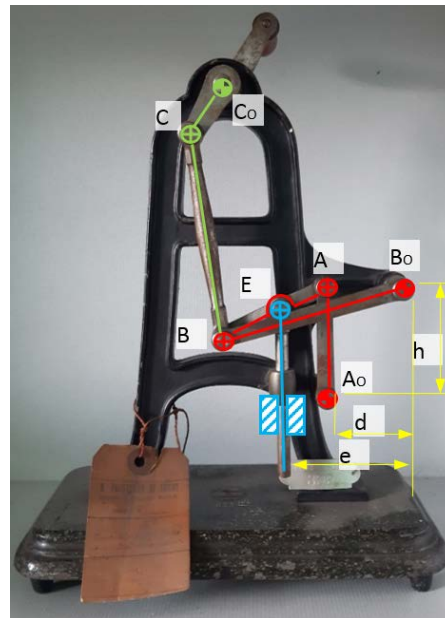


Figure 8. The model of the Evans four bar approximate straight line mechanism: the input mechanism (green); the main mechanisms (red); the visualization mechanism (light blue).

Table 2. Main dimensions of the mechanism of **Figure 8**.

CoC = 30 mm	CB = 105 mm	BoB = 95 mm	AoA = 60 mm	AB = 60 mm
AE = 25 mm	EB = 35 mm	d = 35 mm	h = AoA = 60 mm	d = 60 mm

Always considering the example of **Figure 8**, it is didactically interesting to note that while the number of degrees of freedom of the main mechanism (four-bar linkage) is equal to one, and the same occur for the mechanism consisting of the input mechanism and the main mechanism, the whole mechanism, also including the viewer, has zero degrees of freedom (**Table 3**). In reality, this does not occur since the point E moves almost rectilinearly and the real prismatic joint of the viewer has a minimum backlash.

Modeling. Using a software for kinematic analysis, like GIM (Petuya et al., 2014), the students must create a model of the given mechanisms. To do this, every student is called to identify and neglect rightly all the constraint redundancies. As an example, (**Figure 9**) shows the GIM model of the Evans four-bar approximate straight-line mechanism of **Figure 8**.

Kinematic analysis. After the creation of the GIM model, the simulation software performs the kinematic analysis showing the motion of the whole system or specific points and assessing the effect of the variation of the geometric parameters. The GIM model allows to calculate easily the coupler curves, the fixed and moving centrodes, the position, velocity and acceleration of the points of interest etc. **Figure 10** shows, for example, the velocities of the main points of the mechanism under study, and the horizontal displacement of the point E .

Table 3. Mobility of the mechanism of **Figure 8**.

Mechanism	L	J_1	J_2	M
main	4	4	0	1
input + main	6	7	0	1
input + main + viewer	7	9	0	0

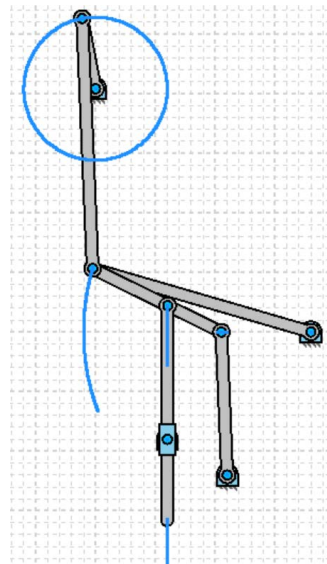


Figure 9. The GIM model of the Evans four bar approximate straight line mechanism. In blue the trajectory of somepoints.

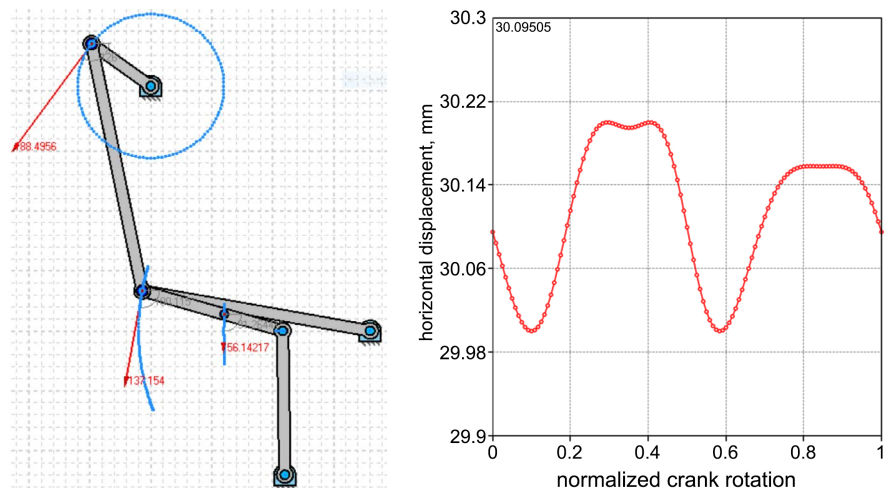


Figure 10. The velocities of the main points of the mechanism under study and the horizontal position of the point *E* versus the normalized crank rotation.

5. Conclusion

The collection of Reuleaux models of Department of mechanical and Aerospace Engineering-DIMEAS—of Politecnico di Torino is one of the most important in the world as regards the models manufactured by company Schröder of Darmstadt. It consists of about 85 models of different types, including linkages, gears, cam-follower systems, belt drives, couplings and clutches. The collection is the legacy of the Regio Museo Industriale Italiano of Turin, established in 1862.

Some models are still used in kinematics practical lectures of a Mechanical Engineering MSc course, “Automatic Machine Mechanics”, aimed to develop knowledge of the main types of mechanisms for the transmission and transformation of motion.

The students, during the experimental workshop, are invited to: 1) make an experimental functional analysis of the real historical models; 2) make the relief and sketch a mechanical scheme; 3) calculate the degrees of freedom; 4) study the role of the main parameters on the kinematic behavior using virtual model.

From the beginning of the didactic experimentation, the students have shown interest regarding the activity. In particular, they appreciated the possibility to check their ability to put into practice the knowledge learned during the theoretical lessons. Indeed, the students can exercise and test their skills in carry out an in-depth kinematic performance analysis of a real mechanism and understand the meaning of the synthesis of the same mechanism carried out by its designer.

In addition, the use of the old models for didactic purposes allows students to appreciate their significant technical and historical value, and to comprehend that the current knowledge in the science of mechanisms and machines is the result of a long path that has solid roots in the past.

The historical models conceived at the beginning of the Science of Mechanisms and Machines, despite being over a hundred years old, have maintained

their effectiveness in reproducing mechanical parts, allowing students of today to play an active role in learning the mechanisms and machine components with a pleasant and interactive methodology.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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