"Towards a History of Technological Thought"

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Technological Systems and Technological Thought

To study the broad canvas of technological change, it is necessary to understand what exactly is changing, and to characterise the general equilibria that massive innovations upset. Technological change cannot be described only as a succession of controversies and minute adaptations, of the kind that the sociology of knowledge takes most of the time into account. Technological change is also the result of global displacements that one can best interpret with the help of the notion of technological system. Historians have proposed various definitions of this notion. But two definitions seem to me especially significant. They are at once complementary in their approach to technological regulations and to technological change seen as system shift.

The French historian Bertrand Gille gave the first of my two definitions in a general survey of the history of technology. Struck by the fact "that within some limits, as a very general rule, all techniques are, to various degrees, depending on one another, so that there should be some coherence between them (1)", Gille tried to define and describe this coherence. He began by considering elementary structures corresponding to what he called "a single technical act", such as the use a tool with the gestures attached to it, or the utilisation an individual machine designed for a specific aim. At a different level, he introduced technological sets as combinations of structures meant to achieve larger goals, such as the production of iron in a blast furnace. Those sets were in their turn part of broader entities, called by Gille technological ways – in French "filières techniques" –, such as the process leading from the mine to the blast furnace. On this analysis, a technological system could then be defined as "the coherence, at different levels, of all the technical structures, of all the technological sets and ways (2)" that coexist at a time. Looking back at the historical development of technology and using his definition of technological system, Gille made for example a crucial distinction between the age of "classical systems", centred on the use of water and wood, and the first industrial system based on steam, coal and iron. In this perspective, major technological changes, such as the first industrial revolution of the late eighteenth and the first half of the nineteenth century, appeared as transitions leading from one system to another.

French historians drawn heavily on Gille's approach. But though it is stimulating, his conceptual frame is difficult to relate to more socially oriented studies of technology and technological change. In filling the gap between Gille's systemic conception and the precise analyses of individual institutions and professions, Thomas P. Hughes's definition of technological systems provides with useful tools(3). His definition is meant to establish a strong link between a technical basis and the institutional and professional organisations that create and run it. It has enabled him to describe the development of electrical power in the Western world in a very convincing way (4). Since Hughes's work is well known among Anglo-Saxon historians of technology, it does not require lengthy presentation. Less global than Gille's systems, Hughes' technological systems are perhaps less closely constructed since they include heterogeneous realities such as human organisations and technical artefacts. What they lack in the field of conceptual closeness is nevertheless amply counterbalanced by their empirical fecundity.

The approaches of Gille and Hughes represent major contributions to the history of technology. In my paper, I should like to propose an addition to these two approaches by taking into account technological thought and its evolution, especially the collective mental frames to which actors of production, such as managers, engineers or workers, are referring to when they think and act. As I shall try to show, those mental frames characterise types of knowledge and reasoning as well as types of behaviour. They give birth to representations and patterns of thought, which apply, at various levels, to very different kinds of realities. There are, for example, very general representations of efficiency, based on associated interpretations of nature and society, and there are more specific representations of the organisation and the techniques of production. Mixing energy with social reflections, the modern concept of work is a typical product of the first kind of representation (5). There are at the same time patterns that apply to supervision of workers whereas others influence problems of design.

The main purpose of my work on technological thought is to suggest a close relationship between such collective mental frames and the notions of coherence on which Gille's technological systems are founded. At the same time, those mental frames have to relate technical bases to the forms of institutional and professional organisation in which they are realised. They play a role in the construction of Hughes' systems. It follows that their evolution is part of the major technological changes. In some recent research, I have tried to show how the transformation of the engineers' mental references influenced the process that led France from the end of the classical age into the industrial era (6). The main part of this article will deal with that specific example and with the lessons that can be drawn from it. By way of preliminary, to precise my type of approach, I begin, however, with some general views on technology and technological thought as a way of clarifying my general approach (7).

Technology, Nature, and Society

Many contemporary historians, from David Landes to François Caron, define technology as a form of social production. At the same time, one must not forget that technology deals with nature. More accurately, it provides an interpretation of nature in connection to the social division of labour. Technology is meant to adapt this division of labour to the principles of efficiency that can be drawn from the observation of the physical world. Those principles are partly the result of mental constructions and representations. There is no universal nature, no enduring principles of efficiency, rather there are historically determined representations of nature and of the principles of efficiency that derive from them (8). Until the eighteenth century and the start of the first industrial revolution, the principle of automatic working was synonymous, for example, with transmission of movement. Engineers such as the famous Renaissance designer Francesco di Giorgio conceived chiefly cinematic devices. With the development of steam engine, automatic working became synonymous with production and transmission of energy during the nineteenth century (9). It has changed again recently to correspond to the circulation of information. Through this kind of evolution, it seems that technology is continually trying to humanise nature by appropriating it to human needs and concerns. It attempts at the same time to naturalise society by adapting the alleged natural principles of efficiency to the organisation of production.

The history of technological thought must take into account the simultaneous representations of nature and of society. The major transformations of technological thought correspond to changes in those representations. For instance, the evolution of French eighteenth-century engineering was linked to a global change in the interpretation of the physical world and the construction of nature it led to. The eighteenth century vision of nature no longer focused on architectonic regularities. It became more and more centred on the natural dynamism of things and beings. Such a change was also linked to a new approach to society and to the role technology was supposed to play in human destiny. In the Enlightenment period, the idea of a collective progress was taking shape. Technological development and social progress seemed more and more closely related.

Technological Thought and Rationality

Technological thought is a complex system functioning at different levels. For each actor of production, it comprises a set of know-how and interiorised rules of decision and action. Know-how plays a role in the worker's manual skill as well as in the engineer's design or in the manager's decision process. Technological thought also includes formalised knowledge such as mechanics, physics or chemistry for the engineer; lastly it embraces themes and representations which belong to an imaginary sphere. The common obsession of engineers with fluidity has clearly something to do with the imaginary. These various levels overlap. The ideal of automatic working appears for example at the intersection of the known and the imaginary.

In this brief analysis, I am referring to collective actors, professional types or professions principally. In other words, the history of technological thought which I should like to promote is more concerned with the shared know-how, knowledge and representations, than with the content of the individual mind. Applied to the question of invention, it means that the history of technological thought is more concerned with the mental context which allows invention to take place, than with the actual process of invention.

Given one actor of production, let us say an engineer, the main problem is how to describe the complex system of his technological thought with appropriate interpretative structures or concepts. The historian must also fashion other structures or concepts should to characterise the common references that different actors share within large firms or institutions. In order to remain concise, I shall concentrate on the first sort of these problems.

One can use the concept of rationality to clarify the specific organisation of know-how, knowledge, and representations that characterises the technological thought of the actors of production. The definition of rationality I am referring to is very different indeed from the classic definition, used especially in economics. First, it does not separate the objectives from the means employed, in the way that Max Weber did when he distinguished between rationality depending on the objectives and rationality depending to the means(10). In my definition of rationality, objectives and means are in constant interaction in technological reflection and action. Secondly, my definition does not limit rationality to rational calculation. It characterises the global attitude of an actor towards the world of production, rather than the specific techniques of decision he uses to cope with it. Thus, rationality is guided by values and representations. Some of these values and representations are ordinarily considered as irrational. In this sense, rationality is a general disposition linking all levels of technological thought and providing a frame for rationalisation schemes. Technical thought and rationality are linked to the devising of schemes or plans. This planning dimension gives them a dynamic quality.

Looking at the history of a number of forms of engineering rationality from the Renaissance to the present, we can distinguish successive ages. For example, there seemed to be an age of classical – i.e. geometrical or Vitruvian, rationality. At the turn of the eighteenth and nineteenth century, this age was supplanted by another that could be described as the age of analytical rationality. Taking the case of French engineers, I shall deal now with this transition from geometrical or Vitruvian rationality to analytical rationality.

From Geometrical to Analytical Rationalities

Since I have emphasised the importance of the representations of nature, I shall begin by evoking the change in the perception of the physical world that took place in eighteenth-century France. In that period, there was a general trend towards a more dynamic perception of nature. Whereas the Classic philosophers, scientists and engineers, used to consider nature as something organised according to the laws of order and proportion, as something essentially architectonic, eighteenth-century elites were increasingly impressed by the mobility of natural elements. While Bossuet wrote that God had created the world with order and proportion, Diderot and D'Holbach declared that change and movement were the main characteristics of nature (11). Mobility was seen as synonym of a vital activity, while immobility became synonymous with decay and death. Efficiency was no longer linked to an ideal arrangement of means ruled by proportions; it was seen as the expression of natural dynamism. Eighteenth-century urbanism and territorial planning were clearly inspired by this conception. Nothing was to prevent water and air to circulate freely in cities. "It is well known that the healthiest water would corrupt without the movement which maintains its purity", wrote for example Parmentier in his *Dissertation sur la nature des eaux de la Seine* of 1787 (12). The suppression of urban ditches with their stagnant water was a consequence of that sort of conviction. The destruction of the houses built on bridges was another since those houses were supposed to prevent the renewal of atmosphere (13). Understanding the natural dynamism was becoming a very general concern of philosophers and scientists as well as a practical issue for architects and engineers.

If natural efficiency was linked to mobility, social happiness and progress had to lie in a similar mobility, embracing the mobility of people, ideas, and merchandises. The fight against the prejudices that prevented free exchanges between men, and the promotion of trade and free enterprise by suppressing custom barriers as well as the corporate organisation of labour, became the priorities of political and economic elites. The Physiocrats and their famous formula: "let do, let pass" illustrate that concern well.

French engineers clearly subscribed to this ideal of natural and social fluidity, especially the Ponts et Chaussées engineer,s whose mission consisted in building bridges and highways to promote trade. In relation to this concern, social evolution in two aeras at least must be taken into account.

First, engineers who had previously been relatively marginal came to be recognised as important agents of economic and social progress. In France, this recognition took place under the patronage of the State, through the creation and development of specialised institutions, administrative corps, and professional schools. While the corps of fortification engineers was created at the end of the seventeenth century, the Ponts et Chaussées and the Mining corps were founded during the eighteenth century (14). A whole range of schools was created as well. The Ecole des Ponts et Chaussées was founded in 1747, the Ecole du Génie at Mézières (a school for fortifications engineers) in 1748, the Ecole des Mines in 1783, the Ecole Polytechnique in 1794. Gaining rapidly prestige, these schools were going to play a deciding role in the recognition of engineers and their rise in status (15).

Simultaneously, the attitude of engineers towards society began to change. Engineers defined themselves less and less as artists serving a prince, on the model of the engineer-architects of the Renaissance and classical age. They considered themselves as responsible for a more collective form of progress; and they saw it as their duty to defend new values, such as public utility and prosperity. "It is the engineer who is in charge of the designs meant to provide happiness (16)," wrote for example one Ponts et Chaussées engineer convinced of the extreme importance of transport infrastructures.

At the intersection of the ideal of fluidity and the evolution of the engineering profession, a radical change in the engineers' field of competence took place gradually. Their knowledge and the way they conceived and designed their projects were going to evolve. Engineers no longer defined themselves through the mastering of purely geometrical knowledge, as designers or as "artist engineers" closely related to architects. They created for that purpose a new science, involving the use of calculus. They adopted new spatial and constructive patterns and, in turn, new methods of design.

Until the end of the eighteenth century, this change in the profile of engineering competence was impeded by a very traditional technological context, by a "classical technological system" as Bertrand Gille would say. It was also prevented by a system of knowledge still based on Vitruvian principles and the intensive use of geometric patterns. What the mots advanced engineers tried to achieve, however, was to understand and to master natural and human process ranging from the floods to the organisation of labour on construction sites or in factories. As they lacked the scientific and technical tools which would enable them to control those realities, they used a provisional method consisting in a systematic decomposition of things and phenomena, a decomposition which should lead in due course to a more rational recomposition. It must be noted that, in accordance with eighteenth-century political philosophy, they also interpreted society as something which could be decomposed into individuals before being recomposed in terms of institutions and nations. This conception inspired for instance to the Ponts et Chaussées engineer, Achille-Nicolas Isnard, a *Traité des richesses* published in 1781. In this treatise, Isnard defined the "science of man" as a kind of mechanics based on the rational decomposition and recomposition of individual interests (17). Territory as well could be decomposed and recomposed. The creation of the departments at the beginning of the Revolution was nothing else than the result of a decomposition of the old system of regions and its replacement in a process of rationalised recomposition (18). Engineers, however, applied this method mainly to technical devices, as as well as to the process of production which they perceived as a combination of workers' moves giving birth to technical operations. This attitude is well illustrated by their approach of engineering and architectural design in terms of basic functions and movements. Once identified, these functions and movements provided with a general frame for the actual design of the equipment, whether a bridge or a building. This approach is also detectable in their studies of human labour, such as Charles-Augustin Coulomb's famous memoir on "the quantity of action men can develop by their daily work, according to the different ways they exert their strength (19)."

This method was very similar indeed to the one used in the descriptions of the arts and crafts given in the *Encyclopédie*. Such a convergence is not surprising since many encyclopedists shared the same concern for rationalisation. In his article on the knitting machine, Diderot unfolded the principles of a satisfactory description. It was based on "a kind of analysis, which consists in distributing the machine in various parts (...), before assembling those parts to rebuild the entire machine (20)." The manufacturing processes could be decomposed and recomposed in the same way. The engineer Jean-Rodolphe Perronet, who was later to become the first director of the Ecole des Ponts et Chaussées, gave a remarkable demonstration of that possibility when he studied a pin factory in 1739-1740(21).

Such a procedure bears also some analogy with the very general analytical method used by philosophers at the time. "Analysis is the entire decomposition of an object and the arranging of its components so that generation becomes at the same time easy and understandable (22)," wrote for example Condillac in his *Cours d'études* of 1775. In that broad sense, we can speak of the emergence of a new kind of rationality which can be called analytical. It was linked to a new way of studying efficiency in natural and social processes. It was founded on new relations between the parts and the whole, and between the local or the instantaneous and the global. Whether characterising a natural phenomenon or an artefact as a machine, parts were supposed to combine in a dynamic way, instead of being composed according to rules of order and proportion analogous to the principles of architecture. What was actually at stake was the transition from a static knowledge of structures to a more dynamic knowledge of operations and functions. Nature and society were taken to be organised through operations and functions that were synonymous with mobility. Eighteenth-century scientists were also examining operations and functions. Lavoisier's chemistry was clearly analytic, just as Diderot's descriptions or Condillac's theory of ideas and language. In their field, engineers tred to put this promising analytic orientation into practice, although the results it led to were quite modest at first.

Rather than describing in more detail this turning point in the history of engineering rationalities, I should like now to evoke some of its main consequences. The first consists in the emergence of a new engineering science based on calculus. From the first half of the nineteenth century, mathematical analysis progressively replaced many of the geometrical tools which engineers used during the classical age. As early as the 1820's, Claude Navier's or Jean-Victor Poncelet's lectures at the Ecole des Ponts et Chaussées and the Ecole du Génie et de l'Artillerie at Metz were based on calculus, on derivations and integrations that linked local or instantaneous laws to global phenomena (23). Some spectacular progress were made in that way concerning strength of materials or applied hydrodynamics. In his famous *Résumé des leçons données à l'Ecole des Ponts et Chaussées sur l'application de la mécanique* published in 1826, Navier analysed for example beams on supports as well as beams with ends built-in. With proper integration, the expression of the local bending moment enabled him to give the formula of the global deflection curve (24). The frame of mind created during the eighteenth century, the new type of relation between the parts and the whole it induced, laid the foundation for this massive introduction of calculus in the technological field.

The new engineering science encapsulated in the work of Navier or Poncelet will be in continuity with the pure sciences that use calculus as well. Whereas most of the Vitruvian engineers subscribed to the idea that there was a gap between science and engineering that could only be filled with a long immersion in technical reality, their successors saw an intimate relation between science and technology. During the nineteenth century, technological education, focused on an apprenticeship of engineering science, developed in this perspective (25).

This new engineering science defined itself as a science of the natural processes. At the same time it established strong links with another new kind of knowledge concerning human processes, that is to say economic calculation. Engineers like Claude Navier or Jules Dupuit rank moreover among the pioneers of this economic knowledge (26). Through these links between engineering science and economic calculation, one can apprehend another important aspect of the age of analytical form of rationality. The preoccupation of the engineers rested no longer in the mastering of space alone, as it was the case during the classical period; it rested now on the simultaneous mastering of space and time, these two dimensions being submitted to economic knowledge. In a way, classical engineers knew only about book-keeping. Their thinking was bounded by the present on one side, by eternity on the other. They either had the means to act immediately, or they had to wait an undefined time. The minuteness of their tasks was counterbalanced by the ideal of eternal monuments of technology comparable with the great works of the Romans. What is emerging is in fact the middle-term of modern economics.

Last but not least, a new approach to the processes of production also appeared. Production was now seen, as we have said, as a combination of elementary moves organised into a succession of technical operations. Introduced by engineers like Coulomb, this new grid of interpretation enabled the engineer to rationalise production by exposing its components, workers' moves and elementary operations, and submitting them to the principles of science. In connection with this conviction, a kind of "proto-taylorism" can be traced among French engineers of the second half of the eighteenth century (27). This "proto-taylorism" reached its climax with the "revolutionary productions" of powder, weapons and guns organised during the Terror (28). Its practical results were a failure on short-term, but it gave birth to the modern notion of work. Used to find a common measure between the various gestures and operations engineers deal with, between human effort and mechanical power above all, this notion received its mathematical translation during the first half of the nineteenth century, while economists stressed its fundamental importance in the task of understanding social and economical process (29).

From the coupling of science and technology to the stress put on the notion of work, the emergence of analytical rationalities corresponded to the construction of a new collective mental frame. Some features of this new collective mental frame, such as the engineers' ideal of fluidity, are still influential in the industrial world that surrounds us. At the same time, the reflections on the transition from Vitruvian to analytical rationalities that I have been summarising are inseparable from a broader program of research. This program is linked to the changes we are experiencing in our own day in the field of technology and industrial organisation. Are we on the brink of a new transition between the analytical ideals we have inherited from the industrial revolution and new conceptions of efficiency ? When we consider the recent evolution of our interpretation of nature, or when we take into account some of the changes induced by the use of computers, some signs can make us believe in such a transition. Until now, efficiency was synonymous with the rational regulation and management of the dynamism created by mass production and consumption. But now, the complexities of our contemporary world and its uncertainty, seem to call for a more systemic efficiency based on the identification of levels of technological and managerial relevance. How are we to articulate those different levels? In some advanced fields, engineers and managers are looking for new design and decision procedures taking into account the effects of complexity and uncertainty. Computer-assisted in most cases, these procedures try to order logically the possible events that can affect production and marketing. Whereas analysis of operations and functions was clearly the basis of former dynamic regulations, the use of logical structures is perhaps conveying a new approach of technological efficiency (30).

Technological Thought and Culture

As a conclusion, I should like to offer two comments on the history of technical thought as I have tried to present it. The first concerns the definition of the engineer. In a recent article, the American sociologist Peter Whalley rejected what he called "essentialist definitions" because of the extreme diversity of engineers' aeras of competence and employments (31). To cope with this diversity, he suggested that we should define engineers by their status, a status of privileged employees trusted by the owners of capital and by the managerial power. The interest of such an approach is undeniable. At the same time, I think it is necessary to counterbalance it by taking into account the history of engineers' rationalities. After all, engineers can also be characterised by the constant pursuit of a systematic knowledge that provides the organisation of production with efficiency. The historical forms taken by this pursuit can perhaps throw some light on the possible definition of the profession.

A second remark concerns the relationship between the history of engineers' rationalities and social history. It must be clear that this relationship is mainly achieved through the mediation of culture. The history of rationalities provides with a means of connecting technological change and cultural evolution. Such a connection is in no way determinist, that is to say that the transformation of technological thought is not always a necessary condition for technical innovation. The steam engine, for instance did not develop because a new frame of mind emerged during the eighteenth century, leading to an analytical engineering science. Engineering science was stimulated rather by the development of the steam engine. However, one can easily demonstrate that without a new analytical frame of mind and the scientific results it led to, machine development would have stagnated at the end. Instead of a direct link of causality between technological thought and innovation, one is often faced with indirect or deferred causality. Lewis Mumford pointed out the interest of that kind of causality when he saw the remote origin of the possibility of mechanisation in the precise measurement of time introduced in medieval monastic life (32). On a smaller scale, the history of engineering rationality contributes to explanations of the same type. It helps us to understand the meaning of technological change before trying to assign definite causes to it.

NOTES

(1) B. Gille, "Prolégomènes à une histoire des techniques", *Histoire des techniques* (Paris, Gallimard, 1978), 1-118, on p. 19.

(2) B. Gille, "Prolégomènes", p. 19.

(3) T.-P. Hughes, "The Evolution of large technological systems", W.-E. Bijker, T.-P. Hughes (ed.), *The Social construction of technological systems* (1987, re-issue Cambridge, Massachusetts, M.I.T. Press, 1990), p. 51-83.

(4) T.-P. Hughes, *Networks of power. Electrification in western society 1880-1930* (Baltimore, John Hopkins University Press, 1983).

(5) See A. Rabinbach, *The Human motor. Energy, fatigue and the origins of modernity* (Berkeley, Los Angeles, University of California Press, 1992), as well as below.

(6) A. Picon, *L'Invention de l'ingénieur moderne. L'Ecole des Ponts et Chaussées 1747-1851* (Paris, Presses de l'Ecole nationale des Ponts et Chaussées, 1992). Some of the themes studied in this book are also dealt with in A. Picon, *French architects and engineers in the age of the enlightenment* (1988, English translation Cambridge, Cambridge University Press, 1992).

(7) I have recently developed the theoretical bases of my approach of the history of technological thought and engineering in A. Picon,*Pour une Histoire de la pensée technique. Rapport pour l'habilitation à diriger des recherches* (Paris, 1993).

(8) In this respect, I suscribe entirely to the approach of nature developed by contemporary sociology of knowledge, by Michel Callon and Bruno Latour in the French context for instance. See M. Callon and B. Latour (ed.), *La Science*

telle qu'elle se fait. Anthologie de la sociologie des sciences de langue anglaise (Paris, La Découverte, 1991), on p. 29-35.

(9) J.-P. Séris, *Machine et communication* (Paris, Vrin, 1987).

(10) M. Weber, *Economie et société* (1921, french translation Paris, Plon, 1971).

(11) See for instance J.-B. Bossuet, *Introduction à la philosophie, ou de la connaissance de Dieu et de soi-mesme* (Paris, R.-M. d'Espilly, 1722); D. Diderot, *Pensées sur l'interprétation de la nature* (1754); P.-H.-D. D'Holbach, *Système de la nature, ou des lois du monde physique et du monde moral* (1770, Paris, E. Ledoux, 1821).

(12) A.-A. Parmentier, *Dissertation sur la nature des eaux de la Seine, avec quelques observations relatives aux propriétés physiques et économiques de l'eau en général* (Paris, Buisson, 1787), p. 21.

(13) On these major preoccupations of eighteenth-century urbanism, see, for example, B. Barret-Kriegel, B. Beguin, B. Fortier, D. Friedmann, A. Monchablon, *La Politique de l'espace parisien à la fin de l'Ancien Régime* (Paris, 1975); J.-C. Perrot, *Genèse d'une ville moderne. Caen au XVIIIe siècle* (Paris, La Haye, Mouton, 1975); A. Guillerme, *Les Temps de l'eau. La cité, l'eau et les techniques*(Seyssel, Champ Vallon, 1983); B. Lepetit, *Les Villes dans la France moderne (1740-1840*) (Paris, Albin Michel, 1988); A. Picon,*French architects and engineers*.

(14) About those different corps, see for instance A. Blanchard, *Les Ingénieurs du "Roy" de Louis XIV à Louis XVI. Etude du corps des fortifications* (Montpellier, Université Paul Valéry, 1979); J. Petot, *Histoire de l'administration des Ponts et Chaussées 1599-1815* (Paris, M. Rivière, 1958); A. Thépot, *Les Ingénieurs du corps des Mines au XIXe siècle. Recherches sur la naissance et le développement d'une technocratie industrielle*, thesis (Paris, 1991).

(15) R. Taton (ed.), *Enseignement et diffusion des sciences en France au XVIIIe siècle* (Paris, Hermann, 1964); C.-C. Gillispie, *Science and polity in France at the end of the Old Regime* (Princeton, Princeton University Press, 1980); A. Picon, *L'Invention de l'ingénieur moderne.*

(16) P. Planier, French essay of 1779, manuscript of the Ecole nationale des Ponts et Chaussées, Carton "Concours de style et concours littéraires 1778-1812".

(17) About Isnard, see J.-C. Perrot, "Premiers aspects de l'équilibre dans la pensée économique française", *Annales Economies Sociétés Civilisations* (1983) 5: p. 1058-1074.

(18) See M.-V. Ozouf-Marignier, *La Formation des départements. La Représentation du territoire français à la fin du 18e siècle* (Paris, Editions de l'Ecole des Hautes Etudes en Sciences Sociales, 1989).

(19) C.-A. Coulomb, *Résultats de plusieurs expériences destinées à déterminer la quantité d'action que les hommes peuvent fournir par leur travail journalier, suivant les différentes manières dont ils emploient leurs forces* (Paris, 1799, re-issue in C.-A. Coulomb,*Théorie des machines simples*, Paris, Bachelier, 1821, p. 255-297). On Coulomb's memoir, see C. Stewart Gillmor, *Coulomb and the evolution of physics and engineering in eighteenth century France* (Princeton, Princeton University Press, 1971); M. Valentin, "Charles-Augustin Coulomb (1736-1806)", *Sécurité et médecine du travail* (1974-1975), 33: p. 19-26; F. Vatin, *Le Travail. Economie et physique 1780-1830* (Paris, P.U.F., 1993).

(20) D. Diderot, "Bas", *Encyclopédie, ou dictionnaire raisonné des sciences, des arts et des métiers* (Paris, Briasson, 1751-1772), 1, 98-113, on p. 98. About this article, see J. Proust, "L'article *Bas de Diderot", M. Duchet, M. Jalley (ed.), *Langue et langages de Leibniz à l'Encyclopédie* (Paris, 10/18, 1977), p. 245-271. About the analytic method used by the encyclopedists, see also A. Picon, "Gestes ouvriers, opérations et processus techniques. La vision du travail des encyclopédistes", *Recherches sur Diderot et sur l'Encyclopédie*, (1992), 13: p. 131-147.

(21) J.-R. Perronet, *Explication de la façon dont on réduit le fil de laiton à différentes grosseurs dans la ville de Laigle*, 1739, manuscript of the Ecole nationale des Ponts et Chaussées, Ms 2383 ; J.-R. Perronet, *Description de la façon dont on fait les épingles à Laigle en Normandie*, 1740, manuscript of the Ecole nationale des Ponts et Chaussées, Ms 2385. Some of the drawings made by Perronet on this occasion were later used in the Encyclopédie.

(22) E. Bonnot de Condillac, "Cours d'études pour le prince de Parme", "V. De l'art de penser", *uvres philosophiques de Condillac*(Paris, P.U.F., 1947-1951), 1: p. 769. About Condillac's definition of analysis an the later interpretations given to this key term of eighteenth century philosophy, see J.-G. Granger, *La Mathématique sociale du marquis de Condorcet* (1956, re-issue. Paris, O. Jacob, 1989); E. Brian, "La foi du géomètre. Métier et vocation de savant pour Condorcet vers 1770", *Revue de synthèse* (1988), 1, p. 39-68.

(23) A. Picon, *L'Invention de l'ingénieur moderne*, p. 469-505.

(24) Cl. Navier, *Résumé des leçons données à l'Ecole des Ponts et Chaussées sur l'application de la mécanique à l'établissement des constructions et des machines* (Paris, F. Didot, Carilian-Gury, 1826).

(25) On the development of technological education in France and in Europe, see for instance J. H. Weiss, *The Making of technological man. The socials origins of French engineering education* (Cambridge Massachussetts, M.I.T. Press, 1982); A. Picon, *L'Invention de l'ingénieur moderne*; R. Fox and A. Guagnini (ed.), *Education, technology and industrial performance in Europe, 1850-1939*(Cambridge, Paris, Cambridge University Press, Editions de la Maison des Sciences de l'Homme, 1993).

(26) F. Etner, *Histoire du calcul économique en France* (Paris, Economica, 1987).

(27) A. Picon, *L'Invention de l'ingénieur moderne*; A. Picon, "Gestes ouvriers, opérations et processus techniques".

(28) C. Richard, *Le Comité de Salut Public et les fabrications de guerre sous la Terreur* (Paris, F. Rieder et Cie, 1922) ; P. Bret, *La Pratique révolutionnaire du progrès technique. De l'Institution de la recherche militaire en France* (1775-1825), thesis (Paris, 1994).

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