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# An Essential Definition of Engineering to Support Engineering Research in the Twenty-First Century

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**Abstract:** The concept of engineering is problematic. Despite of the ancient practices of engineering, may be as old as humanity, engineering recently appeared as an academic discipline: engineering studies in universities can be traced back to the nineteenth century. Engineering has been defined as a practice, a process, a profession, and the application of scientific knowledge. However, if engineering is the application of scientific knowledge, there is a tacit assertion of the impossibility to count with proper engineering knowledge, leading to the impossibility, or at least the difficulty, for engineering to own a proper body of knowledge and the rational possibility of doctoral studies in engineering. The main concern in this research is to state a conceptual definition of engineering enough strong that serves as a building block for ontological and epistemological research in philosophy of engineering. It is shown that science and engineering pursue different objectives and produces different results. Therefore, it is possible to make a distinction between one and the other. In this dissertation, epistemological elements of engineering are set apart from ontological elements that compose the concept of engineering to emphasize its nature and the genuine possibility to produce new knowledge of engineering independent of scientific knowledge. However, it is also recognized that even methodologically different, science and engineering are intertwined and interdependent, therefore scientific knowledge does not necessarily precede engineering knowledge. Consequently, there is no hierarchical relationship between science and engineering.

**Keywords:** Philosophy of Engineering, Definition of Engineering, Epistemology of Engineering, Engineering Knowledge

## 1. Introduction

The widespread belief that engineering is just application of scientific knowledge, even without knowing what scientific knowledge (actually) is [4, 21, 44], or confusing engineering with science, or applied science or defining it as a branch of science [7, 41] evidenced the need to review and propose a solid concept of engineering for the twenty-first century. Acceptance that engineering is the application (with judgment) of knowledge of the mathematical and natural sciences experience and practice is problematic. Certainly, scientists apply scientific knowledge (with judgement) too. Scientists should follow ethical principles to get results of their work "for the benefit of mankind". On one hand, this does not allow to distinguish what a scientist do from what an engineer do. On the other hand, if accepted that engineering is the application of scientific knowledge, engineers should remain in inaction waiting for results of knowledge from scientists' endeavors. Consequently, research in engineering would make no sense and neither a doctoral degree in engineering.

As a response to this situation, a research was conducted leading to a solid, non-ideological, essential definition of engineering is introduced, free of the notions of "need" or human benefit". This definition also recognizes the existent of immaterial engineered systems, limited by the ideas of "new materials" and "nature forces".

The structure of this document is as follows: first, the core section where a dissertation around the new definition of engineering is developed. Then a section introducing the relevant role of knowledge in the construction of an epistemology of engineering, referring to a comparison between the engineering research method and the scientific method, as well as additional epistemological elements.

# 2. Distinguishing Engineering from Science

### *2.1. An Essential Definition of Engineering*

Definitions are central ontological and methodological elements for Aristotle philosophy. From Aristotle (384–322 BC) point of view, the definition of a species consists of *genus proximum* and *differentia specifica*. *The differentia specifica* is that part of the definition not provided by the *genus* [39]. Other categories of definition are etymological, prescriptive (nominal formal, and stipulative), persuasive, and genetic definitions. Since then on, definitions are corner stones in epistemological constructions of concepts in philosophy and science.

To define "engineering" seems to be the strategy of some engineering philosophers to state what engineering is, this is the case in this research. The approach of this research to this endeavor falls into the category of essential definitions. The key issue is to conceptualize what engineering is. Not just to follow the positivist assumption that a single tangible reality exists and, therefore, a single approach to "the" reality, but to bring a building block that underlies both ontological and epistemological reasoning and constructions in philosophy of engineering.

Concepts are corner stones in how human beings make sense of the world [19, 50]. Besides categorization [48, 49] concepts drive human actions on "things" in those categories and the way of thinking. Researchers in science permanently reveal and insist on the importance on the clarity of concepts [4] and the method to produce scientific knowledge [42].

This research states that engineering is the human activity that deals with creative design, construction or manufacturing, deployment, maintenance, development, improvement, operation, and control of systems which have been engineered.

Therefore, not any artifact or object in the universe is an engineered artifact or engineered system. Besides, not any system [38] is a result of an engineering endeavor, *exempli gratia* the solar system. An engineered system is a system (which in turn is a technological artifact) involved in an economic process, this is to say that the product (either an item or service) conforms to quality, performance, and features to meet constraints for its usage. Efficiency, which seems to be the Holy Grail in engineering, is immersed either in quality, performance or features constraining the engineered system. Efficiency, as well as other features of maximization or minimization, grouped by the concept of optimization, is more an economic consequence of constrains than a technological feature. The critical feature of engineered systems is that they are aimed to consciously transform an actual environment into a desired environment.

Engineered systems may exhibit physical materiality or not. Those exhibiting physical materiality are, for instance, building structures, machines, devices, energy plants, chemical plants, bridges, and dams. Those lacking materiality may be organizational processes and procedures, industrial processes, and computer software.

It must be highlighted in this conceptualization of engineering that the notions of "need", "scientific knowledge", "problem solving", and "to benefit humanity" are not included. First, because they are not part of the essential definition of engineering, and second, because using either of the three would lead to "import" the conceptual dilemmas and paradoxes of those items.

The definition of engineering that is being introduced is neutral in values. So, engineering is defined in terms of what it "actually" is, not in terms of knowledge involved in engineering activities. Not in terms of the "problem-solution" dyad because it refers to a paradigm. And this paradigm cannot be exclusively assigned to engineering. A definition of engineering in terms of "solving problems" is an ideological definition: it does not characterize what engineering is and what engineers do [11, 15, 27], even more, neglects the political, social, ecological, and economical nature of engineering [13, 14, 32, 45]. Other professionals solve problems too: physicians solve health problems –or solve problems to keep people healthy-, lawyers solve legal problems [22, 23], by way of illustration. In a knowledge-based economy [28], problem-solving is an essential skill for every twenty-first-century worker, not just for engineers.

### *2.2. Previous Approaches to the Concept of Engineering*

The definition of engineering as "the application of scientific knowledge for practical purposes, especially in industry" is a second post-war construct introduced in the report "Science: The Endless Frontier" [8] marking the beginning of modern US science and technology policy [17] for the second part of the twentieth century. The purpose of such assertion was to rise US public funds for research and development both for science and engineering. Similarly happened in the UK with the former British Prime Minister Harold Wilson's 1963 speech [43] setting a stage to give Britain renewed economic supremacy. The inclusion of the statement 'engineering as applied science' in a political agenda was not a matter of philosophical development but a need to adopt a defense policy in the context of the twentieth century cold war.

Whereas "science-based technology" may lead to think about a (previous or at least concomitant to science) strong technological development to support science activities, the conception of engineering as "applied science" lead to a cause-effect reasoning in reverse order. If it is to accept that engineering is the application of scientific knowledge, then scientific knowledge should appear before engineering activities. The availability of scientific knowledge would be a precondition for engineering. However, history and the wide practice of engineering shows that there is no chronological precedence relationship between science and engineering. As many engineering authors have remarked: engineering is different from science [7, 11, 41]. Furthermore, engineering and science are interdependent and intertwined [7].

#### *2.2.1. Engineering Is Different from Science*

Twenty-first century definitions of engineering have emphasized that engineering is different from science [19, 41]. Furthermore, engineers aware that there are misconceptions in engineering coming from ignoring that science and engineering obey to distinct rationalities [19] and produce different results.

These two broad differences refer to epistemological differences. First, knowledge involved in engineering and the method to produce "new" engineering knowledge. A specific section is devoted to this topic ahead.

#### *2.2.2. Engineering as a Process*

Engineering is also recognized as a process of creation, maintenance, design, development, and application of things [7, 41] for society. But not any "thing" in the universe, but those "things" that have not existed in the natural world [7] and made by human-mind conception and human-labor action. The distinction between the natural and artificial "things" as the difference in the scope of science and engineering respectively is stressed since Theodore Von Karman, who received his Ph.D. in engineering at the University of Göttingen in Germany in 1908, "Scientists discover the world that exists; engineers create the world that never was" [5]. It is also emphasized in the statement "science aims to understand the world, whereas engineering aims to change it" [33], and the distinction "Science is the study of what is, and engineering is the creation of can be" [7], which is a sort of Heideggerian *dasein* of engineered systems.

However, the key factor is understanding engineering as the process to meet requirements expressed by society or a group within society as a part of a set of stakeholder requirements formalized in specifications on a project. The notion of project is an ontological element in an Aslaksen's ontology [2]. This ontology of engineering introduces a class of processes framing engineering in a three orthogonal axes space where one is art (esthetic and creative aspects), other science (knowledge about nature and for its analytical procedures), and the last craft (experience and heuristics), and projects as a key element in engineering ontology framework. Then, engineering is defined as the process of the execution of an application project [2].

#### *2.2.3. Engineering as a Profession*

The discussion if engineering is a profession is rhetoric since the different conceptions of what a profession is in diverse cultural and economic contexts. There are different arguments in favor and against [12] viewing engineering as a profession [41]. However, because it is not a critical criterium to determine the ontological category of engineering, this issue can be omitted to address the concept of engineering. Specifically, to understand what the essence of engineering is.

#### *2.2.4. Engineering as a Field of Study*

Other approaches define engineering as a "field of study" of human created artifacts [7]. Even some authors conceiving engineering as a process, define engineering as the study of technology that acts as an extension of human capabilities [7]. This may be problematic because there may be many other technologies which do not function as extensions of human capabilities, fungicides, herbicides, for instance.

Literature reports a comparison between engineering and humanities [7], between engineering and Law [23. 24] and science which sheds lights on similarities and differences. Examining the 'origin of the studied object' and the way creation an analysis are taught, it is easy to find strong similarities between engineering and humanities (literature). The values above the 'minor diagonal' (Table 1) shows affinity between engineering and literature (humanities). The values below the 'minor diagonal' exhibit affinity between literature (humanities) and science.

***Table 1.*** *Comparison between engineering, literature (humanities), and science.*

| Criteria | Engineering | Literature (Humanities) | Science |
|---|---|---|---|
| Origin of the studied object. | Human created artifacts. | Human created artifacts. | Natural phenomena. |
| Teach creation. | Engineering design. | Creative writings. | Theories, laws. |
| Teach analysis. | Engineering analysis. | Literary criticism. | Scientific analysis. |
| Linked to | Needs and desires of society. | Needs and desires of society. | Needs and desires of society. |
| Formal higher education started (aprox.) | Morril act (1862) in United States of America. | University of Bologna (founded 1088). | University of Bologna (founded 1088). |

The public misconception about engineering understanding it with just making of things (i.e. the creation of artifacts) becomes evident from the approach of engineering as a field of study.

The conception of engineering related exclusively to the creation of artifacts is limited to the (technological) craft tradition of engineering. For the twenty-first century, engineering does not limit to this occupational restriction. Engineering deals both with engineered systems (technological artifacts) and the related processes to engineer those systems.

#### *2.2.5. Engineering as a Human Activity*

Far beyond understanding engineering as the transformation of the natural world, using scientific principles and mathematics, to achieve some desired practical end [2], engineering is a rich human activity. It is well understood that it is an ancient human activity [7]. However, as a formal 'university' body of knowledge appeared around the late eighteenth century.

Undoubtedly, engineering deals with transformation, but not just the natural world, but also makes and transform the artificial pre-existent world: "engineering is par excellence the science of the artificial" [47]. Besides, engineering is not of contemplative nature. Engineering does not limit to observe, describe, explain or, even, predict. It is well embedded in human life (Figure 1) highly interwoven in daily activities.

Since the pressure to procure satisfiers for subsistence, protection, understanding, participation, leisure, creation, identity, and freedom, human beings live in a production domain. Whatever the mode of economic production, engineering is embedded in human life.

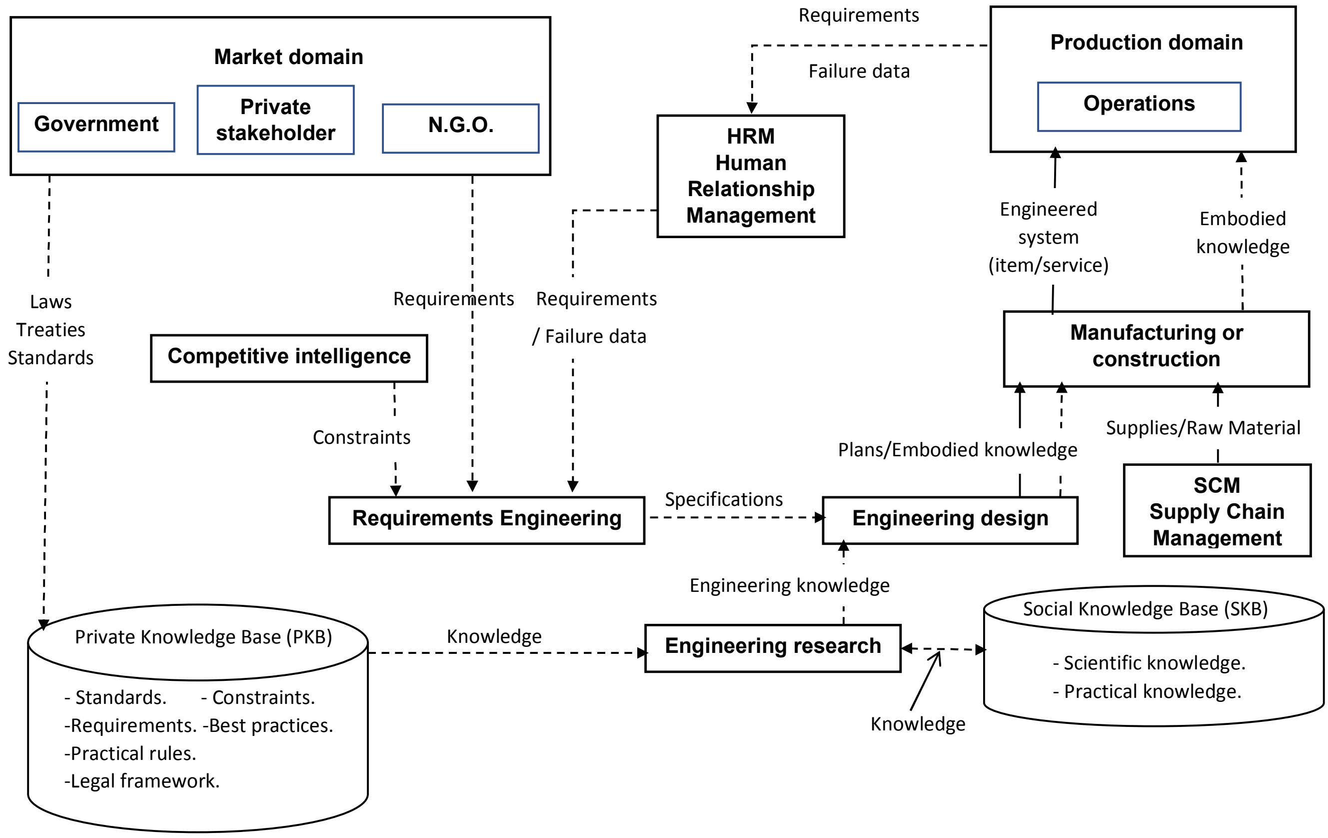


***Figure 1.*** *Engineering is a social, economic, political, and cultural human activity. In this diagram, dashed lines represent non-physical entities flowing between processes (such as information). Solid lines represent flows that include physical entities (physical raw materials are not mandatory in engineering).*

From this environment, because of the social division of labor [29] human beings communicate requirements and reports failures in the available technological artifacts, if any, (mismatches between what the technological artifact does and what it is thought the technological artifact is intended to do).

These data are socially recollected (human relationship management) and submitted to a process now known as 'requirements engineering'. Besides, in modern occidental societies, the requirement engineering process is restricted to government regulations, non-governmental organizations requirements and other stakeholders. Engineering activities, seen from an enterprise perspective, gain data (constraints) from a 'competitive intelligence' process also.

The requirements engineering process translates the set of related constraints (and requirements) into specifications to be used as input in the engineering design process. However, next to specifications, a specific 'bundle' of engineering knowledge which arises from a process of engineering research. As any research process, proper engineering knowledge appears because of research in engineering. Engineering research is enriched from social knowledge, represented in a social knowledge base – SKB (Figure 1). This SKB is formed by scientific knowledge and, in addition, any practical knowledge, including traditional and culturally biased knowledge. This is to say that engineering does not limits to scientific knowledge.

Recently, in knowledge-based societies, particular or private knowledge bases (PKBs) are explicitly conformed by standards, best practices, practical rules, legal issues, and any form of constraints, including requirements.

The output of the engineering design process produces a concrete result, a plan (a layout) to build (manufacture or construct) a physical item or service. In the experience of the University of Manitoba in Canada [4, 9] engineering design produces unique results that depend on input constraints. This object (a plan or layout) embodies the knowledge incorporated in the engineering design process. This output passes into the manufacturing/construction process. When needed, raw material or any supply is provided as input from the Supply Chain Management - SCM process. Once the manufacturing/construction process ends, an engineered system (either item or service) with the corresponding embodied knowledge comes to the production domain where this cyclic process began.

Some researchers assert that science and engineering use similar reasoning processes for problem solving; but they diverge in that despite constraints are common to both processes, constraints are fundamental to engineering design [6, 41]. In other words, while "constraints" in science play de role of undesirable conditions that prevent generalizations or exactness, the role of the same "constraints" in engineering are key factors to define specifications. Some constraints come in the form of requirements that, once translated into specifications, the result of the engineering action must meet.

The preceding dissertation challenges the definition of engineering as "the profession in which a knowledge of the mathematical and natural sciences gained by study, experience, and practice is applied with judgment to develop ways to utilize, economically, the materials and forces of nature for the benefit of mankind" [1].

# 3. Engineering Knowledge

### *3.1. To Engineer*

Engineering is a noun and 'to engineer' is a transitive verb. There is no direct translation of the verb 'to engineer' into Spanish, for instance. A verb evokes action. To engineer, as previously held, is a human activity dealing with a specific set of activities. The undertaking of engineering actions may be seen as a profession [41] performing totally or partially the activities introduced before, as a process or a practice [7, 41] of the activities previously introduced. Results of those actions are the products as well the knowledge embodied into the products.

As seen before, engineering applies socially available knowledge, which includes practical knowledge and scientific knowledge. This taxonomy seems to be a conservative one. However, evidence shows that effective knowledge management is a prerequisite of innovation [10, 51] which, in turn, is expected on engineered products involved in the cyclic engineering activities introduced above (Figure 1). Beyond thinking human knowledge in a taxonomy of formal and factual sciences [6], an alternate approach to knowledge is through different taxonomies. For instance, technological and technical knowledge [44], tacit or explicit knowledge [20, 35, 36]. Clearly, scientific knowledge is classified as explicit knowledge.

Knowledge in engineering practice may be comprised into four dimensions: social sciences, basic sciences (which is scientific knowledge), design, and practical realization [16]. However, this is another categorization of knowledge involved in engineering, not a discussion on the nature of engineering knowledge.

### *3.2. Engineering Knowledge*

The nature of knowledge proper to engineering became evident as a key epistemological concern in philosophy of engineering. Philosophy of engineering became a discipline in 2010. This does not mean that before there was no research at all. Just that to be a philosophical discipline requires to meet at least research agenda, broadcasting media, and academic community. All these three were available since 2010 (Figure 2). The Forum of Philosophy of Engineering and Technology (FPET) was established since 2010.

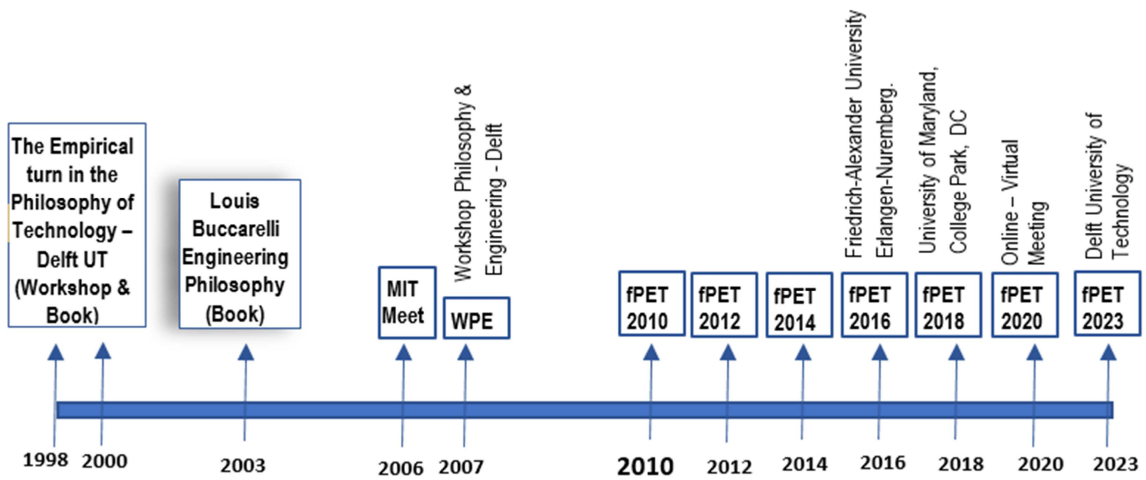


***Figure 2.*** *Philosophy of engineering timeline. (FPET 2022 programmed to be held in Chile was reprogrammed to be held the next year in Delft, Netherlands.*

Engineering knowledge is different from scientific knowledge. Research has shown differences between engineering and science at the epistemological structures, research methods and aims [11, 18, 30, 31, 34, 37, 43, 46]. The specific research method differs from the scientific method (Figure 3), when compared to the defined engineering research method [24-26] (Figure 3).

While the scientific method in sciences aims to test hypothesis to validate truth of a statement and decide if it is scientific knowledge, the engineering method, which is a sort of heuristics, validates if it functions in a specific context. After a statement is proved to be truth, it is incorporated in a theoretical framework or, with a convenient change in paradigm, a new theory appears. This may lead to invalidate pre-existent theories and, previously valid scientific knowledge could be invalid. Engineering knowledge does not look for universality. It is enough if it functions in a contingent conjuncture. Besides, science looks for universality of its knowledge, but engineering knowledge is hardly generalizable. While models in science are mainly used to represent the world that exists and must attend laws of science, models in engineering are designed for guiding knowledge through functional abstractions and further design of systems.

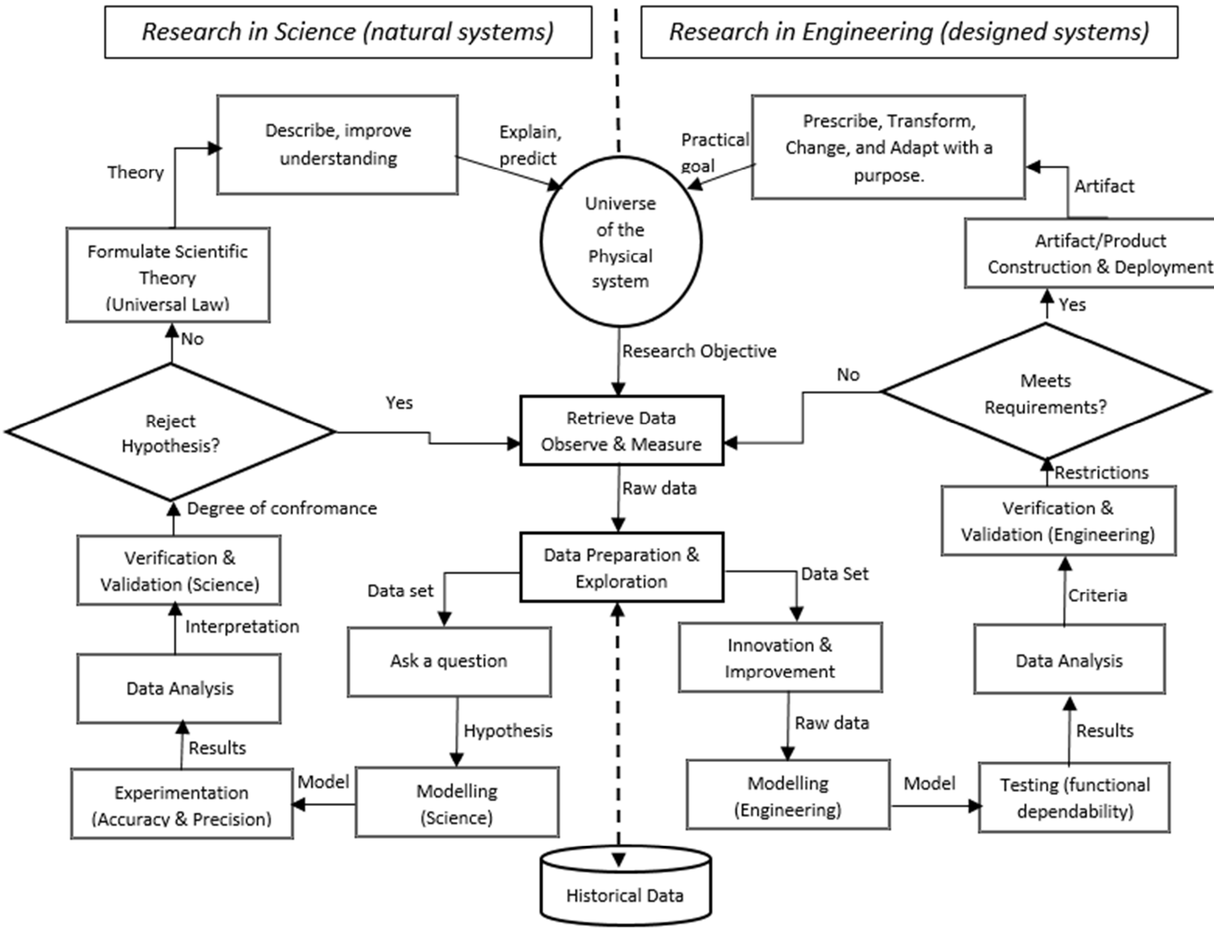


***Figure 3.*** *A comparison of the research process in science (left) and the research process in engineering (right) [31].*

In the definition of engineering, creative design refers to the set of plans to engineer a system [40, 52], as well as the process that take the plans into its related results. Construction or manufacturing is the process to engineer a system that accomplishes the specified functionality by the stakeholders.

The process of maintenance integrates activities and supplies to be integrated into an engineered system (item or service) refurbishing it to avoid depletion or loss of functionality during the system life cycle.

Systems development appears when a functioning system under externalities (for instance, substitute goods) or endogenous factors (results of "research units" deriving in innovations) the systems is modified. The modification is known as a "system update" also.

# 4. Conclusion

The strategy to define 'Engineering' was undertaken to lay solid foundations for e coherent epistemology of engineering. The result of this research is the definition of engineering as the human activity that deals with creative design, construction or manufacturing, deployment, maintenance, development, improvement, operation, and control of (engineered) systems. The aim of engineered systems is to transform (in a conscious manner) an existent situation/environment into a desired situation/environment.

This definition is ideological free. Conceptually independent from the notions of "need", human benefit", recognizes the existent of immaterial engineered systems omitting the reference to the ideas of "new materials" and "nature forces", allowing to think about financial engineering and cybersecurity engineering, for example. Financial principles and information security fundamentals are not science principles.

Moreover, under this definition, 'engineering' is neutral in values. However, this does not mean that engineering actions are value-free. In spite that 'what engineering is' determines 'what engineers do', they must respond also to what society expect from them. Ever since historical records reveal, 'What engineers do' are highly committed to life, individuals, society and specific cultural, historic, economic, and political conditions. This concept of engineering involves engineers in a wider experience than science, embracing all human history and life [43]: Engineering is different from science.

Although it is true that traditional engineering such as civil, mechanical, and electrical engineering are linked to the principle of conservation of energy or the law of conservation of momentum, engineering is more than just the application of scientific knowledge, as was introduced in the report “Science: The Endless Frontier” [8] since the end of the second-world war. Furthermore, engineering pursues different aims than science and, engineering knowledge is different from scientific knowledge [11, 18, 30, 31, 34, 37, 43, 46]. Moreover, it is open the possibility to name engineering in new and changing ways such as bioengineering or nuclear engineering.

What characterizes ‘what engineers do’ is the way they address more decisively incomplete, imprecise, flawed or even ill-defined situations and expectations. An engineer knows that ‘a specification’ could be the result of preconceptions or just inappropriate communications. Therefore, the good engineer is not limited to deliver “a solution” that a user or client “requests” [40]. The good engineer works next to other people to devise and find out the best change.

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