Critical Thinking and Judgment on Engineer´s Work: Its integration in Engineering Education

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Abstract

In the present work we develop some core ideas to strengthen the inclusion of humanistic knowledge in scientific and technical education sustained in the mainstream definition of engineering provided by the Accreditation Board for Engineering and Technology (ABET). In order to achieve such a goal we developed a novel formal definition of the term 'judgment' to enlighten the conceptual links between technical rationality and critical thinking in the context of the engineering profession. The analysis intends to overcome some obstacles still present when integrating humanities in engineering training rather than including them as a mere afterthought.

Keywords: Engineering Education, Technological Rationality, Critical Thinking, Judgment

1. Introduction

Proposals to expand engineering programs to include more humanistic content have a long and controversial history. However, it seems that we have not finished answering questions like how to integrate these disciplines into the curriculum, or what humanistic concepts to focus on. In the present work we develop some core ideas that address this issue. Our proposal is motivated by the definition of engineering provided by the Accreditation Board for Engineering and Technology (ABET), the body that accredits engineering education programs, primarily in the United States. This definition states that specific engineering knowledge must be applied 'with judgment' by engineers. As we will show, the particle 'with judgment' links epistemological aspects of engineering (i.e., aspects associated with knowledge) with pragmatic aspects referring to the purposes that such knowledge should have. We have developed a novel formal definition of 'judgment' that enlightens the conceptual links between technical rationality and critical thinking in the context of the engineering profession.

In the following, we will first explore the definition of Engineering given by ABET to highlight the terms that it contains that require, in our opinion, some additional analysis. Some of these terms may be vague enough to require clarification, and some provide opportunities to link engineering with the humanities. Then, we will present our formalization of what we consider one of the most important concepts of the ABET definition: the notion of engineering judgment. Such formalization will allow us to link the ABET proposal to contemporary debates on the teaching of humanities in engineering.

Finally, we will create a dialogue between our proposal and current analyses in the literature and present some conclusions.

2. Opening the Concept of 'Judgment' in Engineering

As mentioned, our proposal for furthering the inclusion of the humanities in engineering education is based on the classical definition of engineering, in all its complexity, proposed by ABET:

> Engineering is the profession in which 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*. (Emphasis added)

The complex concepts of 'judgment', 'economic use of resources', and 'benefit of mankind', stand out in the definition of engineering proposed by ABET. Judgment here is assessed based on the optimization of efficiency in the use of resources and the benefit of mankind. That is to say, the ‘law’ that determines judgment in the work of an engineer is optimization and human benefit at the same time. They are inseparable. We speak of 'law' with reference to the etymological origin of the word judgment that comes to us from the Latin *iudicium*, derived from *ius* (right, law) and from *dicare* (indicate). Then we ask: what is the general law that governs the optimization and benefit of humanity in the case of engineering? Is knowledge of mathematics and natural sciences sufficient to grasp it?[8]

When faced with a problem, engineers judge both the means to a solution and the ends to which the solution is applied. These judgments are usually of a qualitative nature. If the conclusions, decisions, or suggestions that we arrive at through reasoning were strictly quantitative, the type of reasoning would not be ‘judgment’ in the intended sense, but rather the reading of the result of a calculation, something that a well-programmed machine could perform, without problems and in an unambiguous way. In this sense, it seems clear that ‘judgment’ as it appears in the ABET definition should not refer to pure ‘statements of fact’ in the Humean sense[9]: For quite some time now, but especially after the collapse of the fact/value dichotomy by Hilary Putnam,[10] it has become untenable to think that a complex human activity such as engineering practice can be reduced to the construction and use of only ‘pure factual statements’ such as ‘the column is 24 inches in diameter’. A large body of literature has pointed to the influence of pragmatic and evaluative factors in engineer´s activity.[11] ‘Judgment’ in the ABET sense must necessarily reflect the complex nature of the factors to be considered in the decision making of engineering professionals, and thus cannot be reduced strictly to the epistemic values of mathematics and the natural sciences (such as accuracy, simplicity, and empirical fit, among others). Engineering judgment needs these elements, but at the same time, it transcends them.

For example, if we say that 'the design of the structure, of which the column is a part, is good', we are entailing a conclusion from a judgment. There is freedom in this case, two engineers may therefore legitimately differ as to what they consider to be a good or a bad design. This type of judgment does not fully agree with the Humean notion of ‘value judgment’, since it is not purely factual nor purely evaluative: whether the structure is ‘right’ does not depend only on the designer's tastes. If the profile selected for the beam does not meet certain constraints, the structure will collapse, and under practically no rationality will it be right to design a collapse-prone structure. The fact that judgments of value necessarily include factual statements, and factual statements include value judgments, has been clear at least since the work of Putnam.

'Judgment', in the sense that we consider it here, is a qualitative ordinal variable, so it is not possible to use a quantitative scale to establish that one agent possesses twice the judgment of another agent, nor that one of those agents possesses a judgment of 3 while the other, much more judicious, possesses one of 8. However, it is possible to answer questions like: is it more judicious to install a solar thermal power plant or a hydroelectric power plant to supply a city with electricity? Of course, such an answer is not unique, except in extreme cases, even using appropriate assessment and decision-making methodologies. The relationship between a problem and the design that can solve it is practically never univocal: each individual problem can be solved by a variety of possible designs.[12] Some methods of selection, for example cost-benefit analysis, may reduce the space for alternatives, but many projects will still have more than one viable path, requiring some form of additional judgment to be applied that transcends such methods. Moreover, no method of selecting design alternatives is totally objective and politically neutral: even algorithmic methods that appear to reduce decision-making to mechanistic calculation incorporate assumptions that necessarily embody ideological preferences and contextual conventions.[13]

It seems clear that the notion under analysis is in part relative to each individual and to each socio-historical context: it is cultural, in a broad sense. However, the analysis cannot stop here since each individual in each cultural context is not completely free to hold any position. For example, in today´s democratic society where child labor is prohibited, it is not a real option to design machines that can be operated by children as was common during the First Industrial Revolution. Or the fact that while it is not possible to operate in a country with strong environmental policies factories that do not comply with a high pollution standard, in other less restrictive countries it is still possible to install them. We cannot talk about judgment without this type of contextual evaluation. Engineering decisions, as Fernando Broncano suggests, are also subject to constraints external to the individual engineer: regulations, culture, environment, and other factors may restrict technically feasible design paths.[14]

As we will see in the next section, judgment is then related to the symbiotic interaction between theoretical and practical rationality, as pointed out by Kroes, Franssen and Bucciarelli:

> Theoretical rationality concerns what beliefs about the world it is rational to entertain, whereas practical rationality concerns what actions are rational to perform. Both forms of rationality are of paramount importance to engineering practice. Since this practice is primarily aimed at action in the sense of changing our physical environment, practical rationality is of direct significance, but theoretical rationality is equally relevant, because engineering without knowledge of the actual state of what is to be changed or of means-end relations is hardly conceivable. Within an engineering context reliable knowledge is a necessary (but not sufficient) precondition for effective and efficient action. [15]

3. Logical Formalization of the Foundation

3.1. First step: including extended rationality

With the aim of deepening the foundation, we developed a novel formalization of the concept of judgment in engineering inspired by the logical analysis of the normativity of the artifacts. But, while these studies try to answer questions like: "Is this a good hammer?", we transformed the question into: is she a judicious engineer?[16]

As we have already said, no matter how many restrictions may exist, there are still degrees of freedom for engineering decision making. Even in the most restrictive context, the agent continues to have the flexibility to select the design that solves any problem from a range of possible courses of action. Edward Krick's pioneering work in engineering design thematizes this fact under the name of 'fictitious constraints' which he contrasts with 'real constraints'. While the latter are common to all designers, the former are specific to each engineer, her culture, preferences, and values. Design is always an underdetermined task.[17] More precisely:

> *An agent A uses judgment if and only if, when given a space of possible courses of action C, agent A chooses course of action Ci, where Ci is the best according to rationality R.*

This formalization entails, in the first place, that 'judgment' is a prerogative of a generic individual (agent *A*). In this sense, it could be an engineer, an artificial intelligence or an ordinary person.

Secondly, each problem that can be tackled almost never leads deterministically to only one course of action, but instead a multiplicity of alternative solution paths may be followed by the agent. But, as we have already expressed, the space of courses of action has restrictions of a different nature. Some of them are cultural, which implies that they vary by individual, by society and by historical moment. All these restrictions configure the form that the space of courses of action, *C*, takes.[18]

Ci, the best of the courses of action relative to rationality *R* is included in *C*. Whenever an evaluative attribute is used (such as 'better' or 'worse') it should be kept in mind that values are relative. In our definition we affirm that judgment will be relative to a rationality *R* that should be made explicit in order to be able to evaluate if the course of action followed is *Ci* or is one that is not the best *according to R*. In that case we will be able to state if the agent has behaved with judgment or not.

The requirement that *Ci* be *the best* course of action should be somewhat weakened in the final formulation that we will arrive at later on. Being able to establish beyond all doubt that *Ci* is the best decision requires agent *A* to be omniscient. However, the practice of engineering is actually done from a bounded, imperfect rationality. Therefore, we cannot wait for the perfect decision. We may then be satisfied with the judgment of a kind of agent like those theorized by Herbert Simon.[19] The real engineer has a partial understanding of things (since she does not know the consequence of all the courses of action with certainty). Instead of trying to maximize her results on the basis of a (impossible) full understanding, she is satisfied just with reaching a 'good enough' solution for the proposed objectives according to the rationality and the culture in which she stands.

We affirm that judgment will be relative to a rationality *R*. For example, if the horizon of our rational system *R* is shaped by neo-classical economics, the central criteria to discuss the judgments about the decisions *Ci* of our engineer will be dominated by individual order values of utility (*homo economicus*). On the other hand, if our horizon were guided by sustainable development ideas, the argumentation of the *Ci* would be centered on minimizing the environmental and societal externalities (*homo solidarius*). Then, it is possible that different agent rationalities conflict with each other by pointing toward different decision alternatives. This is a problem that is difficult to solve, even impossible in some cases in which the different positions defend opposing interests. The important thing here is that each engineer acknowledges her own rationality in order to be able to recognize that in her positioning, whatever it may be, there is always a valorative anchor, an individual standpoint.

3.2. Second step: including critical thinking

The problem becomes more complex as another question arises: how can we base our arguments to judge the rational system itself or the culture where it is inscribed? Robert Nozick argues that no rationality of an instrumental nature allows us to weigh up the rationality of the ends themselves:

> There is, of course, a familiar criticism of the notion of instrumental rationality as purporting to exhaust the whole domain of rationality. Something is instrumentally rational with respect to given goals, ends, desires, and utilities when it is causally effective in realizing or satisfying these. But the notion of instrumental rationality gives us no way to evaluate the rationality of these goals, ends, and desires themselves, except as instrumentally effective in achieving further goals taken as given. Even for cognitive goals such as believing the truth, we seem to have only an instrumental justification. At present, we have no adequate theory of the substantive rationality of goals and desires, to put to rest Hume’s statement, 'It is not contrary to reason to prefer the destruction of the whole world to the scratching of my finger'.[20]

We believe that the third issue that we have highlighted from the definition of the ABET comes into play here: the statement regarding 'the benefit of mankind'. We are faced with an ethical dimension that challenges us and that we commonly respond to by qualifying the human act as either ‘good’ or ‘wrong’. But evaluative conclusion is neither binary, nor permanent, nor uniform across people, groups, and cultures. Justifying ourselves implies the recognition of some kind of freedom underlying the act under observation. If not, the need for justification would not make sense since the effects would be fully explained in their causes as happens with physical phenomena: they can be reduced to their causes. In the free act there is an inexplicable remainder, what we might call the ‘uncaused’. This is the case of the justification of the ‘benefit of mankind’ to which ‘judgment’ aims in the actions of engineering.[21]

If a given design meets the previously stated objectives and we assume that the engineer believes that she is acting deliberately for the benefit of mankind, then a philosophical analysis of the design and its impact can provide us with evidence regarding the rationality that led to the selection of the course of action followed. This type of analysis has already been done on several occasions, as illustrated by the classic case presented by Langdon Winner with respect to the politics of artifacts.[22]

But, how do we judge if an engineering action benefits humanity? We are entering into the complex field of ethics and philosophical anthropology. Without detriment of its variety, one of its statements proposes that 'human being is being in relation’: in relation to nature, in relation to others, in relation to itself, and in relation to the unknown (in the broad sense that perhaps all we perceive is not the totality). Insofar as we keep these four constituent relationships of the human healthy and in harmony , we are able to say that something is good: we judge the circumstances and the historical becoming as good. Without wishing to exhaust the topic, which would require further analysis, we can say in advance that if engineering decisions start including the human being from a holistic perspective, such as the anthropological conception of ‘human being as being in relationship’, proposing, and making sure that their actions do not hinder (even less break) any of the four constituent relationships mentioned above, we could conclude that we are acting somehow for the benefit of mankind. It is through the proper study of humanities that engineers should at least be able to recognize this complexity in order to act responsibly according to what is stated by the ABET definition.

We have reached the point where we believe that it is necessary to broaden the horizons of instrumental rationality through critical thinking. Following Nola and Irzik:

> The core aim of education is: to produce people who can be rational and critical inquirers into whatever subject matter or discipline in which education is being acquired. This is a broad aim that allows any subject matter to be the object of critical inquiry. It also includes being a critical inquirer into the other various aims of education listed above, thereby subverting faulty or inadequate or tendentious aims, or recognizing what are the most worthy aims, and what are good means for achieving them. Thus, once a person becomes a critical inquirer, they are then able to see, if one’s aim is self-development, both what this really means and what are the best means to achieve it.[23]

As Lionel Claris and Donna Riley point out, such critical thinking should be applied both to the consequences of engineering, as well as to engineering itself:

> We have long ago reached a certain 'situation critical' in engineering, in which engineers may have abundant logical thinking skills but no practice of thinking critically about problem framing, power relations within the profession, hegemonic epistemologies of the discipline, or reproductive practices of engineering education.[24]

Lavinia Marin has already highlighted the importance of critical thinking in engineering education. She argues that although educating engineers for the challenges of the 21st century should include not just technical skills but also societal and ethical competencies, ethical reflection is often difficult to teach because it has not been defined and operationalized enough to make it distinguishable from other forms of thinking. She proposes to operationalize the under-determined concept of ethical reflection in education by drawing inspiration from the competency of critical thinking. She highlights that the ‘critical’ in ‘critical thinking’ is a characterization of the process itself, not a characterization of the outcome of the judgment:

> CT [critical thinking] is not just about being logical in one’s practical judgments or arriving at a correct answer, but about being careful, taking as many different aspects as possible into consideration while also being sensitive to one’s own cognitive biases.[25]

As she notes, ethical reflection uses an overall critical approach in its processes, such as questioning the very premises from which one builds moral knowledge, including the cultural and religious foundations of norms, values and practices.

Gary Downey also introduces an image of engineering practice as ‘problem definition and solution’ that necessarily includes this type of reasoning at the center and not at the margins of the engineering curricula. The term 'problem definition' need not be alien or external to problem solving but could be 'a simple extension' of it. He wonders:

> Were engineering science curricula unwittingly preparing learners to follow without question those who define problems for them and to expect co-workers from other fields, especially beyond engineering, to lack knowledge and value? What kind of service performed myopic practices without critical analysis of those practices? Was the absence of attention to agents who might understand their work differently be a key feature of practices defining engineering as technical work without politics?[26]

3.3. Third step: putting it all together

With all the analytical elements pointed out so far, we can finally arrive at the following extended definition of the use of engineering judgment:

> *An agent A uses judgment if and only if, given a space of possible courses of action C, agent A chooses course of action Ci, where Ci is satisfactory according to rationality Rj; and Rj is the rationality that agent A considers the most suitable to reach the ends E, selected within a space of rationalities R by means of critical thinking.*

At this point we have finally got to the heart of the problem through the formal foundation. It is important that the engineer, by means of adequate study of the humanities, develops the bases for critical thinking such that it allows her to identify, select or *create* a rational system directed towards the 'benefit of mankind'. Otherwise, rationality could be *imposed* by her education, her socio-institutional context (for example, the organization in which she performs her duties), mass media or basically by any ideological bias that operates in a veiled way, which would turn the engineer into an uncritical agent,[27]. Therefore, in order to argue that the engineer has good judgment, she must have the possibility of putting critical thinking into practice, in addition to the technical rationality of the natural sciences and mathematics. She would then be able to justify her actions from rational paradigms that go beyond mere technique[28].

4. Relating our proposal to current analysis

With the intention of renewing analysis in this important matter, in 2015 *Engineering Studies* devoted a double issue to the presentation and discussion of Louis Bucciarelli and David Drew's proposal for a "Bachelor of Arts in Liberal Studies in Engineering … [for students] who have sufficient interest to enroll in a program that keeps open the possibility that they might pursue a career in engineering".[29] The special issue includes the critical opinion of thirty-one scholars who reflected on the topic under discussion, representing an unprecedented contribution that deepens the relevance and possibilities of implementing such a reform.

Bucciarelli and Drew is in line with the interest of the Accreditation Board for Engineering and Technology (ABET) in promoting critical reflection in order to allow future graduates to have the skills to contextualize their professional practices[30]. They hold that a new curriculum must be designed in order to provide, among other functionalities, "exemplary, substantive engineering content from the perspectives of the humanities and social sciences".[31] As we also attempt to show in our proposal, Bucciarelli and Drew affirm that this new curriculum would train engineers not only in acquiring traditional engineering skills, such as instrumental rationality, empirical testing and transformation of ideas into products, but also in analytical thinking, management of multiple frameworks of analysis, critical thinking and practical reasoning.

Our work is part of the same concern about the capacity of engineering to influence society that motivated Drew and Bucciarelli to initiate the debate on a special curriculum for humanistic engineering. During the aforementioned debate, a number of responses appeared from prominent engineering education scholars who, while recognizing the need to incorporate humanities knowledge into the engineering curriculum (many of them are strong supporters of this idea), at the same time denounced epistemic and, above all, institutional obstacles to effective implementation of the proposed modifications. There is a widespread concern that the addition of humanistic knowledge to the engineering curriculum should not end up resulting in an engineer with less technical knowledge who is incapable of being able to cope in the world of work.

Pitt[32] and Didier[33] considered that training in the humanities is necessary to know and value the real needs and possible futures in a world with a technological base. It is not that 'classic' engineers are not necessary, but this other type, trained in a broader way and able to lead changes is also needed. Kroes[34] agreed with this view, stating that the humanities should teach students to apply critical thinking to answer central questions about the goals of engineering and the values it embodies. Nieusma[35] observes that rather than merely *augment* the existing technical core of our engineering programs, humanities courses should strives to *frame* the entire educational experience of students, providing curricular, conceptual, and pedagogical frameworks to situate students’ engineering coursework as well as their identities within a more expansive vision of engineering as occupation as well as of engineering in society more broadly.. In line with Nieusma, Riley[36] claims that we are not managing to teach the humanities correctly, as they are presented in a very shallow way. According to her, humanities should be taken seriously, above all for developing critical thinking. Finally, Downey[37], following Bruno Latour, goes a step further when he argues that the distinction between content and context must disappear, since this traditional view keeps social sciences at the periphery of engineering education.

Our work indicates that the humanistic knowledge that these (and other) educators insist on incorporating into engineering is not foreign to it, but rather a constitutive part: the notion of judgment that we have formally reconstructed was obtained from philosophical reflection on the very definition of engineering proposed by ABET. This suggests that judgment, as we understand it and make it explicit here, is a constitutive part of engineering practice; since its correct development requires the aforementioned humanistic knowledge, its incorporation into the engineering curriculum is thus fully justified.

4. Conclusions

With the differentiation between technical and humanistic knowledge we do not intend to return to the old distinction between objective and subjective knowledge. What we are trying to convey is that a distinction can be made between a knowledge proper to the natural sciences and another from the social sciences, where both epistemic and non-epistemic values are ubiquitous. The ABET definition only explicitly states the need for knowledge of the former; no explicit mention is made of the latter. Our proposal is that these are essential for applying the notion of judgment in the sense intended by ABET itself.

To achieve this goal we have developed a formal definition of judgment in order to ground the importance of including humanities in engineering on the basis that technical-instrumental rationality – as only one of many possible rationalities – operates at a lower epistemic level than the space of other rationalities that we have described. The ability to solve problems in a technical manner allows one to select good courses of action within a given rationality but does not allow one to question the validity of that rationality or its adequacy for a range of ethical, aesthetic or other social values that should constitute responsible modern engineering, as long as 'the benefit of mankind' is intended.

We hold that limiting the training of students exclusively to technical content leads to uncoupling such constitutive values from the courses of action chosen in solving complex engineering problems and therefore from the product of their work. Hence, we encourage an education in critical thinking that can operate at a higher epistemic level than technical solutions in order to relate them to the values of the engineer.

We hope that this new formal analysis can help to dispel the doubts that may still exist inside the universities regarding the inclusion of humanities in the engineering curriculum.

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[8] The concepts highlighted here were addressed by other authors in previous works, but, as far as we understand, they did not focus explicitly on the central concept of 'judgment'.

[9] Hume established a dichotomy that persisted in philosophy until the end of the 20th century, especially because of its assimilation by logical positivism, between statements of fact (purely factual and empirically verifiable) and value judgments (purely evaluative and without empirical meaning). Hume, *A Treaty of Human Nature.*

[10] Putnam, *The collapse of the Fact-Value Distinction and Other Essays.*

[11] See for example Bucciarelli, *Designing Engineers*.

[12] Dym and Little, *Engineering Design: A Project-Based Introduction.*

[13] For a discussion in this regard on the cost-benefit method, see Steel *Philosophy and the Precautionary Principle*.

[14] Broncano, *Mundos Artificiales*.

[15] Kroes, Franssen and Bucciarelli, "Rationality in Design": 574.

[16] See for example Franssen, "Artefacts and Normativity".

[17] Krick, *An Introduction to Engineering and Engineering Design.*

[18] Broncano, *Mundos Artificiales*.

[19] Simon, *Administrative Behavior*.

[20] Nozick, *The Nature of Rationality*: 139-140.

[21] Taebi, *Ethics and Engineering. An Introduction*.

[22] Winner, *The Whale and the Reactor.*

[23] Nola and Irzik , *Philosophy, Science, Education and Culture:* 7.

[24] Claris and Riley, "Situation critical: critical theory and critical thinking in engineering education": 102.

[25] Marin, "Ethical reflection or critical thinking? Overlapping competencies in engineering ethics education": 1355.

[26] Downey, "What is engineering studies for? Dominant practices and scalable scholarship": 62.

[27] Downey and Lucena, "Knowledge and professional identity in engineering: code-switching and the metrics of progress", offer a very good analysis of this point.

[28] A novel proposal that can help in the definition of criteria of judgment is 'Honest Technologies', Quintanilla, *Tecnologías Entrañables. ¿Es posible un modelo alternativo de desarrollo tecnológico?*

[29] Bucciarelli and Drew, "Liberal Studies in Engineering – A Design Plan"

[30] In addition, it aims to attract young people who are still undecided about their vocation to engineering, and female students who do not identify with the classical instrumental engineering approach. It also intends to mitigate racial biases.

[31] Ibid.: 107.

[32] Pitt, "Motivating an engineer to be a leader".

[33] Didier, "A good answer to (perhaps) not such very good questions".

[34] Kroes, "Critical thinking and liberal studies in engineering".

[35] Nieusma, "Conducting the instrumentalists: a framework for engineering liberal education".

[36] Riley, "Facepalms and cringes: liberal education misapprehended".

[37] Downey, "Opening up engineering formation".