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Mini Review

On the Principle of the Minimum Dependences

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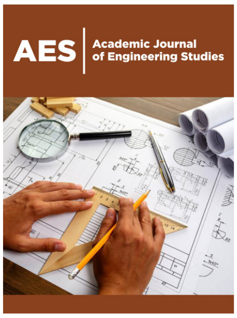

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Submission: July 23, 2021

Published: August 27, 2021

Volume 2 - Issue 3

How to cite this article: Efrén M Benavides. On the Principle of the Minimum Dependences. Academic J Eng Stud. 2(3). AES.000539. 2021.

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In 1994 I was challenged. I was hired to design the inline fuel injection pump of a novel two-stroke turbocharged diesel engine which was been designed from a scratch in order to thrust a long-range Unmanned Aerial Vehicle (UAV). For the purpose of this discussion, the list of engineering specifications that I received may be condensed in just this sentence: introduce the required fuel in each condition of operation with an inline system as versatile, reliable, fast and cheap as possible. Then, I studied the available options: inline mechanical injection pumps and common-rail systems. Finally, I selected the common-rail; not because it was by that time considered the best system on the automotive sector, but because I considered it was the one that, as an inexperienced engineer as I was, I could design. Here, design meant to undergo the long process that begins selecting a concept and ends making a first operative prototype.

Obviously, the project manager rejected my selection: too much risk. At that time, such manager's decision seemed quite reasonable to me because the proposed engine was a controlled-risk innovative project. That is, it had subsystems which were going to be new, assuming a higher (but controlled) risk and others which were going to be standard, assuming a lower (and hence non-problematic) risk. The injection system belonged to the second group, where the standard at that time was the inline mechanical pump. It was clear in the specification order, "Inline Fuel Injection Pump, we do not want you to design a Common-Rail". A couple of years later, I discovered that this episode resulted to be the best engineering lesson I have ever received. Why did I feel able to correctly design the system with the highest risk and not the other?

Meanwhile I was reading the beautiful Suh's book "The Principles of Design" where Professor Suh stated that there are principles which determine the correctness of a design regardless of the statement you are solving [1]. Professor Suh postulated that there are two key and universal principles: firstly, the Independence Axiom stating that good designs are those which keep independent the Functional Requirements (FR); and secondly, the Information Axiom stating that good designs are those which keep high the probability of success (in Professor Suh's words, the information content). Professor Suh was so confident on its universality that gave them the status of axioms.

Both axioms work as follows:

1. As a consequence of the Independence Axiom, the best solution is the one that has only one FRs assigned to a given Design Parameter (DP); and,

2. As a consequence of the Information Axiom, the best solution is the one that has only one DP assigned to a given FR. Therefore, a universal definition of best has been born in the engineering field: best designs are those which have a diagonal design matrix.

This definition of best design is a beautiful and a powerful result and, as soon as I read it, I started applying it to everything I found around. In particular, to my previous question, which I reformulated as: Is it possible that I felt able to correctly design the common-rail because it was the best design and hence the risk-free option? If the answer were yes. Immediately, I discovered that the fuel injection system had two FRs: The injected amount of fuel and the injection pressure. The first one ensures the required torque in the engine and the second one ensures a high combustion efficiency and a low contamination. I studied both systems from the new perspective and I discovered that the inline fuel injection pump completely broke the independence of both FRs whereas the common-rail kept them independent. That is, the common-rail was a better system than the inline one! This was an awesome discovering for me because the conclusion had raised in a somehow objective way.

I was shocked because I had really discovered that my impression that the online system was more difficult to design than the common-rail was related to this definition of best. It took me several months of introspection to identify the connection between my intuition and the two axioms. Finally, I found the missing link: I felt unable of designing the inline fuel pump because of an excessive number of dependencies (many more than one) which I did not know how to handle whereas such problem seemed less problematic to me in the common-rail system. The difference lies in the number of dependences. Suh's definition states that the inline pump has a dependence between the two FRs and the common-rail does not. This means that the first system has at least one dependence more than the other. Here, the first key was to understand that the axioms had detected a dependency that should not be there, and the second key was to understand that my intuition had detected many more problematic dependences.

At that time, my design of the inline system for the UAV was in the test bench where it performed worse than expected. I had clear evidence that the difficulties in meeting the operational specifications came from a main source: the coupling between all the elements prevented the correct optimization of the response. This fact turned out to be a serious cost issue. In effect, every hour in the test bench was spending resources: money and time. In addition, the manufacturing tolerances of almost all the parts (cam and follower, impulsion barrel, retraction valve, high pressure tube, injector…) became extraordinarily strict. Hundreds of parameters were affecting the response of the system and most had to be known accurately enough. Critical tolerances appeared everywhere. This drift exacerbated the cost problem because any attempt to redesign any part was very expensive. A new coupling spoiled again the chances of finding a satisfactory solution within the proposed budget. In this case the coupling was between reliability and geometry: nitride-hardened surfaces were required to increase the reliability in some parts with tight tolerances. This was an explosive mixture that sent parts prices skyrocketing. By that time, it was already very clear that fulfilling the specifications was unfeasible. My main purpose changed to finding out where the budget deviation started, and I had a good clue. Meanwhile, I had finished a mathematical model to describe the system response in terms of the input parameters.

The physics involved can be summarized as:

1. high-pressure injection means that the fuel has to be treated as compressible in all the elements (pump, retracting valve, line and injector),
2. short injection times means that pressure waves has to be followed through the system and
3. fast closing of the retracting valve creates cavitation pockets that spread through the system.

In a closer look, more couplings appear: the speed of sound changes with the temperature and with the amount of dissolved air that the fuel has previously absorbed, the elasticity of all the solid parts (mainly the high-pressure pipeline) modifies the speed of sound in the system and all the clearances modify the real flows that pass through the different elements. This is a small sample of the difficulties of writing a mathematical simulator for this system. The idea was to use this model to select the best set of input parameters, those which ensured that the response was within specifications in the whole range of operation. This way, the mathematical optimization would reduce cost and time, keeping in a minimum the number of conducted tests in the prototype bench.

Developing the mathematical model was very enlightening and the conclusion was clear to me: the inline system had to be designed as a whole, any change in any part of it required modifications in all the other parts at the same time. During the hours I spent in front of both, the mathematical model and the prototypes running in the test bench, I found dozens of evidences corroborating this fact. Among them, there was one which completely broke the game. The mission of the retracting valve was to ensure a sharp ending of the fuel injection (required to reduce the amount of unburnt fuel and smokes) thanks to its fast closing; however, the cavitation pocket generated by this fast displacement depended severely on the geometry and the operation conditions. This cavitation pocket modified the initial conditions for the next injection leading to a general oscillation of the engine as a whole. To solve this problem, a constant-pressure retracting valve was required, however we could not find a suitable one because any change in the retracting valve required also a change in the cam profile. After several redesigns, the result was an improved system which does not meet the consumption and contamination requirements.

The conclusion was that the injected mass flow rate and the injection pressure evolution depended on everything as a whole. This excessive number of dependencies imposes that the best optimum response which is achievable with such system is inexorably worse than the required specification. In other words, no matter how many hours of optimization and redesign are put into the matter because the best optimum that such a system could reach would never meet the specs. The inline injection pump was not the adequate solution for the given specs, that's all. And it seems that the automotive sector also knew it because after several decades using inline (or rotary) pumps they finally moved themselves to the Common-Rail. Could we know before spending the budget? Yes, we do because Suh's axioms anticipates this conclusion. My personal quest had led me to position Suh's axiomatic approach as an ethical framework: better and worse is defined with independence of the particular problem which is being solved. However, my study on the inline pump also indicated to me that something was missing in Suh's axiomatic approach. I identified this missing piece of information as: not only the dependences between the FRs are problematic, but that in general all unnecessary dependences are bad. I had just built my own ethical framework. Obviously, there has to be a minimum number of dependences in any solution because there must be a link between what the designer is proposing and the specs. But this is precisely the important compass guiding a design process to the success: discovering the minimum number of dependencies which ensures the success and discovering a solution just implementing them. The Principle of Minimum Dependences had just been stated.

In the case of the injection system for a Diesel engine there are three crucial dependences to support the value, from here, all the others only subtract value. The common-rail has two independent systems to achieve it: a pressure regulator and an electronic injector. And hence, it is possible to show that this design has only three critical tolerances (each ensures one crucial dependence): the accuracy on the pressure sensor and the accuracy on timing the start and the end of the injection through a calibrated nozzle. All the other tolerances does not affect the performance of the common-rail system. This means that the high-pressure pump for example can be designed using any cam profile, any plunger and barrel, any check valve, etc. Therefore, the dependences introduced by the pump, for example, are very weak because they do not affect significantly either the injection pressure or the injection rate. The check valve can be replaced by any other and the overall performance does not change. Design, manufacturing, assembly, adjustment, operation and maintenance costs drop dramatically whereas the performance of the system increases due to a better control of the pressure and metering in all the operational points. In contrast, the inline system had hundreds of critical dependences. Thus, finally, we have found a winner design: the common-rail wins against the inline pump in almost all the fields.

During such abstraction process I made the following analogy with a simple mathematical problem. Suppose two designers who wants to achieve y=0 and that they design a system with two parameters x_1 and x_2 which ensure the desired result by means of the following relation $y=(x_1-1)^2+(x_2-2)^2$. Obviously, the optimum design is placed at $x_1=1$ and $x_2=2$, that is, their design has two dependences to solve the spec y=0. However, in addition, suppose that a hidden dependence exists between x_1 and x_2 (for example, a physical one like the one introduced by the compressibility in the inline injection system). Say that the new dependence looks like $x_1=3x_2$. Now, they have three dependences. The best design point now is $x_1=3/2$ and $x_2=1/2$, which leads to the minimum value of y=5/2 very far away from the desired value of y=0. The design has failed because the best design now does not fulfil the spec! What can the designers do? They can add new parameters to solve the problem. For example, they can add x_3 in such a way that they attempt to modify the dependence as $x_1=3x_2-x_3$ (for example, changing the initial retracting valve by the constant-pressure one proposed in the inline injection system). Now, they have four dependences and the following design point $x_1=1$, $x_2=2$ and $x_3=5$. Intuitively, we can infer that the larger the number of design parameters, the larger the probability of having problematic (hidden or not) dependences between them. This is a real and true source of risk that designers should avoid since the onset of the design process. How the designers should have been proceeded? They should have conceived a single parameter design in the form $y=x_0$ with the design point at $x_0=0$. Obviously, this is not a straightforward process, but we can anticipate that if they success, they will be ahead of an innovation (like the common-rail versus the inline). Note that there is a few number of designs (probably only one) with one dependence but that there are a huge number of designs (probably infinite) with more than one dependence.

In 1997 I was challenged again. There was an opportunity to impart lectures on the design of fuel injection systems at the School of Aeronautics (ETSIA-UPM, Polytechnic University of Madrid). I accepted and began to teach all those systems under the new perspective. Now, the important thing to be transmitted was not the architecture of the system itself or its expected performances, but the number of dependences created by each attempt to solve the problem. It was not a technical problem it was an ethical one! Thus, I had a new game and teams to play it: the match played more times was carburettors vs fuel-injection systems. This new approach shocked the students who were not prepared to understood that almost all the parameters in the system could be selected using a criterion not based on the theory of reciprocating engines but in a universal design principle. I used this principle in almost every problem I met, and in almost every lecture I imparted. The outcome always resulted better than expected. The idea of developing a small start-up (or spin-off) to sell this new way of designing turn out during those years and this led me to contact an important international consultancy firm. Several studies done for them shown that the Principle was suitable for addressing problems under incomplete information and for assessing the technological maturity of a given solution.

In this reflection about how the Principle of Minimum Dependences was born in my mind it is necessary to recall the attempts I made in order to link it with the Suh's axioms. Obviously, minimizing all the Dependences tends to remove the dependences between the FRs and hence fulfil the Principle of Minimum Dependences leads to fulfil the Suh's first axiom. In addition, decreasing the number of dependences to a minimum reduces the risk of unexpected perturbations, ensuring a higher probability of success and a fulfilment of the Suh's second axiom. This way, the fulfilment of the Principle implies the fulfilment of the Suh's axioms. However, the real value of the Principle of Minimum Dependences is that it reduces costs and increases performance. That is, it increases the added value to the society. In this reflection, a final target appears: for a given challenge, the solution with the minimum number of dependences always wins: If it always wins, it is always the better. If it is always the better, it is unbeatable. If it is unbeatable, it cannot be improved any more. At this point, the only way to advance is to change the challenge. Hence, the important question that a designer should wonder before beginning any design process is: am I willing to accept that for a fixed and determined challenge there is always an unbeatable solution? Be careful with your answer because if you choose "yes" you are under a universal umbrella (for example, the Principle of Minimum Dependences) but if you choose "no" you are wandering a winding non-universal design process.

Thus, the assumption that there exists a universal principle driving the design of a solution is similar to the assumption that the making-decision process is objective. Furthermore, if the process is objective, all the designers who share the same challenge statement (which includes the universal principle to be used) should arrive to the same objective solution. This objective solution, by definition should be the unbeatable one. In effect, as long as the universal principle holds the same for all the design teams, the best solution cannot change. The other way round, we can anticipate that the best solution will change if the ethical framework changes. As a conclusion, I anticipate that the coexistence of non-universal ethical frames are the main loss of sustainability. Why? Because it is the main source of future rejections. The subsequent redesigns are an unstoppable sink of resources. How can the society fix this problem? Stopping the change in the ethical frameworks. How? Using a universal ethical framework.

In my experience I have observed that the most stable principle I have found is the Principle of Minimum Dependences. It is easy of understand: if a solution removes dependences, it is better. What does "to remove dependences" mean? It means to have a net reduction of the total dependences, that is, to remove all the unnecessary dependences and in case of having to create any, to select the weaker ones. Indeed, we could use this result to say that an innovation is the solution with the weaker dependences. Following this line, the Principle is the door also to redefine sustainability. The sustainable solution is the one with the weaker dependences. And, in general, the unbeatable solution is the one with the weaker dependences. As long as weakening dependences leads to remove them, the Principle of Minimum Dependences states that the unbeatable solution is the one which has a minimum number of dependences and a minimum strength of the surviving dependences.

My personal search for a universal definition of the best design or as I prefer to say of the unbeatable design led me invariably to explore ethics. Readers interested in having a deeper vision can found it in references [2,3], which describes a general principle out of the scope of engineering. This principle differs from the one discussed here although it is connected to it through the efficiency: the moral criterion for sustainability discovered in that essay is based on comparing the efforts associated to efficiently make and efficiently unmake, and invariably take the action with a higher figure. As long as having more dependences deteriorates efficiency, it can be stated that the former includes the latter. In the scope of the engineering field, my first incursion to this complex problem is summarized in reference [4], where the main contribution was that the required information (final entropy minus initial entropy, do not confuse it with the available information or with the information content) had to be kept low to find the best solution. As long as the entropy increases when the number of dependences increases, the principle of keeping low the required information is also connected with the Principle of Minimum Dependences.

The mathematical rigor of the Principle of Minimum Dependences is addressed in two articles [5,6] and one PhD Thesis [7]. Finally, the final exposition of the Principle in the scope of engineering design along with an extensive dissertation about how sustainability requires a stable ethical framework and how the fractal nature of the design process makes the use of a single universal ethics difficult is presented in [8]. Here, the new ethical framework is used to give new definitions of innovation and sustainability. These new definitions have the advantage of being more practical than the ones normally used. The importance of using these kind of ethical frameworks in the industry can be found in [9,10], where the necessity of having a value-driven design process is investigated. In particular, it is studied how Design Thinking requires an external input specifying an objective value proposition. The Principle of Minimum Dependences can fill this gap. Real examples of how the Principle fills this gap are collected in [8]. This long reflection leads me to conclude that the priority task (still running) that human beings should close as soon as possible is finding out a universal ethics or, failing that, a moral criterion for guiding the new technological development. This will eventually happen when enough resources came into this line of action. For the moment, I invite the reader to investigate and use the Principle of Minimum Dependences as a good approach.

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