Chapter 11
Efficiency Animals: Efficiency as an Engineering Value

Byron Newberry

Abstract In the literature on the study of engineers and engineering practice, the pursuit of *efficiency* is often claimed to be a prime directive for engineers. The objective of this chapter is to examine that claim. It starts with an exploration of the concept of efficiency, which has a multitude of meanings, some very technical and precise, and some more broad and equivocal. Some important philosophical distinctions are made, such as between the notions of efficiency as an instrument of conservation and efficiency as an instrument of growth, between efficiency at a micro-scale and efficiency at a macro-scale, and between efficiency and effectiveness. Questions of how the concept of efficiency relates among the arenas of technology, nature, and economics are also addressed.

Keywords Engineering • Efficiency • Effectiveness • Economics • Optimization • Nature

Introduction

As an engineer who in recent years has become engaged with the philosophy of technology and engineering, I am particularly intrigued by the ideas that scholars in this field – often non-engineers – have with respect to the methods, motives, or values attributable to engineers. One such value – which serves as the topic of this chapter – is the engineer's perceived regard for *efficiency* as a core engineering design value.

There are many works that discuss the role of efficiency in technological activity in a broad sense – at a societal level – such as in Jacques Ellul's classic critique of *technological society* (1964). Ellul famously defines his all-encompassing notion of *technique* as, "the totality of methods rationally arrived at and having absolute

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efficiency in every field of human activity." In technological society, according to Ellul, efficiency has become the end-in-itself. In a recent homage to Ellul's lasting intellectual influence, Wha-Chul Son (2013) suggests that even in cases where technological actions are really motivated by values other than efficiency, such actions are often nonetheless justified "in the name of efficiency," as if the very invocation of the name provides the imprimatur of necessity.

More specifically for the engineering profession, many authors have suggested that efficiency is a foundational, if not *the* foundational, design value for engineers. Carl Mitcham wrote (1991), "The thesis here is that the internal value constitutive of and operating in engineering is the ideal of efficiency." Eugene Ferguson (1979) ranked efficiency as a primary "imperative of engineering." Stanley Carpenter (1983) wrote, quite strongly, that, "Technical efficiency, with its quantified precision, is introduced early in engineering education, and its pursuit thereafter by each engineer tends to take on a character of a quest for the 'holy grail'." More recently, Joe Pitt (2011) wrote that, "For engineers, the design of an artifact or a system is approached with questions of utility and efficiency foremost in mind." Finally, I once heard philosopher of technology Peter Kroes refer to engineers as *efficiency animals*, an appellation I subsequently adopted for the title of this chapter. So at both the level of technological society in general, as well as at the level of the engineering profession in particular, strong claims are made that give efficiency a telic character.

Is this portrayal of the centrality of efficiency accurate with respect to engineers and engineering? For engineering, is efficiency really a 'constitutive value', a 'primary imperative', or the 'holy grail'? The goal of this chapter is to explore these questions.

A simple-minded starting point for this exploration was to peruse a bookshelf loaded with standard engineering design textbooks. Out of 12 contemporary texts, there was not a single entry for the word efficiency in any index. This does not guarantee that the word does not appear somewhere in each of these texts; in fact, it was found in all of them. But it was always narrowly construed in the context of a specific problem or example, and was not itself the focus of the ideas being explicated. Though not conclusive of anything, this absence from these texts seems at odds with the notion that the idea is the *holy grail* of engineering design. This, however, is congruent with my own experience as a teacher of design for more than two decades. Never has efficiency been a focus of my course in any general or explicit way. The subject does get discussed at times, but, again, in fairly narrow, ad hoc, and context-specific ways.

This discrepancy about the perceived role of efficiency in engineering suggests two possibilities. Either the premise which claims that efficiency is a quintessential value of engineering – what might be called the *holy grail* thesis – is wrong, or, if it is correct, perhaps efficiency is so elemental to engineering, insinuating itself into the very fabric of what engineers do, that the tacit centrality of its role has largely become transparent to practitioners. In what follows, I will argue that both of these statements are correct in their proper contexts. That is, I will argue that efficiency is not a unique, distinctive, or signature value of engineering per se, that it is not generally pursued by engineers in any macroscopic sense connoted by the *holy grail* metaphor. However, it is elemental and pervasive to engineering in a microscopic sense, in a way that transcends engineering inasmuch as engineering is an economic activity.

What Is Efficiency?

What is efficiency? The question may seem trivial since most people have a relatively common understanding of what efficiency is. Efficiency has to do with avoiding unnecessary time and effort, with not being wasteful, with getting things done in a clever and intelligent way, and with saving energy. But these commonplaces notwithstanding, efficiency is an elusive concept. The fact that engineers have some very precise and quantitative definitions of it does not necessarily help avoid this elusiveness. Returning for a moment to Ellul, Peter Fitzgerald-Moore (1997) criticizes him for having too non-specific a definition of efficiency. "Ellul's proposition conceals…fundamental difficulties," writes Fitzgerald-Moore, "…there are very many distinct kinds of efficiency and the concept of a generalized *efficiency* is not very useful." Likewise, Jennifer Alexander (2008, Kindle Locations 134–135) writes,

> Efficiency is a slippery concept. As the previous examples illustrate, it has taken on not only a variety of technical configurations but also a bewildering array of more common meanings.

In the context of engineering science, technical efficiency is often a precisely-defined parameter – typically the ratio of output energy or power to input energy or power, which provides a measure of how much loss occurs in an energy transformation process. This type of efficiency corresponds to what Alexander calls *bounded* efficiency. That is, the values are bounded between zero and one, or 0 % and 100%. This might also be called an *absolute* efficiency. A particular numerical value *is* the efficiency in an absolute sense, independent of the observer. And 60 % is more efficient than 50 %, regardless of the perspective. This type of bounded or absolute efficiency can be extrapolated to other situations besides energy conversion. For example, efficiency in a quality control process intended to catch defective parts can be defined as the ratio of defective parts identified to total defective parts. Again this ratio is bounded by 0–100 % and the efficiency can be referred to as a number, such as a defect-catching efficiency of 98 %.

Such measures of efficiency pervade engineering science textbooks. Interestingly, while engineering science texts typically define efficiencies and then utilize them in a variety of quantitative problems, very little is actually said about efficiency in a qualitative or value sense. That is, problems are stated in forms such as, "For the given system, calculate the efficiency," or, "If the efficiency of the given system is X, calculate its output work." But it is difficult to find in engineering science texts many explicit normative statements. For example, if a higher efficiency is thought to be better than a lower one, that belief is not typically expressed in the text. Perhaps the most forceful articulation I found comes from a thermodynamics text, which states, "Heat engines are built for the purpose of converting heat to work, and engineers are constantly trying to improve the efficiencies of these devices since increased efficiency means less fuel consumption and thus lower fuel bills and less pollution" (Çengel and Boles 2002, p. 386). This quote appears more or less as a throwaway line buried deep into a text devoted to energy conversion. Thus, in the absence of other clues, the overall conclusion one might draw from a collection of engineering science and design texts is that engineering students are either expected to enter school already having a belief about the purpose and value of efficiency – absorbed perhaps from the wider culture – or to develop such beliefs through informal professional socialization mechanisms in school and beyond. At first glance, the formal mechanisms of engineering education appear to simply teach the proper ways for measuring or calculating various efficiencies without elaborating much on their significance.

In addition to the energy conversion type of definition, there is a more generalized set of technical efficiency measures, a set that comprises a relatively open-ended variety of ratios that relate the value of a performance characteristic – or output – of an engineered device or system to the value of one of the system inputs or resources. Thus we speak of cost efficiency, weight efficiency, energy use efficiency, materials efficiency, time efficiency, or labor efficiency. These indicate an achievement of some performance objective – strength, say, or speed – with a minimum of, or at least a savings of, respectively, cost, weight, energy, materials consumption, time, or labor. In effect, these are manifestations of a class of technical efficiency measures that derive from an economics-like definition of efficiency. Unlike energy conversion efficiency, which conveys fundamental scientific information about a physical system or process, these types of efficiency measures are arbitrarily defined for the purpose of gauging performance relative to human wants; that is, they allow us the opportunity to maximize outputs for a given set of inputs, or to minimize inputs for a given set of outputs, in order to further some technological or organizational objectives. Also, in contrast to the definition of energy conversion efficiency, which is a dimensionless ratio having a range of zero to one, with *one* being an unobtainable perfection, efficiency in this sense is often a ratio between incommensurables, and its numerical value is only meaningful relative to alternatives. For instance, aircraft structural components might be judged on their ratios of strength-to-weight, with higher values generally considered more desirable, all other things being equal, but with the absolute values being effectively meaningless. This is consistent with what Alexander calls *arbitrary* efficiency measures. They might also be called *relative* efficiency measures.

The phraseology is different for these arbitrary or relative efficiency measures. If the tensile-strength-to-weight ratio of a particular steel is 264,000 psi/(lb/in^3), one typically does not say that the efficiency of the steel is 264,000. One would say that with respect to strength-to-weight, this steel is more efficient than another type of steel that has a ratio of 220,000. That is, one thing is more or less efficient than another by comparison of the values, but a thing does not have an efficiency value in-and-of itself. Also, in this example the implicit assumption is that a higher strength-to-weight ratio is more efficient than a lower one. This is true in airplane design, for example, but it may be just the opposite dam design. Or, to borrow an example from Sunny Auyang (2004), a low drag coefficient is efficient for designing a wing, but it is inefficient for designing a parachute. For arbitrary efficiency measures, *more* or *less* efficient is relative to the objective.

Optimization as Efficiency

For most engineering designs, however, there exist multiple performance-based relationships of critical importance, which leads to the related concept of optimization. Roughly speaking, optimization is the process of trying to achieve the most desirable balance of all relevant quantities – "minimizing the most significant undesirable effects and/or maximizing the most significant desirable effects" (Ertas and Jones 1996, p. 292). In the case of the aircraft structural components, we might want to optimize – or find the best balance of – relationships between strength, stiffness, weight, machinability, environmental tolerance, availability, and cost. The typical result is a situation in which none of the individual efficiency relationships – such as strength-to-weight, for example – achieves the level it has the potential to achieve independent of other considerations. Rather, analogous to economic Pareto-optimality, a compromise is sought such that no relationship can be further improved without an unacceptable degradation in another. In biological evolution, this is known as the *principle of frustration*: "This principle captures the notion that different needs will often have (partially) conflicting solutions, so that the overall optimal design for an organism will rarely be optimal for any of the specific tasks it needs to perform" (Marshall 2006).

Regarding optimization, and lending credence to the *holy grail* thesis, engineer Walter Vincenti writes that optimization is "a constant element, implicitly or explicitly, in engineering thinking. For the engineer optimization has the nature of an ethos" (1990, p. 165). Optimization methods, from relatively simple heuristic approaches, to more sophisticated mathematical computations, are discussed to varying extents in many engineering design texts. As Herbert Simon (1996) points out, however, such methods result not in real-world optimal solutions, but rather in satisfactory ones – ones that are deemed acceptable given the finite bounds on our knowledge and resources. And, importantly, whether in economics or in engineering, formal optimization efforts typically occur at lower, rather than higher, levels; that is, optimization methods are most likely to be applied to arranging deck chairs in the most efficient way, whereas the ship itself was likely set sailing on the basis of a top-level, experienced-based, exercise of judgment and/or speculation. Put another way, formal optimization methods always presuppose a generic design that has been articulated well enough to create a mathematical representation of it, to define an *objective function* that rationalizes the balance of desirables and undesirables. Thus the optimization is local in the sense that we might find the "best" solution within the bounds of our assumed optimization space, which includes a generic design morphology, along with constraint factors that we have identified as important. But there is no guarantee that our generic design is at or near the optimum of the set of all possible generic designs, or that the constraint factors that we have included represent the most relevant or most complete set we could have defined. The initial – and higher-level – choice of the generic design and constraints might often be made on the much more informal basis of experience, socio-cultural preferences, habit, and so forth.

Common in design texts are quantitative optimization example problems, such as finding the optimum spacing and positioning of towers along a route for an electrical transmission line. Presupposed in the problem, however, are the route and the design of the towers themselves, both of which could of course be different, not to mention that the higher-level decisions that led to the choice of having an electrical power transmission line in the first place are taken for granted. Further, it is difficult to include in such optimization procedures factors such as social and environmental impacts of the transmission line, including aesthetic concerns, habitat alteration, and so forth. Thus, the results of an optimization calculation may ultimately be modified or overruled altogether by other, more intangible, considerations. This is not to say that optimization procedures are not useful, just that they are never optimum in some macroscopic sense, and are typically most useful in defining lower-level details once higher-level decisions have been made. Auyang (2004) writes, "To assert what is the best is difficult….Engineers are too hardheaded to dream about the universal best, which anyone sensible knows to be infeasible. Optimization theories aim at the best relative to a specific objective criterion and a range of options and constraints." Likewise, engineer Billy Vaughn Koen (2003) says that engineering optimums do not "pretend to be the absolute best in the sense of Plato," only best relative to the specific objectives people have.

But what objectives ought people to have. Just because something can technically be made more efficient according to a specific criterion, or optimized relative to a specific objective function, it does not follow that we have done anything meaningful, useful, or good. "In a society of cannibals," writes Koen colorfully, "the engineer will try to design the most efficient kettle" (2003).

Judging by the example problems in textbooks, we might guess that maximizing a ratio of just about any desirable thing relative to cost is universally good, while, as we have seen, maximizing strength-to-weight ratio, for example, is good in certain applications, but is indifferent – or even undesirable – in others. But once again, engineering textbooks largely seem to suggest, via their silence, that beliefs about the kinds of relationships among variables that should be valued are either patently obvious, are context dependent, or are otherwise externally acquired.

Efficiencies or optimums are ostensibly pursued in a utilitarian fashion, for their effectiveness in furthering the pursuit of our current goals. Efficiency "cannot be said to be an intrinsic value if it is primarily an instrument for implementing the other values that define the context of its use" (Alexander 2008, Kindle Locations 150–151). But when efficiency targets are set, or objective functions for optimization defined for a specific end in a specific context, they risk being undeservedly reified if conceptually divorced from those ends and contexts. As a result, achieving some optimum or some measure of efficiency can potentially seduce one into thinking that such an achievement is objectively good, or that one has advanced toward the positive end of some absolute scale. In reality, the achievement is such only relative to the limited criteria that were set in the beginning. Someone else with different criteria can just as easily define and pursue different efficiencies or optimums for purposes that may be orthogonal. As Fitzgerald-Moore (1997) writes, "efficiencies are often in conflict or contradiction with one another."

This observation provides a good entrée into another meaning of efficiency. Sometimes phrases such as "the efficient use of resources" mean more than simply saving money on the inputs to a process; rather, a concern with the long-term preservation of some set of resources is literally implied. Efficiency in this sense is related to the notions of sustainability and conservation. The normative content of this meaning of efficiency is fairly clear; a high value is placed on maximizing the long-term stability of either some specific resources or of the biospheric system in general. A distinction can be made between couching efficiency in the language of scarcity and couching it in the language of plenty. In cases of plenty, efficiency promises more, bigger, and better. In cases of scarcity, such as is implied by the conservational meaning of efficiency, the efficiency is required to preserve what exists, if even that is possible. It is fairly easy to illustrate the conflicting nature of efficiencies using this meaning. Sustainability-related efficiencies are frequently perceived to be at odds with economic efficiencies defined in terms of profit and growth by individuals, corporations, or societies. This distinction roughly parallels Alexander's (2008) distinction between *static* and *dynamic* efficiencies, or the efficiencies of equilibrium and growth. Distilled to their essence, definitions of efficiencies define things upon which people place value, and provide a quantitative metric for assessing that value. But different people, or the same people at different times and in different circumstances, value different things. "Subsuming efficiency in context suggests that it is a shell, ready and waiting to take on the values and objectives of whoever uses it but with little content or character of its own" (Alexander 2008, Kindle Locations 142–143).

When put this way, efficiency appears less of an *end* and more of a *means*. This is the point Alexander makes when she writes that efficiency is a tool that allows us to bring things under our control. Efficiency can be put in the engineering toolkit alongside scientific understanding, methods of visual representation, methods of reduction and simplification, and other forms of knowledge and technique that engineers routinely utilize to achieve their aims. Auyang writes, "It is important to note that the choice and evaluation [of objectives and constraints] are made by engineers, who use optimization theories as tools and stay outside the theories" (2004).

But saying that efficiency is more properly a *means* than an *end* does not necessarily make the case that efficiency is not somehow an overarching goal of engineering; it does not in itself guarantee that it has not taken on the character of an end. As the old saying goes, *to a man with a hammer, everything looks like a nail*. The implication is that while a hammer is clearly a tool, a person who has a hammer may make finding things to hammer his or her end objective. Or more generally, those who possess what they consider to be a powerful tool or technique, may come to extol the virtues of that tool or technique to the point of making the application of it an end in itself, an elixir to cure all ills. And this effect is likely a factor in why people – including engineers – seem to have a very definite popular notion of efficiency as being something inherently desirable, despite the fact that the popular meaning is rather vague and ambiguous.

One way this can manifest itself is when someone argues *this* instead of *that* should be done because *this* is more efficient, without a clear definition of efficient. Others may be confounded, at a loss as to how to counter that argument. This is the point made by Son (2013), that often efficiency is blindly invoked as justification. Two subtle things have happened in such an argument. First, a *specific* or *limited* definition of efficiency has been conflated with the more *general* notion, which preys on prevailing perceptions that to disregard efficiency would be some sort of sacrilege. Second, efficiency has been slipped into the role of primary decision-making criterion, the trump card. And these are likely the effects that bothered Ellul in his wide-ranging criticism of the pursuit of efficiency: (i) that considerations of efficiency had become *the* litmus test for decision-making, rather than simply informing the decision-making process, and (ii) that the specific definitions of efficiency upon which decisions are made are mistakenly viewed as essential rather than arbitrary, and might most often be ones favorable to specific interests, rather than to society at large.

Engineering, Nature, and Economy

It is instructive to note that while Vincenti (1990) asserts that optimization is a pervasive element of the engineering ethos, he first qualifies that assertion by recognizing that optimization is in no way unique to engineering – that optimization alone cannot be used as a basis for differentiating engineering from some other types of activities. In fact, my own thinking about this topic was initiated from a non-engineering source – upon rereading Darwin's *The Origin of Species* in preparation for a teaching a history of science course. Darwin writes,

> [N]atural selection is continually trying to economize in every part of the organisation. If under changed conditions of life a structure before useful becomes less useful, any diminution, however slight, in its development, will be seized on by natural selection, for it will profit the individual not to have its nutriment wasted in building up a useless structure. (1985 Penguin Edition)

What Darwin calls economizing, might now be called *fitness* optimization, an efficient allocation of resources that increases the organism's chance of success in the face of competition and scarcity. Care must be taken, though, with the terminology. Nature, through evolution, does not strictly optimize. Optimization implies a conscious evaluation of a range of options followed by the selection of the one which best accomplishes an objective. Nature does not perform a predictive evaluation of options, and it knows nothing of *best*. Nor does it have objectives. Rather, nature proceeds by a trial-and-error method that can only build upon existing structures and which charts a historically contingent course that is guided by differential success in the presence of potentially fluctuating resources and constraints. People often tend to overlay their interpretations of that success post facto in terms of efficiencies. This must be kept in mind even though the language may be used loosely in what follows.

Darwin's choice of the word *economize* is instructive. An economy, defined as an arena in which resources are extracted, produced, allocated, and consumed by entities competing for their own welfare and propagation, holds the key to the notions of efficiency and optimization, whether that arena is a natural ecology, a household, an organization, or a society. "Economics," writes Auyang, "features decision makers, households and business firms, each intentionally trying to find what is best for itself. They are engineers except they are designing different sorts of things" (2004). And when discussing optimization and satisficing, Simon draws frequent parallels between processes in biological evolution, market economics, and technological development. Technological development is itself wholly subsumed under the umbrella of socioeconomic activity more generally conceived. "The 'demand' for technology," writes Joel Mokyr (1990, p. 151), "is a derived demand, that is, it depends ultimately on the demand for the goods and services that technology helps produce; there is little or no demand for technology for its own sake."

But when we talk about efficiency and optimization in real-world economies, whether natural or social, we are invariably talking about *localized* efficiency and optimization. Like falling drops of water molded into teardrops by the pull of earth and the push of wind, economic entities continuously streamline, other things being equal, in response to the pressures of their respective arenas. But such streamlining is myopic; for nature, strictly so, and to varying degrees for human-constructed entities. The water drop knows nothing of the ground upon which it will soon fall, the organism knows nothing of the invasive species against which it will soon compete, and the company may know little of the incipient technological development that will soon render its products obsolete. Yet all continue to optimize – to be molded by their environment, consciously or unconsciously, into more efficient forms or behaviors. But that environment is potentially an ephemeral one, so what is efficient today may in fact be terribly inefficient tomorrow.

This might be called *micro-efficiency*, the ineluctable tendency of a given economic entity to pursue efficiency within a context that pits its current internal morphology against its short-range (both spatially and temporally) external environment. With respect to technological change in particular, Mokyr (1991) distinguishes between *microinventions* and *macroinventions*, where microinvention denotes the stream of improvements that a technology, once developed, undergoes with time in an effort to make it more and more efficient. This is congruent with the meaning of micro-efficiency intended here. It is also consistent with what is called in the economics literature *process innovation* (e.g., Adner and Levinthal 2001; Quintanilla 1998). Process innovation is the streamlining over time of both the basic product design and the production process for that product for the sake of economic efficiency. Interestingly, and germane to an important point to which we shall return, process innovation starts out relatively slowly at the birth of a new technological product type, reaches a peak of activity sometime in the midlife of that product type, and then decreases as the product type ages. In this timeline, which is subject to great variation, a newly conceived product type exploits some opening in the economic arena and may enjoy a period of relatively unfettered success. Only after competition arises does the need to optimize fully assert itself. This need intensifies in concert with the competition until eventually a point of diminishing returns may be reached and further improvements are exhausted.

But as is well known in both biology and economics, this pursuit of micro-efficiency, in and of itself, holds no guarantee for efficiency or optimization on a more global scale; entities often condemn themselves to paths of extinction, or else marginal existence in backwaters of the economic arena as substantial changes occur in the external conditions of that arena. One needs only to think of horse-drawn carriages and mechanical watches. Entities sometimes can even enjoy various degrees of long-term success having locally optimized what globally is recognized as a non-optimal situation. This phenomenon has been explored in-depth in the literature on the economics of technological change under the headings of *path dependence* and *lock-in* (e.g., Cowan and Gunby 1996; Stack and Gartland 2003; Arthur 1989; Liebowitz and Margolis 1995). In these cases, the development of a technology along a globally non-optimal path (as a result of the inevitable myopia that exists) results in the non-optimal technology becoming permanently entrenched because of the daunting economic costs of later switching to a better path once that better path becomes known. But these persistent technological inefficiencies are in a real sense still economically efficient when factoring in the transaction costs associated with correcting them.

Gains in micro-efficiency are not guarantees of any long-term or long-range efficiency or optimization; i.e., they do not guarantee *macro-efficiency*. They are not leading monotonically toward some social, economic, technological, or natural optimum. They lead instead toward some local maximum, which could be a stagnation point, or could be wiped out altogether with changes in the landscape. So the whole notion of pursuing efficiency is a localized, not a generalized, concept. Earlier, I suggested optimization occurs more often at lower, rather than higher levels of abstraction. Similarly, it occurs in engineering and socioeconomic systems more often in the shorter-range, rather than in the longer-range. Human-constructed systems can be optimized, or made more efficient, with intentionality, as opposed to natural systems that cannot. But when human socio-technological systems are taken in larger, more complex aggregates, and as they operate over longer time spans, the intentionality becomes noisy and the types of efficiency that prevail degenerate closer to those of nature. Intentional optimization depends on prediction and control, both of which become more difficult with increases in scale and complexity. In short, while we can make a product or manufacturing process more efficient, and likewise with a company's financial operation, the overall long-range development of economies and technologies are historically contingent and largely unpredictable.

The pursuit of micro-efficiency is an imperative of economic entities inasmuch as competition is a fact of economic arenas. Engineers, as agents of economic entities and designers of economic goods, are unquestionably immersed in and contribute to that pursuit, and quite often do so consciously and deliberately. This fact undergirds the suggestion that efficiency is elemental to engineering, and in two main ways. First, many of the problems to which engineers get assigned are problems of optimizing technologies for the sake of incremental gains in efficiency. And second, engineers, just as much as other people, are possessed by the ghost of *homo economicus*, and therefore have an intrinsic understanding of, and susceptibility to, the imperatives of economic efficiency.

The other half of the equation is exemplified by Mokyr's *macroinventions*, or economists' *product innovation* – development with the primary aim of *effectiveness*, in contrast to *efficiency*. My thinking about these notions was influenced by the work of biologist Geerat Vermeij. Vermeij writes,

> I believe the emphasis on efficiency is misplaced. Economic success depends on absolute performance, and very often – in human-economic contexts as well as in the evolutionary marketplace – high levels of performance go hand in hand with reduced efficiency. (Vermeij 2004, p. 124)

There are basically two ways to increase power or performance. One is to become more efficient; that is, to find ways to increase the system output for a given set of inputs. The other is the brute force method of simply consuming more inputs, regardless of how efficiently they are used. In fact, with sufficiently elevated quantities of inputs, losses in efficiency can still correlate to gains in output. Which path an economic entity takes, according to Vermeij, will depend on the competitive nature of the environment and the availability of resources. "Although supply of resources dictates what level of metabolism can be achieved, it is demand – imposed by consumption and by competition – which drives some entities toward higher metabolic rates" (Vermeij 2004, p. 136).

A good example of this comes from the work of Anders G. Finstad and colleagues (2011) on energy efficiency of salmonid fishes. They found that Arctic char convert input resources (food) into body mass twice as efficiently as brown trout, which might seem like a significant advantage for the char. But the more docile char only outcompete the trout in colder, resource-poor environments. The char might be said to adopt a static, equilibrium, or conservative efficiency strategy, a strategy that enables them to extract the most benefit from meager resources. In contrast to the char, in warmer, more resource-rich environments, the less efficient (in terms of food-mass conversion) trout grow dominant by aggressively consuming resources in such high quantities that they more than offset their greater "wastefulness" in converting those resources. They might be said to adopt a dynamic, growth-oriented efficiency strategy. But the trout's strategy is dependent upon sustained high levels of resources.

Vermeij provides other detailed data on the various types and classes of organisms with respect to energy consumption and biomass production. Higher performance organisms, ones typically larger, more complex, and higher in the food chain – ones we might say have superior natural technology – have a much higher ratio of energy consumed to biomass produced than lower performance organisms. That is, in the overall natural economy their biomass energy conversion output-to-input ratio is relatively poor. But that overall inefficiency is secondary to the absolute economic power conferred by the high metabolic rate. Flying organisms, for example, comprise the class of organisms with the highest energy consumption per unit of body mass. But the benefits for evolutionary success of exploiting air as a transport medium, which include speed of fleeing and/or pursuing, range of forage, and seasonal migration to avoid weather extremes, are worth the investment, provided the resources are available to sustain consumption levels. Cold-blooded animals, according to Vermeij, absorb energy passively from the ambient environment and are thus at the mercy of environmental conditions for their physiological performance. Warm-blooded animals have invested in their own internal power-generation mechanisms, which provide them with more autonomy from the current thermal conditions of the environment, but at the cost of committing them to dependency on a consistently abundant food supply. But this in turn requires the existence of an overall large economy. Large, high-performing mammals, for example, aren't generally found on smaller islands due the inability of the economy to supply the requisite resources. And warm-blooded animals have energy conversion efficiencies, for example, an order of magnitude below those of cold-blooded animals. "In fact," writes Vermeij,

> …a problem for active warm-blooded animals is disposing of excess heat produced by an inefficient engine. This is why we sweat, dogs and birds pant, and bees and termites ventilate their nests. In our technological world, internal combustion engines and atomic power plants give off vast amounts of unused heat, but their power yield is so great and provides such clear economic advantages that their inefficiency is tolerated, much as it is in warm-blooded animals.
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> …In all economies…efficiency becomes important when power is low and output cannot be increased in absolute terms. This occurs when energy or raw materials are sufficiently scarce that reducing the cost of acquiring them is the only way of not losing ground. Increases in power, however, are sufficiently beneficial that considerations of efficiency are secondary, especially if productivity also benefits the supply of raw necessities. In such cases, absolute performance is far more important than efficiency. Thus it pays to be efficient for subordinate members of an economy, and it pays to increase in performance for those in power. (2004, p. 125)

In concert with this development of macroscopic inefficiency – justified on the basis of exploiting an open avenue for economic power – is a parallel process of micro-efficiency. For example, over time flying organisms evolve lighter weight tissues, more streamlined shapes, and more precisely tailored flight mechanisms (just as human flight technology has). This is the process described earlier as process innovation or micro-invention. But such trends in micro-efficiency, while increasing an organism's competitive advantage incrementally, will never completely reverse the overall commitment to very high levels of consumption inherent in the base technological adaptation.

Inefficient Specifications

In a similar way, technologically advanced societies have levels of per capita resource consumption many times greater than those of most less developed countries. They also have greater absolute levels of economic power. But they are not necessarily more efficient in terms of the ratio of economic output to resources consumed, and often less so. Technologically advanced societies are analogous to organisms with high metabolic rates. The investment in energy intensive technology confers power in the form of better control over wider ranges of resources, the ability to specialize and decentralize functions, the storage of vast reserves, quicker response times, and more flexibility in adaptation, all of which tend to buffer the entity against the uncertainties of short-to-medium-range spatial and temporal fluctuations in the environment of the economic arena. The Faustian bargain for this economic stability is the dependence on long-term, sustained, and abundant inputs. The book *Collapse* by Jared Diamond (2005) chronicles past societies whose technologically-driven, rapid metabolisms exhausted their input resources, leading to precipitous societal failures. This is the ultimate in macro-inefficiency, and it parallels the extinction of higher-performing species in the wake of major environmental changes, species which have staked their economic power, stability, and success on high levels of resource consumption.

Consider the example of the *sport utility vehicle* (SUV) type automobile, which is quite popular in the United States. For the automobile manufacturers they are economically efficient in that they produce large profits due to high demand. But why are they in high demand? They are expensive both to buy and to maintain. From a technological point of view, it could be argued that they are inefficient. But they do confer absolute economic power, provided the resources are available to sustain them. They provide safety to the passengers in collisions. They enable the transport of many persons at once. They can be used to pull a trailer. They can go into four-wheel-drive mode and drive through mud. They confer prestige. For all these reasons they provide a much wider range of performance than many other vehicles, and so confer economic power. But for most owners the vast majority of miles driven by SUVs are not driven in the mud, nor with the trailer, nor carrying the soccer team. The vast majority of miles are driven by a single person to the store to get milk, or some such. Because of that, the powerful, low gas mileage engine, the large body size and corresponding heavy materials consumption, the expensive four-wheel-drive systems, and so on, are grossly underutilized and hence effectively wasted except for occasional events. The economic power that the vehicle confers with its wide range of abilities is at the expense of tremendous resource consumption, resources that are largely held in reserve due to the extremely low duty cycle of extreme requirements on the vehicle. We might compare it to a lion, a large powerful animal with a high metabolic rate, but which spends large amounts of time inactive, burning resources on idle, and only utilizing its high performance characteristics sparingly. And like the lion, its continued success is dependent on the abundance of resources, whether large herds of game, or large herds of deep-pocketed consumers coupled with large deposits of oil and iron.

So in many respects SUVs are not efficient from a technological point of view. They are favored because they increase power and performance, at least so long as resources are abundant (and in fact their favored status fluctuates with resource availability in terms of fuel prices, wages, etc.). But we could also consider them efficient in other respects, such as relative to personal convenience or corporate economics. And engineers are constantly engaged in making the finer details of both the vehicle designs and their production processes more efficient. Thus, economic entities are engaged in parallel processes of pursuing micro-efficiency and macro-power. In the former, an entity seeks to find ways to get more for less from its current technological paradigm, and this is compatible with our typical notions of efficiency. In the latter, an entity seeks to develop new technological paradigms that confer greater economic power by either exploiting new resources or exploiting old resources in a new way, and this represents an absolute increase in performance made possible by the availability of resources that may in fact be used inefficiently. Engineers are instrumental in the achievement of both objectives – pursuing savings through efficiency and exploiting resources for power-enhancing innovation. And while engineering considerations constrain and influence both objectives, the objectives themselves are socioeconomically mediated. For the engineer, the common denominator for both kinds of work is the notion of *specifications*, and if efficiency is ever a design value in any macroscopic sense, it is only so because it was specified to be so. If there is a *holy grail* of engineering it is surely the *meeting of specifications*.

I have previously worked as a structural analyst for a large aircraft modification company, and in the course of that work had the occasion to inspect work being done to a 747 that belonged to the monarch of an oil-rich country. Since the monarch was himself a pilot who occasionally liked to fly his own plane, the aircraft's throttle was quite literally gilded. That is just one example of what might be considered excesses that were part of the aircraft's design, excesses that seemingly violated the rules an aerospace engineer would consider part of good, efficient aircraft design. For another example, a different customer desired to install a granite conference table in an airplane. Not only was the weight of a granite tabletop contrary to the aircraft design principle of choosing the lightest weight materials, but its susceptibility to cracking required engineers to design an elaborate mounting system that would allow the table to float stress free while the underlying structure to which it was attached flexed during flight. Counterintuitive (with respect to efficiency) designs such as these happened because they were specified by a customer possessing the resources to afford such inefficiencies. The engineers worked to meet those specifications in as efficient or optimal a way as practical. But such efficiency or optimality was only local, defined within the context of what might be considered globally inefficient or even outrageous specifications.

In describing the phases of matter to students, science teachers will often define a gas as having neither definite shape nor volume, but rather expanding to fill the limits of the space that ultimately constrains it. Similarly, the work of engineers will often expand to fill the limits of the specifications that constrain it. In teaching engineering design, I have the students work on projects in which they must design, build, and test an electromechanical (mechatronic) device. The specifications given to the students define performance objectives, and constrain the design with respect to such factors as budget, time, physical size, and energy sources. These constraints are imposed with a general rationale related to efficiency (i.e., practical resource limitations), but the particular values chosen for the projects are somewhat arbitrary and can reasonably vary by an order of magnitude or more. While there may be a practical lower limit on the constraint levels (that is, a particular set of performance objectives may not be practically achievable below certain levels of cost or size or energy, say) there is not as clearly an upper limit (that is, more resources could always be invested in the design).

My anecdotal experience is that when constraints are set near the lower limit, issues of efficiency come to the forefront and significantly influence solution approaches. If constraints are set much more loosely, a highly efficient design is still very much a possible solution, but it will generally not be realized in the presence of excess resources. Questions of efficiency typically fade into the background, and the designers will absorb those excess resources into enhancing the power of the device or system; that is, making it more robust, more flexible, more accurate, or more elegant. In fact, the particular *value* which excess resources are employed to enhance varies greatly with individuals and teams.

One of my engineering students once wrote in an essay on engineering, "An engineer as an individual is not interested in adhering to tight schedules, nor to minimizing cost." His suggestion was that efficiency, rather than being the *holy grail* of engineers, is more appropriately the *bane* of engineers because it constrains what they truly want to do, which is to make things that are bigger, faster, more powerful, and more sophisticated. This sentiment complements the *macroinvention*, or *innovation*, side of engineering. But engineers also operate in the *microinvention/process innovation/micro-efficiency* world in which technologies and products are continuously refined and improved for efficiency's sake. But in these cases, issues of efficiency take on the explicit role of performance objectives rather than constraints. That is, the problem may be to find a way to manufacture a given product for ten percent less cost. In that case, that gain in efficiency itself becomes the technological challenge, and as such can become the focus of the engineer's drive for technical achievement and satisfaction, not because it is efficiency per se, but simply because it is now the performance specification to be conquered. And conquering performance specifications is what engineers like to do.

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