THE CONCEPT OF EFFICIENCY: AN HISTORICAL ANALYSIS

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1 INTRODUCTION

The concept of efficiency expresses a specific form of rationality, used in attempts to control a changing situation by bringing it into conformity with a vision of how the world works. Efficiency became an important technological value during the nineteenth and twentieth centuries, as part of the construction of modern industrial society. It was integral in achieving the purposeful and measurable effects in an industrial modernity that championed rationality, foresight, and planning in the control and manipulation of the social and material worlds, and it remains an important post-industrial value, particularly in continuing concern about waste and wise resource management.

This article examines efficiency both as a concept in contemporary engineering use and as a historical artifact. The article begins with a discussion of how efficiency might be described currently, in colloquial use and as defined both generally and technically. Especially important in characterizing efficiency is its identity as a form of control. The article then examines efficiency's historical background, as it moved from a philosophical concept describing the workings of the Christian God in the medieval and early modern periods to its linking with human powers and abilities during industrialization. Its history offers important illustrations of the breadth of efficiency, and of nuances and valences not apparent in an analysis of its current use. In particular, efficiency's history reveals a deep and long association with power and authority; how integral was its use of tools of surveillance, accounting, and control; and its support of visions for reforming or remaking the world. The section that follows suggests several terms that are useful currently in distinguishing between varieties of efficiency, both in engineering and common use. The distinctions turn on the metaphors used, how efficiency is measured, and whether the context is one of abundance or scarcity. The final two sections survey efficiency as a design value in contemporary engineering, and discuss important critiques of the concept and its use.

Two observations lay the foundation for what follows. First, efficiency is a central value in engineering. It is, and has been, most salient where project or system specifications are governed by clear and unambiguous parameters setting limits that must be observed. The most fundamental of these is energy and its

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availability. Efficiency is thus central to projects concerned with thermodynamics, heat transfer, or power generation, and it has historically been more important in mechanical engineering than in the other engineering professions. Efficiency is also central to projects whose specifications pose limits other than energy availability, limits for example on materials, costs, or physical size. In these instances, efficiency may be valued not for its own sake but because it is part of specifications that must be met [Newberry, 2005].

Second, in its technical sense efficiency is an intellectual construction designed to bring machines, systems, or processes under material control. Efficiency is not an exercise in pure intellect. Its goal is not knowledge but an intellectual understanding that can be made practically effective. Efficiency is a way of bringing human will to bear in the world. It is a measurement with an apparently objective form, but it carries with it a history as a tool designed to make the natural world conform to the way in which it is intellectually understood. Even as a technological concept, efficiency carries inherent social and political implications.

2 THE SCOPE OF EFFICIENCY

2.1 Definitions: fundamental features

Efficiency may be used in two different ways, as a general term, usually of approval, indicating a job well and economically done; and as a specific technical assessment, growing out of the experience of industrialization and tied to measurements of performance in machines and the thermodynamics of energy. Efficiency in general use may be quantified; in engineering traditions it is quantified, almost without exception.

The interplay of these technical and common uses characterizes contemporary forms of efficiency. One may speak of thermal efficiency, for example, or of mechanical efficiency, different yet precise concepts and with an identical form of measurement: a mathematical ratio of yield achieved to resources used. In contrast, one may use efficiency colloquially, referring not to a precise measurement but to the ease, speed, and good sense with which a task is performed. People speak of an efficient administrator, or of the efficient use of time. This may be an informal reference to an output/input relationship, but it may also be a remnant of its pre-industrial use, in which efficiency was not measured but was a qualitative reference to competence and power. However understood, efficiency in this common sense generally denotes approval: better efficient than not.

The *Oxford English Dictionary* (OED) offers a suite of useful definitions of efficiency.[1] Its first meaning, "The fact of being an operative agent or efficient cause",

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[1] These are definitions in English, of course. *Efficiency* had no exact counterpart in French. *Rendement*, or performance, is perhaps the closest equivalent. *Efficacité* denotes planned effectiveness more generally and does not refer primarily to comparative measurements. Historically, the term *perfectionnement* encompassed much of the same territory as efficiency, denoting not only the mathematical ratio of output to input but also broader issues of the social and economic

is now only in philosophical use, and in fact such uses are increasingly antique, as mentioned below in the discussion of historical background. But this definition does emphasize the role of efficiency as the tool of an agent seeking to have active effect in the world. The OED's second definition comes closer to what people now mean when they use the term: "Fitness or power to accomplish, or success in accomplishing, the purpose intended; adequate power, effectiveness, efficacy." This establishes the connection of efficiency to material power and the achieving of goals, but it is not yet precise enough to describe its engineering use. The OED's next definition is: "The ratio of useful work performed to the total energy expended or heat taken in." The OED definitions, general and technical, buttress the important point that the concept of efficiency is not merely an intellectual conception but is intended to have material effect in the world.

This becomes especially clear in engineering uses. Nayler's *Dictionary of Mechanical Engineering* gives three meanings of efficiency: "(a) The performance of a machine as a percentage of its theoretical performance. (b) The ratio of the energy output to the energy input of a machine.... (c) The ratio of the mechanical advantage to the velocity ratio...." [Nayler, 1985]. These definitions come from efficiency's mechanical core, from the engineering discipline with which efficiency is most closely allied and in which it was most rigorously defined. Efficiency had to do with machines, as Nayler's definition makes clear. Not so apparent is that engineering efficiency is allied not only with machines but with engines; this is the key to the second of Nayler's definitions, the energy ratio.

Significant about an engine, as opposed to a mere machine, is that it generates motion itself, and does not merely transmit or transform motion introduced from outside. A pulley is a machine, but it cannot move things itself; it requires an outside source of motion. Someone or something must pull the cord. In contrast, an internal combustion engine itself generates the motion it then transfers to its working parts. An engine is not a closed system, because it relies on fuel supplied from outside, but that fuel, although it can be converted to motion or work, is not motion itself.

This conversion, of fuel to motion or work, is at the heart of engineering efficiency. Such a conversion operates through the intervening medium of heat, and the association with heat links efficiency to the science of thermodynamics, especially to the laws of energy codified by physicists and engineers in the mid-nineteenth century. The first law of thermodynamics recognized heat as a form of energy and specified that energy is conserved, and that although energy may be transformed it is neither created nor destroyed. The first law does bear on efficiency, as may be seen in the term "first law efficiency" or "plant efficiency", which denotes the ratio of useful energy out to energy available in the fuel used

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performance of machines. In German, the term *Wirkungsrad* expresses the engineering measurement of efficiency, especially in terms of energy use. *Wirtschaftlichkeit* and *Leistungsfähigkeit* are also sometimes translated as efficiency. *Wirtschaftlichkeit* is a general term, denoting economic efficiency. *Leistungsfähigkeit* is similar to the French *rendement*, describing performance, or more properly the capacity to perform.

by a power plant, for example.

It is the second law of thermodynamics that has been more closely allied with conceptions of efficiency. According to the second law it is inevitable that some energy will be lost, by being rendered irrecoverable, in the process of converting energy from its native forms, as in coal or sunlight, into useful forms such as electricity, mechanical work, or heat. This arises because there is a preferred direction to the process of energy conversion and transfer, as Rudolf Clausius made clear in a classic formulation: "Heat can never pass from a colder to a warmer body without some other change, connected therewith, occurring at the same time" [Clausius, 1867, p. 117]. William Thomson (Lord Kelvin), himself the author of a classic formulation of the law, put it more plainly in an 1851 draft of a paper on heat: "Mechanical effect escapes not only from agencies immediately controlled by man, but from all parts of the material world, in the shape of heat, and escapes irrecoverably. . . ." [Thomson, 1851/1989]. The complete conversion of energy from one form into another was impossible, for there would always be losses through processes like friction or radiant heat. The second law thus made the issue of lost or wasted energy important for engineers and physicists interested in measuring the performance of machines, because it provided them with a theoretical upper limit: an engine or machine could at best, and only theoretically, give out as much energy as it had taken in. Efficiency became a matter of accounting for the transformation of energy through an engine or machine.

Definitions cannot fully capture the variety of ways in which efficiency is used, but they do underscore several of its fundamental features. First, efficiency is more than an intellectual conception, for it is connected to material power and material effect in the world. Second, it is linked not only with machines but with engines, in other words not only with the transmission of motion but with its generation. Efficiency is thus not only managerial but also creative. Third, important varieties of efficiency are fundamentally linked with the notion of scarcity, through their reliance on the laws of the conservation of energy and the recognition that energy is lost irrecoverably when it is converted into a useful form.

2.2 Efficiency in use: control, effects, and means-ends rationality

In use, efficiency evinces a commitment to bringing things under managerial control. The issue of control bears significantly on how efficiency is characterized, whether as an intrinsic or instrumental value. Contemporary engineering efficiency uses techniques of observation and control to guarantee that action will be effective, and detailed accounting principles, tracking the use and transformation of materials, to measure that effect and balance it against costs, whether in energy, materials, or funds. Efficiency operates through the control and management of resources.

Efficiency is linked with control because it is a means 'to produce predetermined effects' through systematic and rational processes [Levin, 2000, p. 16]. This is apparent in general uses of efficiency, in which it describes a job well and economically done. Efficiency does not necessarily provide full control, however; in any given instance the parameters important to efficiency are many and complex. An internal combustion engine provides an example. To measure its efficiency a variety of different factors, such as heat value of the fuel and the torque on the driveshaft, must be converted into equivalent units, usually of energy, and their interconversions must then be tracked through the system. Attempts to increase the engine's efficiency require observing it closely enough to find avenues of greater control. Efficiency operates as a technique of control both by providing a model of how a machine or process should function, and a technique for measuring how closely that functioning matches the model. The model thus functions as a benchmark or yardstick.

Its reliance on techniques of control helps to distinguish efficiency from the closely allied concept of effectiveness. Efficiency, through control, describes actions that are more than simply effective; it describes effectiveness achieved through the precise apportioning of resources to task, so that enough resources are used but no more. The power of efficiency lies not in producing a great effect, but in producing a desired effect using precisely the desired amount of resources. Effectiveness, in contrast, may often be achieved by dumping resources into a problem, by using more resources than a desired outcome might in fact require if the problem could be specified with precision [Mitcham, 1994, pp. 226-227]. Efficiency is more elegant than effectiveness; it is narrow and targeted. The precise apportioning of means to ends is not integral to effectiveness as it is to efficiency, so it is easier to see effectiveness as an instrumental value. The characterization of efficiency is complicated by its necessary intertwining of means and ends.

Efficiency is thus more than a form of means-ends rationality, and more than a mere instrumental value. Its close association with control, and particularly its function as a way to measure control, indicates that efficiency is a value attached to processes rather than to goals. Although efficiency does entail the apportioning of means to ends, it does not follow that means may be considered mere instruments for achieving such ends. With efficiency, the end to be achieved is the mastery of the process itself, or, more precisely, the relationship between means and ends. "[N]ew horizon[s] of efficiency calculations" will indeed emerge in different social and cultural contexts, and they will emphasize different goals and use different means [Feenberg, 1999, p. 97]. Such calculations nevertheless, as far as they continue to concern efficiency, will also continue to measure mastery or control.

3 HISTORICAL BACKGROUND: ENDURING NUANCES

Efficiency has a wide variety of meanings in contemporary use, but its history suggests a deep and shared resonance beneath them. Consistent throughout efficiency's history has been its equation with direct and effective action, from the Aristotelian system of causes through medieval conceptions of the nature of the Christian God. Uniting the variety of efficiency's contemporary meanings is not only the pursuit of control but also overarching concerns for productivity and economy, and an acceptance of Enlightenment values of calculating rationality. Efficiency is often accompanied by a seemingly moral imperative, occasionally made explicit but more often understood: that efficiency is a good thing, on its face, in the way that good use is opposed to waste, and that planning and foresight are opposed to accident and happenstance.[2] The resonance of efficiency is with both intellectual and material power, in its association with the ability to take precisely effective action in the world. Although these connections may be extrapolated from the definitions offered above, in Section 2, only a survey of historical developments can reveal the depth of such resonances and their accompanying moral valences.

Two historical junctures were particularly important: the transition from pre-industrial to industrial society, and the perceived crises of western industrial society at the turn of the twentieth century. In the transition to industrial society a medieval and early modern conception of efficiency as an attribute of the creator fell away and efficiency came to be described as a value rather than an attribute, and as something achievable by humans themselves. In the crises of industrial civilization at the turn of the twentieth century efficiency became widely popular and offered policy makers the possibility of remaking societies destroyed by war.

Although historical examples appear through this article, as illustrations supporting arguments about efficiency's contemporary character, it is important to note that in this section not only the examples but the argument itself is historical. The point is that efficiency has a character of its own, developed over a long period and in tandem with the development of industrial culture. Its historical character means that efficiency is not merely a neutral instrument without inherent qualities of its own – in other words, it is not an empty shell waiting to take on the values and goals of whomever invokes it. Its history reveals not only that efficiency has character, but that it has depth.

3.1 Pre-industrial conceptions

Pre-industrial conceptions of efficiency differed importantly from the definitions of the term offered above. Examining these early conceptions makes clear both a deep continuity in the association of efficiency with power and goodness, and discontinuities in the use of the concept, which was neither quantified nor associated with human powers.

Two pre-modern sources for efficiency are plausible: scattered examples of comparisons of output and input in machines that scholars have traced back to antiquity; and a tradition growing out of philosophy and theology associating efficiency with action and with the power and goodness of God. The first plausible source, of output/input comparisons, helps to account for efficiency's contemporary math-

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[2] Economist and Nobel Laureate Robert William Fogel notes the persistence of "the widely held assumption that technological efficiency is inherently good" in a recent lecture on the history of debates over slavery's efficiency [Fogel, 2002, p. 46].

ematical form but also illustrates important discontinuities, for such comparisons were incidental and not general, and not quantified. The second, the philosophical and theological tradition, does help to account for efficiency's later moral and value-laden character, although it came to be associated with human rather than divine action.

3.1.1 Output/input comparisons

Although contemporary efficiency may be accurately described as an output/input relationship, an interest in such relationships can actually be traced back quite far. Archimedes asserted, as legend has it, that given a lever long enough he could "raise the world," implicitly comparing the accomplishment of a task with the resources he would need to achieve it. Pseudo-Aristotle's analysis of simple machines, including the lever, suggests a similar comparison [Mitcham, 1994]. Historians have also seen an interest in efficiency in the seventeenth-century, in Galileo's theory of machines, and in the early British Royal Society's interest in improving mining, transportation, and military technologies. Although early investigations of output/input relationships do provide antecedents for the technical and comparative varieties of efficiency, they do not account for its later emphasis on quantification, nor for its later value-laden character. Neither Galileo nor the Royal Society used the term "efficiency", nor did they quantify their comparisons [Cardwell, 1995, pp. 83-91; Merton 1938, pp. xx-xxi, 521]. Ancient output/input comparisons also remained unquantified, having been expressed in geometrical ratios. Such comparisons suggest an antecedent for efficiency's contemporary mathematical form while simultaneously underscoring the lack of a general concept to express such relationships.

3.1.2 Wisdom and actions of power

Antecedents for the moral and value-laden qualities of efficiency appear in premodern conceptions of the simplicity, economy, and power of the deity, for whom the term efficiency was largely reserved. Pre-modern conceptions of God's goodness, power, and simplicity informed the developing idea of efficiency through doctrines of divine economy. In the fourteenth-century Gabriel Biel described God's omnipotence in terms of efficiency [Lindberg, 1992, pp. 241-244, 390; Funkenstein, 1986, pp. 117-201]. Early ideas of economy associated with William of Ockham and Ockham's razor, or the principle of economy, were also influential; according to Ockham's razor, the simple or economical explanation of an event or phenomenon was always to be preferred [Grant, 1977; Adams, 1987; Copleston, 1950-; Gilson, 1961]. The term economy had been used to describe household management since at least 1530, but it also referred to God's managing of the cosmos, and through the eighteenth century economy denoted the "grand organization and government of life on earth" with God as "Supreme Economist" who had designed the household and kept it functioning [Worster, 1994, p. 37; Screpanti and Zamagni, 1993, pp. 20-23]. Efficiency of this sort was neither a measurement nor a comparison. It denoted adequacy or sufficiency for accomplishing something, rather than a precise match between abilities or resources and task.

The term efficiency itself suggests a particular antecedent in the medieval concept of the efficient cause, based upon the ancient Aristotelian system of four causes, in which the efficient was the active and immediate principle that produced change.[3] Thomas Aquinas was prominent among the medieval scholars who adopted Aristotle's system as part of a thirteenth-century program reconciling the pagan philosopher's work with the principles of Catholicism; the intellectual tradition of Scholasticism was founded upon this Aristotelian-Catholic synthesis. One outgrowth of this synthesis was the description of God as the efficient cause or prime mover [Kaiser, 1997], a practice that endured into the seventeenth century and can be seen in Spencer's analysis of God as "the Efficient Cause of man," for he had given human form to base matter [Spencer, 1628, p. 31]. The philosophical concept of efficient cause accentuates three characteristics of what efficiency came to mean: it was active, its actions were immediate, and they were effective.

Pre-industrial concepts of efficiency included interest in output/input relationships in mechanics (although the term was not used), theories of divine economy and simplicity, and the Aristotelian idea of the efficient cause. Such sources help account for the moral character efficiency took on as people came to see in it a positive social and economic good. They also help explain efficiency's association with authority and power, and especially with managerial power. The modern concept of efficiency resulted from the intersection of output/input measures with theories of divine simplicity, economy and power, and with a theory of immediate causal agency. What would prove discontinuous with later conceptions were the lack of a quantified, general sense of output/input relationships, and efficiency's association with the creative power of God.

3.2 Conceptions during and after industrialization

The meanings and uses of efficiency changed greatly during industrialization. Although non-quantified uses of the term did endure, quantified measures of performance became increasingly important, especially for people dealing with machines. As important as quantification were the developing recognition of the natural limits or boundaries that surrounded and contained human efforts, the most conspicuous of these being the law of the conservation of energy, and the variety of mechanical devices and observational techniques that made it possible to recognize, analyze, and record ever smaller mechanical effects.

Dropping out in the transition between pre-industrial and industrial efficiency was the idea of efficiency as mere effectiveness, or as mere adequacy or sufficiency. This was increasingly replaced by a similar but more exacting idea, in which efficiency referred to adequate or sufficient powers *and nothing more.* Anything more generated waste. This idea turned on the closeness of the match between

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[3] The other three Aristotelian causes dealt with the material and formal aspects of change, and with its ultimate purpose, or final cause.

resources expended and effect achieved, and although it is especially evident in the developing mathematics of efficiency, it is also reflected in the more general sense in which efficiency came to be opposed to waste. This more exacting use of efficiency corresponded to interest in the natural limits increasingly seen as governing what one could expect to get out of a machine. It also helped to distinguish efficiency from the related concept of effectiveness.

In this transition, efficiency became a human rather than divine attribute, in keeping with a developing belief in the possibilities of rational, systematic, and effective human action. Two attitudes deriving from the Renaissance and the Enlightenment were crucial: a humanistic view of people and their achievements as valuable in and of themselves; and a reliance on measurement and quantification in understanding and manipulating the world.

Three features of efficiency's industrial development have particular significance in discussions of its contemporary uses and meanings: industrial efficiency's roots in technical practices of motion control in machines, which underscore its alliance with control more generally; differences between the limiting parameters that efficiency could not overcome (in thermodynamics) and those it could (in economics, for example), which inform a fundamental distinction between efficiency when allied with balance and when allied with growth; and visions of efficiency as a way to remake society in response to social crisis, which illustrate the historical connection between efficiency and visions of how the world should or does work.

3.2.1 Motion control in machines

Industrial efficiency has its roots in technical practices of motion control in machines. It is closely linked to physical and mechanical measurements, developed from the eighteenth through the mid-nineteenth centuries to help quantify the performance of machines, and stemming from a tradition of analyzing machines and their effects in terms of motion. This tradition gave rise to a variety of devices both to contain and direct motion in machines and to assess and measure that motion, although the term "efficiency" was not in common use until well into the nineteenth century. Mechanics and engineers used instead a variety of terms, such as "mechanical effect" and "mechanical power".

Mechanical traditions have long linked efficiency to how things move. Efficiency in machine performance came to emphasize a mechanical discipline that used physical structures to eliminate extraneous and wasteful motions, and to control and direct productive motion along predetermined paths. British engineer John Smeaton, in a series of celebrated experiments on waterwheel efficiency in the 1750s, designed his model to minimize splashing and turbulence, and to eliminate disturbances that might keep the water from moving smoothly and directly through the system [Smeaton, 1759; Skempton, 1981, pp. 35-57; Alexander, 2008a].[4] Gerard Joseph Christian, French machine theorist and director of the *Conservatoire des arts et métiers* during the Restoration, described the most

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[4] Smeaton did not use the term "efficiency"; he wrote instead of "mechanical effect."

perfect machine in terms of efficiency, as the one that produced "the greatest mechanical effect, while using the least amount of fuel," only possible if all but a machine's working parts were immobilized [Christian, 1825, II p. 374, III pp. 18, 37; Alexander, 1999]. In the mid-nineteenth century, W. J. M. Rankine, at the University of Glasgow, found in efficiency a way to link the precise mathematical formulations of the energy concept with measurements of machine performance: the best or most efficient machines lost the least energy in useless and extraneous motion [Marsden, 1992; Wise and Smith, 1989-1990]. The influential machine theorist Franz Reuleaux defined a machine in terms of motion control: a well-designed and effective machine allowed only predictable and controlled motions [Reuleaux, 1876].

Motion control offers a particularly potent illustration of the types of control affiliated with efficiency. It requires that disturbances be eliminated, that the machine or system be kept under detailed surveillance, and that only predicted motions be allowed. The most efficient machine is the most thoroughly controlled.

3.2.2 Thermodynamics, balance, and growth

Two developments of the mid-nineteenth century were important to the maturing concept of efficiency: the working out of the laws of thermodynamics, including the conservation of energy and the tendency to entropy; and a shift in the sciences away from ideas of balance to ideas of growth. In establishing relationships between motion, heat, and energy, and by postulating that although these quantities could be transformed they could not be created, conservation laws provided a theoretical upper limit to the efficiency of a machine. Glasgow engineer and physicist W.J.M. Rankine relied on the conservation laws in giving efficiency its mechanical definition, which expressed the effectiveness of a machine in terms of its use of energy, in the ratio of effect produced to energy used.

Also important were new concepts of dynamism and change that characterized work in the physical sciences during the period in which Rankine gave efficiency its mechanical definition. Dynamic understandings of natural phenomena increasingly replaced characterizations of nature or natural systems as in equilibrium, in which changes had been seen as offsetting each other and resulting in a balanced state. The shift from ideas of balance to ideas of growth or dynamic change was expressed most clearly in Darwin's theory of descent through natural selection [Wise and Smith, 1989-1990]. Efficiency also began to be applied in economics, where it was allied with rational management in pursuit of growth [Alexander, 2008a].

Thus, by the turn of the twentieth century, efficiency had both matured in applied mechanics and become part of a larger intellectual shift in how natural systems were conceptualized. Efficiency had been named, and given a formal mathematical definition in the classic form of the output/input ratio, as the ratio of work performed by a machine or system to energy used in producing that work. In this formal sense, efficiency was allied with the notion of the balance. The term also came to be used in ways corresponding with growth, most commonly in economics. These developments underlie the metaphors of the balance (statics) and the engine (dynamics) that inform efficiency's contemporary meanings, as discussed below in Section 5.1.

3.2.3 Response to industrial crisis

Efficiency was a central concern in the reform efforts that characterized American and European history from the turn of the twentieth century until the Great Depression, reforms spurred by worries over the effects of industrialization and urbanization in a changing international order, and expressed in efficiency movements tied to national health, governmental reform, military prowess, and protection of empire, nation, or race. Efficiency became ubiquitous in the United States during the progressive era, a time of intellectual, social, and political turbulence. Efficiency described not only technical matters, like the thermal economy of an engine, but personal ones as well: careful spending habits, fastidious bodily hygiene, and good childhood education. Technical features like quantification and calculation jumbled together with social, governmental, and personal concerns to produce a word resonating of technical expertise, personal integrity, and good government. Efficiency expressed both sober qualities of hard and patient work, and enormous hopes for remaking society and the world. Frederick Winslow Taylor's system of scientific management is the most recognizable American efficiency marker of this era.[5]

Efficiency as a response to crisis is best illustrated by the efficiency and rationalization movements that characterized European society and politics early in the twentieth century. In Britain, at the turn of the century, embarrassment over how long it had taken the Empire to subdue the rebels in the Boer War led to worries about national efficiency and calls for efficiency reform [Searle, 1990]. The ravages of the First World War and threatened economic collapse led to widespread enthusiasm for efficiency in Italy, France, and especially Germany; "rationalization" was the key term describing the prominent international movement of the interwar years that sought in efficiency a solution to problems of economic scarcity and social turbulence [Brady, 1933; Maier, 1970; Weiss, 1987; Nolan, 1994].

These movements sought in efficiency a way to achieve visions of how society

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[5] Although Taylor was a mechanical engineer, and one-time president of the American Society of Mechanical Engineers, his system of scientific management lay outside the mechanical tradition; many did not consider his management work to be engineering and the Society refused to publish his seminal management papers [Kanigel, 1997]. The discipline of industrial engineering traces its roots to Taylor, and it is from Taylor's system that confusion has arisen over the nature of efficiency in engineering. Scholars have seldom noted the differences between Taylor's system of management and the techniques used with the engines and machines at efficiency's mechanical core. Connecting the two were Taylor's early experiments with the cutting of metals, which established his international reputation and which turned on control of the precise angle and conditions of the cutting blade: this work was placed firmly within engineering traditions. Taylor's system of management was concerned with the control of labor as much as with increased productivity; this concern linked him with management traditions rather than engineering.

should be organized and how it should function. They were responses to social crises, in some cases extreme, and they illustrate a significant feature of how efficiency has often been used in the contemporary world: in attempts to control changing or threatening situations by bringing them into conformity with visions of how the world ought to behave [Alexander, 2008a].

4 A VOCABULARY OF EFFICIENCY: IMPORTANT CONTEMPORARY DISTINCTIONS

Efficiency takes on a variety of forms in modern and contemporary use. This section develops three distinctions that are useful in analyzing how the concept functions in any given case, and that suggest ways to narrow and focus discussions of an enormously broad issue. Discriminating between these varieties of efficiency reveals subtle but significant shadings in connotation and use: social distinctions in how efficiency is applied; varying emphases on human agency depending on how efficiency is measured; and the paradoxical nature of the concept itself, which addresses scarcity but is most effectively applied in contexts of abundance. The sections that follow use historical examples, but in an argument about efficiency's contemporary use.

4.1 Root metaphors: static and dynamic forms of efficiency

Efficiency appears in two ways that are conceptually distinct, where the difference lies not in how they are measured but in the root metaphor they employ. The two root metaphors are the balance, illustrating static efficiency, and the engine, illustrating dynamic efficiency.[6] Static efficiency emphasizes conservation and predictable performance, and dynamic efficiency emphasizes effective management rewarded by growth [Alexander, 2008b]. Although efficiency in its formal sense emphasizes balance (through the conservation of work, mechanical effect, or power), people also use the term in ways in which it corresponds with growth, or more specifically with visions of change and progress. In this sense efficiency connotes rational management in pursuit of the greatest effect. What is efficient is effective, and available inputs, whether resources, or existing systems or institutions, do not limit possible output in the narrow mathematical sense, but instead challenge the management skill of whomever is in charge. In pursuing a dynamic efficiency of growth, a manager is not bound by an equation of conservation or balance, but is free, in the pursuit of profits, to broaden what he or she considers the raw materials, or inputs, in his or her control.

The distinction between efficiency's static and dynamic forms lies not in how efficiency is measured nor does it lie in whether something remains at rest or moves. The distinction lies instead in the connotations that accompany efficiency's use.

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[6] The steam engine provided the most potent illustration of the new possibilities offered by engines in the nineteenth century, but the metaphor of the engine need not be limited to steam.

When efficiency measures are emphasized as tools to generate stability, predictability, and manageability, the root metaphor is of the balance. The connotation is one of things evening out, moving smoothly and without turbulence. When efficiency measures are emphasized as tools of transformation the root metaphor is of an engine, which creates motive force from materials themselves at rest. The connotation is of change and progress, progress here meaning procession toward a goal, which may or may not be itself a positive good. Through industrialization steam power was transforming society, bringing people from the countryside into the factories of the cities and stimulating deeper scouring of the earth in search of coal for its fuel. But the steam engine, because it not only produced motive force but also generated irrecoverable losses of energy through waste heat, also carried the world further on the path of energy dissipation described in the second law of thermodynamics. Opinions are, and were, divided on the benefits of industrialization and the new engines, but there is concensus on their transformative effects [Smith, 1998; Landes, 1969].

Although efficiency's static and dynamic connotations exist side-by-side, an important social distinction has come to govern how they appear. In its static and balanced sense, efficiency describes machines, processes, and people who are subject to management; in its dynamic sense, it describes the efficiency of those who do the managing. Those efficient in the static or conservative sense provide the stable and balanced elements manipulated by those in positions of relative privilege in pursuit of the greater rewards of dynamic efficiency.

A detailed example will help to make clear not only the distinction itself, but also the significant issues that can be at stake. This is illustrated in the painful development of Robert William Fogel's thinking on efficiency and slavery in antebellum America. Fogel, Nobel Laureate (1993), economist, and cliometrician, devoted his early career to demonstrating that plantation agriculture in the American south had been efficient because of the good work ethic of slaves, and because slaves were well treated by their masters. He offered the analysis in an attempt to recover a respectable past for slaves' descendants, and to find something in which they could take pride. His work, published in 1974 with co-author Stanley Engerman, was met with widespread and acrimonious criticism, and occasioned one of the most public academic disputes in post-war America. Devastating criticism led Fogel to reevaluate his position on slavery and efficiency, and to confront his own earlier assumption that efficiency was itself a positive good. Fifteen years later Fogel admitted that his assumption had been false, and that the efficiencies he had found in plantation agriculture were the result not of a good work ethic or personal initiative on the part of slaves, but of exploitation through gang labor, brutally enforced. The efficiencies he had measured had accrued to the owners and masters of slaves; they were dynamic efficiencies, measured in profits and growth. But the profits and growth were built on static efficiencies, which required keeping slaves in order and hard at task, and, in particular, in preventing them from creating any disturbance or turbulence, or change, in the plantation system [Fogel and Engerman, 1974; Fogel, 1989, 2002; Alexander, 2008a].

4.2 Measurements: bounded and arbitrary forms of efficiency

Another important distinction in how efficiency is used concerns the terms by which it is quantified. Efficiencies that are quantified take one of two forms: a bounded form or an arbitrary form. The distinction was first noted during the American progressive era by Walter Polakov, engineer and contemporary of the well-known efficiency theorist Frederick Winslow Taylor. Polakov used the term "arbitrary" to emphasize the element of human choice in constructing efficiency ratios that are not measured in terms of energy. Bounded forms of efficiency are dependent upon quantities limited by natural law such as energy; efficiency is bounded by the laws of the conservation of energy in that they pose an upper limit beyond which it cannot reach. Arbitrary forms of efficiency take the form of ratios between otherwise independent quantities, in which a particular value of the ratio is chosen as the standard of one hundred percent efficiency, and against which other values of the ratio are measured. Using efficiency measurements predicated on the laws of energy may also be described a matter of human choice, specifically the choice to use highly authoritative scientific law rather than to create arbitrarily a practical measurement suited to the quantities at hand.

Arbitrary measures allow a very broad use of efficiency, making it possible to apply the term, precisely and quantitatively, to almost anything. Historical examples provide the clearest illustrations of this breadth; Polakov himself used the ratio of cost per BTU of coal as an example. Measurements of efficiency based on the ratio of the number of widgets produced per hour to the rate of ventilation in a factory would also take the arbitrary form. One arbitrarily sets a standard of 100 percent efficiency (a certain cost per BTU of coal, or so many widgets per hour at a certain ventilation rate), and measures other examples of the same ratio against it. Setting an arbitrary standard of 100 percent efficiency for the yield of potatoes at 100 bushels per acre, Polakov calculated that the potato yield efficiency champion in 1907 was the "desert state of Wyoming," with an average yield of 200 bushels per acre, for an efficiency of 200 percent [Polakov, 1909].

Arbitrary measurements of efficiency remain in widespread use. The distinction between efficiency's bounded and arbitrary forms is sometimes used to illustrate the difference between engineers and economists. Engineers, governed by natural limits such as the second law of thermodynamics, cannot reach a one hundred percent return on energy invested in a machine. Economists, in contrast, can exceed the one hundred percent limit by arbitrarily setting efficiency standards according to terms other than energy, which allow them to achieve profits, (i.e., returns greater than one hundred percent).

4.3 Root contexts: efficiency under scarcity or abundance

Efficiency may be worked out elegantly and carefully over time, or it may be adopted in desperation as a response to scarcity. The distinction lies not in the type of efficiency measures adopted or in why they are chosen. It depends instead on the context within which efficiency is pursued. Engineering uses of efficiency generally depend on resources allowing time for the analysis of a problem, the formulation of various approaches, and the careful and managed implementation of whatever option is chosen. The context is one of abundance. Frederick Winslow Taylor's well-known system of scientific management depended on an abundance of resources allowing time for management and consultants to analyze the flow of work and to consider various efficiency approaches. Even if the point of efficiency measures is to maximize the use of scarce resources, a context that allows careful consideration and a variety of options remains a context of abundance.

Efficiency measures are also adopted in desperation as a response to a scarcity of resources. The context of scarcity refers not only to the scarcity of resources generally but of efficiency resources, when the time, expertise, and materials needed to analyze a problem thoroughly and choose a well-suited plan of action are unavailable. This is efficiency in the sense in which most people use it, in the everyday decisions they make about how to apportion their limited resources — people may make a few calculations but do not generally mount a full-scale efficiency analysis. But efficiency in a context of scarcity is especially marked by desperation, by the attempt, in a true crisis of resources, to make a few variables under one's control stand in for other matters that cannot be helped. An example may be found in attempts by the Kaiser Wilhelm Institute for Labor Physiology to stimulate the productivity of coal miners in Germany during the last years of the Second World War. Institute researchers were unable to ameliorate the inhumane treatment of the miners, many of whom were Soviet prisoners of war and subjected to conditions described by the Red Cross as appalling. Improving the efficiency of the miners came down to improving their diets; the racial commitments of the Reich did not allow it to ameliorate other factors recognized as crucially important to efficiency, such as working and living conditions. Dietary measures were adopted in desperation, when a scarcity of political and material options allowed little other intervention [Alexander, 2006b].

5 EFFICIENCY AS A DESIGN VALUE IN ENGINEERING

The concept of efficiency plays an important role in engineering design in several ways. It is important in the design of engineering systems and artifacts, but perhaps even more fundamental has been the importance of engineering artifacts themselves, and their design, in the formulation of efficiency theory. The theoretical apparatus of efficiency was built on close observations of machines at work. In practice efficiency analysis also remains closely tied to the particular configuration of an artifact or system, and especially to the arrangement of its mechanical parts. General principles of efficiency may be derived from practice, that certain types of motor are more mechanically efficient for example, but even motors of the same design will evidence differences in efficiency when put to the test. Also important is the prestige that its association with physics brings to efficiency, and its scientific status may be offered as proof of technocratic expertise on the part of members of a design team. Efficiency is not so apparent an indicator of optimal engineering design, principally because of its malleability; what is to be optimized must first be decided, and then there will remain a variety of options for efficient achievement of the goal. That said, efficiency does serve as a design criterion when it is included among project specifications, and may be an important consideration in both the original conceptualization, and any necessary re-conceptualization, of the design problem itself. What efficiency can offer most potently is its recognized value as a goal, to which members of a design team may share a commitment despite contests over how it should be reached.

5.1 Reflects the role of design in building theory

Formal definitions of efficiency in thermodynamics were historically linked to attempts to understand and quantify the performance of machines. They give evidence not only of the interrelationship between engineering theory and scientific theory, but of the importance of the design of the technological object in the process of theory building. Peter Kroes gives as an example Pambour's nineteenth-century theory of the conservation of steam in steam engines; another example is the role of the configuration of the test waterwheel in the famed studies of its mechanical effect made by eighteenth-century British engineer John Smeaton [Kroes, 1992; Reynolds, 1983; Alexander, 2008a]. In both cases, the physical configuration of the machine bore directly on how it was theoretically construed. The most famous example is Sadi Carnot's work on the ideal engine cycle, which was fundamental to the formulation of engineering definitions of efficiency. Carnot's conceptual design of an ideal engine played a crucial role in the development of thermodynamics theory [Cardwell, 1971].

5.2 Brings the prestige of science to bear on the design process

The concept of efficiency brings the prestige of science into the design process, especially when energy is at issue, because it is founded on one of the most authoritative conceptual structures in modern physics. Appeals to efficiency may trump other claims of value in the design process. Efficiency's value here depends on a ladder of assumptions: most generally that science is a good foundation for engineering design, but also that the laws of thermodynamics do reflect how things work (that they are true) and that they are an adequate guide to building real systems in the world; and that science offers a politically neutral ground for consensus. This can be seen in the appeal to science as an authoritative and consensual basis for the redesign of society according to principles of efficiency and rationalization in Weimar Germany. Germany's *Reichskuratorium für Wirtschaftlichkeit* offered scientific measurements of efficiency as a non-political and culturally neutral solution to social and political strife, when it was charged by the *Reichstag* in the 1920s with ameliorating the tensions of a nation experiencing extreme economic and social dislocation following the First World War [Maier, 1970; Nolan, 1994].

Efficiency is perceived as especially valuable in design considerations that bear on environmental use and sustainability, because of its association with waste reduction in addition to its scientific foundations. In such cases efficiency offers not only scientific prestige, but also a way to set goals and gauge progress. In discussions of the design of environmental systems, claims to efficiency often carry with them claims of technocratic expertise [Hays, 1959; Worster, 1994].

5.3 Offers a measure of optimal design

The concept of efficiency plays an important role in considerations of the optimal, or most perfect, design of engineering systems. Efficiency offers a measure of perfected design in cases that bear on the use and transformation of energy; the closer efficiency approaches 100 percent, or perfect unity, the more perfect the design. But it is important to note that even with energy efficiency there remain a wide variety of ways to measure it, and how it is to be measured may become an issue of significant disagreement among persons involved in the design process. With regard to engines, questions that will remain may include whether thermal or mechanical efficiency should be maximized, and what instruments should be used to measure it, for example an indicator within the engine or prime mover itself or a brake or other device at the output end of the system, or both. Even the heat value of the fuel may be calculated by various methods. In general, efficiency offers only a very indistinct guide for optimal design, and even when it is agreed that a design will be chosen on efficiency grounds, there will remain a wide variety of efficiency options.

That said, there does remain a sense in which efficiency is indeed an important guide for optimal design, and that is when control of a moving or changing system is the primary desired function. Control values include stability of operation, predictability of results, and minimal interference or turbulence. When control of a system is the desired output, rather than some other measure of productivity, the concept of efficiency offers a model for optimal design: a system under complete surveillance, where motion is restricted to predetermined paths and resources are primarily directed toward preventing turbulence. This is efficiency in a totalizing sense and it is not restricted to engineering use. Below, in Section 6, I discuss several important critiques of efficiency's totalizing function within society more generally.

5.4 Serves as a design criterion

Efficiency serves as a design criterion when it is among the design specifications that a project must fulfill. In such cases efficiency is not regarded as having a value of its own, but is instead valued as one among many limiting parameters specified by the owner or manager of a project. It functions to guide the design process insofar as it is congruent with the other limiting parameters, and may be accorded higher or lower priority if it comes into conflict with them. If specifications do come into significant conflict with each other, a design team generally turns to the project owner or manager to have them resolved, and does not itself choose which values to give priority. The issue then becomes one of re-conceptualizing the design problem itself.

Efficiency can offer a common language to those involved in the design of a project, and because it is so widely presumed to be valuable it can serve to legitimate a wide variety of engineering options. The very breadth of its presumed value means that even competing groups may make claims to efficiency during the design process. Rather than imposing a rigid set of requirements, efficiency may instead provide a shared general goal. Those involved in the design process might see efficiency in an economic sense, or as reflective of social or cultural values, but may, despite such differences, nonetheless be able to design a project within a shared commitment to the general goal of efficiency [van de Poel, 1998].

6 CRITIQUES OF EFFICIENCY

The most famous critics of efficiency have been critics of industrial society more generally, seeing in efficiency not a harbinger of progress but a technique of control and exploitation. The American architectural critic and author Lewis Mumford rejected capitalist uses of efficiency, which he believed were tied to profit-seeking and individual enrichment at the expense of true social and cultural advance [Mumford, 1963]. A much more influential critique was mounted by the early Frankfurt school critical theorists Max Horkheimer and Theodor Adorno. Members of the Institute for Social Research, Frankfurt am Main, sought to emancipate society from ideological captivity by "bringing to awareness the conditions of our own knowledge of the world" [Anderson, 2000]. In their famous and provocative work *The Dialectic of Enlightement* (1947), Horkheimer and Adorno described efficiency as encapsulating a form of instrumental rationality that had been dominant since the Enlightenment. Efficiency bespoke the human attempt both to know and to manipulate the world; the test of true knowledge was how completely it allowed its object to be controlled. The greater the knowledge the greater the control; the greater the control the greater the efficiency. As Horkheimer and Adorno put it, writing in response to the nightmare of Nazism, "The totalitarian order has granted unlimited rights to calculating thought .... Its canon is its own brutal efficiency" [Horkheimer and Adorno, 2002, pp. 67-68]. Important support for Horkheimer and Adorno's argument was found in the influential concept of rationalization advanced earlier by sociologist Max Weber; rationalization described the efforts of Calvinist Protestants to reassure themselves of their salvation through the good and measurable effect of their works in the world. Such effectiveness seemed proof that God was disposed graciously and positively toward them [Weber, 1904-5, 2001].[7] An influential and sustained critique of Horkheimer and Adorno came from a member of the second generation of the Frankfurt school,

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[7] It should be noted that the term 'rationalization' encompassed a variety of efficiency measures as part of the rationalization movement in Europe between the world wars.

Jürgen Habermas, who found Horkheimer and Adorno's condemnation of rationalization so far-reaching as to undercut the possibility of critical theory itself. Such a dark description of rationality tainted even the critical and constructive use of reason, Habermas maintained, and in a series of works he painstakingly developed important distinctions between rationalization's various forms [Habermas, 1984]. Habermas's concern was to identify the conditions that would allow human interrelationships to flourish, free from controlling or dominating interests [Anderson, 2000]. In particular he offered an analysis of how the public sphere, under the right circumstances, could function as a critical check on political and economic authority, in contrast to the fragmented and weak check it had posed to Nazism. To buttress this argument, it was important that Habermas develop a respectable ground for rationality and thus for the critical theory that could be used to identify and help to create conditions more open to humane progress [Habermas, 1989].

The most sustained and far-reaching critique of efficiency has come from the French jurist and theologian Jacques Ellul. Like Horkheimer and Adorno he saw in efficiency a totalizing function, arguing that the quest for efficiency is antithetical to human freedom because it ultimately requires all things human to be analyzed and integrated into orderly and manageable systems [Ellul, 1964]. But Ellul's method was notably opaque and his work cannot be considered to be within the framework of critical theory. His rejection of critical theory was in fact radical, for he argued that planning itself is implicated in the dominating effects of efficiency; the requirement that critical theory be not only theoretical but practical was itself an invitation to strategy and planning, moves that themselves give rise to the desire for efficiency. Ellul's work is not as widely known as that of the Frankfurt school, in part because no theorist has yet interpreted his deeply disturbing work in as constructive a manner as did Habermas in response to the despair evidenced in the work of Horkheimer and most particularly Adorno. Another reason for its neglect is that Ellul's work demands to be interpreted within a theological framework. His analysis of efficiency does not rest on theological argument nor does theological argument play a role in his major work on the subject (*The Technological Society,* 1964), but it is apparent in the important role he gives to human hope in much of his other work, in which hope offers an open system in contrast to the closed system that requires efficiency.

More limited critiques of efficiency have been mounted in recent years, most notably of efficiency in law and economics. In American law criticism of efficiency has been direct, whereas criticism of efficiency in economic practice, particularly of globalization, has taken the form of analyses of foundational practices that invoke efficiency.

Efficiency is an important and contested concept in American law, and there, as elsewhere, it has several different meanings. Efficiency describes measures to streamline the settling of lawsuits, where it is promoted as a tool to help manage increasing burdens on the legal system. It has other and more potent meanings, more particularly legal, in constitutional law, where it is recognized as an important interest to be balanced against claims such as free speech, and among jurists who see efficiency as itself the embodiment of justice. Both efficiency's practical and administrative use, and its normative role in determining judicial or legal action, are disputed. Chief among critics of efficiency in the law has been Thane Rosenbaum, who objects to the bureaucratic streamlining of the legal process and its emphasis on settling criminal cases through negotiated pleas. Truth, he argues, has become a "hostage" to efficiency [Rosenbaum, 2004].

The critique of efficiency in economics takes two primary forms. The first is embedded within a critique of economic globalization, and characterizes market efficiency as incompatible with equality. It sees efficiency in markets as a strategy of wealthy industrial or post-industrial societies for maximizing their own benefits; protests at the meeting of the Ministerial of the World Trade Organization in Seattle in 1999 can be construed as part of this critique. The second form of critique lies in an analysis of the foundational suppositions of economic theory, tying them directly to the "gospel of efficiency" of the American progressive era, and describing efficiency in economics as in essence a religious value [Okin, 1975; Porter *et al.*, 2001; Nelson, 2001].

It should be noted that the Chicago school of law and economics combines law and economics by seeing in economic efficiency a demonstration of natural principles the law should follow. It has been criticized for attaching an especially high value to efficiency, and justifying that high valuation by an analysis of the common law that finds it to have achieved an especially efficient distribution of resources. A good illustration of Chicago school theory may be found in Richard A. Posner, *Economic Analysis of Law* [Posner, 1983].

Critiques of efficiency underscore the broad reach of the concept. That they are embedded in more general social criticism highlights the deep resonance between efficiency and industrial and post-industrial society, and that important strands of critique have emphasized efficiency's association with domination further substantiates the concept's identity as a form of control. Theorists have not mounted a full-scale defense of efficiency; its continued use in engineering contexts constitutes a rebuttal in practice.

7 CONCLUSION

The concept of efficiency is central to contemporary engineering, and it remains fundamental in both industrial and post-industrial contexts. It is broad and complex, and there is such great flexibility in how it is measured that it can be applied, precisely and quantitatively, to nearly any situation. But beneath its complexity and breadth lie three fundamental features. First, efficiency is a practical tool, an intellectual construct designed to make intellectual understanding of the world practically effective. It is not primarily about understanding the world but about acting in it. Second, efficiency is comparative and thus requires a vision of how the world ought to work, against which it may be measured or with which it may be compared. Without a vision of how a system or process should perform, there is no standard against which efficiency can be assessed. Third, efficiency functions by eliminating resistance to achieving the vision, by controlling change or motion in the process or system to which it is applied. Controlling resistance increases the likelihood that the vision will be achieved, and lessens the costs of achieving it by reducing the waste that is associated with resistance. It is important to note that resistance may take many forms, such as turbulence in the tailrace of a waterwheel or shirking by slaves in a cotton field.

These last examples, of possible sites of resistance to efficiency, illustrate how its engineering and social implications overlap. Engineering efficiency has a mechanical core, tied to mechanical engineering traditions and to the physics of energy and thermodynamics through historical attempts to understand and to control the performance of machines. Efficiency's reliance on control is key, for it distinguishes efficiency from the closely allied concept of effectiveness. Efficiency is associated not only with being effective, but with having such control over a process that effect is achieved with the least waste. Efficiency thus turns on the controlled apportioning of resources, whereas effectiveness denotes an effect but not the costs of achieving it. Its alliance with control suggests that efficiency is not only a tool but an ideology. This suggestion is supported by many of the historical instances in which it has appeared, such as debates over the productivity of slavery, and it is against efficiency as an ideology that its most potent critics have raised their voices.

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BIBLIOGRAPHY

[Adams, 1987] M. M. Adams. *William Ockham.* University of Notre Dame Press, 1987.

[Alexander, 1999] J. K. Alexander. The Line Between Potential and Working Machines: César Nicolas Leblanc and Patent Engravings, 1811-1835. *History and Technology,* 15, 175-212, 1999.

[Alexander, 2006a] J. K. Alexander. Efficiency and Pathology: Mechanical Discipline and Efficient Worker Seating in Germany, 1929-1932. *Technology and Culture,* 47, 286-310, 2006.

[Alexander, 2006b] J. K. Alexander. An Efficiency of Scarcity: Using Food to Increase the Productivity of Soviet Prisoners of War in the Mines of the Third Reich. *History and Technology,* 22, 391-406, 2006.

[Alexander, 2008a] J. K. Alexander. *The Mantra of Efficiency: From Waterwheel to Social Control.* Johns Hopkins University Press, 2008.

[Alexander, 2008b] J. K. Alexander. Efficiencies of Balance: Technical Efficiency, Popular Efficiency, and Arbitrary Standards in the Late Progressive Era U.S. *Social Studies of Science*, 38, 323–34, 2008.

[Anderson, 2000] J. Anderson. The "Third Generation" of the Frankfurt School. *Intellectual History Newsletter* 22 (2000). http://www.phil.uu.nl/ joel/research/publications/3rdGeneration.htm.

[Brady, 1933] R. A. Brady. *The Rationalization Movement in German Industry: A Study in the Evolution of Economic Planning.* University of California Press, 1933.

[Cardwell, 1995] D. S. L. Cardwell. *Norton History of Technology.* W.W. Norton & Co., 1995.

[Cardwell, 1971] D. S. L. Cardwell. *From Watt to Clausius: The Rise of Thermodynamics in the Early Industrial Age.* Cornell University Press, 1971.

[Cardwell, 1993-94] D. S. L. Cardwell. Steam Engine Theory in the 19th Century: From Duty to Thermal Efficiency, from Parkes to Sankey. *Transactions of the Newcomen Society*, 65, 117-28, 1993-94.

[Carnot, 1960] S. Carnot. *Reflections on the Motive Force of Fire and Other Papers.* Dover, 1960.

[Channell, 1989] D. F. Channell. *The History of Engineering: An Annotated Bibliography.* Garland, 1989.

[Channell, 1982] D. F. Channell. The Harmony of Theory and Practice: The Engineering Science of W. J. M. Rankine. *Technology and Culture* 23, 39-52, 1982.

[Christian, 1825] G.-J. Christian. *Traité de mécanique industrielle,* Bacherlier, 1825.

[Clausius, 1867] R. Clausius. "On a Modified Form of the Second Fundamental Theorem in the Mechanical Theory of Heat," trans. John Tyndall, in Clausius, T. Archer Hirst, ed., *The Mechanical Theory of Heat, with its Applications to the Steam-Engine and to the Physical Properties of Bodies.* John van Voorst, 1867.

[Copleston, 1950-] F. C. Copleston. *A History of Philosophy.* Newman Press, 1950-.

[Ellul, 1964] J. Ellul. *The Technological Society.* Knopf, 1964.

[Feenberg, 1999] A. Feenberg. *Questioning Technology.* Routledge, 1999.

[Feenberg, 2002] A. Feenberg. *Transforming Technology: A Critical Theory Revisited.* Oxford University Press, 2002.

[Fogel, 1989] R. W. Fogel. *Without Consent or Contract: The Rise and Fall of American Slavery.* W. W. Norton & Company, 1989.

[Fogel, 2002] R. W. Fogel. *The Slavery Debates, a Retrospective 1952-1990.* Louisiana State University Press, 2002.

[Fogel and Engerman, 1974] R. W. Fogel and S. L. Engerman. *Time on the Cross: The Economics of American Negro Slavery.* W. W. Norton & Company, 1974.

[Funkenstein, 1986] A. Funkenstein. *Theology and the Scientific Imagination from the Middle Ages to the Seventeenth Century.* Princeton University Press, 1986.

[Grant, 1977] E. Grant. *Physical Science in the Middle Ages.* Cambridge University Press, 1977.

[Gilson, 1961] E. Gilson. *Saint Thomas Aquinas and Philosophy.* Saint Joseph College, 1961.

[Haber, 1964] S. Haber. *Efficiency and Uplift: Scientific Management in the Progressive Era, 1890-1920.* University of Chicago Press, 1964.

[Habermas, 1984] J. Habermas. *The Theory of Communicative Action, Vol I. Reason and the Rationalization of Society.* Harvard University Press, 1984.

[Habermas, 1989] J. Habermas. *The Structural Transformation of the Public Sphere: An Inquiry into a Category of Bourgeois Society.* MIT Press, 1989.

[Hays, 1959] S. P. Hays. *Conservation and the Gospel of Efficiency: The Progressive Conservation Movement, 1890-1920.* Harvard University Press, 1959.

[Horkheimer and Adorno, 2002] M. Horkheimer and T. W. Adorno. *Dialectic of Enlightement: Philosophical Fragments.* Stanford University Press, 2002.

[Kaiser, 1997] C. B. Kaiser. *Creational Theology and the History of Physical Science: The Creationist Tradition from Basil to Bohr.* Brill, 1997.

[Kanigel, 1997] R. Kanigel. *The One Best Way: Frederick Winslow Taylor and the Enigma of Efficiency.* Viking, 1997.

[Kortabinski, 1965] T. Kotarbinski. *Praxiology: An Introduction to the Sciences of Efficient Action.* Pergamon, 1965.

[Kroes, 1992] P. Kroes. On the Role of Design in Engineering Theories: Pambour's Theory on the Steam Engine. In *Technological Development and Science in the Industrial Age*, P. Kroes and M. Bakker, eds., pp. 69-98, 1992.

[Landes, 1969] D. S. Landes. *The Unbound Prometheus: Technological Change and Industrial Development in Western Europe from 1750 to the Present.* Cambridge University Press, 1969.

[Levin, 2000] M. R. Levin. Contexts of Control. In *Cultures of Control*, M. R. Levin, ed., pp. 13-69, 2000.

[Lindberg, 1992] D. C. Lindberg. *The Beginnings of Western Science.* University of Chicago Press, 1992.

[Maier, 1970] C. Maier. Between Taylorism and Technocracy: European Ideologies and the Vision of Industrial Productivity in the 1920s. *Journal of Contemporary History* 5, 27-61, 1970.

[Marsden, 1992] B. Marsden. Engineering science in Glasgow: economy, efficiency and measurement as prime movers in the differentiation of an academic discipline. *British Journal for the History of Science,* 25, 319-46, 1992.

[Merton, 1938] R. K. Merton. Science, Technology, and Society in Seventeenth Century England. *Osiris*, 1938.

[Mitcham, 1994] C. Mitcham. Thinking Through Technology: The Path Between Engineering and Philosophy. University of Chicago Press, 1994.

[Mumford, 1963] L. Mumford. *Technics and Civilization.* New York, 1963.

[Nayler, 1985] G. H. F. Nayler. *Dictionary of Mechanical Engineering.* Butterworth's, 1985.

[Nelson, 1992] D. Nelson. *A Mental Revolution: Scientific Management Since Taylor.* Ohio Sate University Press, 1992.

[Nelson, 1980] D. Nelson. *Frederick W. Taylor and the Rise of Scientific Management.* University of Wisconsin Press, 1980.

[Nelson, 2001] R. H. Nelson. *Economics as Religion: From Samuelson to Chicago and Beyond.* Pennsylvania State University Press, 2001.

[Newberry, 2005] B. Newberry. Efficiency as a design value in engineering. Unpublished paper, 2005.

[Nolan, 1994] M. Nolan. *Visions of Modernity: American business and the modernization of Germany.* Oxford University Press, 1994.

[Okin, 1975] A. M. Okin. *Equality and Efficiency: The Big Tradeoff.* The Brookings Institution, 1975).

[Polakov, 1909] W. Polakov. Efficiency in the Purchase of Fuel for Power Generation. *Engineering Magazine* 38, 215-225, 1909.

[Porter *et al.*, 2001] R. B. Porter *et al.*, eds. *Efficiency, Equity, Legitimacy: The Multilateral Trading System at the Millennium.* Center for Business and Government of Harvard University, and The Brookings Institution, 2001.

[Posner, 1983] R. Posner. *Economic Analysis of Law*, 3^{rd} ed. Little, Brown. 1983.

[Rabinbach, 1990] A. Rabinbach. *The Human Motor: Energy, Fatigue, and the Origins of Modernity.* Basic Books, 1990.

[Reuleaux, 1876] F. Reuleaux. *The Kinematics of Machinery: Outlines of a Theory of Machines.* Macmillan, 1876.

[Reynolds, 1983] T. S. Reynolds. *Stronger than a Hundred Men: A History of the Vertical Water Wheel.* Johns Hopkins University Press, 1983.

[Rosenbaum, 2004] T. Rosenbaum. *The Myth of Moral Justice: Why Our Legal System Fails to Do What's Right.* HarperCollins, 2004.

[Screpanti and Zamagni, 1993] E. Screpanti and S. Zamagni. *An Outline of the History of Economic Thought.* Clarendon Press, 1993.

[Searle, 1990] G. R. Searle. *The Quest for National Efficiency: A Study in British Politics and Political Thought, 1988-1914.* Ashfield Press, 1971, 1990.

[Skempton, 1981] A. W. Skempton, ed. *John Smeaton, FRS.* Thomas Telford Limited, 1981.

[Smeaton, 1759] J. Smeaton. "An Experimental Enquiry concerning the Natural Powers of Water and Wind to turn Mills, and other machines, depending on a circular motion," *Philosophical Transactions of the Royal Society,* 51, pt. 2: 100-174, 1759.

[Smith and Wise, 1989] C. Smith and M. N. Wise. *Energy & Empire: A Biographical Study of Lord Kelvin.* Cambridge University Press, 1989.

[Smith, 1998] C. Smith. *The Science of Energy: A Cultural History of Energy Physics in Great Britain.* University of Chicago Press, 1998.

[Spencer, 1628] T. Spencer. *Logick*, 1628.

[Thomson, 1851/1989] W. Thomson. Draft for 'Dynamical theory of heat' (1851). In *Energy and Empire: A Biographical Study of Lord Kelvin*, C. Smith and M. N. Wise, p. 317. Cambridge University Press, 1989.

[van de Poel, 1998] I. van de Poel. "Why are Chickens Housed in Battery Cages?" in *Getting New Technologies Together: Studies in Making Sociotechnical Order,* C. Disco and B. v.d. Meulen, eds., 143-178, Walter de Gruyter, 1998.

[Weber, 2001] M. Weber. *The Protestant Ethic and the Spirit of Capitalism.* University of Chicago Press. 1904-5, rpt 2001.

[Weiss, 1987] S. F. Weiss. *Race hygiene and national efficiency: the eugenics of Wilhelm Stallmayer.* University of California Press, 1987.

[Wise and Smith, 1989-1990] M. N. Wise and C. Smith. Work and Waste: Political Economy and Natural Philosophy in Nineteenth Century Britain. *History of Science*, pt. I, v. 27, 263-301, 1989. Pt. II, v. 27, 391-449, 1989. Pt. III, v. 28, 221-261, 1990.

[Worster, 1994] D. Worster. *Nature's Economy: A History of Ecological Ideas*, 2^{nd} ed. Cambridge University Press, 1994.