Chapter 11: Optimization of efficiency

11. 1 Introduction

"Efficiency", "optimization" and "progress" are all related concepts that are used with favorable connotations in the normal language of our industrial society. This chapter breaks down what we mean by these terms and uses these concepts to analyze all types of processes from energy transfer in ecosystems to resource use in agriculture. Although there are benefits to increasing production-- efficiency often being one of them— the assumption that efficiency is always good or that there are clearly waste products that should be reduced does not hold all the time. Especially as we attempt to apply "green" or ecological principles to industrial processes it is important that we understand that cooperative ecological communities can be more complex and less efficient than simple manufacturing. This chapter will isolate the components of efficiency and describe how this can be optimized for different types of outputs. The key point to remember is that the different products of a system (including what we may call "waste") may all be necessary; for example, optimizing the production of one product may interfere with or decrease the production of another.

To reiterate one of the themes of this book, it can be a dangerous mistake to apply a simple solution (improve efficiency) to a complex problem (ecosystem management). In this chapter I will employ more complete descriptive terms, such as "energy use efficiency" or "embedded energy" to remind you that we are being very specific. But much of the public discussion fails to, or deliberately avoids, being this specific and clear. The reasons for this are probably due to the attempt of some to put the imprimatur of engineering or science on their arguments. For example, it might sound more persuasive to argue that old growth forests are very inefficient at producing timber than it is to state that the large trees in these forests contribute a substantial amount of energy to regulating microclimate and providing a wide diversity of ecological niches. Optimization and efficiency are powerful concepts, concepts that lead to both opportunities for building new knowledge and potential for abuse.

11.2 Efficiency of production

The efficiency of a process is the ratio of the output to the input. This can be high or low. We should use the awkward but more descriptive compound phrase “high efficiency” or “low efficiency” to clarify that we are not assuming that “efficiency” means “high efficiency”. For example, the efficiency can be calculated based on the ratio of product to the input of ingredients. The production of beer is dependent on large inputs of clean water. The efficiency of beer produced to water consumed in the process can be in the range of 1 pint of beer for 170 liters of water (1 liter of beer requires 300 liters of water in production). This is often referred to as the “embedded water” in beer, i.e. the amount of water that you are using when you consume 1 liter of beer. Another example is the amount of fertilizer needed to produce corn. For each ton of corn that is eventually harvested, it might require a minimum of *** lbs of nitrogen or *** lbs of phosphorus added. Another dimension is the amount of land used, i.e. how many tons of corn can be produced per season per acre of land. The amount of water needed to grow the crop and whether it comes from rain, existing soil water or has to be provided through irrigation is another dimension of the efficiency of production. Other factors include the amount of labor, machinery and energy to run machinery. Obviously optimizing the production of corn against land usage might require more fertilizer and water.

A commercial corn farmer has to choose how to use these resources most efficiently to get the best yield. The problem for farmers is much more complicated than just getting the ratios of water and fertilizer correct, the farmer has to consider factors relating to weather, risk of crop failure and subsidies or supports for production. However, as a commercial, for-profit enterprise, the farmer is really managing for the return on investment for growing and handling the corn. All the inputs and activities are collapsed onto a single dimension of money. This allows the farmer to make rational investment decisions and optimize the financial outcome. We must keep in mind that the business of growing corn is not maximized for corn production but rather financial return.

Many of the environmental problems that society need to address will involve the same range of potential inputs, with more possible outcomes and the inability to reduce the cost of all inputs and outputs to a single monitorization. For example, a natural treatment wetland might be managed to reduce nutrient runoff from a farm, increase local biodiversity, provide crucial habitat for an endangered species, create recreation opportunities, generate employment and meet aesthetic criteria (i.e. look naturally beautiful). The owner or manager of this wetland will have all the complications of a farmer plus the added burden of making judgments about the relative value of habitat, local employment, and aesthetics. It is very unlikely the scientific basis for the management of such a wetland is derived from simply optimizing the efficiency of any part of the overall process. We will deal with the issues of tradeoffs across multiple parameters later.

11.3 Progress is often thought of as increased efficiency

Progress, in some sense the advancement of civilization, is often equated with the ability to use resources more efficiently to create more product. This includes the underlying idea that industrialization is able to gain access to some resources that weren't previously available. For example, modern civilization uses a huge amount of energy, and it may be argued that we use it inefficiently. On the other hand, hydropower wasn't available until we built dams, and fossil fuels have to be mined before they can be converted to fuel sources. The ability of society to employ other resources to exploit energy, mineral and water resources is a type of increased efficiency. However, we need to make this argument carefully so that it is not a simple tautology, we have more *** energy because we are able to efficiently exploit resources. Such an argument sidesteps crucial questions of motivation and values. We need to ask "why are we increasing our consumption (and dependence) on more and more energy, and how has this really improved our lives". These are not questions that can be answered with efficiency ratios, and we can't blindly assume that increased use of energy or pursuit of efficiency will be beneficial to all of us.

As we've seen elsewhere, questions like these come to the fore when comparing worldviews (chapter ***). One of the cornerstone beliefs of the Cornucopian worldview is that continued innovation will increase resource availability and lead to a growth in the economy. Similarly, the Industrial Ecologist worldview sees using the current resources more efficiently as a central factor in how we can reduce environmental impact. Thus beliefs about progress and efficiency are central to two of the major worldviews and we need to understand how these intellectual tools reinforce these beliefs.

11.4 Optimizing Efficiency

An optimum is when the particular set of conditions and parameters that results in the highest efficiency. This means that no other changes would increase the output and also that other conditions will be sub-optimal. In this chapter we will focus on the optimization and efficiency of processes in ecosystems and industrial processes.

Not all processes have a range of efficiencies. For example a single process in which one input is changed to one product may have the same efficiency for all conditions; any increase in the inputs leads to more products. The ratio, or efficiency of the process may stay the same and thus there is a whole family of conditions that lead to this efficiency.

Optimization of multi-step processes is much more interesting. Consider a process in which the outcome of one sub-process makes A and that combines with the output of another sub-process that makes B to make the final output C (see figure 11.1). More or less of the machinery that makes component A will make A at a faster or slower rate, respectively. The same holds for B. The optimal production efficiency is where just enough A is made to match the production rate of B. At the optimum, there is no excess machinery for either A or B. Another way of explaining this is that if there is an excess of the machinery for making A, it will make A faster than B is being produced. A little less of machinery A and a little more of machinery B would move toward optimization.

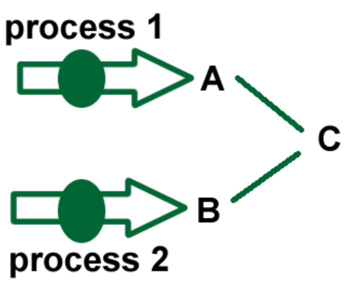

Figure 11.1 Schematic of a multi-step process. One set of machinery makes A and another set of machinery makes B. The final outcome is to use a fixed ratio of A and B to make C.

Let’s consider three examples of optimization for mechanical, physiological and ecological processes.

- A familiar mechanical optimization is the construction of cars on an assembly line. Parts come in on conveyor belts to an assembly area and the workers attach new parts to the growing automobile. The optimal speed to put on new bumpers is to get one set for each car. Running the bumper conveyor belt faster doesn't create cars faster; in fact, it may interfere with the assembly line and slow down the whole process.

- In plant physiology, light trapping reactions in the chloroplast are matched to the process of fixing carbon dioxide into organic compounds such as sugar. The light harvesting reactions provide the high-energy intermediate compounds that are used in a particular ratio by the enzymatic pathway that reduces CO2 to trioses. Plants that grow in low light environments will have more pigments to trap more of the available light and plants that grow in high light will have more enzymes to process CO2 into trioses. The low and high light adaptations represent optimization strategies to use the available resources in the most efficient manner possible.
- Ecological systems such as grasslands are very efficient at capturing solar energy and converting that energy to new biomass. One of the tradeoffs that determine their efficiency is the amount of water that these plants transport from the soil to the air compared to the amount of energy captured for photosynthesis. If there is abundant water, the grasses will move more water that brings in more nutrients from the soil and supports higher net growth. If water is limited, for example during a dry period, the plants will close down their stomata which leads to less water transport and less nutrient transport and slower growth. However, the shift in plants from those that do well in wet conditions to those that do better in dry conditions results in far more growth than if the "water loving" plants were just grown with less water. This bonus is the consequence of shifting to a more efficient use of water during dry conditions.

These examples illustrate how we can describe the use of resources and machinery in ways that increase efficiency and tend toward optimization. Whereas the oversight of a factor should attempt to be as efficient as possible, please don't jump to the conclusion that plants or wetlands only operate with a goal of simple optimization. We will discuss the limits to optimization later.

11.5 Dynamic Optimization

As discussed above, the optimal allocation of machinery or biosynthetic components to a process or biological pathway results in a balance of intermediate products so as to just meet the need for creating the final product. If there were one set of conditions and resources, then there would be one optimal ratio of all of the components necessary to turn those resources into the final product. However, there is often a constantly changing composition of resources and turnover in the machinery or biosynthetic components. In these situations, we need to understand the process of dynamic optimization, which continually adjusts the process toward a better or more optimal ratio of resources and machinery.

Replacement and reinvestment cycles are a crucial part of dynamic optimization. In mechanical systems, machinery can wear out and need to be replaced or the machinery can be removed and replaced. In either situation, management can either decide to increase or decrease the capacity of those particular machines or to shift investment to some other part of the processing. For example, if an automobile factory has too much machinery for making car bumpers, when one machine wears out they can manage toward more optimal balance by not replacing it at all. This same logic drives the algorithms evident in biological systems. If a plant has too much light harvesting membrane and pigment, new growth will have higher investments in carbon fixation enzymes. Some biological systems also have the potential for breaking down current components to molecular building blocks and resynthesizing new components (the Lego model). This extreme version of dynamic optimization is most often found in stress response systems and not used as a matter of normal vegetative growth, simply because there is a high energy cost to breaking down proteins and then resynthesizing the amino acids into new proteins. Continual growth and turnover provide a favorable framework for dynamic adjustments and optimization.

A simple algorithm for optimization depends on tracking the intermediates in the chain of production or biosynthesis. For example, as seen in Figure 11.2, if component A builds up, that means there is too much A being produced. Shifting the investment to favor making more of the machinery for process 2 will help the system catch up by making more B. The reinvestment could be from the profits created by selling the product (C). In biological systems, the production of building blocks will be allocated to biosynthesis of proteins and lipids that make up the machinery of the processes. For example, the balance of photosynthesis between light-harvesting reactions and enzymatic synthesis of fixed, organic carbon molecules are tightly controlled by the build up of the high-energy intermediates (NADPH and ATP) that are created in the light-harvesting reactions. If these are too high, synthesis of new enzymes is stimulated. The details of biosynthesis regulation is much more complicated than this, but this is the underlying logic of the algorithm.

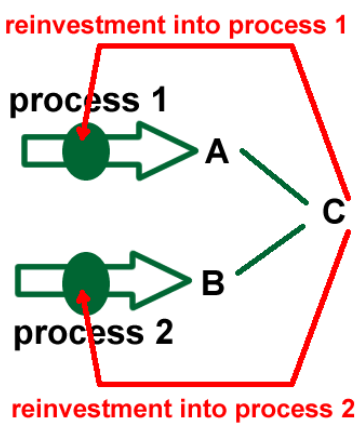

Figure 11-2. Dynamic reinvestment algorithm for a system with two processes.

Dynamic optimization must deal with time lags and threshold responses. Time lags occur between the time a signal is detected until the system can react. Take, for example, a supply chain. By the time the store realizes that it doesn't have enough beer, it's already too late to order more from the distributor who passes orders on to the brewery. This particular example is the key to the famous beer game simulation. If you are playing the part of the retail outlet, you have to predict the demand for beer and order ahead of time in order to smooth out wild oscillations that can occur if you order late, end up with too much beer on hand, and then wait until the supply decreases to order again. In these cycles, the system becomes inefficient due to the wild oscillations in product levels. More complex algorithms are required to manage systems that are susceptible to such oscillations, and some of these algorithms employ multi-scale strategies that smooth out the process over time. These strategies are not strictly optimal at any one point in time, but do very well over longer periods and through fluctuations in conditions. The previous examples show that optimization algorithms are challenged by linear resource regimes and the assumption of linearity is even worse in regimes that contain thresholds. A threshold might be something like a potential dramatic loss of a particular resource. Often it is simple optimization algorithms that drive systems over the thresholds. Complex resource availability or uncertainty requires a shift to resilient strategies rather than strictly optimization.

11.6 Biological metaphors

Biological models are often used as models for efficiency based on the appreciation for the benefits of long-term natural selection in the highly complex natural world. There are three lessons we can learn from this comparison: 1) it is not possible to be strictly optimal for all conditions, i.e. there is no “super organism”, 2) tight coupling in regulation and multiple levels drive biological regulation but come at a significant cost, and 3) extrapolating from biological systems to human management strategies is dangerous because the context is so different. First, in the biological world, “costs” are the losses from being less than fully competitive, and this drives the need for improved efficiency. Individual situations and sets of parameters favor particular efficient solutions, but there is no one solution that is best under all conditions. This is a consequence of the nature of optimization; if there is an optimum (rather than a broad spectrum of conditions that lead to the same output), then changes in the conditions will lead to a sub-optimal condition. For example, this explains why there can’t be a “super algae” that is most competitive at low light and at high light. At low light, the algal cells need more pigments and fewer enzymes, and at high light, the reverse is true. If an algal strain has high pigments and high enzymes, then at low light another strain with fewer enzymes would be more efficient and grow faster. Second, biological systems are tightly controlled through the coupling of processes and embedded regulation. Regulation of biological metabolism is keyed to several global variables as well as the idiosyncrasies of each reaction. For example, enzyme reactions in photosynthesis are dependent on the cell-level availability of the reductant NADPH, the local concentration of the substrates for the reaction (including NADPH again), the ion content of the local solution and the specific location of the enzyme relative to other enzymes. Thus there are at least four levels of control that have differing time and space scales. Another example is the regulation of human body temperature. This is often compared to a thermostat, which is a gross understatement of the complexity of this bodily process. If you are exposed to higher ambient temperature, you respond at five different time and space scales (Table 11.1)– you don’t just turn on and off a heating or cooling mechanism.

Table 11-1: Five overlapping mechanism for the human response to increased heat.

1. Skin flushing with more blood near the skin
2. More blood flow in general
3. Sweating
4. Increased breathing rate, i.e. ventilation
5. Behavior such as fanning yourself or moving to shade

These mechanisms for control are all embedded into the overall physiology of the organism and take energy to maintain. The "goal" of regulation isn't to optimize but rather to survive a broad range of conditions, to live in a smaller range and thrive in a narrower range still. Regulation needs to guarantee survival first, resiliency next and optimization or expansion last. The lesson from biological systems is that there are broad areas of inefficiency that must be tolerated in order to maximize survival either of the individual, population, or species globally. The third lesson from studying biological systems is that we need to be very careful about extracting small bits of the mechanism and generalizing to human processes. I call this "fracturing the metaphor", in which the full context is abandoned to make a point. The most common and pernicious example of this is to extract one aspect of biological evolution, "survival of the fittest", and extend this to social and management activities. An example of a fractured metaphor is how biological evolution is used a metaphor for efficiency, when the metaphor should really be limited to the competition that takes place within the entire process of evolution. Biological evolution is the outcome from three inter-related mechanisms that must work together. These three parts are: 1) competition in which fitness is expressed through more offspring, 2) barriers to over-production such that no one solution will immediately wipe out all potential diversity in the current population, and 3) mechanisms to continually generate new diversity in the population. In animals and plants, mechanism 2 is accomplished by having multiple alleles for each gene in the population, and mechanism 3 results from sexual reproduction (and to a lesser extent mutations) that continually mix and provide new versions of gene combinations. In the "fractured metaphor", the power of natural selection is a loaded onto the fitness function and this is over-extrapolated to be a natural law that should apply to human social and economic systems. Instead, natural selection is much messier and two of the crucial components that make it work are related to sex. You'd think people would be more interested in sex. There is a wealth of knowledge that we can gather by studying the regulation and optimization of relevant biological systems and one of the key points should be to learn how to transpose the understanding of complexity to human systems, not to extract simple snippets that can be dangerously oversimplified.

11.7 Multi-parameter optimization

Optimization of processes that involve multiple parameters is a challenge of seeking efficiency among the tradeoffs. For any particular input, there could be an optimum relative to the other factors but there is no joint optimal point. For example, if we are growing tomatoes in a greenhouse, there could be an optimum output of tomatoes for water relative to the light, a different optimum light level relative to the fertilizer added and a third optimum ratio for fertilizer in relationship to the water. There is no guarantee that there will be a single optimum for water, light and fertilizer. If, as we saw for corn production, everything can be collapsed onto the amount of money you spend for the resources and the profit, then it is easy for the grower to find the best cost-effective solution. However, in similar ecosystem restoration and ecological problems there may be no comparable cost structure for work put in, resources used and output. For example, if restoring a wetland, how does one compare the values of local employment, water quality improvements, bird diversity, fish habitat, and recreation opportunity? Economists are trying to develop methods that will help support these decisions, but these methods are still going to seek tradeoffs, not optimization. We are faced with these sorts of tradeoffs all the time in agriculture and ecosystem restoration. What is the appropriate allocation of water, energy, materials (such as fertilizer), land and labor? Or put another way, what is the distribution of forms of capital between natural capital (water, land), built capital (machinery and infrastructure), human capital (labor and know-how) and the expenses of operation (for example energy)? Industrial, large-scale organic, high-intensity and artisanal farming enterprises all reach different viable mixes of these forms of capital and expenses. Ecosystem restoration and management activities are faced with the same set of choices on inputs but also challenged by a range of possible outputs between social, ecological and economic products. For example, a lake could be restored by installing small wetlands requiring consistent local labor and natural capital, or the lake could be restored by contracting with a large external firm to come in and treat the lake. The choice between these is not clear, and it would be difficult to make a good decision without considering how the project would impact the local community. Optimization, or looking for the most cost-effective solution, may miss the opportunity to bring real benefits to this community.

11.8 Limits to efficiency

Natural limits to the efficiency of any process lead to diminishing returns on effort and investment. If a process has been optimized for the ratio and amount of inputs, it will take increasingly more effort to provide those inputs at higher and higher rates, i.e. each increment of increase in the production requires an even higher increment in the effort to supply the inputs. This is the law of diminishing marginal returns, and it is a crucial consideration in the limits to optimization. A simple example is the spiral of increases that need to take place for a plant to grow faster than its optimum; more light needs to be intercepted, but as the plant gets more leaves, the upper leaves will shade lower leaves. In addition even more leaves will require more water has to be transported, which means more tissues in the stems and the roots to collect and transport the water. Each increment in growth rate requires a more than a linear increase in the supply chain, with increasing inefficiency. Another aspect of diminishing returns is the increased demand for regulation as the process is stressed, which often leads to more complex regulation strategies and higher operating costs. Increasing regulatory costs with industrial expansion has been proposed to be the reason that developed countries have such high levels of government regulations (Adams 1988), and the increase in complexity with the growth of societies has been proposed to be one of the major contributing factors to the collapse of civilizations (Tainter 1988). Thus the decrease in marginal return is not just an academic exercise that pertains to small environmental projects trying to get bigger. There are two important concepts that relate diminishing marginal returns to economic markets. The first is called the "rebound effect" (Hertwich 2005), also know as Jevon's Paradox (http://www.eoearth.org/view/article/155666/). This principle states that increasing the efficiency of any particular component of a process will result in more use of that parameter. For example, making aluminum recycling more efficient led to an increase in the use of aluminum. Similarly, increasing energy efficiency of industrial motors actually increases the use of energy. In both cases, increased efficiency led to that resource becoming cheaper and thus a market force, profitability, overshadows the environmental effort to reduce consumption. There is a similar economic principle that states that profit maximization will be at the point where marginal revenue equals marginal cost. Increasing the efficiency of a component lowers the marginal cost and thus will lead to more production. Both of these related principles illustrate the gap between optimizing a process that in turn reduces environmental impact and optimizing the process in a market-driven situation. The law of diminishing returns often pits market mechanisms against good environmental planning.

11.9 Analysis to improve and optimize efficiency

A straightforward approach to analyzing the efficiency of any process starts by determining the scope and extent of your study that would be included in the life-cycle of the process or product. This is essentially a systems approach. Second, you need to identify all the initial inputs and the final products. This depends on how far back and how far forward you want to go in the production, i.e. which components do you start with and what are the final products? For example if you are studying the life cycle of cars you might want to start from the mines that produce iron and aluminum all the way to the recycling of the cars back to these base-level components. Or if you are studying food, you might be able to assume the final outcome for food will be the same, and you can focus on comparing the starting production. Third, after you have identified all the inputs and outputs, then you need to identify all the internal processes that can be controlled or invested in separately. Again this is an exercise in which you might want to lump or separate processes depending on your intended goal. The forth step is to determine the tradeoff factors for the controlling factors. If this is a strictly economic/market exercise, this means monitorizing all the components into dollars. If this is a socio-ecological project, you will then be faced with a more daunting task of determining relative values for inputs and outcomes. Stating your assumptions on the relative value as objectively as possible is often the only real choice at this step. For example, you might conclude that creating wetlands will, in addition to meeting the goals of the project, create more local jobs but treatment of the lake with an industrial method might lessen the disruption on the local recreation industry. Again, value statements are a key part of our work and the evaluation of relative value claims is best left up to the community, not obscured in the equations of a management model.

11.10 Summary

Efficiency, optimization, progress and growth are inter-related concepts in our industrial society. We need to unpack these concepts, study them and re-apply our knowledge to environmental problems. Biological models and metaphors, when taken in their full messiness, demonstrate that the costs of increased production are often related to more complex and embedded regulation. A systems approach illuminates how the law of diminishing marginal returns is the flip side of optimization, and that there will be increasing costs to pay for any growth past the optimum. In fact, in many cases the optimum for environmental health may be quite below the resource consumption level that would be reached by an efficient profit-seeking market, even if all the externalities are included! This is because of the nature of profits being the integration of the efficiency and costs of all goods produced rather than a point of optimal production. Life cycle analysis that includes the tools from systems and accounting is a valuable approach to all environmental problems.