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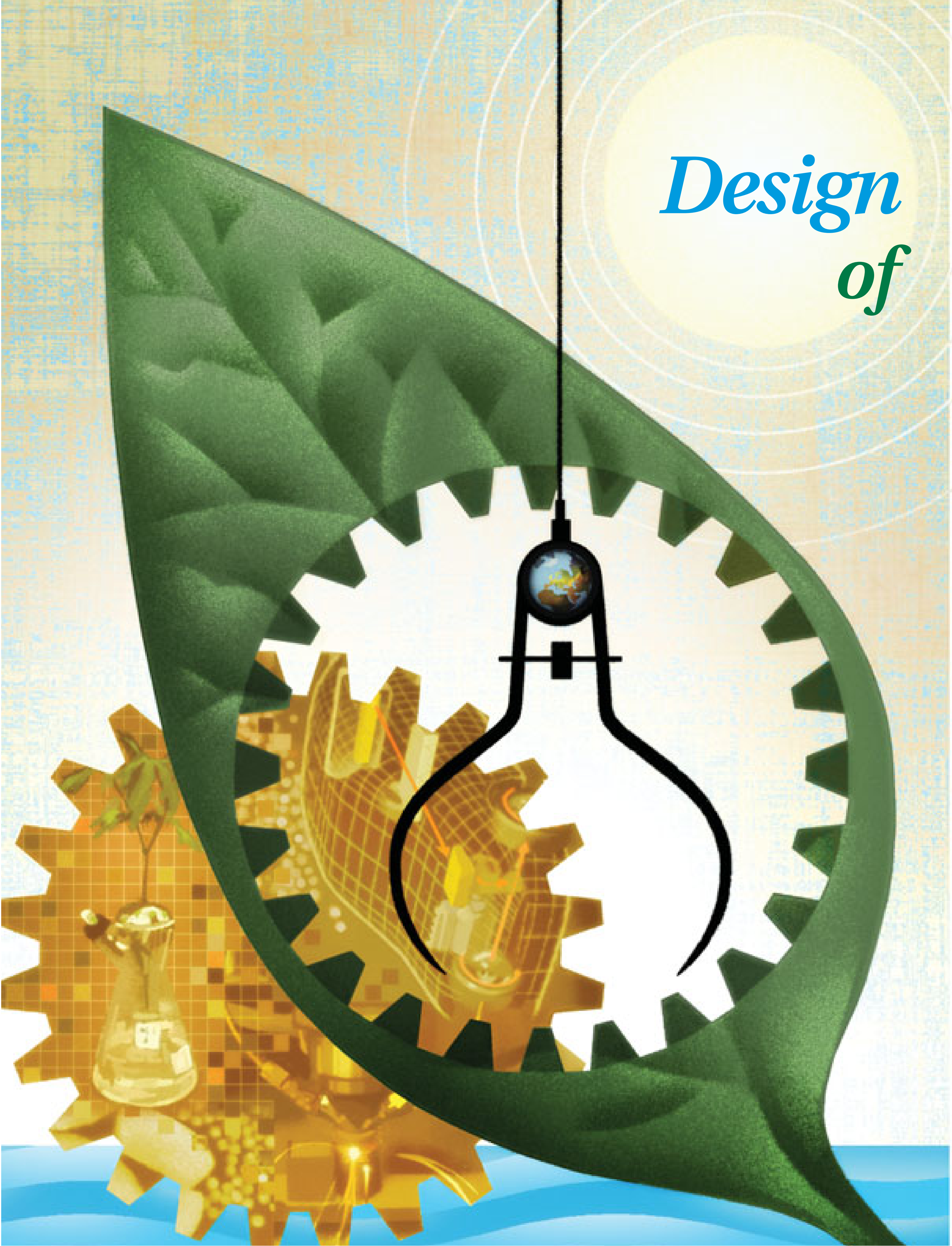

Through *the* 12 Principles GREEN *Engineering*

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Sustainability requires objectives at the molecular, product, process, and system levels.

In recent years, numerous papers, books, and conferences have centered on the subject of lessening the negative human impacts on the planet and on its ability to sustain life (*1–7*). Often, from these discussions, specific goals have emerged, such as minimizing waste, increasing recycling, or approaching sustainability (*8–10*). Goal statements can be very useful in providing a vision of what needs to be achieved, and many of these discussions contribute to important parts of that vision. Yet, goals are only effective when they become reality. Approaches are being developed to achieve these goals across disciplines, industries, and sectors. It is clear, however, that these approaches are currently neither systematic nor comprehensive.

Green engineering (*11*) focuses on how to achieve sustainability through science and technology (*12–14*). The 12 Principles of Green Engineering (see box on the next page) provide a framework for scientists and engineers to engage in when designing new materials, products, processes, and systems that are benign to human health and the environment. A design based on the 12 principles moves beyond baseline engineering quality and safety specifications to consider environmental, economic, and social factors.

The breadth of the principles' applicability is important. When dealing with design architecture—whether it is the molecular architecture required to construct chemical compounds, product architecture to create an automobile, or urban architecture to build a city—the same green engineering principles must be applicable, effective, and appropriate. Otherwise, these would not be principles but simply a list of useful techniques that have been successfully demonstrated under specific conditions. In this article, we illustrate how these principles can be applied across a range of scales.

It is also useful to view the 12 principles as parameters in a complex and integrated system. Just as every parameter in a system cannot be optimized at any one time, especially when they are interdependent, the same is true of these principles. There are cases of synergy in which the successful application of one principle advances one or more of the others. In other cases, a balancing of principles will be re-

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quired to optimize the overall system solution. There are, however, two fundamental concepts that designers should strive to integrate at every opportunity: life cycle considerations and the first principle of green engineering, inherency.

The 12 Principles of Green Engineering

Principle 1: Designers need to strive to ensure that all material and energy inputs and outputs are as inherently nonhazardous as possible.

Principle 2: It is better to prevent waste than to treat or clean up waste after it is formed.

Principle 3: Separation and purification operations should be designed to minimize energy consumption and materials use.

Principle 4: Products, processes, and systems should be designed to maximize mass, energy, space, and time efficiency.

Principle 5: Products, processes, and systems should be "output pulled" rather than "input pushed" through the use of energy and materials.

Principle 6: Embedded entropy and complexity must be viewed as an investment when making design choices on recycle, reuse, or beneficial disposition.

Principle 7: Targeted durability, not immortality, should be a design goal.

Principle 8: Design for unnecessary capacity or capability (e.g., "one size fits all") solutions should be considered a design flaw.

Principle 9: Material diversity in multicomponent products should be minimized to promote disassembly and value retention.

Principle 10: Design of products, processes, and systems must include integration and interconnectivity with available energy and materials flows.

Principle 11: Products, processes, and systems should be designed for performance in a commercial "afterlife".

Principle 12: Material and energy inputs should be renewable rather than depleting.

Life cycle and inherency

The materials and energy that enter each life cycle stage of every product and process have their own life cycle. If a product is environmentally benign but is made using hazardous or nonrenewable substances, the impacts have simply been shifted to another part of the overall life cycle. If, for example, a product or process is energy efficient or even energy generating (e.g., photovoltaics), but the manufacturing process consumes energy to a degree that offsets any energy gains, there is no net sustainability advantage. Accordingly, designers should consider the entire life cycle, including those of the materials and energy inputs.

The life cycles of materials and energy begin with acquisition (e.g., mining, drilling, harvesting) and move throughout manufacturing, distribution, use, and end of life. It is the consideration of all of the impacts that is needed when applying the green engineering principles. This strategy complements the selection of inherently benign inputs that will reduce the environmental impact across life-cycle stages.

Making products, processes, and systems more environmentally benign generally follows one of the two basic approaches: changing the inherent nature of the system or changing the circumstances/conditions of the system. Although inherency may, for example, reduce the intrinsic toxicity of a chemical; a conditional change can include controlling the release of, and exposure to, a toxic chemical.

Inherency is preferable for various reasons, most importantly to preclude "failure". By relying on technological control of system conditions, such as air scrubbers or effluent treatment, there is a potential for failure that can lead to a significant risk to human health and natural systems. However, with an inherently more benign design, regardless of changes in conditions or circumstances, the intrinsic nature of the system cannot fail.

In those cases in which the inherent nature of the system is predefined, it is often necessary to improve that system through changes in circumstances and conditions. Although technological and economic factors may often preclude the adoption of an alternative system design that is more inherently benign, incremental changes in circumstances can have a very significant effect on the overall system. One example is the choice between designing personal transportation in the most environmentally benign and sustainable way versus designing a gasoline-powered sport utility vehicle to be the most sustainable.

The 12 Principles of Green Engineering provide a structure to create and assess the elements of design relevant to maximizing sustainability. Engineers can use these principles as guidelines to help ensure that designs for products, processes, or systems have the fundamental components, conditions, and circumstances necessary to be more sustainable.

The principles

More details about the application of the 12 principles across the four design scales are found in Tables 1–11 in Supporting Information at http://pubs.acs.org/est.

Principle 1: Inherent rather than circumstantial. Although the negative consequences of inherently hazardous substances (whether toxicological, physical, or global) may be minimized, this is accomplished only through a significant investment of time, capital, material, and energy resources. Generally, this is not an economically or environmentally sustainable approach. Designers should evaluate the inherent nature of the selected material and energy inputs to ensure that they are as benign as possible as a first step toward a sustainable product, process, or system. Similarly, molecular designers are developing methods and technologies to create inherently benign material and energy sources (*15–18*).

For cases in which inherently hazardous inputs are selected, the hazard will either be removed in the process, usually during purification or cleanup steps, or incorporated into the final output. Hazards that are eliminated in-process from the final product by optimized operating conditions will require constant monitoring and containment and may also require eventual removal to a permanent off-site storage and disposal facility. Each step requires engineered safety precautions that could fail. What if these hazards are not removed but instead incorporated into the

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final product? Strategies for incorporating hazards into a product or process as long as the hazard is continually recycled and reused do exist, but this approach requires resource expenditure for monitoring and control throughout the hazard's lifetime. Furthermore, these methodologies depend on the transport of these hazards to maintain "closed-loop" cycling, thereby increasing the risk of release through accidents, spills, and leaks. Ideally, inputs to the system will be inherently less hazardous, which significantly reduces the risks of failure and the resources expended on control, monitoring, and containment.

Principle 2: Prevention instead of treatment. Proposals for manufacturing processes or service systems that are "zero-waste" are often criticized as ignoring the laws of thermodynamics and enthalpic considerations. An important point, often overlooked, is that the concept of waste is human. In other words, there is nothing inherent about energy or a substance that makes it a waste. Rather it results from a lack of use that has yet to be imagined or implemented. As such, waste is assigned to material or energy that current processes or systems are unable to effectively exploit for beneficial use. Regardless of its nature, the generation and handling of waste consumes time, effort, and money. Furthermore, hazardous waste demands even greater additional investments for monitoring and control.

Although it may seem obvious that waste generation should be prevented or avoided wherever possible, there are plentiful examples where it is not inadvertently generated; rather, waste generation is thoughtlessly designed into the process. Technologies targeted toward waste-free design at any scale are based on the same fundamental concept: inputs are designed to be a part of the desired output. This concept has been described at the molecular scale as "atom economy" (*18*) and can be extended across design scales as the "material economy".

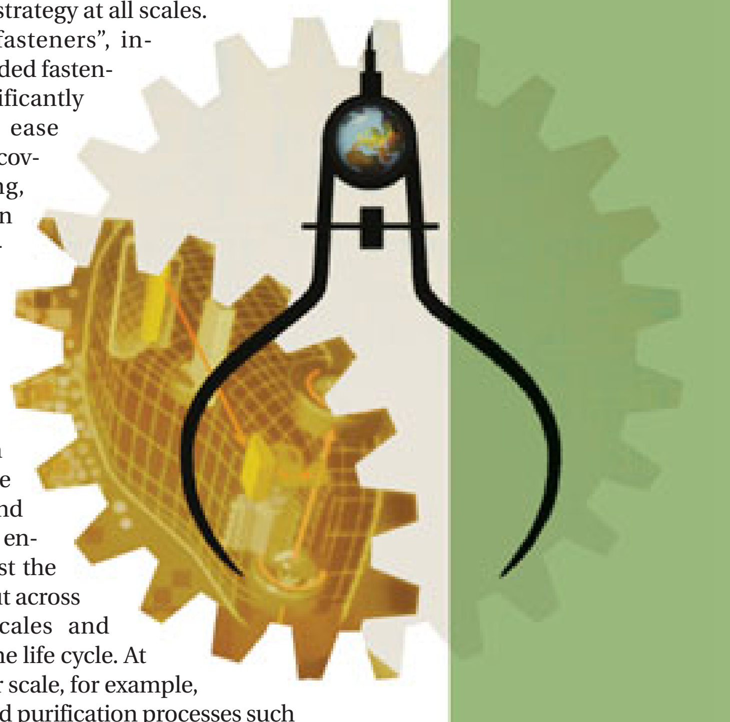
This principle can be illustrated by the design of current power generation systems based on fossil fuels, which inherently produce waste at each life cycle stage. Although waste is also generated during mining and processing, most is produced during use. Burning fossil fuels releases greenhouse gases and particulate matter, which contribute to global climate change and its subsequent impacts (*19*).

However, power generation systems do not have to produce waste, as exemplified by fusion energy. Although still unrealized, fusion energy could move energy systems toward sustainability (*20*). Fusion will eliminate the release of chemical combustion products because fossil fuels are not used. In addition, fusion energy does not form dangerous fission products that are associated with nuclear energy sources. Applying this strategy to energy systems illustrates that products, processes, and other systems can be designed to prevent the production of waste through elemental design considerations.

Principle 3: Design for separation. Product separation and purification consume the most energy and material in many manufacturing processes. Many traditional methods for separations require large amounts of hazardous solvents, whereas others consume large quantities of energy as heat or pressure. Appropriate up-front designs permit the self-separation of products using intrinsic physical/chemical properties, such as solubility and volatility rather than induced conditions, decrease waste and reduce processing times.

A similar design strategy can be applied across scales such that the final product, process, or system is shaped from components with desired properties. This approach minimizes the energy and materials necessary to isolate the desired output from a complicated matrix of undesirable and valueless extraneous matter. Furthermore, the components of the unwanted matrix are often classified as waste, which requires time, money, and resources for handling, transportation, disposal, and possible monitoring.

Additionally, design decisions at the earliest stage can impact the ease of product separation and purification for later reuse and recycling of components. Economic and technical limitations in separating materials and components are among the greatest obstacles to recovery, recycle, and reuse (*21*). These obstacles can be overcome by avoiding permanent bonds between two different materials wherever possible. Fasteners that are designed for disassembly should be incorporated into the basic design strategy at all scales. "Reversible fasteners", including threaded fasteners, can significantly improve the ease of material recovery, recycling, and reuse in cellular telephones to cars.



Up-front consideration for separation and purification avoids the need to expend materials and energy to harvest the desired output across all design scales and throughout the life cycle. At the molecular scale, for example, separation and purification processes such as column chromatography and distillation are often inefficient. Column chromatography can require large quantities of hazardous solvents (*22*), whereas distillation consumes significant amounts of energy, both in terms of cooling and heating requirements.

However, if chemical reaction products can be designed to self-separate from the reaction medium, it would eliminate the need for these additional resources. Polymers, for example, can be used to control the solubility of substrates, ligands, and catalysts for separation and reuse. Up-front consideration for separation and purification avoids the need to expend materials and energy to harvest the desired output across all design scales and throughout the life cycle (*23*).

Principle 4: Maximize mass, energy, space, and time efficiency. Because processes and systems often use more time, space, energy, and material than required, the results could be categorized as "inefficiencies", but the consequences are often broadly distributed throughout the product and process life cycles. If a system is designed, used, or applied at less than maximum efficiency, resources are being wasted throughout the life cycle. The same design tools traditionally used by engineers to increase efficiency can be even more broadly applied to increase intensity. That is, space and time issues can be considered along with the material and energy flow to eliminate waste. Furthermore, in optimized systems there is a need for real-time monitoring to ensure that the system continues to operate at the intended design conditions.

Historically, only a part of the available volume of large batch reactors in chemical manufacturing has been commonly used during the reaction period, often at dilution levels far more than required. Through process intensification techniques, such as microreactors that operate continuously at very low volume with efficient mixing, high productivity can be obtained from small amounts of material (*24*). Similar strategies designed for maximum efficiency and intensity can be applied across the molecular, product and process. Examples of how this applies across the hierarchy of systems scales include spinning-disk reactors replacing batch reactors (*24*), powder coatings instead of paints, digital information rather than printed media, and eco-industrial plants to eliminate urban sprawl.

Principle 5: Output-pulled versus input-pushed. Le Châtelier's principle states that when a stress is applied to a system at equilibrium, the system readjusts to relieve or offset the applied stress. A stress is any imposed factor, such as temperature, pressure, or concentration gradient, which upsets the balance between the forward and reverse transformation rates. For example, increasing the input to a system will cause a stress that is relieved by an increase in output generation. Often a reaction or transformation is "driven" to completion based on this principle by adding more energy or materials to shift the equilibrium and generate the desired output. However, this same effect can be achieved by designing transformations in which outputs are continually minimized or removed from the system, and the transformation is instead "pulled" to completion without the need for excess energy or material.

Approaching design through Le Châtelier's principle, therefore, minimizes the amount of resources consumed to transform inputs into the desired outputs. This is well known at the molecular level in chemical transformations such as condensation reactions in which water is eliminated from the product stream to "pull" the reaction to completion. This same technique, though not necessarily in the traditional context, can be applied across design scales.

For example, manufacturing systems can be based on "just-in-time" manufacturing—goods produced to meet end user demand exactly for timeliness, quality, and quantity. This can be more broadly defined such that the end user can be the final purchaser of the product or another process further along the production line. Just-in-time manufacturing requires that equipment, resources, and labor are only available in the amount required and at the time required to do the job. Only the necessary units are produced in the necessary quantities at the necessary time by bringing production rates exactly in line with demand (*25*).

Planning manufacturing systems for final output eliminates the wastes associated with overproduction, waiting time, processing, inventory, and resource inputs. For example, direct metal deposition produces less final waste than metal casting (*26*).

Principle 6: Conserve complexity. The amount of complexity that is built into a product, whether at the macro, micro, or molecular scale, is usually a function of expenditures of materials, energy, and time. For highly complex, high-entropy substances, it could be counterproductive and sacrifice value (down-cycling) to recycle the material. High complexity should correspond to reuse, whereas substances of minimal complexity are favored for value-conserving recycling, where possible, or beneficial disposition, when necessary. Natural systems should also be recognized as having complexity benefits that should not be needlessly sacrificed in manufacturing transformation or processing.

Silicon computer chips have a significant level of complexity invested in them, and it may not be efficient to recycle a silicon chip in order to recover the value of the starting materials. The complexity of a brown paper bag also may not, however, warrant the time and energy for collection, sorting, processing, remanufacturing, and redistribution as an intact shopping bag. End-of-life design decisions for recycle, reuse, or beneficial disposal should be based on the invested material and energy and subsequent complexity across all design scales.

By targeting durability and not immortality as a design goal, the risk to human and environmental health at end of life is significantly reduced.

Principle 7: Durability rather than immortality. Products that will last well beyond their useful commercial life often result in environmental problems, ranging from solid waste disposal to persistence and bioaccumulation. It is therefore necessary to design substances with a targeted lifetime to avoid immortality of undesirable materials in the environment. However, this strategy must be balanced with the design of products that are durable enough to withstand anticipated operating conditions for the expected lifetime to avoid premature failure and subsequent disposal. Effective and efficient maintenance and repair must also be considered, so that the intended lifetime can be achieved with minimal introduction of additional material and energy throughout the life cycle.

By targeting durability and not immortality as a design goal, the risk to human and environmental health at end of life is significantly reduced. For example, single-use disposable diapers consisting of several materials, including nonbiodegradable polymers, have represented the single largest nonrecyclable fraction of municipal solid waste (*27*). Although this product has a short useful lifetime, it remains a significant environmental problem well beyond its targeted and defined need. One solution is a new starch-based packing material, Eco-fill, which consists of food-grade inputs (starch and water) that can be readily dissolved in domestic/industrial water systems at the product's end of life, and is competitive with traditional polystyrene packing (*28*). By designing durability, but not immortality, into this product, Eco-fill achieves its intended use without long-term environmental burdens.

Another example on the molecular scale is using biologically based polylactic acid to create plastics and fibers instead of petroleum-based polyacrylic acid, which is not biodegradable (*29*).

Principle 8: Meet need, minimize excess. Anticipating the necessary process agility and product flexibility at the design stage is important. However, the material and energy costs for overdesign and unusable capacity or capability can be high. There is also a tendency to design for worst-case scenarios or optimize performance for extreme or unrealistic conditions, which allow the same product or process to be used regardless of local spatial, time, or physical conditions. This requires incorporating and subsequently disposing and treating components whose function will not be realized under most operating conditions.

The tendency to design an eternal, global solution (e.g., chlorofluorocarbons, PCBs) should be minimized to reduce unnecessary resource expenditures. Drinking water disinfection using chlorine is a good example. Water distributed from a centralized location is treated to ensure that the water remains disinfected to the furthest receiving point. However, water at a shorter distance from the drinking water treatment plant in the system will have higher-than-necessary levels of disinfection byproducts because some dissipate with time. An alternative and potentially more sustainable strategy would be to install actuator and control systems throughout the distribution system that regulate the dose of chlorination (*30*). This reduces the environmental and human health burdens of chlorine production and the subsequent release of chlorination byproducts, such as trihalomethanes (*31*).

Although this example does not move toward a nonchlorinated disinfection system, it provides an example of a significant, if incremental, improvement on the current system. This strategy can be applied across design scales to limit the expenditure of underused and unnecessary materials and energy. For example, enzyme catalysts that operate at mild conditions can replace more reactive reagents. Technologies that target the specific needs and demands of end users also offer an alternative to "off the shelf" solutions.

Principle 9: Minimize material diversity. Products as diverse as cars, food packaging, computers, and paint all have multiple components. In an automobile, components are made from various plastics, glasses, and metals. Within individual plastics there are various chemical additives, including thermal stabilizers, plasticizers, dyes, and flame-retardants. This diversity becomes an issue when considering end-of-useful-life decisions, which determines the ease of disassembly for reuse and recycle. Options for final disposition are increased through up-front designs that minimize material diversity yet accomplish the needed functions.

At the process level, this is being done by integrating desired functionality into polymer backbones and thereby avoiding additives at a later stage in the manufacturing process (*32*). Tailoring polymer properties can have a positive environmental effect in cases in which leaching of additives may be an issue and in cases in which ease of recycling is important.

On the product scale, selected automobile designers are reducing the number of plastics by developing different forms of polymers to have new material characteristics that improve ease of disassembly and recyclability. This technology is currently applied to the design of multilayer components, such as door and instrument panels. For example, components can be produced using a single material, such as metallocene polyolefins, that are engineered to have the various and necessary design properties. Through the use of this monomaterial design strategy, it is no longer necessary to disassemble the door or instrument panel for recovery and recycling (*33*).

On the molecular scale, this principle is illustrat-

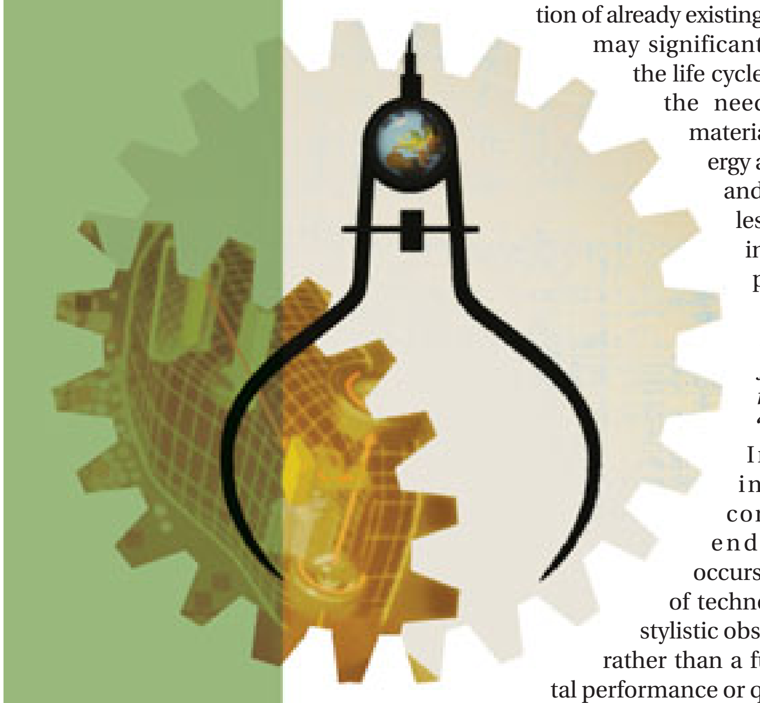
ed with “one-pot” or cascading reactions, or self-assembly processes that replace multistep reactions.

Principle 10: Integrate local material and energy flows. Products, processes, and systems should be designed to use the existing framework of energy and material flows within a unit operation, production line, manufacturing facility, industrial park, or locality. By taking advantage of existing energy and material flows, the need to generate energy and/or acquire and process raw materials is minimized.

At the process scale, this strategy can be used to take the heat generated by exothermic reactions to drive other reactions with high activation energies. Byproducts formed during chemical reactions or through purification steps can become feedstocks in subsequent reactions. Cogeneration energy systems can be used to generate electricity and steam simultaneously to increase efficiency. In this manner, “waste” material and energy can be captured throughout the production line, facility, or industrial park and incorporated into system processes and final products.

This principle is also illustrated by regenerative braking systems in hybrid electric vehicles. In these systems, heat generated by braking that is typically wasted is captured, reversing the electric motor. This turns the motor into an electric generator, creating electricity that is fed back into a battery and stored as energy to propel the vehicle. Integrating the drive train with the regenerative braking system reduces the vehicle’s fuel demands and significantly improves fuel efficiency (*34*).

As this example demonstrates, it is important to consider the availability of energy and material for a product or process. Energy inputs from sources, such as waste heat from adjacent processes or incorporation of already existing materials, may significantly benefit the life cycle, reducing the need for raw materials and energy acquisition and requiring less processing and disposal.



Principle 11: Design for commercial “afterlife”. In many instances, commercial end of life occurs as a result of technological or stylistic obsolescence, rather than a fundamental performance or quality failure. To reduce waste, components that remain functional and valuable can be recovered for reuse and/or reconfiguration. This strategy encourages up-front modular design, which reduces the need for acquiring and processing raw materials by allowing the next-generation designs of products, processes, or systems to be based on recovered components with known properties.

By incorporating commercial “afterlife” into the initial design strategy, rather than as an afterthought at end of life, the value added to molecules, processes, products, and systems could be recovered and reused at their highest value level as functional components. This case is most compelling when end of life is premature and not a fundamental quality failure, as in the case of personal electronics. Cellular telephones, personal digital assistants, and laptop computers are often retired as styles change or technology advances (*35*); however, the physical components are still fully functional and therefore valuable. Designing products with components that can be recovered would significantly reduce end-of-life burdens and manufacture of duplicate components in the next-product generation. For example, approximately 90% of Xerox equipment is designed for remanufacture (*36*). Converting old industrial buildings to housing is an example at the systems scale.

Principle 12: Renewable rather than depleting. The nature of the origin of the materials and energy inputs can be a major influence on the sustainability of products, processes, and systems. Whether a substance or energy source is renewable or depleting can have far-reaching effects. Every unit of finite substance used in a consumptive manner incrementally moves the supply of that substance toward depletion. Certainly, from a definitional standpoint, this is not sustainable. In addition, because virgin substances require repetitive extractive processes, using depleting resources causes ongoing environmental damage.

Renewable resources, however, can be used in cycles in which the damaging processes are not necessary or at least not required as often. Biological materials are often cited as renewables. However, if a waste product from a process can be recovered and used as an alternative feedstock or recyclable input that retains its value, this would certainly be considered renewable from a sustainability standpoint. Examples include recovering biomass feedstocks, treating wastewater with natural ecosystems (*37*), and biobased plastics.

Although it is certainly true that all human processes and actions will have some impact on the environment, minimizing those actions that irreversibly, significantly alter the sustainable supply of a resource can lead to the design of more sustainable products, processes, and systems.

Final points

Innovation in design engineering has resulted in feats ranging from the microchip to space travel. Now, that same innovative tradition must be used to design sustainability into products, processes, and systems in a way that is scalable. By using the 12 Principles of Green Engineering as a framework, the conversation that must take place between designers of molecules, materials, components, products, and complex systems can occur using a common language and a uni-

The principles are a set of methodologies to accomplish the goals of green design and sustainability.

versal method of approach. The principles are not simply a listing of goals, but rather a set of methodologies to accomplish the goals of green design and sustainability.

Because of practical, logistical, economic, inertial, and institutional reasons, it will be necessary in the near term to optimize unsustainable products, processes, and systems that are currently in place. This is an important short-term measure, and the green engineering principles provide a useful framework for accomplishing this optimization. However, through re-engineering of entire systems (e.g., personal transportation systems), greater degrees of freedom with potential benefits for sustainability are obtained, and therefore, the principles become more essential. Ultimately, a redefining of the problem, from the molecular to the systems level, is where fundamental and even inherent sustainability can be achieved. This is where the 12 principles are most powerful.

Although each principle can be demonstrated at each scale, the 12 principles have neither been implemented systematically nor across all scales. Systematic integration of these principles is key toward achieving genuine sustainability in the design of molecules, products, processes, and systems, for the simultaneous benefit of the environment, economy, and society, and the ultimate goal of sustainability.

Acknowledgment

The authors wish to thank numerous engineers and designers around the world for their discussions and contributions, especially Mary Kirchhoff for her invaluable assistance with this paper.

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