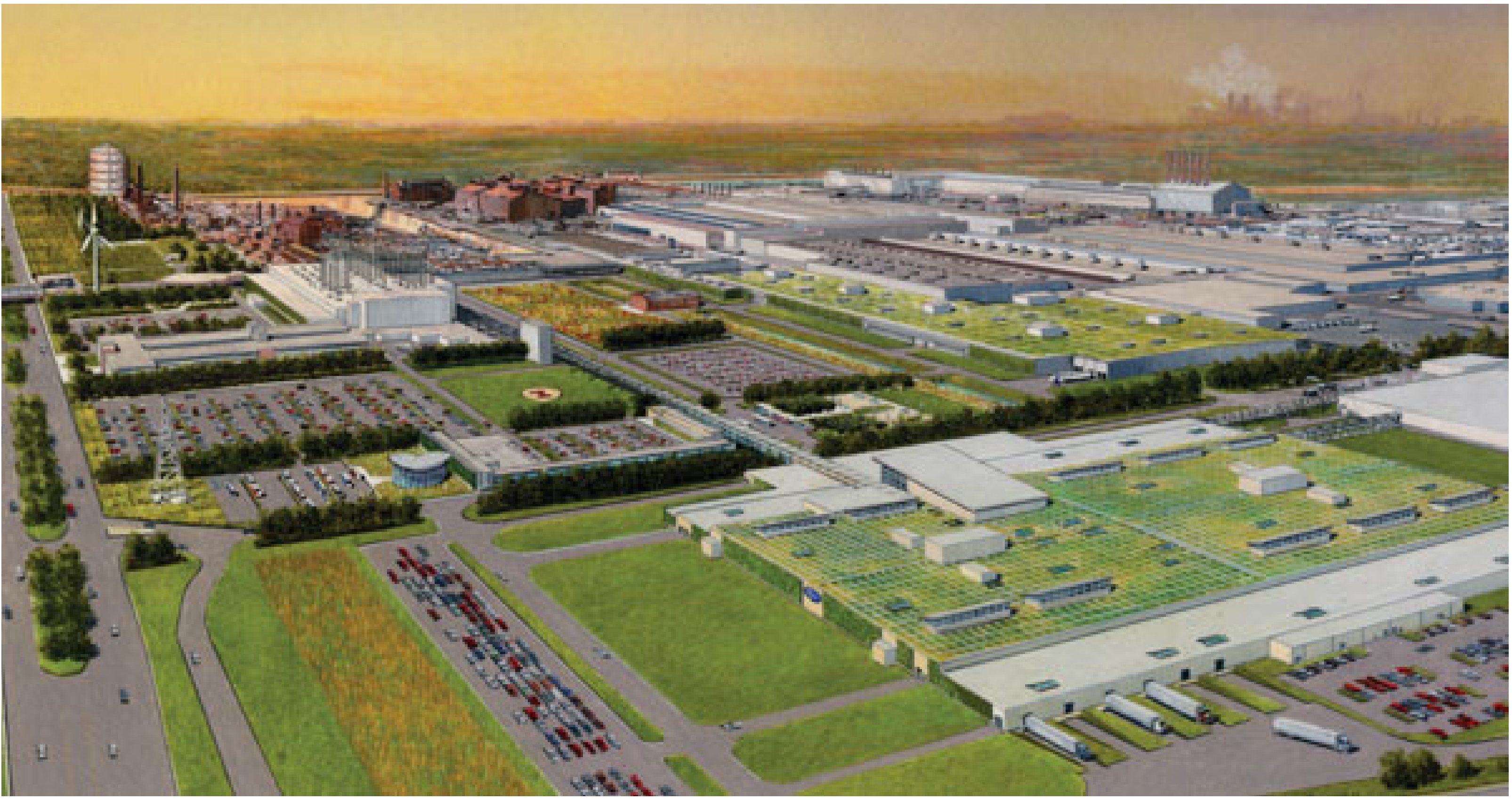
Applying *the* Principles Engineering



Industry is using these tenets and principles to work toward sustainability.

Doing the right things right. It's not as easy as it sounds. Working smart may be easy, but working smart without perspective or guiding principles can ultimately become an efficient pursuit of the wrong goals.

Consider historical approaches to industrial problem solving: Applying engineering strategies to make a wasteful or hazardous process more sustainable might seem like a beneficial course of action—there are many such examples—but is fine-tuning a fundamentally flawed system actually the goal we want to pursue? Conversely, engineers can be headed toward positive ends yet be undermined by tools that will never get them where they want to go. For example, in early approaches to the manufacture of photovoltaic cells, more energy was often consumed in their construction than could ever be recovered over the systems' lifetimes. (It should be noted that advances in recent generation photovoltaics have addressed this issue with some success.)

So what are the right goals? The proper tools? Approaching sustainability from a design perspective demonstrates the need for a fundamental conceptual shift away from current industrial system designs,

# of GREEN to Cradle-to-Cradle Design

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which generate toxic, one-way, "cradle-to-grave" material flows, and toward a "cradle-to-cradle" system powered by renewable energy in which materials flow in safe, regenerative, closed-loop cycles.

The Cradle-to-Cradle Framework (C2C) articulates this conceptual shift (*1*). C2C is a science- and values-based vision of sustainability successfully applied over the past decade that enunciates a positive, long-term goal for engineers. Simply put, C2C designs industrial systems to be commercially productive, socially beneficial, and ecologically intelligent.

The 12 Principles of Green Engineering provide guidance for realizing this vision by suggesting ways that designers and engineers can optimize products, processes, and systems (*2*). Green engineering addresses the key issues at all levels of innovation; however, as Figure 1 illustrates, for a given investment of time, money, or other resources, the greatest returns often come from redefining the problem.

In this article, we provide an overview of the C2C framework, suggest how engineers might apply the 12 Principles of Green Engineering, and describe examples of projects that have put this approach into practice.

Sustainability from the C2C perspective

The C2C framework does not reach for sustainability, as typically defined. In the industrial sector, sustainability is often understood as a strategy of "doing more with less" or "reducing the human footprint" to minimize troubling symptoms of environmental decline (*3–5*). From an engineering perspective, conventional sustainability too often suggests simply retrofitting the machines of industry with incrementally cleaner, more efficient "engines" to secure ongoing economic growth. But this strategy is not an adequate long-term goal. While being eco-efficient may indeed reduce resource consumption and pollution in the short term, it does not address the deep design flaws of contemporary industry. Rather it addresses problems instead of the source, setting goals and using practices that sustain a fundamentally flawed system.

FORD MOTOR CO.

Ford Motor Co. is in the process of applying the cradle-to-cradle approach to the renovation of its River Rouge site in Dearborn, Mich. An artist's rendition of the site (left) includes acres of living roofs, which are composed of plants and other layers (schematic below).

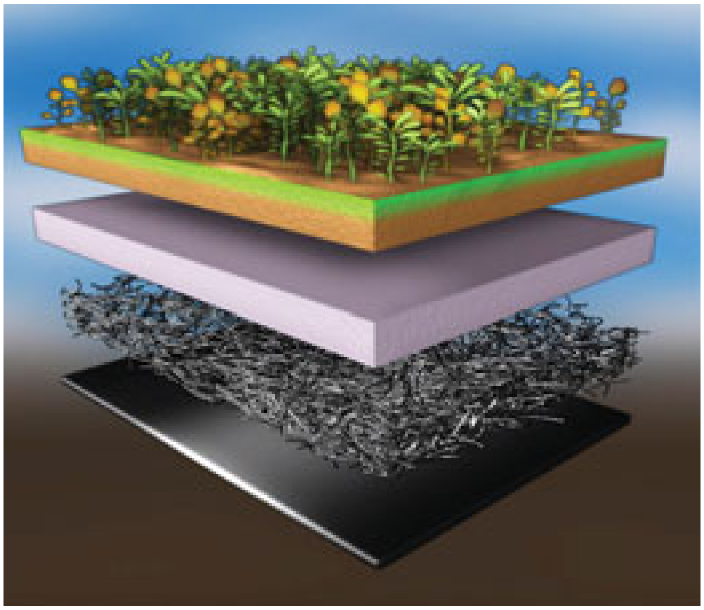
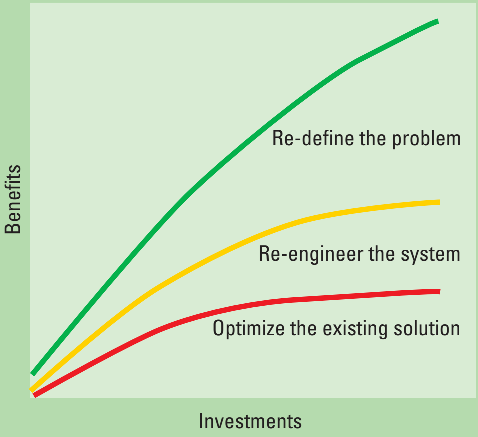


FIGURE 1

Benefit of time, money, and resources for decisions at different levels of design

According to this schematic, the greatest return on investments in design usually comes from re-defining the problem.



The C2C framework, on the other hand, posits a new way of designing human systems to eliminate conflicts between economic growth and environmental health resulting from poor design and market structure. Within this framework, which is based on the manifested rules of nature and redefines the problem at hand, eco-efficient strategies can serve a larger purpose.

Tenets of C2C design

The operating system of the natural world is an unrivaled model for human design. In essence, natural systems largely operate on the virtually limitless energy of the sun. This energy drives the biogeochemistry of the earth to sustain productive, regenerative biological systems. Human systems designed to operate by the same rules can approach the effectiveness of the closed-loop cycling of earth's diverse living systems in which almost no waste remains unused. Therefore, C2C identifies three key tenets in the intelligence of natural systems that can inform human design: waste equals food, use current solar income, and celebrate diversity.

Waste equals food. Waste virtually does not exist in nature because each organism's processes contribute to the health of the whole ecosystem. A fruit tree's blossoms fall to the ground and decompose into food for other living things. Bacteria and fungi feed on the organic waste of both the trees and the animals that eat the fruit, depositing nutrients in the soil. Because of the brilliance and tenacity of the evolutionary timescale, one organism's waste is food for another and nutrients flow indefinitely in cycles of birth, decay, and rebirth. In other words, waste equals food.

Understanding these regenerative systems allows engineers and designers to recognize that all materials can be designed as nutrients that flow through natural or designed metabolisms. Although nature's nutrient cycles comprise the *biological metabolism*, the *technical metabolism* is designed to mirror them; it's a closed-loop system in which benign, valuable, high-tech synthetics and mineral resources circulate in cycles of production, use, recovery, and remanufacture.

Within this framework, designers and engineers can use the principles of green engineering to create and select safe materials (Principle 1) and optimize products, processes, and services in designing closed-loop material flows (Principle 10) that are inherently benign and sustainable. Materials designed as biological nutrients, such as textiles and packaging made from natural fibers, can biodegrade safely and restore depleted soil nutrients. Materials designed as technical nutrients, such as carpet yarns made from synthetics that can be repeatedly depolymerized and repolymerized, are providing high-quality, high-tech ingredients for generation after generation of synthetic products. To achieve these types of improvements, engineers must integrate the parameters of material and energy flows (Principle 10), durability (Principle 7), and disassembly (Principle 3) into all aspects of their design.

Use current solar income. Trees and plants use sunlight to manufacture food. Human energy systems can be nearly as effective. C2C systems—from buildings to manufacturing processes—could directly collect solar energy or tap into passive solar processes, such as daylighting, where natural light can be "piped" into an indoor space. Wind power—thermal flows fueled by sunlight—can also be captured. Engineers using the principles of green engineering can ensure that both energy and material inputs are renewable rather than depleting (Principle 12).

Green engineering is already beginning to change the energy marketplace. For example, the city of Chicago, Ill., has committed to buying 20% of its electricity from renewable sources by 2006, which spurred local development of renewable energy technology. The city recently opened the Chicago Center for Green Technology, an "ecologically intelligent" facility built on a brownfield site, which houses companies that develop local capacity for renewable energy. In addition, the European Union plans to generate 22% of its electricity from renewable sources by 2010.

Celebrate diversity. From a holistic perspective, natural systems thrive on diversity. Healthy ecosystems are complex communities of living things, each of which has developed a unique response to its surroundings that works in concert with those of other organisms to sustain the system. Each organism has its place, and in each system, the fittest—or most adaptable—thrive. However, we need a long-term per-

The 3 Tenets of Cradle to Cradle

Tenet 1	Waste equals food
Tenet 2	Use current solar income
Tenet 3	Celebrate diversity

spective—introducing an invasive species enhances diversity now, but it can destroy that diversity over time.

Nature's diversity provides many models for humans to imitate. When designers celebrate diversity, they tailor designs to maximize their positive effects on the particular niche in which they will be implemented. Engineers might profit from this principle by considering the maxim "All sustainability is local." In other words, optimal sustainable design solutions draw information from and ultimately "fit" within local natural systems. These solutions express an understanding of ecological relationships and, where possible, enhance the local landscape.

Those practicing green engineering draw on local and available energy and material flows to enhance integration and interconnectivity (Principle 10) and take into account both the distant effects of local actions and the local effects of distant actions. Instead of one-size-fits-all solutions (Principle 8), designs that celebrate and support diversity and locality grow more effective and sustaining as they engage natural systems. When a process is designed for a specific locality, materials and energy are expended as needed; this approach is better than building for the worst-case scenario, which would require materials and energy that may never be needed.

One example is the office complex for the clothes manufacturer Gap, Inc., in San Bruno, Calif. The building was designed with an undulating roof blanketed in soil, flowers, and grasses that mirror the local terrain. This approach reestablished several acres of the coastal savannah ecosystem that was destroyed. Because the living roof also effectively absorbs storm water and provides thermal insulation, the landscape is an integral part of the building's energy systems.

In addition, a raised-floor cooling system allows evening breezes to flush warmth from the building while concrete slabs beneath the floor provide a cooling effect during the day. Windows open, and the delivery of fresh air is individually controlled; daylighting provides natural illumination. In short, by modeling human designs on nature's operating system—generating materials that are "food" for biological or industrial systems, using solar energy, and celebrating diversity—C2C design creates a new paradigm for industry in which human activity generates a wide spectrum of ecological, social, and economic value.

Incorporating principles of green engineering

Although the C2C vision sets a course for "What do I do?" the 12 Principles of Green Engineering answer, "How do I do it?" Figure 1 shows the principles as a toolbox that can be used systematically to optimize a system or its components. This approach builds on the technical excellence, scientific rigor, and systems thinking that have addressed the issue of science and technology for sustainability and sustainable development in recent years (*6–21*). In any complex multiparameter system, engineers will need to contextually understand when to balance one principle, or a collection of principles, with another. Understanding may not be obvious or transparent, and often questions must be asked that are relevant locally and across a life cycle.

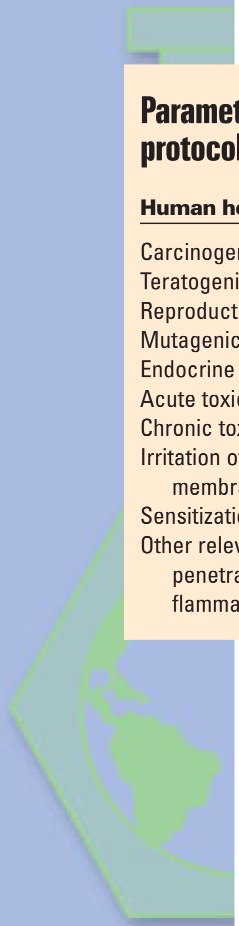
Applied thoughtfully, however, these principles can turn vision into reality. Consider Principle 1: "Designers need to strive to ensure that all material and energy inputs and outputs are as inherently nonhazardous as possible." From a C2C perspective, human systems approach optimal effectiveness when inputs and outputs are as safe and beneficial as those in the closed-loop cycles of natural systems. With this in mind, engineers who design products and systems must begin the process by analyzing the chemistry of materials to determine which are inherently safe and which should be avoided. A material should not only be nonhazardous but also provide nourishment for something after its useful life—either "food" for biological systems or high-quality materials for subsequent generations of high-tech products (Principle 11).

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.

Principle 2 complements this approach and follows from the "waste equals food" aspect of nature's design. Principle 2 says: "It is better to prevent waste than to treat or clean up waste after it is formed." By designing safe, healthful materials that can flow in closed-loop systems, designers and engineers are eliminating waste by putting filters in the heads instead of on the ends of pipes. That is, rather than managing the costly or potential liabilities of flawed designs, designers conceive products and materials that add value at every step of their life cycle. Engineers who strive to meet Principle 2 lay the groundwork for systems in which all the materials produced in the process have a value-added application.

Managing waste is a limited goal. And each green engineering principle, in its own way, offers engineers a way to go further—to move away from managing liabilities and hazards and toward designing effective and ecologically intelligent materials, products, and systems. The brief case studies that follow show some of the ways in which designers and engineers have already begun to apply the principles in developing models for industry that embody the C2C vision of sustainability.



Parameters for MBDC's materials assessment protocol

Human health criteria

Carcinogenicity
Teratogenicity
Reproductive toxicity
Mutagenicity
Endocrine disruption
Acute toxicity
Chronic toxicity
Irritation of skin/mucous membranes
Sensitization
Other relevant data (e.g., skin penetration potential, flammability, etc.)

Ecological health criteria

Algae toxicity
Bioaccumulation
Climatic relevance
Content of halogenated organic compounds
Daphnia toxicity
Fish toxicity
Heavy metal content
Persistence/biodegradation
Other (water danger list, toxicity to soil organisms, etc.)

Designing biological and technical nutrients

Biological nutrients. By 1993, the Swiss firm Rohner and the U.S.-based textile design company DesignTex had already developed a textile that is a biological nutrient. The product was so benign that natural systems could assimilate it without any toxicological concerns (*22*). These fabric designers worked with the chemical company CibaGeigy to select only the most inherently benign chemicals and materials to finish and dye natural fabrics (Principle 1). The team eliminated from consideration chemicals that contain any form of mutagen, carcinogen, heavy metal, endocrine disrupter, or bioaccumulative substance. In the end, they identified 38 chemicals suitable for a material destined to "feed" soil and produce a textile meeting all their quality standards, an imperative consideration when designing green products and processes.

The mill chosen to produce the fabric initially faced an interesting problem. Although the mill's director had been diligent about reducing levels of dangerous emissions, government regulators had recently defined the fabric trimmings as hazardous waste. In stark contrast, the trimmings of the new biological nutrient fabric serve as mulch for the local garden club, which eliminates the need to treat and handle a hazardous waste (Principle 2).

This example of C2C design benefits from many of the tools that the green engineering principles supply. By following Principle 1, engineers choose the most suitable available chemicals, and molecular designers strive to make new chemicals that have environmental and health benefits built in. Rohner and DesignTex recognized the need for Principles 1 and 2, whereas CibaGeigy embraced Principles 7 and 11.

Technical nutrients. In this issue of *ES&T* (pp 5269–5277), Bradfield et al. describe how Shaw Carpet gained significant, quantifiable benefits by adopting a C2C strategy. Shaw scientifically assessed the chemistry of its face fibers and backing using McDonough Braungart Design Chemistry's (MBDC) materials assessment protocol outlined in the box (see "Parameters for MBDC's Materials Assessment Protocol" at left) and Figure 2. Everything that goes into carpet—from dyes and pigments to finishes—was examined. Each ingredient selected met the specific environmental health parameters of the protocol. The result is a fully optimized carpet tile—a completely safe technical nutrient that cycles in closed loops. In recognition of its work, Shaw earned the 1999 Georgia Governor's Pollution Prevention Award and the 2003 Presidential Green Chemistry Challenge Award (*23*).

In designing a carpet, there are two primary elements to consider: a face fiber and a backing. Shaw's face fiber is made from nylon 6, which easily depolymerizes into its monomer, caprolactam, and repolymerizes repeatedly to make high-quality carpet fiber. The main competing face fiber, nylon-6, 6, cannot be depolymerized effectively for recycling (*24*).

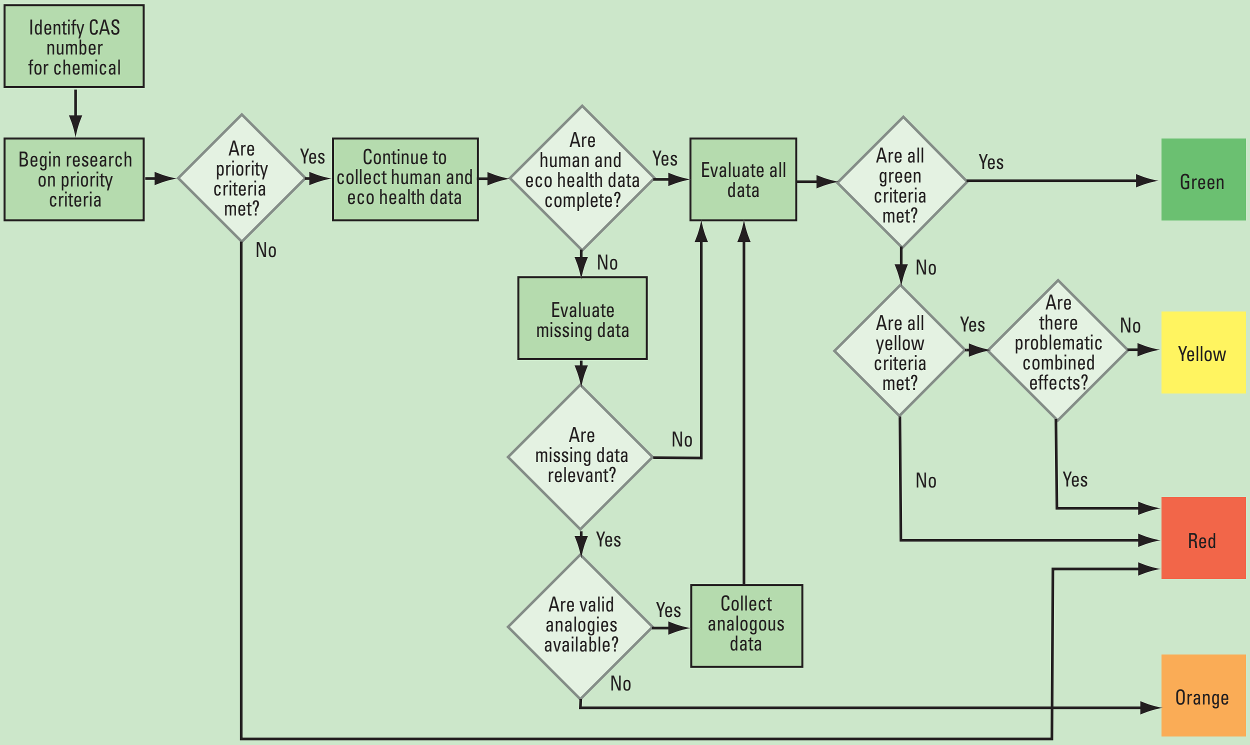
Polyvinyl chloride (PVC) has been the dominant component of carpet backing for 30 years. PVC is a cheap, durable material widely used in building construction and various consumer products, including toys, apparel, and sporting goods. The vinyl chloride monomer used to make PVC is a chemical of concern due to its potential carcinogenicity, and incineration of PVC has been reported to result in dioxin emissions (*25*). There are also issues about the health effects of many additives commonly used in PVC (*26*). Responding to widespread scientific, consumer, and public concern, Shaw developed a polyolefin-based backing system with all the performance benefits of PVC. Polyolefins have been shown to be inherently safe throughout their life cycle (*27*). Furthermore, Shaw guarantees it will take back this new carpet tile and recycle it into new backing.

The material that goes into the Shaw carpet will continually circulate in technical nutrient cycles. The impact of this new design will be very significant. Every year, hundreds of millions of pounds of face fiber and backing are sent to landfills, incinerated, or recycled into products of lesser value. From a green engineering perspective, the Shaw carpet de-

FIGURE 2

Preliminary chemical assessment steps from MBDC's materials assessment protocol

This flow chart describes how each chemical in a process is evaluated. A green rating indicates that a chemical presents little or no risk and is acceptable for the desired application. A yellow rating indicates low to moderate risk, and this chemical can be used acceptably until a green alternative is found. An orange rating means that the chemical is not necessarily high risk, but a lack of information prevents a complete assessment. A red rating means high risk. Chemicals with a red rating include all known or suspected carcinogens, endocrine disrupters, mutagens, reproductive toxins, teratogens, and chemicals that do not meet other human health or environmental relevance criteria.



sign recognized material flows (Principle 10). The product development process illustrated how "complexity viewed as an investment" (Principle 6) can be put into practice. By designing up front for commercial after-life (Principle 11), the team prevented waste (Principle 2) and engineered the separation and purification processes, in this case depolymerization, to be less material- and energy-consumptive (Principle 3).

A materials assessment protocol

MBDC's analytical assessment protocol for materials is applicable to a wide range of industries. The apparel and footwear manufacturer Nike used the protocol to determine the chemical composition and environmental effects of the materials used to produce its line of athletic shoes (*28*). Focusing primarily on Nike's global footwear operations, teams collected samples of rubber, leather, nylon, polyester, and foams and information on their chemical formulations during factory visits in China.

Materials that meet or exceed the company's emerging criteria for sustainable design are added to a "Positive List", a growing palette of materials that Nike will increasingly use in its products. These ingredients can be safely metabolized naturally at the end of a product's useful life (Principles 1 and 11) or repeatedly recovered and reused for new products (Principles 10 and 12).

Nike's systematic effort to develop a positive materials palette has produced tangible results, such as the phasing out of PVC in 2002 from footwear and non-screenprint apparel. That same year, Nike highlighted two of its PVC-free products, Keystone Cleats and Swoosh Slides, as a way to begin a dialogue with consumers about its PVC-free commitment.

Companies like Nike can drive green engineering even further by requiring their feedstock suppliers to meet specific environmental and health criteria. By implementing Principle 1, influential companies can push vendors to design next-generation materials to be intrinsically less hazardous and more sustainable. These new materials can also eliminate the need for other additive substances and accomplish Principle 9 by allowing easier disassembly and value retention.

Integrating design strategies

The U.S. furniture company Herman Miller has gone a long way toward integrating C2C principles into its product development process. In 1995, Herman

Herman Miller design for environment assessment criteria

Human health and eco-toxicological assessment

No problems identified or expected, or extremely low risk.
Low to moderate risk.
Lacking sufficient data to make a determination.
Severe problems or high risks identified or expected.

Human criteria

Carcinogenicity
Disruption of endocrine system
Mutagenicity
Reproductive toxicity
Teratogenicity
Acute toxicity
Irritation of skin/mucous membranes
Chronic toxicity
Sensitization
Others (e.g., carrier function, skin penetration potential)

Ecological criteria

Fish toxicity
Daphnia toxicity
Algae toxicity
Toxicity to soil organisms
Persistence/biodegradation

Bioaccumulation

Content of halogenated organic compounds
Heavy metal content
Climatic relevance/ozone depletion potential

Recyclability

Material is a technical or biological nutrient, and a commercial infrastructure exists.
Material can be down-cycled, and a commercial infrastructure exists.
Material can be incinerated for energy recovery.
Material is normally landfilled.

Recycled/renewable content

Percentage of total product weight
Post-industrial recycled content
Post-consumer recycled content
Renewable content

Disassembly

Can the component be separated with no dissimilar materials attached?
Can common disassembly tools be used (pry-bar, hammer, drivers, utility knife, pliers)?
Can one person disassemble the component in 30 seconds or less?
Can the material type be identified through markings, magnets, and so on?

Miller formed an interdisciplinary Design for Environment (DFE) team that implements materials assessments on the basis of the MBDC protocol, extends design goals throughout the company, measures environmental performance, and engages its supply chain in implementing design criteria (*29*). Herman Miller's DFE team built a chemical and materials assessment methodology for the firm's designers and engineers (see "Herman Miller design for environment assessment criteria" above). The team's multifaceted assessment, which is used throughout the design process, emphasizes Principles 1, 2, 3, 10, 11, and 12.

The DFE team includes a chemical engineer, who incorporates findings from assessments into an evolving materials database, and a purchasing agent, who acts as a data source and conduit between the supply chain and Herman Miller's purchasing team. This strategy engages both groups as partners in implementing new design criteria, thereby ensuring the consistent procurement of safe materials (Principle 1). As one Herman Miller engineer said, "Getting a handle on supply chain issues from an environmental standpoint has also helped us get a handle on the organization and prioritization of materials." For example, Herman Miller now performs materials flow analyses on the new database, which provides figures the company did not previously track.

Sustainable manufacturing facilities

Sustainability principles can also help restore industrial landscapes, which Ford Motor Co. is doing at its historic Rouge River manufacturing complex in Dearborn, Mich. (*29*). Ford opted for a C2C approach—a manufacturing facility that would connect employees to their surroundings, create a habitat, make oxygen, restore the landscape, and invite the return of native species. The result is an automotive assembly plant with a 10-acre green roof (450,000 square feet) that, in concert with porous paving and a series of constructed wetlands and swales, cost-effectively filters storm water runoff, which is typically managed with expensive technical controls. The living roof effectively filters storm water runoff for $35 million less than a traditional system would cost to meet regulations. The roof and the swales also create on-site habitats for native birds, butterflies, insects, and microorganisms, which generate a larger biological order and encourage diversity.

Phytoremediation, the process of using plants to absorb or neutralize toxins in the soil, is also used at the Rouge site (*30*, *31*). Ford has cultivated 20 native plants and is monitoring how well each breaks down polycyclic aromatic hydrocarbons, a prevalent on-site toxin. So far, big bluestem and green ash seem to be the most effective. More of these plants have been planted in phytoremediation gardens along Rouge's main thoroughfare. Researchers systematically test which plants most effectively absorb toxins and look for plants that can trap heavy metals and other compounds. Rather than introduce synthetic materials or machinery, engineers use the natural systems material and energy to effectively remediate the site. With this work, Rouge River has implemented Principles 10 and 12.

Remaking an industry

Transforming a wide range of mobility transportation systems is a key objective on the path to sustainability. Given that long-range projections estimate that global vehicle registrations could reach 2 billion during the second half of this century, this industry seems like a good place to start.

Building a truly sustainable automobile industry means developing closed-loop systems for manufacturing and reusing auto parts. In Europe, the End-of-Life Vehicle Directive, which is legislation enacted by the European Union that makes manufacturers responsible for automotive materials, encourages companies to consider green engineering approaches, such as Principles 3 and 12. Systems are being built for effective resource recovery and conservation. In such systems, every car component is returned to the soil or recovered and reused in the assembly of new cars; this approach also generates extraordinary productivity and consistent employment.

For example, Ford has developed the Model U, the world's first automobile designed to explore the concept of inherently safe C2C materials. The Model U includes Milliken and Co. polyester upholstery fabric. This is a technical nutrient made from chemicals chosen because they are inherently safer and are capable of cycling in closed-loop systems (Principles 2, 3, 10, and 11). The car top is made from a potential biological nutrient, the corn-based biopolymer polylactic acid produced by Cargill Dow, which can be composted after use (Principles 2, 11, and 12).

This first step lays the foundation for a clear, long-term vision in which consumers see automobiles as products of service. In this scheme, customers buy the service of mobility for a defined use period, not the car itself. This strategy for design of next-generation automobiles incorporates Principles 1, 2, 3, 10, and 11.

The foundation of sustainability

Engineers across a wide spectrum of industry are already providing the foundation for green manufacturing. Throughout this special issue of *ES&T* are examples that illustrate various approaches to sustainability. When considered through the lens of the principles of green engineering, we can see them as steps toward a fundamental shift in the industrial framework.

From a C2C perspective, green engineering represents a practical approach to the transformation of industry. Applying the 12 Principles of Green Engineering to C2C can help achieve the long-term goal of designing a commercially productive, socially beneficial, and ecologically intelligent industrial system. The combination provides a useful framework for doing the right things right.

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References

(1) McDonough, W.; Braungart, M. *Cradle to Cradle: Remaking the Way We Make Things*; North Point Press: New York, 2002.
(2) Anastas, P.; Zimmerman, J. *Environ. Sci. Technol.* **2003**, *37*, 94A–101A.
(3) The World Commission on Environment and Development. *Our Common Future*; Oxford University Press: New York, 1987.
(4) National Research Council Board on Sustainable Development. *Our Common Journey: A Transition Toward Sustainability*; National Academy Press: Washington, DC, 2000.
(5) Kates, W. K.; et al. *Science* **2001**, *292*, 641.
(6) Anastas, P.; Warner, J. *Green Chemistry: Theory and Practice*; Oxford University Press: London, 1998.
(7) Benyus, J. M. *Biomimicry: Innovation Inspired by Nature*; William Morrow: New York, 1997.
(8) Bishop, P. *Pollution Prevention: Fundamentals and Practice*; McGraw-Hill: New York, 1997.
(9) U.S. Congress. *Green Products by Design: Choices for a Cleaner Environment*; Office of Technology Assessment, Document OTA-E-541, 1992.
(10) Desimone, L. D.; Popoff, F. *Eco-Efficiency: The Business Link to Sustainable Development*; MIT Press: Boston, MA, 1997.
(11) Dodds, F. *Earth Summit 2002: A New Deal*; Earthscan Publications, Ltd.: London, 1997.
(12) Ehrenfeld, J. *J. Cleaner Prod.* **1997**, *5* (1–2), 87–95.
(13) *Design for Environment: Creating Eco-Efficient Products and Processes*; Fiskel, J. Ed.; McGraw-Hill: New York, 1998.
(14) Graedel, T. E.; Allenby, B. R. *Industrial Ecology*, 2nd ed.; Prentice Hall: Englewood Cliffs, NJ, 2002.
(15) Graedel, T. E.; Allenby, B. R. *Design for Environment*; Pearson Education POD, 1997.
(16) Keoleian, G. A. Pollution Prevention through Life-Cycle Design. In *Industrial Pollution Prevention Handbook*; Freeman, H. M., Ed.; McGraw-Hill: New York, 1994; pp 253–292.
(17) Panjabi, R. K. L.; Campeau, A. H. *The Earth Summit at Rio: Politics, Economics, and the Environment*; Northeastern University Press: Boston, MA, 1997.
(18) Rees, W. E.; Testemale, P.; Wackernagel, M. *Our Ecological Footprint: Reducing Human Impact on the Earth*; New Society Publisher: British Columbia, Canada, 1995.
(19) United Nations Environment Program. *Global Environmental Outlook 2000*; Earthscan Publications Ltd.: London, 2002.
(20) Allen, D. T.; Shonnard, D. R. *Green Engineering: Environmentally Conscious Design of Chemical Processes*; Prentice Hall: New York, 2001.
(21) Anastas, P.; Heine, L.; Williamson, T. *Green Engineering*; American Chemical Society: Washington, DC, 2000.
(22) Kaelin, A. The Development of Climatex Lifecycle. In *Sustainable Solutions*; Charter, M., Tischner, U., Eds.; Greenleaf Publishing: Sheffield, U.K., 2001; pp 393–401.
(23) Ritter, S. *Chem. Eng. News* **2003**, *81* (26), 30–35.
(24) Mihut, C.; et al. Review: Recycling of Nylon from Carpet Waste. *Polym. Eng. Sci.* **2001**, *41* (9), 1457–1470.
(25) Yasuhara, A.; et al. *Environ. Sci. Technol*. **2001**, *35*, 1373–1378.
(26) Ertl, J.; Ottlinger, R. *Kunstst. Plast Europe* **2001**, *91* (10), 87–88, 244–246.
(27) Scott, G. *Polym. Degrad. Stab.* **2000**, *68* (1), 1–7.
(28) Nike Corporate Responsibility Report, 2001, www.nike.com/nikebiz/gc/r/pdf/environment.pdf.
(29) Ford Motor Co., Rouge Renovation, www.ford.com/en/goodWorks/environment/cleanerManufacturing/rougeRenovation.htm.
(30) Bizily, S. J.; Rugh, C. L.; Meagher, R. B. *Nat. Biotechnol.* **2000**, *18*, 213–217.
(31) Rugh, C. L. Design and Construction of Phytoremediation Demonstration Facility, Poster Presentation for Society for Environmental Journalism Annual Meeting, Oct 2000, www.css.msu.edu/phytoremediation/poster2000.html.