Save more, pay less

Imran Sheikh and **Amory Lovins** chart the next industrial revolution and hope to transform engineering education on the way

THE converging problems of climate change, energy security, and degradation of ecological systems largely result from the increased throughput conversion of natural resources into waste that occurred after the first industrial revolution. The higher throughput provided more people with greater affluence, but it also had a heavy environmental impact. Impact is a function of population, affluence, and technology, and since no one can peacefully or equitably reduce population or affluence, technology is the key. Engineers are gifted problem solvers, and it will be their responsibility and privilege to develop technology that minimises the impact of a growing, more affluent population. To develop such technologies and avoid unintended consequences, engineers will need a new whole-system mindset. The first step in the next industrial revolution is teaching engineers how to think integratively about design.

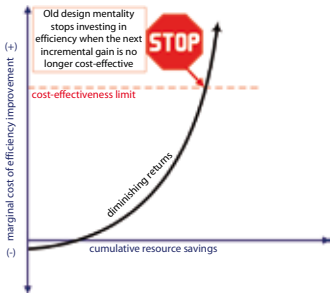
Engineers have been eliminating waste for centuries. One of the greatest was Taiichi Ohno, father of the Toyota Production System, who sought to eliminate any form of "muda", or "human activity that absorbs resources but creates no value." Eliminating muda is not only resource-efficient, but also economically efficient. Getting to the goal of perfection, where no waste remains, is a better target than being simply as efficient as your competitors. Achieving no muda requires fundamental changes in how we think about design.

Typical economic thinking leads you to believe that the more resources you save, the more the next increment of savings costs. Yet this theory of diminishing returns holds only if each additional increment is achieved in the same way as the last, and in a manner that has no other benefits. The theory ceases to be relevant when the design looks at the system as a whole. Whole-system engineering – optimising an entire system for multiple benefits, not isolated components for single benefits – can often "tunnel through the cost barrier." As a result, very large, even order-of-magnitude, savings can cost *less* than small or no savings, by capturing the interactive effects between components.

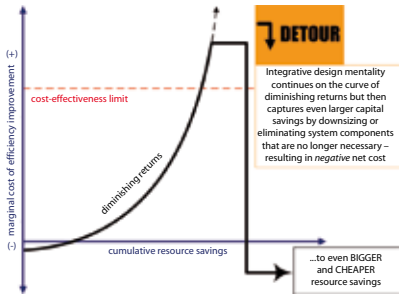
Rocky Mountain Institute's (RMI, www.rmi.org) headquarters, built in 1984, illustrate tunnelling through the cost barrier. Piecemeal design traditionally optimises a building's thermal insulation against avoided heating-energy costs – but ignores the avoidable *capital cost of the heating equipment*. RMI eliminated that equipment in a climate that can get as cold as –44 °C, whilst reducing total capital cost by around $1100: superinsulation, superwindows, and air-to-air heat exchangers cost less up front than the furnace, ducts, fans, pipes, pumps, controls, wires, and fuel-supply apparatus they displaced. Other new buildings have similarly eliminated cooling equipment, maintained comfort, and cut capital cost in climates of up to +46 °C.

Looking at problems with expanded system boundaries makes such efficient design possible. In the building example above, the design goal was to create a comfortable energy-efficient space, rather than designing an efficient heating, ventilation, and air conditioning system. Taking this approach made it possible to identify discontinuities in the cost curve, where efficiency investments in one area create even greater capital savings elsewhere – for example, more costly superwindows can downsize or eliminate heating equipment. Taking a broader view of a problem makes previously uncontrollable variables controllable, and optimising the building for multiple benefits, not just its isolated components for single benefits, yields big savings at lower cost than small savings.

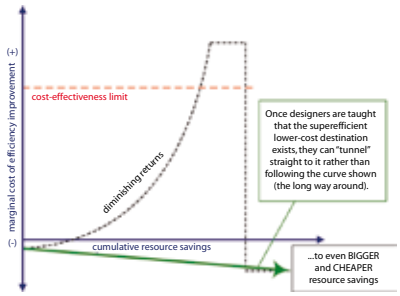
RMI explored the vast potential for such whole-system design in *Natural capitalism* (1999, www.natcap.org). Since then, RMI's engineers have helped firms in 29 sectors redesign more than $30b worth of diverse facilities. In retrofit cases, RMI typically finds energy savings around 30–60% that repay the incremental cost of efficient design in a few years. New-facility savings often reach 40–90%, typically with *lower* capital cost.



Old design mentality



Integrated design mentality



Tunnelling through the cost barrier

Such radical savings would not be possible if the facilities had been properly designed in the first place, so the root problem is in engineering education. Traditional engineering curricula do an excellent job at teaching students to analyse and design components, but unfortunately students seldom learn how to synthesise whole systems. Today, and even more so in the future, a new breed of engineer is needed who can think across disciplines and consider the complex technical, economic, environmental, and social interconnections within their designs.

RMI aims to create this new breed by speeding the reform of engineering pedagogy through an initiative entitled

"Factor Ten Engineering", or 10xE (www.10xE.org). 10xE aims to demonstrate how current and future engineers can gain an order of magnitude more work, productivity, and value from each unit of resources. A tenfold resource productivity gain is a bold, challenging, yet feasible goal. It will require original, trans-disciplinary thinking and a willingness to question familiar practices. With the help of leading engineering practitioners and teachers worldwide, RMI aims to develop a casebook and associated instructional methods to bring integrative design education into the mainstream.

Over the course of an intensive two-week summer study, an outstanding group of diverse, credible, and creative engineering practitioners and teachers will write the casebook collaboratively. The draft casebook's diverse cases are now being collected, seeking the clearest, highest "brain-velcro" examples. We welcome your cases, contacts, and ideas.

The book will include a thorough engineering analysis of several dozen of the most interesting cases, organised in facing columns alongside standard-practice versions to contrast whole-system with dis-integrated design methods and results. Our aim is to have the design principles build on each other to rearrange irreversibly the readers' "mental furniture" so they can never go back to piecemeal design (at least without wincing). Whole-system solutions are of course situation-specific, but we aim to elucidate the common threads of efficient design. The cases will span the range of engineering disciplines and common applications, so that all engineers will find at least a few cases that they can directly relate to. Through astonishing but, once understood, obvious cases we aim to bring to firms and classrooms worldwide a sound and compelling pedagogic basis for the non-violent overthrow of bad engineering.

Consider this early engineering case. Atlanta-based carpet maker Interface's Shanghai factory needed a runaround heat-transfer loop. A top European engineering firm specified 14 pumps using a total of 70.8 kW_e. But then fresh thinking cut pumping power to just 9.7 kW_e, 86% less, with lower capital cost and better performance in every respect – thanks to two changes in design mentality.

First, small pipes and big pumps were replaced by big pipes and small pumps. Traditional optimisation compares the cost of fatter pipe with only the value of the saved pumping energy, but ignores the size and hence the capital cost of the pumps, motors, and electrical components needed to overcome pipe friction. Friction drops as nearly the fifth power of pipe diameter – that is, a pipe with twice the diameter will have about 2^{-5} times the friction, equating to about a 97% reduction. The size and (roughly) the capital cost of the pumping equipment falls accordingly. Yet the capital cost of fatter pipe increases as only about the *second* power of diameter. Optimising the pipe sizing without considering the capital cost savings of smaller pumps will thus pessimise the system. Optimising the *whole* system together yields fat pipes, tiny pumping equipment, *and* lower capital and operating costs.

Second, the new pumping system was designed backwards – laying out the pipes first, *then* locating the equipment they connect. Typical pipe runs twist and turn to hook up equipment that's placed far apart, separated by extraneous equipment, facing the wrong way, and mounted at the wrong height. This raises friction by about three- to sixfold – delighting pipefitters, who are paid by the hour, mark up the extra pipes and fittings, and don't pay for the bigger pumping equipment or electricity bills. Optimal piping systems – fat, short, and straight – require a whole-system design mentality, rewards for low friction, new CAD software that assists in optimising layouts, and pipefitters trained to lay out supply pipes *as if they were drains*.

This example illustrates an important principle of efficient design: look for downstream savings first. It is vital to do the right steps in the right order. By reducing flow or pressure first, the upstream hardware can be downsized or eliminated, and primary fuel consumption greatly reduced, because compounding losses (from fuel to flow) turn round backwards into compounding *savings* (flow to fuel). Saving one unit of energy in fluid flow may save two units of energy at the motor, and ten units of primary energy at the power plant.

Good design doesn't compromise; it optimises. The optimal solution often solves problems you didn't even know you had. Interface's redesign yielded not only lower capital cost and sevenfold lower pumping power, but also 70 kW less heat loss via easier insulation of short, straight pipes (a two-month payback). Free bonuses included simpler and faster construction, smaller floorspace and weight, easier maintenance access but less need for it, higher uptime, and longer life via fewer erodable elbows. Further optimisation for these additional benefits could have saved even more energy and capital.

Integration differentiates 10xE from other sustainable engineering programmes sprouting round the world. Efficient design is about more than designing clever, highly efficient components. In nature, individual species and organisms create a lot of waste, and hence might be considered inefficient. But integrated eco*systems* are highly efficient because outputs of some components are inputs to others, reducing total net waste to zero (each organism's wastes are another's food). We aim to apply this same theme of design integration between components through the 10xE project. While other sustainable engineering programmes teach how to use green materials and achieve lower lifecycle cost through efficient design, none are teaching how to achieve radical efficiency at comparable or negative net capital cost *up front*. Tight design integration makes this possible.

We believe competitive pressure will be the key driving force that makes design integration a standard practice. Both engineering firms and their clients stand to gain decisive competitive advantage from deploying whole-system design principles. Graduates of engineering programmes teaching integrative design will become much in demand; schools or firms that are slow to adopt will lose market share. There are buried treasures in even the simplest designs, and 10xE aims to illustrate how engineers can uncover them. As Einstein said, "The significant problems we have cannot be solved at the same level of thinking with which we created them."

10xE aims to develop this new level of thinking, and we need gifted partners. We know they're out there. Please help us find them. If you want to learn more about 10xE, if you think this way about design or know another engineer who does, or if you can share a compelling, elegant, and repeatable case-study of radical efficiency (preferably at lower capital cost), please visit www.10xE.org or write to us at casebook@10xE.org. Our profession and the world will thank you. tce

Amory Lovins has advised energy and other industries for three decades, as well as the US Departments of Energy and Defence. He has won more awards and recognitions than we have space to mention, advises industries and governments worldwide and has briefed 19 heads of state. He is co-founder, chairman, and chief scientist of Rocky Mountain Institute, an independent, market-oriented, nonprofit think-and-do tank in Snowmass, Colorado US. Imran Sheikh, an analyst in Lovins' office at RMI, worked for several years as a biomedical engineer prior to joining RMI two years ago. At RMI Sheikh drives the Factor Ten Engineering project