1 Introduction

The December 1968 issue of *Science* published a controversial paper by Garrett Hardin titled “The Tragedy of the Commons”. Although the author was addressing the problem of human over-population, the phrase he coined, *the tragedy of the commons*, has since been used to describe a dilemma in which the freedom of individuals to maximize their personal utility of common resources/goods (water, air, land, and so forth) leads to the destruction of those resources.

Almost fifty years later, the ‘tragedy’ takes its most poignant forms in the large-scale use/abuse of natural resource inputs and the overwhelming accumulation of waste outputs accompanying mass urbanization. Although its locus initially resides in economic, socio-political, and ecological systems, in the end, it is also an engineering systems problem since many current and future solutions depend on engineering systems design and implementation. As a systems design/implementation problem, it is amenable to the consideration of optionality (i.e., flexibility), both at the level of the engineering system and that of the city.

This paper is dedicated to the conceptual exploration of a single aspect of the problem – construction and demolition (C&D) waste. It examines current C&D waste management practice and proposes a taxonomy in which flexibility/optionality is utilized to transform failed C&D waste management systems into effective systems for resource recovery. A real-world case example is presented that demonstrates the attractiveness of the flexible C&D waste remanufacturing system and the potential it offers to successfully address the problem.

2 The Literature

There is a far-reaching literature on the use/abuse of natural resources and common goods and the waste management dilemma. Coming from academia, government, NGOs, industry, specialty trades, and professional practice, this literature is fragmented and often rather dated. Thus, for practical reasons, the literature search has been limited to those books, publications, and internet sites that represent “best-in-class” for certain directly relevant categories: urbanization; biophilic city design; road ecology; ecological engineering and economics; current and proposed best practices for C&D waste management and recovery; and land/environmental policy. Due to the conceptual breadth of this paper, references to the literature will not be provided in a section of their own but will, rather, be woven into the text throughout.

3 Nature and Magnitude of the Challenge

As with other resource waste and recovery problems, the nature and magnitude of the C&D waste problem involves both the use of non-renewable resource inputs and the generation of waste material outputs for which there is no current or future use. Consider rock aggregates as an example: “Aggregates play a major role in the construction industry as they are the major component of roadways, bridges, airport runways, concrete buildings, drainage systems, and many other constructed facilities. Because aggregates are the major component of much of the nation’s infrastructure, their use is engineered to provide the necessary performance in place. For instance, concrete is approximately 75% aggregate . . .

“In the past, when concrete structures reached the end of their service life or needed to be repaired or replaced, the resulting materials were considered waste and were disposed of in embankments and landfills. The costs of transporting these materials to waste areas were considered a necessary part of the replacement work. Likewise, the costs associated with the mining of new aggregates, the production of the replacement concrete, and the transportation and placement at the project were also considered a necessary part of the work.” (CMRA 2012)

This is the description of an ecological and economic input-output problem on a very large scale, with highly inflexible systems treatment (e.g., dig and discard).

3.1 Urbanization as a driver of C&D waste

It is fair to say that the majority of C&D inputs and waste outputs are directly or indirectly generated to support urban growth and development.

While the definition of an *urban area* differs from country to country, the blistering pace of urbanization over the last 60 years and the expected pace of continued urbanization in the future is uncontested. Most sources state that over half of the world’s population (e.g. 3 billion) now lives in cities, with at least 500 cities with populations of over 1 million. The forecast for 1015 is 50 megacities, 23 of which will boast a population over 10 million. CEIC Data Company Ltd, the U.N. Population Division, and *The Economist* forecast that by 2025, urbanization will be approximately 90% in Western Europe, the U.S., and Brazil, 60% in China, 50% in Southeast Asia, and 38% in India.

By way of contrast, in 1950, less than 30% of the world's population lived in cities. Two hundred years ago, Peking was the only city with a population as large as 1 million.

Demographic shifts of the scale suggested above affect not only established cities. They also affect the surrounding suburbs/exurbs, rural areas, and the design of new cities in significant ways and for all related systems. Illustrations from the United States (U.S.) and The People's Republic of China (PRC) follow.

U.S.: Since the mid-1900s, "[v]irtually every city in the country had a downtown where, where the commercial life of the metropolis was conducted; it had a factory district just beyond; it had districts of working-class residences just beyond that; and it had residential suburbs for the wealthy and the upper middle class at the far end of the continuum. As a family moved up the economic ladder, it also moved outward from crowded working-class districts to more spacious apartments and, eventually, to a suburban home. . . People moved ahead in life by moving farther out, . . ." (Ehrenhalt 2012) leaving behind them a wasteland, populated by the urban poor, urban slums, and the equivalent of Cleveland's 15,000 vacant lots and 3,300 acres of vacant land, much of it polluted and covered with asphalt and trash.

While the last decade has seen a number of signs of a suburban-to-urban demographic inversion, assisted by the removal of tens of thousands of "the great high-rise public housing projects that defined squalor in urban America," (Ehrenhalt 2012) the interiors of American cities, except for certain exclusive areas, remain in need of ecological renewal – all of which will generate untold tons of C&D waste.

As for America's rural areas, an enormous amount of C&D and other waste has made its way into them as suburbs expand, cities attempt to renew themselves, and remote landfill space becomes a necessity.

PRC: The PRC has experienced many similar challenges related to urbanization. One example is its *ChengZhongCun*, or 'urbanizing villages'. "Since the late 1970s, China has launched various reforms in different sectors to speed up its economic and urban growth. Concomitant with China's economic reforms, rural-to-urban migration and urbanization are the most influential social factors that are profoundly changing China's rural and urban settings. . . According to official estimates, by the end of 2000, there were about seventy million rural-to-urban migrants . . . working and living in urban areas. . . Needless to say, housing the rural migrants in the era of rapid urbanization in urban China is an immense challenge. . . . Excluded from the urban housing market, rural migrants are seeking shelter beyond the urban housing provision system. Villages within cities (*chengzhongcun* in Chinese . . .) are a unique product of China's urban and rural land dichotomy [in which] . . . [i]nadequate urban infrastructure and high housing and population density have together caused problems such as congestion, environmental pollution and waste disposal . . . ." (Song, Zenou, Ding 2007)

As a result, not only are urban areas experiencing population density, housing, and waste disposal crises, rural lands and people have inadvertently been subjected to ecological catastrophes, often due to the dumping of urban C&D and other waste in rural areas. According to Ma Jun, Director of the Institute of Public and Environmental Affairs and China's pre-eminent environmental watchdog, 300 million rural Chinese do not have access to safe drinking water and 12 million tons of crops are contaminated by heavy metals. (Fast Company 2012)

Current economic, socio-political, ecological, and engineering systems are incapable of addressing such resource challenges. Instead urban systems around the globe are in gridlock.

3.2 Size of C&D waste streams in the U.S.

Further understanding of the magnitude of C&D resource use and waste streams can be gained from the following – quite dated – U.S. statistics. It is notable that, while research continues to be performed on certain specific topics, there appear to be few current top level updates available and remarkably few indicators of wide-spread improvement in the status of these issues.

Landfill: In 1999, Staten Island, New York, contained what was the world's largest landfill. It received 26 million pounds of commercial and residential waste per day. In 1999, it contained 2.9 billion cubic feet (100 million tons) of trash. This was only 0.018% of all the waste generated in the U.S. on a daily basis. Total annual waste in the U.S., excluding wastewater, exceeded 50 trillion pounds per year. Wastewater added another 200 trillion pounds. Less than 2% of the total waste stream was being recycled. (Hawken, Lovins, Lovins 1999)

Construction & demolition waste: Prior to 1999, 40% of all U.S. material flows were construction materials. 15%-40% of U.S. landfill space was taken by waste from these flows. (Hawken, Lovins, Lovins 1999)

In 2006, un-recycled construction and demolition (C&D) waste in the U.S. was estimated at 325 million tons per year. (Bouley 2006)

In 2011, the Northeast Recycling Council (NERC) published a summary of state C&D recycling regulations and material disposal bans. The survey indicated that, of 49 states plus the District of Columbia, only 13 have some form of C&D material disposal ban or recycling requirement.

In 2013, *Forbes* magazine reported that “an astounding 78,000 abandoned buildings [were] still standing in the Motor City [i.e. Detroit] . . . [and that] every city in the country is facing similar problems . . .” (CMRA 2014)

C&D World states that “Annually, new or replacement roof installation generates an estimated 7 million to 10 million tons of shingle tear-off waste and installation scrap. More than 60 manufacturing plants across the U.S. generate another 750,000 to 1 million tons of manufacturing shingle scrap.” (CMRA 2013) While a growing proportion of this valuable resource is being remanufactured for use in pavement, only 26 states permitted its use in 2010 and 32 in 2011. The percentage of recycled asphalt shingles (RAS) permitted in asphalt mixtures is still only 3%-7%.

Roads: The U.S. has 3.9 million miles of public roads and an unknown number of miles of private roads. “The pervasiveness of roads and their cumulative effect on the environment are now of increasing concern . . . ” (Deen (ed) 2003) C&D waste is generated on a large scale from road building, rebuilding, and resurfacing. Recycled C&D waste is a potentially important resource for transportation applications.

CalTrans, the California Department of Transportation, conducted a 2012 survey regarding concrete recycling by state and Canadian transportation agencies and found that, of 30 agencies surveyed, 26 allowed crushed/recycled concrete for transportation applications. However, the only uses generally permitted were for fill, embankments, or noise barriers.

4 Current U.S. Waste Management & Resource Recovery Systems

4.1 Waste management

Waste management is performed throughout the U.S. on organic and inorganic waste streams from municipalities, industry, healthcare, agriculture, and other sources. Current waste management systems are massive in scale, long-lived, capital intensive, and costly to run and replace. They are also centralized, stand-alone and single purpose, and toxic (even with best environmental efforts). With a far-reaching footprint, they are over-burdened with current use but lacking in scalability, and tightly bound to layers of conflicting public policy and funding – making them unresponsive to both planned change and unforeseen events. With regards to C&D waste, standard practice is to incinerate or landfill it all.

These are highly inflexible systems and they create further inflexibility in the economic, socio-political, and ecological systems that support them. Their entire function contributes to the *tragedy of the commons* because: 1) they utilize large amounts of common resources to operate; 2) they are themselves considered common goods by the populations they serve, and are not stewarded carefully; and 3) they produce further waste streams that are disposed of in the commons.

4.2 Resource recovery

In the U.S., resource recovery is still a relatively narrowly-applied approach to waste management. Wikipedia defines *resource recovery* as: *the selective extraction of disposed materials for a specific next use, such as recycling, composting or energy generation. The aim of resource recovery is to extract the maximum practical benefits from products, delay the consumption of virgin natural resources, and to generate the minimum amount of waste*.

"Resource recovery is the practice of reclaiming materials that were previously thought of as unusable. . . Unlike the management of waste, resource recovery recognizes that there is still value in those materials. The intention of resource recovery is always to make the best and highest use of all materials, and landfill only those materials for which there is no current use." (http://recology.com/)

However, at this time, most of the efforts of resource recovery practitioners are focused in a few areas: recycling of residential waste, wastewater treatment, and one or two others. Resource recovery systems are fragmented, heavily dependent on ever-changing, multi-level government regulation and funding, and conducted in industry/waste stream silos, much like their traditional waste management system peers. Unfortunately, they provide only a temporary relief for the *tragedy of the commons*, since their outputs end up back in traditional waste management systems, generally in less recoverable condition than they were the first time around.

4.3 State of the system

Environmental protection and sustainability have been a major topic of public discourse in the U.S. since the 1960s. The effects of waste streams on urban areas, rural land, flora and fauna, and humans are well and publicly documented. Decades of environmentalists have protested and proposed solutions based on four *eco-efficient* strategies – *reduce, reuse, recycle, and regulate*. (McDonough and Braungart 2002) Many *eco-efficient* solutions have been applied by government, commerce, and academia, codified in thousands of regulations, and become common practice.

"**But ultimately a regulation is a signal of design failure. In fact, it is what we call a *license to harm*:** a permit issued by a government to an industry so that it may dispense sickness, destruction, and death at an "acceptable" rate. . . **[G]ood design can require no regulation at all**. . . . Eco-efficiency is an outwardly admirable, even noble, concept, but it is not a strategy for success over the long term, because it does not reach deep enough. It works within the same system that caused the problem in the first place, merely slowing it down with moral proscriptions and punitive measures. It presents little more than an illusion of change." (McDonough and Braungart 2002)

This paper proposes a paradigm shift involving system reconfiguration that will correct current design failure through incorporating flexibility.

5 Flexibility in Natural Resource Recovery Systems (NRRS)

To gain an appreciation of the nature of the paradigm shift represented by the proposed flexible NRRS, we first define flexibility. We then use and enhance a taxonomy of complex systems suggested by (Baldwin, Felder, Sauser 2011) to describe the conceptual framework foundational to a flexible NRRS. Finally, this framework is applied to a real-world C&D NRRS, built and operating in Maine, United States.

5.1 Flexibility

Flexibility is a term that describes a system's capacity for dealing dynamically with uncertainty. Flexible system design builds components into the system that provide for system change capacity, should it be desirable in the future. Not everything that might be needed is built into the system from the outset.

"The right kind of flexibility in design gives . . . three kinds of advantages. It can: (1) greatly increase the expected value of the project or products; (2) enable the system manager to control the risks, reducing downside exposure while increasing upside opportunities, thus making it possible for developers to shape the risk profile. This not only gives them greater confidence in the investment but may also reduce their risk premium and further increase value; and (3) often significantly reduce first costs of a project – a counterintuitive result due to the fact that the flexibility to expand means that many capital costs can easily be deferred until prospective needs can be confirmed.” (de Neufville and Scholtes 2011)

5.2 Taxonomy of the proposed flexible NRRS

The proposed flexible NRRS has certain attributes that are in direct contrast to the rigid, massive, costly system configurations currently in use. Each attribute allows the proposed system to deal dynamically with uncertainty and can be applied to NRRS for all types of natural resources.

“Waste is food” philosophy: “Our move toward sustainable cities will require an important shift in thinking of cities not as linear resource-extracting machines but as complex metabolic systems with flows and cycles, where, ideally, the things that have been traditionally viewed as negative outputs (e.g., solid waste, wastewater) are re-envisioned as productive inputs to satisfy other urban needs, including food, energy, and clean water.” (Beatley 2011)

Maintains an explicit, respectful city-rural partnership: The proposed NRRS may be a city-based system. But, it receives from and contributes to the well-being of its rural context rather than viewing that context as nothing but a dumping ground for its own waste.

Local: As a local, rather than regional or even mega-city-wide, system, the proposed NRRS responds to local needs, “fits into the character of the land and its topography, soils, climate” and utilizes “locally available materials, regional construction techniques, . . . labor-saving functionality, and minimal cost to build, operate, and maintain.” (Thorbeck 2012)

Small scale, modular, decentralized, and scalable: Unlike current systems, the proposed NRRS is built on a smaller scale and can be modular. It is a decentralized system, allowing it to be flexible and scalable – even mobile – to meet local needs and growth. Its scale and decentralization also allow it the options to change and innovate at a low cost, or to shut down at modest cost without leaving behind massive system remains.

Adaptive: Adaptive behavior is “the ability to alter one’s own functions or goals . . . to adjust to environmental changes without significant changes to the system configuration.” (Baldwin, Felder, Sauser 2011) The proposed NRRS’s flexibility allows it to adjust and adapt to environmental or technological change with far less stress and disturbance to its context than its current peers would engender under similar change scenarios.

Small footprint: Current resource waste management systems have an enormous, far-reaching technological and ecological footprint. The proposed NRRS reduces this footprint wherever and however possible through its flexible, adaptive design.

Simple, reasonably priced and cost-effective: Driven by private industry cost-benefit concerns, proposed NRRS components are as simple, accessible, and cost-effective as possible. Where components are initially more complex and costly, their flexible uses create operating efficiencies and short payback periods.

Self-organizing: Self-organization is “the unprompted organization caused by the constituent systems interacting . . . [without] external force.” (Baldwin, Felder, Sauser 2011) Free market economic systems attest to the success of self-organization in bringing about creation, innovation, and growth and in navigating uncertainty and change effectively. While the proposed NRRS can and does function under tightly regulated government oversight, it is designed to be most successful when self-organized and self-regulated.

The proposed NRRS does not look to government to be the owner and keeper of the commons, with citizens as tenants and passive benefits recipients. Instead, each iteration of the proposed system is to be created and owned by private citizens who view themselves as active stewards of the resources and the waste products belonging to them and their communities.

6 Case example: CPRC Group, Scarborough, Maine

CPRC Group (Commercial Paving & Recycling http://www.cpcrs.com/) was founded in 1945 as a traditional asphalt paving company. In 1990, its original owner discovered that his cold-mix equipment, used to make asphalt, could turn contaminated soil into fully usable construction fill. Further experimentation led to uses of the same machinery for other C&D waste remanufacturing. Since 2004, current owners, John Adelman and Jim Hiltner, have turned CPRC into a leader in *conversion technology*, a classic example of flexibility in engineering design, and a poster child for the proposed NRRS.

The company focuses on *making the turn* – i.e., taking in C&D (and other) waste materials and converting them into useful, saleable construction, landscaping, and agricultural product. At CPRC, *waste equals food.*

One of its four divisions operates and manages the City of Portland’s Riverside Recycling Facility. The others receive and convert: asphalt pavement, concrete, bricks, rock, ledge, and miscellaneous aggregate-based material; residential asphalt shingles of any size, shape, and color; asbestos-tested commercial asphalt roofing material; catch basin and sand-blast grit; stumps, branches, wooden pallets, demo woods, clean wood, leaves, brush, grass clippings; gypsum board that is free of paint, wallpaper, and contamination by wood, cans, paper or other debris; glass and porcelain materials (except containers that once held hazardous products, automotive headlights, and residential incandescent light bulbs); uncontaminated inert materials such as unscreened loam; soil containing heating oil, motor oil, and waste oil; and institutional food waste.

Once waste materials are sorted, CPRC remanufactures reusable components into an array of conversion products, such as:

- C&R gravel that is crushed, screened and blended from pavement, concrete, and rock materials, asphalt shingles, glass, and inert materials in various proportions, and then used to build roads, parking lots, bridge approach ramps, embankments, shoulders, construction project sites, and other heavy infrastructure projects;
- erosion control materials made from converted green waste;
- licensed inert fill dirt (made from converted petroleum-containing soil) that is highly compactable and uniform and is both structurally and environmentally sound;
- screened loam made from converted non-contaminated soils;
- biomass fuel made from demolition wood and clean wood;
- bark mulch for landscaping purposes;
- organic compost for agricultural uses.

Based in a rural suburb of Portland, Maine, CPRC is local, but maintains an explicit, respectful city-rural partnership through its use, conservation, and improvement of both urban and rural land and resources. Because CPRC is decentralized and modular, it is also adaptive and scalable, allowing management to invent and implement new uses for its technologies as new needs arise.

Operations are designed to be highly flexible, providing the company and its customers abundant options. Land, buildings, and technologies are multi-use. Employees are cross-trained and incentivized to implement lean manufacturing methods. Waste inputs can be transported to CPRC facilities by the customer, picked up by CPRC, or converted on-site by CPRC’s mobile equipment. Remanufactured waste outputs can be pre-mixed or custom mixed, based on customer specifications, and either picked up by customers at CPRC facilities or delivered to the customer by CPRC.

While C&D remanufacturing facilities involve sizeable land allotments and large-scale technologies, CPRC manages its technological and ecological footprint with care. The company is not a passive tenant without incentive to steward its resources. It owns its land and intends to keep it pristine for a range of future uses.

Is the CPRC system simple, reasonably priced and cost-effective? It is, for the customer. In addition, although C&D conversion technologies are becoming increasingly sophisticated and costly, CPRC has consistently demonstrated that older, simpler machinery can be re-engineered and used effectively. When new, more expensive technologies are purchased, they are cost-effective because they are long-lived, mobile, and can be redeployed for multiple uses with a minimum of retrofitting.

Finally, while all environmental activities in the U.S. are tightly enforced by regulation, CPRC and the industry of which it is a part exhibit a high degree of self-organization within the proscribed limits. Both industry and other literatures suggest that the complexity and arbitrariness of the regulatory environment and its slowness in accepting C&D conversion products currently present the single most substantial hindrance to further beneficial contributions by this industry and the NRRS it represents.

7 Critical Future Considerations

7.1 System Valuation

Genichi Taguchi insisted that manufacturing waste creates a significant cost to society. The same could be said about natural resource use/abuse and the *tragedy of the commons*. Thus, the NRRS problems discussed in this paper are problems of value, as well as of ecology, socio-politics, or engineering.

How do we value the commons? How do we value the systems that might contribute to its recovery and restoration? Can we compare current waste management practices with proposed and/or already-implemented NRRS practices in a quantitative and meaningful way? Can we determine and quantify the effects on system value of regulation versus deregulation? Where can real options thinking help address such issues?

Although the scope of this paper does not allow for more than a brief mention, government-sponsored academic research and the engineering disciplines have made useful contributions toward answering them. For example, *ecological economics* seeks “to reinvent economics with connections to ecology” (Kangas 2004); and the work of de Neufville &

Scholtes (2011) suggests a portfolio of screening and valuation techniques that designers to directly address uncertainty and flexibility in engineering systems.

While there is more work to be done, these are thoughtful, provocative beginnings.

7.2 Extended Applications of Flexible C&D NRRS

While any number of potential applications of flexible C&D NRRS exist, two offer immediately appealing value propositions: landscape architecture/ecological engineering; and new city design and construction.

Landscape architecture and ecological engineering both concern themselves with natural resource use and restoration as well as innovation in urban fabric, infrastructure, and material technologies. The small-sample literature search performed for this paper indicates that there is little to no current use of remanufactured C&D waste in landscape architecture or ecological engineering projects. Yet, C&D conversion products seem like ideal candidates for such projects.

New city design and construction might also benefit from the use of C&D conversion products. Imagine bringing conversion equipment on site and using both the C&D waste from site preparation and the C&D waste generated during ongoing new construction to build out the baseline infrastructure of the city. What a powerful illustration of *waste equals food* – a city that ‘builds itself’ from its own remanufactured C&D waste.

7.3 Change needed in the regulatory environment

Government regulation has been a large factor in jump-starting and formalizing the environmental movement in many countries. However, there is now a pressing need for more agility and flexibility in the regulatory environment to allow for important innovations to flourish and self-regulation to become normative. Public policy studies in the area of natural resource recovery systems might be a first place to begin.

8 Conclusions

The conclusions to be drawn are simple. In a world in which financial resources are becoming increasingly limited but natural resource use and waste increasingly prevalent and threatening, we can continue to design and build huge, costly, inflexible systems that exacerbate the very problems they purport to address and then impose these systems on stakeholders by regulatory diktat and tax schemes.

Or, we can begin to explore and adopt flexible, smaller-scale, affordable systems that transform problems into benefits and self-organize through ingenious local capabilities and initiatives. If we choose the latter, we can look to C&D conversion technologies and the flexible NRRS they embody to show us a practical approach to reversing the *tragedy of the commons* and addressing the urgent global challenges created by mass urbanization.

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