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Article

Optimizing Urban Material Flows and Waste Streams in Urban Development through Principles of Zero Waste and Sustainable Consumption

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Abstract: Beyond energy efficiency, there are now urgent challenges around the supply of resources, materials, energy, food and water. After debating energy efficiency for the last decade, the focus has shifted to include further resources and material efficiency. In this context, urban farming has emerged as a valid urban design strategy, where food is produced and consumed locally within city boundaries, turning disused sites and underutilized public space into productive urban landscapes and community gardens. Furthermore, such agricultural activities allow for effective composting of organic waste, returning nutrients to the soil and improving biodiversity in the urban environment. Urban farming and resource recovery will help to feed the 9 billion by 2050 (predicted population growth, UN-Habitat forecast 2009). This paper reports on best practice of urban design principles in regard to materials flow, material recovery, adaptive re-use of entire building elements and components ('design for disassembly'; prefabrication of modular building components), and other relevant strategies to implement *zero waste* by avoiding waste creation, reducing wasteful consumption and changing behaviour in the design and construction sectors. The paper touches on two important issues in regard to the rapid depletion of the world's natural resources: the built environment and the education of architects and designers (both topics of further research). The construction and demolition (C&D) sector: Prefabricated multi-story buildings for inner-city living can set new benchmarks for minimizing construction wastage and for modular on-site assembly. Today, the C&D sector is one of the main producers of waste; it does not engage enough with waste minimization, waste avoidance and recycling. Education and research: It's still unclear how best to introduce a holistic understanding of these challenges and to better teach practical and affordable solutions to architects, urban designers, industrial designers, and so on. How must urban development and construction change and evolve to automatically embed sustainability in the way we design, build, operate, maintain and renew/recycle cities? One of the findings of this paper is that embedding *zero-waste* requires strong industry leadership, new policies and effective education curricula, as well as raising awareness (through research and education) and refocusing research agendas to bring about attitudinal change and the reduction of wasteful consumption.

Keywords: urban waste streams; material flow; closed-loop urban metabolism; zero waste concept; resource recovery; recycling and reuse; reducing consumption; product stewardship; waste avoidance; changing behavior; adaptive re-use of buildings

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1. Introduction

Since the industrial revolution, mankind has constantly expanded and increased industrial production and urbanization, using massive resources of materials and energy. The mass consumption of resources raises serious problems such as global warming, material depletion and enormous waste generation.

This paper explores the notion of sustainable urban metabolism and ‘zero waste’. There is now a growing interest in understanding the complex interactions and feedbacks between urbanization, material consumption and the depletion of our resources. The link between increasing urbanization and the increase of waste generation has been established for some time. However, the impact of urban form and density on resource consumption is still not fully understood. Human population on the planet has increased fourfold over the last hundred years, while—in the same time period—material and energy use has increased tenfold [1]. The United Nations forecast that the world’s urban population will increase by 2.7 billion people between 2010 and 2050. But how can urbanization of our planet continue with such devastating effects?

Based on our wasteful patterns of urban development, it’s time to rethink development practice and urban form [2]. However, to formulate better urban responses requires a full awareness of the impacts and reasons for current global change, which mainly occurs through:

- Demographical changes
- Growing social disparities
- Continuing urbanization processes with rapidly expanding cities
- Growing demand for resources (materials, energy, water)
- Loss of biodiversity and habitat, and
- Continuing production methods of industry and agriculture often too material and energy intensive and therefore unsustainable.

The pace of urbanisation is increasing and cities face new challenges from the effects of human activity on global systems, which in turn impact on urban life. Climate change is a significant one of those challenges. It is apparent that cities are the main consumers of materials, energy, water and food, and hence they are the main sources of greenhouse gas emissions associated with climate change. Holistic understanding and integrated approaches to design, planning and urban management are essential to effective resolution of urban problems. In most countries, cities keep expanding with growing populations. It is particularly important to include the peri-urban areas and suburbs in any research and analysis, as they represent the areas of interaction between the urban and rural contexts, where fertile agricultural land and precious landscape is gradually lost as a food source.

Beyond energy efficiency, there are now urgent challenges around the supply of resources, materials, food and water, and after debating *energy efficiency* for the last two decades, the focus has shifted to include *resource and material efficiency* [3]. Waste was once seen as a burden on our industries and communities; however, shifting attitudes and better understanding of global warming and the depletion of resources have led to the identification of waste as a valuable resource that demands responsible solutions for collecting, separating, nurturing, managing and recovering. In particular, over the last decade, the holistic concept of a 'zero waste' life-cycle has emerged as a cultural shift, as a new way of thinking about the age-old problem of waste and the economic obsession with endless growth and consumption.

Emerging complex global issues, such as health and the environment, or lifestyles and consumption, require approaches that transcend the traditional boundaries between disciplines. The relationship between *efficiency* and *effectiveness* is not always clear: high efficiency is not equal to high effectiveness, while recovery offers another side of those two notions. Today, it is increasingly understood that the same way we discuss energy efficiency; we need also to discuss resource effectiveness and resource recovery. This includes waste minimization strategies and the concept of 'designing waste out of processes and products' (as mentioned, for instance, in [4]).

Every municipality or company can take immediate action to identify its own particular solutions. Separating recyclable materials, such as paper, metals, plastics and glass bottles, and consolidating all identified waste categories into one collection point, are some basic measures. However, a waste stream analysis will have to be conducted at an early stage, which will involve taking an inventory of the entire waste composition, measuring the volumes of different material categories and its origin and destination. A database will then need to be created to enable the municipality to track all waste types and to cross reference by facility type, so the amount and type of waste each facility, district or precinct generates can be identified, thus pinpointing where reductions can occur.

For centuries, waste was regarded as 'pollution' that had to be hidden and buried as landfill. Today, the concept of 'zero waste' directly challenges the common assumption that waste is unavoidable and has no value by focusing on waste as a 'misallocated resource' [5,6] that has to be recovered. It also focuses on the avoidance of waste creation in the first place (e.g., reducing construction waste). That we are a wasteful nation is illustrated by the fact that over 40% of our daily food is thrown out and wasted [7]. Recent research found that family size and household income are primary determinants of household waste, while the affect of environmental awareness on waste generation behavior is surprisingly small.

This, of course, raises much wider social questions of attitude and behavior, and our wastefulness has further implications on future urban development. How will we design, build, operate, maintain and renew cities in the future? What role will materials play in the 'city of tomorrow'? How can we increase our focus on more effective environmental education for waste avoidance? And how we will need to better engage sustainable urban development principles and zero waste thinking? These are some of the topics discussed in this paper.

2. The Link between Waste and Urbanization

2.1. Limits of Growth: Understanding Waste as a Resource and Part of a Closed-Cycle Urban Ecology

In recent years, the need for more sustainable living choices and a focus on behavioural change has increasingly been articulated. The estimated world waste production is now around four billion tonnes of waste per annum, of which only 20 per cent is currently recovered or recycled [8]. Globally, waste management has emerged as a huge challenge, and it's time that we took a fresh look at how we can best manage the waste and material streams of cities and urban development. The issue of our city's ever growing waste production is of particular significance if we comprehend the city as a living eco-system with closed-loop management cycles (see Figures 1 and 2).

There are some serious implications around the topic of waste. It is obvious that it is not just about waste recycling, but also waste prevention, following the waste hierarchy diagram (see Figure 3). We must give prevention more priority, as the saying goes: 'An ounce of prevention is worth a pound of recycling.' Avoidance is the priority, followed by recycling and 'waste engineering' (up-scaling), to minimize the amount that goes to waste incineration.

Figure 1. The flow of natural resources into cities and the waste produced (recovering waste streams) represents one of the largest challenges to urban sustainability. Circular, looping metabolisms are more sustainable, compared to linear ones. This also has economic advantages. Recycling will continue to be an essential part of responsible materials management, and the greater the shift from a 'river' economy (linear throughput of materials), towards a 'lake' economy (stock of continuously circulating materials), the greater are both the material gains and greenhouse gas reductions (Diagram source: [9,10], republished in [11]).

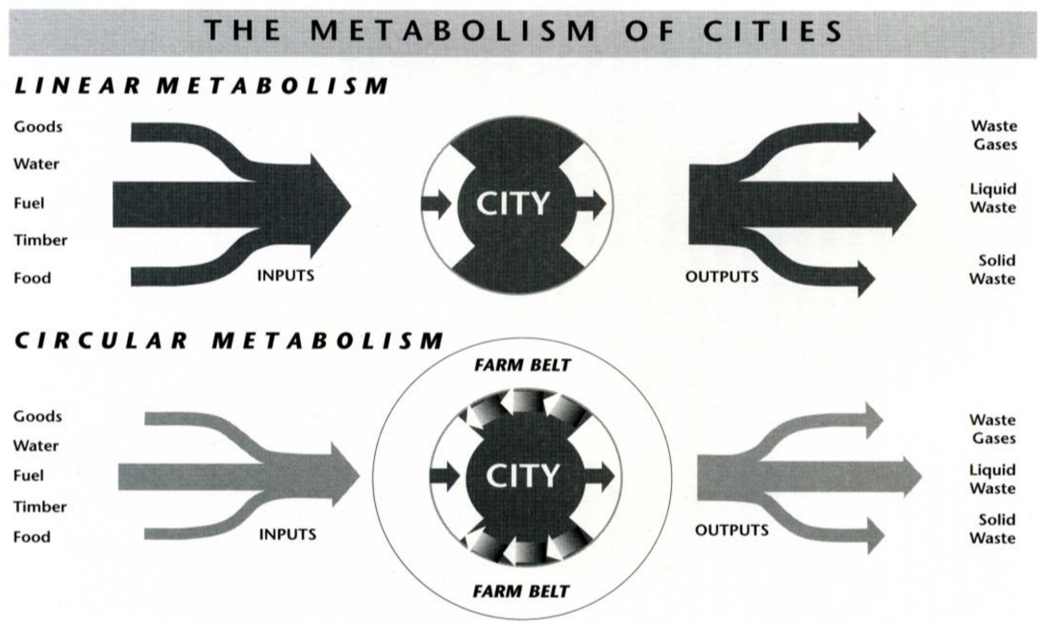

Figure 2. Diagram illustrating the input and output of cities, comparing the 'conventional' city with the more sustainable city on the right (Diagram source: [12]).

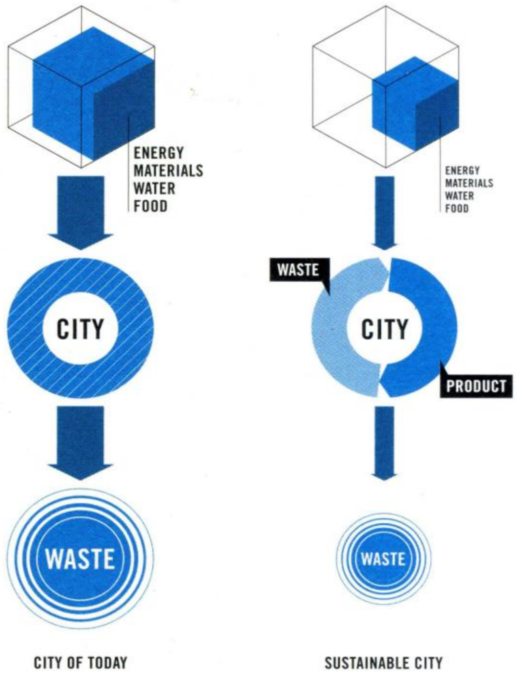

Figure 3. The waste hierarchy diagram illustrates how waste avoidance is preferred, above re-use and recycling. Disposal in landfill represents the lowest level of the waste hierarchy (diagram: courtesy of the author, 2010). On the municipality level, a more strategic charging structure (levies) for waste disposal can accelerate sustainable waste management and reward residents who are separating their waste.

A particular concern is disposal of electrical and electronic equipment, known as *e-waste*. Of about 16.8 million televisions and computers that reached the end of their useful life in Australia in 2008 and 2009, only about 10% were recycled. Most of the highly toxic e-waste still goes into landfills, threatening ground water and soil quality, and an unknown proportion is shipped overseas (legally and illegally), mainly to China, leading to major environmental problems in these importing countries. About thirty-seven million computers, seventeen million televisions, and fifty-six million mobile phones have already been buried in landfills around Australia. This waste contains high levels of mercury and other toxic materials common to electronic goods, such as lead, arsenic, and bromide. Several countries are actively pushing for industry-led schemes for collecting and recycling televisions, printers, and computers, known as extended producer responsibility ('EPR') and product stewardship. In addition, we must expect that the amount of e-waste created in the developing world will dramatically increase over the next decade [13,14].

Discharges are a threat to soil and groundwater, and methane gas discharges (mainly from organic waste in landfill) are a threat in the atmosphere. In the meantime, many large cities are producing astronomical amounts of waste daily and are running out of landfill space. Incineration of waste has gone out of fashion, as it has the disadvantage that it releases poisonous substances, such as dioxins and toxic ash, into the environment. Burning waste with very high embodied energy is generally not an efficient way of dealing with resources. Environmental groups have successfully prevented the construction of new waste incinerators around the world. Such linear systems (e.g., burning waste) have to be replaced with circular systems, taking nature as its model. Much more appropriate is a combination of recycling and composting. Today, recycling 50% to 60% of all waste has become an achievable standard figure for many cities (e.g., the Brazilian model city of Curitiba has managed to recycle over 70% of its waste since 2000; and the city of San Francisco has arrived at 77% diversion rate from landfill in 2010).

Organic waste is playing an increasingly important role. The small Austrian town of Guessing, for instance, activates the biomass from its agricultural waste and has reached energy autonomy by composting and using the bio-energy to generate its power. In the available literature, a recommended split for a city can be found, where no waste goes to landfill:

- Recycling and reusing min. 50–60%
- Composting of organic waste 20–30%
- Incineration of residual waste (waste-to-energy) max. 20%

Steel is by far the most recycled material worldwide (it has the longest 'residence time'). However, recent research from Veolia Research Group [15] shows that recycling in itself is inefficient in solving the problem, as it does not deliver the necessary 'decoupling' of economic development from the depletion of non-renewable raw materials. Grosse and others argue that 'the depletion of the natural resource of raw material is inevitable when its global consumption by the economy grows by more than 1% per annum. The only effect of recycling is that the curve is delayed.' There is evidence that recycling can only delay the depletion of virgin raw materials for a few decades at best. Research shows that only recycling rates above 80% would allow a significant slowdown of the depletion of natural resources. This means that the actual role of recycling to protect resources is not significant for non-renewable resources whose consumption tends to grow above 1% per year.

Even though it's an important component, sustainable development policies cannot rely solely on recycling. Policies need to aim at reducing the consumption of each non-renewable raw material so that the annual growth rate remains under 1%. Decoupling economic development from materiality seems to be the only long term solution. Recycling is not so much the primary goal. The objective is not so much to reduce the amount of waste in general, but, rather, to encourage a reduction in the quantities of materials used to make the products that will later become waste.

Waste is nutrients. Waste is precious. We should learn from Nature: Nature doesn't know 'waste'. In Nature, one species' waste is another species' resource [16-18].

2.2. Zero Waste and Closed Loop Thinking in the Construction Sector

There is a growing interest from architects in zero waste concepts. Cities and urban development are the areas where all concepts come together and can be embedded into practice, into redesigning urban systems with zero waste and material flow in mind, by transforming the existing city and upgrading its recycling infrastructure in low-to-no carbon city districts. It's timely to rethink prefabrication and 'design for disassembly' building resilience into urban systems. This will change the way we design, build and operate city districts in future (acknowledging that zero waste is much wider and complicated than expected at the first glance, and that we still have long distance from zero emission to zero waste in regard to the construction sector). For instance, façade systems made of composite materials create recycling and resource recovery problems. No debris should go to landfill. Concrete companies should use sustainable, recycled aggregates. Concrete was previously regarded as being difficult to be recycled, as closed-loop recycling for concrete structures is expensive. But concrete-related waste is now increasingly used as recycled aggregate (RA) for new concrete structures, and intensive research is carried out in Japan and China on new concrete recycling methods.

Urban planners frequently raise the question about which is the best scale to operate on for introducing 'zero waste'. The city district as a unit appears to be a good, effective scale. It means rejoining the urban with the rural community, therefore neighbourhood and precinct planning must consider the climate crisis. For instance, planning better cities requires that composting facilities and recycling centres are in close proximity to avoid transporting materials over long distances. Reducing energy embodied in construction materials is an important strategy for mitigating our fossil-fuel dependency. Keeping the existing building stock is important, as the most sustainable building is always the one that already exists. Retrofitting existing districts is, therefore, essential.

2.3. Constantly Growing Amounts of Waste—What Can Be Done?

Global population growth is expected to stabilize in 2050 at around 9 billion human beings [19]. However, population growth is far from being the main driver of recent economic expansion and the increase of consumption of materials, water, fossil-fuels and resources. The process by which emerging countries catch up with the standard of living of more advanced economies is, in fact, an even more powerful actuator.

As a consequence of this 'catching up', waste is accumulating in the oceans. In recent years, our oceans have devolved into vast garbage dumps. Thousands of tonnes of waste are thrown into the sea each year, endangering humans and wildlife. Since the world's oceans are so massive, few people seem to have a problem with dumping waste into them. However, most plastics degrade at a very slow rate, and huge amounts of them are sloshing around in our oceans. Wildlife consumes small pieces, causing many of them to die as the plastics are full of poisons. Some plastic products take up to 200 years to degrade. Every year, around 250 million tonnes of plastic products are produced, and much of this produce ends up in the oceans. The 'Great Pacific Garbage Patch' is half the size of Europe, and in the Atlantic huge amounts of plastic garbage have recently been discovered [20]; the highest concentration being found close to Caribbean islands, with over 200,000 plastic pieces per sq km. In the North and Baltic seas, although dumping in them has been illegal for over two decades, the amount of waste found in them has not improved. It is estimated that each year 20,000 tonnes of waste finds its way into the North Sea, primarily from ships and the fishing industry [21]. Experts warn that we've reached a point where it's becoming dangerous for humans to consume seafood. A big problem is the throw-away plastic water bottles made of PET, not only because they significantly contribute to waste creation and CO_2 emissions from transporting drinking water around the globe, but they also release chemicals suspected of being harmful to humans into the water. Together with the largest oil spill in human history, the devastating oil spill in the Gulf of Mexico (2010), it shows how advanced humanity's destruction of entire ecosystems in the oceans has become.

Given these conditions, the international community has been pushing for four decades for massive bureaucratic efforts aimed at clearing the oceans of waste. In 1973, the United Nations sponsored a pact for protecting the oceans from dumping, and in 2001 the European Union established directives that forbade any dumping of maritime waste into the ocean while in port. However, such directives have been ineffective and many experts agree that laws and international efforts aimed at protecting the oceans have failed across the board.

Today, no other sector of industry uses more materials, produces more waste and contributes less to recycling than the construction sector [22].

With the constant increase in the world's economic activity, there has been a large increase in the amount of solid waste produced per head of population. The waste mix (industrial and urban) has become ever more complex, often containing large amounts of toxic chemicals. Obviously, the first aim of a sustainable future is to avoid the creation of waste and to select materials and products based on their embodied energy, on their life-cycle assessment and supply chain analysis. This needs to be understood holistically. Transportation of input materials, as well as the transportation of the final product to consumers (or to the construction site), is a common contributor to greenhouse gas emissions. The way in which a product uses resources such as water and electricity influences its environmental impact, while its durability determines how soon it must enter the waste stream. Care needs to be taken in the original selection of input materials, and that the type of assembly used influences end-of-life disposal options, such as ease of recyclability or take-back by the manufacturer. With a huge amount of waste still going to landfill, drastic action is required in urban planning to develop intelligent circular metabolisms for districts, and waste collection and treatment systems that will eliminate the need for landfills. Even so, recycling is only halfway up the waste hierarchy, the greenhouse gains lying in the upper half (waste avoidance and reduction) are, largely, yet to be tapped. The focus of attention needs now to expand from the downstream of the materials cycle, from a post-consumer stage, to include the upstream, pre-consumer stage, and behavioural change (see diagram Figure 1).

Diagram Figure 1 illustrates the concept of a *circular* (looping) urban metabolism: the current production-consumption system is typically *linear* (as in a pipeline) and extends from manufacturing through use to end of life, followed by either recycling or landfill. The idea that this system must be reconfigured in order to promote a series of closed loops whereby all material and products are re-used or recovered is not new and has been raised many times, however, has not been adapted by the construction sector. Figure 4 illustrates how future buildings will produce energy and even food.

While the worldwide international average for daily waste generation is about 1 to 1.5 kg per capita, countries like Kuwait and United Arab Emirates top the list, generating an average of over 3.5 kg of waste per person per day (in comparison, the average Australian resident dumps 1.1 tonnes of solid waste per year, this is also around 3 kg per day). According to the 'polluter pays' principle, policies penalize those who generate large amounts of waste. Collecting, sorting and treating waste incurs huge costs, so the focus has to be on avoiding and minimizing waste creation in the first place, in the office, in industry, in households. Waste-wood-to-energy has frequently become an important component of energy concepts for city districts. Waste management and recycling schemes have greatly reduced the volume of waste being 'land-filled'. Waste segregation and recycling has also substantial economic benefits and creates new jobs.

Re-using building components and integrating existing buildings (instead of demolition) is a basic principle of any eco-city and eco-building project [23].

Figure 4. Urban farming, designing the 'Carrot City': with finite cropland to feed a growing global population, concepts are now being developed that will build vertical farms, where buildings' roofs and facades become sites for urban agriculture. Rotating hydroponic-farming systems give the plants the precise amount of light and nutrients they need, while vertical stacking enables the use of far less water than conventional farming (Project illustration: [24]).

2.4. Changing Manufacturing and Packaging Processes towards Life-Cycle Oriented Practices

New agreements with industry have to be made to dramatically reduce waste from packaging. On the way towards a zero-waste economy, manufacturers will increasingly be made responsible for the entire life-cycle of their products, including their recycleability, by introducing an 'extended producer responsibility' policy. Luckily, many companies are now doing extraordinary things in the area of recycling and are prolonging the life-cycle of products. For instance, Ohio-based firm *Weisenbach Recycled Products*, a manufacturer of consumer goods made from recycled materials holds numerous patents on recycling, awareness and pollution prevention products. It is both a specialty printing firm and an innovative recycler of waste and scrap, repurposing and 'up-cycling' such materials as plastic caps, glass bottles and circuit boards into over 600 promotional items and retail consumer products. According to the company's president, Dan Weisenbach, there has been a changing perception in the business world, where you are more valued if your company is a 'certified green business': 'Even though conservation has been a core principle in our culture since we started, we believe it is important that we take a step to formalize our commitment to sustainable business. The competitive landscape has shifted and it is important for a company to have a history of environmental leadership and integrity. Choosing to voluntarily document all our efforts in an annual sustainability report is a demonstration of this commitment. We have moved past the *bigger is better* era. People want to do business with companies they can relate to and who share their values' [25].

For centuries, waste was regarded as pollution that had to be collected, hidden and buried. Today, waste is no longer seen as something to be disposed of, but as a resource to be recycled and reused. It's clear that we need to close the material cycle loop by transforming waste into a material resource. Over the next decades, the Earth will be increasingly under pressure from population growth, continuing urbanization and shortage of food, water, resources and materials. Waste management, optimizing waste streams and material flows are some of the major challenges concerning sustainable urban development. There is a growing consensus that waste should be regarded as a `valuable resource and as nutrition' [26,27]. It has been argued that the concept of 'waste' should be substituted by the concept of 'resource'. McDonough and Braungart point out that the practice of dumping waste into landfill is a sign of a 'failure to design recyclable, sustainable products and processes.' All eco-cities have to embed zero-waste concepts as part of their holistic, circular approach to material flows (see diagram Figure 2).

Design for Disassembly means the possibility of reusing entire building components in another future project, possibly 20 or 30 years after construction. It means deliberately enabling 'chains of reuse' in the design, and to use light-weight structures with less embodied energy, employing modular prefabrication. Recycling resources that have already entered the human economy uses much less energy than does mining and manufacturing virgin materials from scratch. For instance, there is a 95% energy saving when using secondary (recycled) aluminium; 85% for copper; 80% for plastics; 74% for steel; and 64% for paper [28]. Through re-use and recycling, the energy embodied in waste products is retained, thereby slowing down the potential for climate change. If burned in incinerators, this embodied energy would be lost forever. It becomes obvious that all future eco-cities will have to integrate existing structures and buildings for adaptive re-use into their master planning. Based on life-cycle assessment, the most sustainable building is likely to be the one that already exists.

In closed-loop systems, a high proportion of energy and materials will need to be provided from re-used waste, and water from wastewater. We can now move the focus to waste avoidance, behavioural change and waste reduction [29].

2.5. A closed-Cycle Urban Economy Will Deliver a Series of Further Advantages

- It avoids waste being generated in the first place (and therefore reduces CO_2 emissions).
- It creates closed-loop eco-economies and urban eco-systems with green collar jobs.
- It helps transform industries towards a better use of resources and non-polluting (non-toxic), cleaner production processes, and extend producer responsibility.

- It delivers economic benefits through more efficient use of resources.
- It supports research into durable, local goods and products that encourage reuse.
- It advocates 'green purchasing' and a product stewardship framework.

'Extended producer responsibility' places the responsibility of the future of an item of waste on the initial producer of that product (instead of on the last owner, as in traditional segmentation) [30,31]. This leads to the practice whereby an increasing number of manufacturers include in the sale of goods a service for the future recovery and the processing of the product at the end of its useful life.

It also includes extending the responsibilities to consumers to participate in recycling schemes. A recent survey showed that 83% of Australians wanted a national ban on non-biodegradable plastic bags, while 79% wanted electronic waste (e-waste) to be legally barred from landfills [32]. Cities will always be a place of waste production, but there are possibilities available that will help them achieve zero-waste, where the waste is either recycled, reused or composted (using organic waste for biomass). The Masdar-City project in the UAE is a good example of a zero-waste city, as is the large Japanese city of Yokohama, which reduced its waste by 39% between 2001 and 2007, despite the city growing by 165,000 people during this period. They reached their goal by raising public awareness about wasteful consumption and through the active participation of citizens and businesses. In Australia, the *Zero-Waste SA* initiative by the South Australian government is highly commendable [33].

2.6. Behaviour Change for Waste Prevention

The growth of the economy cannot continue endlessly (a fact already pointed out by [34]). Our increasing affluence allows us to accumulate massive amounts of stuff, and we build increasingly larger dwellings to store it. So the core question is about how to best change behavior and shift attitudes to reduce consumption (and therefore avoiding the creation of waste in the first place). How do we convince society to consume less? Education programmes aimed at all levels of schooling have proven to be effective. Public education aimed at 'zero waste' participation is surely a key to success. Changing behavior is easier in smaller towns, but is more difficult in large cities. As has already been pointed out, education to raise awareness is essential, but equally important is that the rules of waste separation are well explained. This suggests that the real problem is not technology, but acceptance and behavior change. What is needed is social innovation rather than a sole focus on technological innovation. The necessary connection between waste policies and emission reductions are not always well understood and made.

So, what are the main barriers to *zero waste*?

- Short term thinking of producers and consumers
- Lack of consistency in legislation across the states
- Procurement *vs.* sustainability: the attitude that the cheapest offer gets commissioned
- Lack of community willingness to pay

The increase in world flows of scrap, e-waste, recovered plastics and fibres has turned developed countries into a source of material supply for informal trade in emerging countries [35].

2.7. Introducing Product Stewardship: Consumptive Lifestyle Decisions and Household Practices

There is a clear need for designers to focus more attention on the throughput of material goods consumed in our everyday life rather than just end use energy consumption [36-38]. *Product stewardship* refers to the responsible management of manufactured goods and materials. On the production side, product and industrial designers are critical for stewardship models that go beyond materials recycling (e.g., extended producer responsibility), however, until now design issues have not figured strongly in product stewardship schemes, and there is not enough attention to product stewardship of new goods and their disposal at the end of use.

Drawing on social practice theory [39-44] consumption within the household can be explained as the outcome of the relations between household routines and surrounding material systems of provision. For product/industrial designers, social practice is a relatively new area of study, and practice-orientated design is only slowly moving beyond the tradition of designers (just focusing on products in isolation)—instead acknowledging that "material artefacts themselves configure the needs and practices of those who use them" [45].

However, achieving net reduction in material and energy flows implies changes in design and household practices, and the introduction of product stewardship models. Current household practices around the acquisition, use and disposal of common household furnishings and electronic goods depend largely on household type and urban context, including house size and location to public transport. Dey *et al.* and Perkins *et al.* note that household practices and consumption vary across households and their urban contexts (e.g., suburban dwelling versus inner-city apartment) [46,47]. Products themselves place constraints on how householders may exercise stewardship responsibilities, which indicates that household decisions concerning product stewardship, acquisition and divestment are mainly influenced by a range of factors including the physical spaces of the home, issues of wealth and social status (life stage), cultural values and habits established over time. There is still a need for more research in the question, how can product stewardship be extended through new product design in order to explicitly include household consumers' acquisition and better use of products as well as end of life disposal options.

3. Case Studies of Waste Management

The following case studies include details of how some cities and regions are trying to overcome the barriers to achieving 'zero waste'. The cases are looking at waste stream management in the developed world (Australia and Denmark) and at two large cities in the developing world (Delhi and Cairo, both rapidly expanding cities).

- Case 1: South Australia's leadership in waste management and resource recovery

South Australia, over the last five years, has produced a document on zero waste principles, the 'Draft South Australia's Waste Strategy 2010–2015' [48]. The strategy offers strong guidelines for SA's waste recycling and waste avoidance efforts, and has a five year timeframe. The strategy's focus is on two objectives: 'Firstly, the strategy seeks to maximize the value of our resources; and secondly, it seeks to avoid and reduce waste.' These two objectives are inter-related, and some actions apply to both objectives, proposing new targets for municipal, commercial and industrial and construction and demolition waste streams. *Zero Waste SA* is one of the few zero waste government agencies in the world and is at the forefront of waste avoidance in Australia. Zero Waste SA was established in 2003 and is financed by government levies from landfill. The agency pioneered the introduction of the ban on checkout style plastic bags in Australia, in May 2009, and formulated the campaign slogan: 'I recycle correctly and everyone wins'.

To be able to increase recycling and to reduce consumption, we need to fully understand the composition of household waste. Only by separation at the source (point of waste creation), can we reach high recycling rates. Interestingly, recent research at the UniSA indicates that the composition of waste varies according to the income level of the people producing the waste. For instance, the amount of food waste tends to be greatest among lower-income earners (this is because as income increases there is generally less food waste as consumers purchase greater amounts of prepared food relative to fresh food).

The SA Draft Waste Strategy policy is no unique case or exemption. All of the European Union member states must compile a waste prevention programme by the end of 2013, as required by the 2008 revision of the 'Waste Framework Directive'. The EU guidelines are intended to support the formulation of such programmes based on 30 best practices identified by the European Commission.

- Case 2: The waste situation in New South Wales, Australia: a looming crisis?

Australia is the third highest generator of waste per capita in the developed world. In July 2006, only around 50% of waste collected in the state of New South Wales (NSW) was recycled. Of course, it's always cheaper to simply bury waste than to treat it, but that has dangerous side effects. For instance, electronic waste is still filling up Australian and US landfills (something not allowed in the EU for 10 years), contaminating soil and groundwater with toxic heavy metals. In the meantime, a waste crisis is looming: the City of Sydney's four landfill sites (Eastern Creek, Belrose, Jacks Gully and Lucas Heights) are reaching capacity and will be full by 2015, according to a recent independent *Public Review Landfill Capacity and Demand Report* [49]. The city's annual 2 million tonnes of waste will have to be moved 250 km south, by rail, to Tarago. For a long time, the state government has been inactive and has failed to make the recycling shift. It lacks recycling policies and investment in recycling technology. Recycling needs to be made cheaper than land filling, and strong economic incentives are required, as are strategies to get households to dramatically reduce the creation of waste (for instance, by reducing bin sizes, raising awareness and by introducing the three-bin system to separate organic/garden waste, recycling, and residual waste).

The situation in the UK is similar. Mal Williams, CEO of Cylch (a major recycling company in Wales, UK), points out that '90% of household waste is actually reusable without the need for incineration. Waste means inefficiency and lost profit for all' [50].

While Sydney's landfill sites are rapidly filling up, and the NSW government has currently no clear plan to address the crisis, Sydney's waste is forecast to keep growing by at least 1.4% a year (due to population increase and increasing consumption). Curbside recycling collected in NSW increased from 450,000 tonnes in 2000 to 690,000 tonnes in 2007. To make things worse, the NSW government rose over $260 million in waste levies but returned just 15% ($40 million) of that to local councils for recycling initiatives [51]. By contrast, the state government of Victoria gives better support: it raised $43 million in landfill levies and gave it straight back to the agencies responsible for waste management. Despite the smaller levy, Victoria recycled almost 20% more waste than NSW in 2009. The federal government will introduce a *National Waste Policy* in 2011 (aiming for a 66% landfill reduction by 2014) and hopes are high that this will bring about the urgently required changes.

- Case 3: Waste management case study from Aalborg, Denmark

Developed countries such as Germany, Japan and Denmark are worldwide leaders in waste management. For instance, in some Japanese municipalities up to 24 different categories of waste are separated.

It is timely that we better integrate the linkages between material flow, use and recovery with energy and water consumption. To date, little research has been done on measuring the impact of waste treatment systems themselves and waste management changes over the longer term. For instance, the Danish city of Aalborg has proven that better waste management can reduce greenhouse gas (GHG) emissions and that a municipality can produce significant amounts of energy with sustainable waste-to-energy concepts. Two Danish researchers, Poulsen and Hansen, used historical data from the municipality of Aalborg to gain a longer-term overview of how a ‘joined-up’ approach to waste can impact on a city’s CO_2 emissions. Their assessment included sewage sludge, food waste, yard waste and other organic waste. In 1970 Aalborg’s municipal organic waste management system showed net GHG emissions by methane from landfill of almost 100% of the total emissions. Between 1970 and 2005, the city changed its waste treatment strategy to include yard waste composting, and the city’s remaining organic waste was incinerated for combined-heat and-power (CHP) production. Of this, waste incineration contributed 80% to net energy production and GHG turnover, wastewater treatment (including sludge digestion) contributed another 10%, while other waste treatment processes (such as composting, transport, and land application of treated waste) had minor impacts. ‘Generally, incineration with or without energy production, and biogas production with energy extraction, are the two most important processes for the overall energy balance. This is mainly due to the substitution of fossil fuel-based energy,’ says Poulsen. The researchers calculated that the energy potential tied up in municipal organic waste in Denmark is equivalent to 5% of the country’s total energy consumption, including transport. They also predicted that further improvements by 2020 were possible, by reducing energy consumed by wastewater treatment (for aeration), increasing anaerobic digestion, improving incineration process efficiency and source separating food waste for anaerobic co-digestion.

Understanding of natural systems, this is a pioneering demonstration on how technology can be harnessed to resolve environmental challenges. Aalborg’s progress shows how far-reaching waste management can be in attaining energy and GHG reduction goals, and should offer encouragement to other cities embarking on greener waste management strategies for the future [52,53]. The potential for emission reduction in waste management is very big. It is estimated that within the European Union, municipal waste management reduced GHG emissions from 64 to 28 million tonnes of CO_2 per year between 1990 and 2007, equivalent to a reduction from 130 to 60 kg CO_2 each year per capita. With such innovation in waste treatment, the EU municipal waste sector will achieve 18 % of the reduction target set for Europe by the Kyoto agreement, before 2012.

4. Scarcity of Raw Materials, Metals, Resources

4.1. Using Fewer Materials to Better Exploit the Value of Waste

Energy cost is not limited to heating or cooling energy or lighting energy; it is also related to all material flows relevant to buildings. For instance, waste from the production of construction materials and components can be much greater than all other waste streams. To make it easier for architects and planners to specify materials according to their impact (including impacts caused by material extraction, or waste creation from the production process), information on materials and components needs to be readily available. Different from the *Club of Rome*'s warning of 1971, today, the 'limits of growth' are defined by climate change and the depletion of material resources. We see an increasing challenge through the scarcity of raw materials, especially metals such as lead, copper and zinc. With natural resources and materials about to run out, we need better resource protection and more effective ways to use them. Several essential metals and resources are already becoming less available, e.g., most platinum, zinc, tantalum, lead, copper, cadmium, wolfram and silicon is concentrated in the hands of three countries, under the control of three large companies. This will soon create major challenges for industries in Europe and the US that use many of these metals in their manufacturing (such as televisions or computers). In a resource-constrained future we will see more:

- recycling-friendly designs, with extended producer responsibility,
- multiple-use (multi-function) devices and expanded product lifecycles,
- long-life products and buildings, with optimized material use,
- products using less packaging,
- a variety of ways to avoid the loss of resources during the product's life-cycle,
- resource recovery through forward thinking reuse, remanufacturing and recycling.

Waste that contains precious minerals, rare earth, metals and other nutrients is now understood to be valuable, and organic waste must be returned to the soil. The survival path and rebound effect of materials is understood as extremely critical. Will our landfill sites of today become the 'urban mines' of the future? We can observe the emergence of a new sustainable industrial society, where new industrial systems are introduced that better reuse and recycle waste, and which are based on a new circular flow economy [54,55]. In the meantime, the depletion of several natural deposits is drawing closer. In 2008, the *Institut der Deutschen Wirtschaft* (IDW) estimated the availability and coverage of essential resources and selected metals, as part of a risk assessment for the German industry in response to the threat caused by scarcity of raw materials [56,57]. It found:

Lead	20 years reserves available, estimated
Zinc	22 years
Tantalum	29 years
Copper	31 years
Cadmium	34 years
Wolfram	39 years
Nickel	44 years

These metals are becoming scarce and consequently more expensive, e.g., iron ore, lithium and copper are already much rarer than oil. In addition, it is also important to know what kinds of products we buy. For instance, 40% of the products in our weekly shopping basket contain palm oil, which, if not produced sustainably, can cause deforestation of ecologically precious rainforests. A more conscious use of materials, metals, resources and products is an imperative, supported by reuse and recycling.

Cities are resource-intensive systems. By 2030, we will need to produce 50% more energy and 30% more food on less land, with less water and fewer pesticides, using less material [58].

4.2. The Need for Changing the Practice of Packaging with a 'Product Stewardship' Programme

There is a growing need for use of truly compostable packaging, where everything that arrives at the consumer is useful and does not create waste.

In future, with extended producer responsibility (EPR) the user of packaging will have to pay for the collection of that packaging [59]. The rising costs of waste from landfill levies will become its main driver. Essentially, one needs to ask: How much packaging is really necessary? Can the product be packed in another way? There is a need for leadership from a select group of companies (this is usually not more than 5% of all companies) to show how packaging can be reduced, or how products can be taken back from the consumer once the end of life-cycle has been reached, as is done with old tyres. Ikea and Woolworth have been setting new standards in this area, and BASF only puts new products on the market when there is evidence that the new product has a better life-cycle assessment than the previous one. There have been innovative recycling initiatives for mattresses, bicycles, carpets, paints, construction timber and furniture. We will need more products to be manufactured differently to how they are made now, with zero waste concepts in mind and also taking the extended producer responsibility principle seriously. In the US, 44% of all greenhouse gas (GHG) emissions result from transporting and packaging products, illustrating the large potential in this field.

5. A Lack of Waste Management Frameworks in the Developing World

5.1. Informal Waste Recycling Sectors in the Developing World

A staggering 95% of global growth over the next 40 years will happen in Asia, Africa, Latin America and the Caribbean, according to the Population Reference Bureau's 2009 *World Population Data Sheet*.

There are ways to improve waste management and change behaviour in developing countries, even if there is no budget for it. For instance, in Curitiba, Brazil, innovative waste collection approaches were developed, such as the 'Green Exchange Programme', to encourage slum dwellers to clean up their areas and improve public health. The city administration offered free bus tickets and fresh vegetables to people who collected garbage and brought waste to neighbourhood centres. In addition, children in Curitiba were allowed to exchange recyclables for school supplies or toys.

Cities always need to find local solutions for waste management appropriate to their own particular circumstances and needs. In Delhi there is an army of over 120,000 informal waste collectors (so-called *Kabari*) in the streets, collecting paper, aluminum cans, glass, and plastic who sell the waste to mini-scrap dealers as part of a secondary raw materials market.

It is an informal industry which processes 59% of Delhi's waste and supports the livelihood of countless families. In the Indian capital city, the private sector does the waste management and the business of collecting and recycling is a serious one for many of the poor, and a relatively lucrative source of income. According to Bharati Chaturved, one out of every 100 residents in Delhi engages in waste recycling. Chaturved also estimated that a single piece of plastic increases 700% in value from start to finish in the recycling chain *before it is reprocessed*. This informal sector of waste collectors saves the city's three municipalities a large amount of costs of otherwise arranging waste collection, particularly in inaccessible slum areas. In Delhi, more than ninety-five % of homes do not have formal garbage collection [60].

For countries like India or Bangladesh, the introduction of an industrialized clean-up system and perfected infrastructure like in the developed world would take jobs from thousands of poor peasants who are willing to work hard and get dirty collecting and recycling the waste of the metropolis in order to feed themselves. An estimated six million people in India earn their livelihood through waste recycling. On top of a low standard of living, they now face joblessness with India's new business-model approach to waste management—replacing the preexisting informal Kabari system with a model from developed countries. It is an area where India and Bangladesh could probably learn from their neighbour China, since their cities have similar population densities [61].

Another interesting example for the informal waste management sector is the city of Cairo, the capital of Egypt, which has grown to over 15 million people and is one of the most densely populated cities in the world (with 32,000 people per sq mile). The economy of 'Garbage City' (Manshiyat Naser, the Zabaleen quarter), a slum settlement on the outskirts of Cairo, revolves entirely around the collection and recycling of the city's garbage, mostly through the use of pigs by the city's minority Coptic Christian population. Although the area has streets, shops, and apartments, like any other area of the city, it lacks infrastructure and often has no running water, sewage or electricity. The city's garbage is brought in by the garbage collectors, who then sort through the garbage to retrieve any potentially useful or recyclable items. As a passer-by walks down the road he will see large rooms stacked with garbage, with men, women or children crouching and sorting the garbage into what is usable or what is sellable [62].

Families typically specialize in a particular type of garbage that they sort and sell—one room of children sorting out plastic bottles, while in the next room women separate cans from the rest. Anything that can somehow be reused or recycled is saved. Various recycled paper and glass products are made and sold from the city, while metal is sold by the kilogram to be melted down and reused. Carts pulled by horse or donkey are often stacked 3 metres high with recyclable goods (see Figure 5).

The circular economic system in 'Garbage City' is classified as an informal sector, where people do not just collect the trash, they live among it. Most families typically have worked for generations in the same area and type of waste specialization, and they continue to make enough money to support themselves. They collect and recycle the garbage which they pick up from apartments and homes in wealthier neighbourhoods. This includes thousands of tonnes of organic waste, which is fed to the pigs. By raising the pigs, the Zabaleen people provide a service to those who eat pork in the predominantly Muslim country, while the pigs help to rid neighbourhoods of tonnes of odorous waste that would otherwise accumulate on the streets. Like the famous 'Smokey Mountain' rubbish dump in Manila, Philippines, could this place become an official recycling centre?

As the cases in Delhi and Cairo illustrate, the increase in world flows of scrap, e-waste, recovered plastics and fibres has turned developed countries into a source of material supply for informal trade in emerging countries.

A global paradigm shift in urban development and the use of resources is essential. Clearly, a situation where 20 % of the world's population consumes 80 % of the world's resources cannot go on forever or be allowed to continue [63].

Figure 5. Many developing countries have such active informal sector recycling, reuse, and repair systems, which are achieving recycling rates comparable to those in developed countries, at no cost to the formal waste management sector, saving the city as much as 20% of its waste management budget. Cairo, for instance, has grown to over 15 million people and is one of the most densely populated cities in the world. The economy of 'Garbage City' (Manshiyat Naser, the Zabaleen quarter), a slum settlement on the outskirts of Cairo, revolves entirely around the collection and recycling of the city's garbage, mostly through the use of pigs by the city's minority Coptic Christian population. Although the area has streets, shops, and apartments, like any other area of the city, it lacks infrastructure and often has no running water, sewage or electricity (Photo: courtesy [64]).

5.2. Composting Organic Waste and Improving Urban Ecology

Compost is an important source of plant nutrients and is a low-cost alternative to chemical fertilizers. It has become a necessary part of contemporary landscape management and urban farming, as it uses 'reverse supply chain' principles, giving organic components back to the soil, thus improving the quality of agriculture. Paying attention to the nutrient cycle and to phosphorus replacement is part of sustainable urban agriculture. Industrial composting helps to improve soils. However, a proper composting infrastructure needs to be set up. The important focus on soil, putting nutrients back into agriculture (for instance, the 'City to Soil' program in Australia). In Sweden, for instance, the dumping of organic waste to landfill has been illegal since 2005. It is essential to avoid landfill organics such as food waste. All organic waste should be used for composting or anaerobic digestion (see Figure 6).

Food waste is another major concern. 22% of all waste in Australia is food waste. New biodegradable packaging helps to facilitate processing of food waste. Biodegradable and compostable solutions for food waste recovery systems, using a kitchen caddy with a biodegradable bag that is collected weekly, has become a common solution. Iain Gulland, director of Zero Waste Scotland, points out that 'over 60% of food waste is avoidable. However, if all unavoidable food waste in Scotland was processed by anaerobic digestion, it could produce enough electricity to run a city in size of Dundee' [65]. In South Australia more than 90,000 tonnes p.a. of food waste goes to landfill (on average, each household throws out 3 kg food waste per week). This needs to be taken out of the waste stream and diverted into composting or anaerobic digestion systems [66].

Figure 6. Photo: Organics recycling is important to return nutrients back to the soil, and there are new process improvements on a massive scale. Metropolitan green organics are collected through council curbside and industrial collections, as well as food organics (food scraps) from hotels, restaurants and supermarkets; composting and mulching transforms the material into a range of high-quality compost, mulch and soil products, to be returned to gardens and parklands (photo: [67]).

6. Conclusions and Outlook: Making Zero Waste a Reality

6.1. Decoupling Waste Generation from Economic Growth

Because cities are the main consumers of energy, materials, food and water, it is essential that the delivery of urban services (including waste stream management and resource recovery) is as efficient as possible. The efficiency and effectiveness of urban services is greatly affected by the urban land-form (for instance, the low densities and mono-functional layout of suburbs is leading to highly inefficient conditions, often an increase in consumption and contributes to the problem).

Increased material and energy consumption in all nations, coupled with an inadequate and unsustainable waste management system, has forced governments, industry and individuals to put into practice new measures to achieve responsible, closed loop solutions in waste management and resource recovery. Achieving 'zero waste' remains difficult and requires continued and combined efforts by industry, government bodies, university researchers and the people and organizations in our community.

The topic of reducing urban household consumption by optimising urban form, and the need to reducing the material requirements for buildings (in fact, of the entire construction sector) has only recently emerged as an urgent field of further research [68]. While there is a general acknowledgment that there is a need for improved urban governance processes and rethinking of urban development patterns to reduce material consumption and optimize material flows, this is still a relatively new research field and there is still a lack of reliable data and comparative methodologies. One of the findings of this paper is that embedding 'zero-waste' requires strong industry leadership, new policies and effective education curricula, as well as raising awareness (education) and refocusing research agendas to bring about attitudinal change and the reduction of wasteful consumption. Unlimited consumption and growth on a planet with limited resources 'cannot go on forever and is indeed dangerous' [69].

The construction and demolition (C&D) sector has a particularly urgent need to catch up with other sectors in better managing its waste stream, to increase its focus on reusing entire building components at the end of a building's life-cycle. In Australia, for instance, around 40% of all waste to landfill comes from the building sector [70,71]. Increasing the economic value of recycled commodities, such as rare metals in e-waste, paper, glass and plastics, remains an area for future development and investment.

Energy markets will soon compete with material markets for resources. The recycling sector in Germany employs already over 220,000 people in green jobs (2010). Waste is increasingly being seen in terms of economic sustainability, and it is a policy issue that offers great opportunities for the creation of green jobs.

A particular challenge in waste management is soil degradation. Composting methods are important to return nutrients from organics back to the soil. However, the anticipated global decline in the availability of phosphorous ('peak phosphors'), which is currently lost as waste from urban areas, however, is a vital nutrient for food production.

This paper has touched on some of the complexities around sustainable urban metabolism, waste management and the links between waste streams, urban development, as well as the need for resource recovery. The three case studies are hopeful models of what could be achieved in Adelaide (Australia) and Aalborg (Denmark). These cases are of limited value for the developing world and large, rapidly expanding cities such as Delhi, Cairo and cities in China. Here, the informal sector of waste management deserves a closer look and more research focus. The import of waste to developing countries is obviously another interesting but complex issue: on one side, we criticize developed countries for their export of pollution, on another side; developed cities provide raw materials for workers in developing countries to mine urban waste. These informal sectors might even hold some lessons for cities in the developed world. Due to their greater consumption levels, cities in the developed countries have much higher material and energy consumption, despite the increase of resource efficiency [72-74].

The developing world is fast catching up with consumption levels and will continue to increase its hunger for resources. China, for instance, is urbanizing faster than any other country ever before in history, requiring a huge amount of non-renewable materials, energy and water for the production of the consumer goods, and increasingly contributing to the depletion of raw material resources. The 'new consumer' in Asia, who is part of a newly emerging middle-class, with resource-intensive lifestyle habits, materialistic behaviour and mobility needs, contributes to and accelerates the development. Most of the consumption is going to be in cities. We can define a formula: The environmental impact (I) is a result of the increasing affluence/consumption power (A), a growing urban population (P) and the availability of technology (T). The suggested formula is: $I = P \times A \times T$.

It is essential that we continue to reduce wasteful consumption, to avoid the creation of waste in the first place (waste minimization through avoidance), to promote the cyclical reuse of materials in the economy and to maximize the value of our resources to make resource recovery common practice. Waste is a precious resource. The challenges posed by climate change and the depletion of resources are complex—but as a society we have the skills, knowledge and determination to achieve the necessary changes. Change to behavior, long-held planning habits and design attitudes will be necessary. In his latest book 'A Final Warning', James Lovelock outlined the urgency and that time is critical [75-78]. In 2010, 6.8 billion people on the Earth consume resources, energy and materials in an ever increasing pace and volume. It is therefore essential to utilize 100% of all used resources as new resources, and embed the sustainable city paradigm, while drastically raising the efficiency of the use of resources, energy and materials (see diagram Figure 7).

In the meantime, nothing less than a peaceful revolution has started, changing the way we design, build, operate, maintain and recycle/renew cities and buildings. The urbanization process has emerged as the incubator and platform for revolutionary change: holistic strategies and integrated approaches for urban development indicate that *post-fossil fuel cities* can and must become the most environmentally-friendly model for inhabiting our earth. Waste avoidance has to be considered as one of the main drivers for architectural and urban design. In this context, our objective must be to reconcile the scarcity of our natural resources with the huge quantities of waste produced by our cities and industries, waste which we must, unfailingly, recover [79-81].

Figure 7. Diagram: Waste management is an important key stone in the effort towards achieving holistically a 'Sustainable City' (Diagram: [82]).

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levy varies widely from state to state, between $30 and $60 per tonne. The recycling costs will always be more than landfill costs (except for steel, aluminum and other metals, which have high embodied energy and can easily be recycled). As material values of metals increase, the resource recovery for precious metals is likely to assist in increasing recycling rates.

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19. *World Population Growth Forecast*, 2010; United Nations Human Settlements Programme (UN-Habitat): Nairobi, Kenya, 2010. Note: Global world populations in 2010 were 6.8 billion. It is predicted by UN-Habitat to increase to 9 billion by 2050. While the population in some countries is shrinking (Japan, Germany, Italy, Russia), other countries, such as India, have a fast growing population. The population in India is forecast to overtake that of China's by 2050 (India is predicted to have 1.6 billion people). We will soon reach the limits of the Earth's 'carrying capacity' (what Rees and Wackernagel call 'overshooting', 1996), for instance, the Earth's reduced capacity to supply fresh drinking water to all citizens of a city (as we have seen in Sub-Saharan African cities and in Mexico City). The world's population has been growing significantly since around 1800 due to the improved control of diseases and longer life expectancy. As a consequence, numerous scientists recommend halting further growth in cities in arid, hot climatic regions. At the same time, global agriculture is approaching a natural limit. While the amount of food production needs to keep increasing in pace with population growth, there is hardly any undeveloped farmland left on the planet. Experience shows that birth rates fall when women are well educated, when they aspire to a career, or when they chose to marry later and to have only one child. Clearly to slow down this immense population growth and to delay a food/water/energy supply disaster, we have to succeed in three important areas: reducing consumption and changing behaviour; improving technology; and limiting population growth through education programmes.
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