Industrial ecology and waste infrastructure development:
A roadmap for the Dutch waste management system

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Abstract

Decision-making on waste infrastructures is difficult because waste management is a complex, politically loaded and emotionally charged issue that is neither well structured, nor well understood. While sustainability is the ultimate goal of the EU environmental policy, there is no commonly accepted approach for its realisation. Industrial ecology has been suggested as a roadmap to sustainability. Its prescriptive tier can provide organising principles for more sustainable practices: closed material cycles, cascaded energy use and flexible system configuration. The engineering concepts, grade and recovery, provide a simple yet powerful means to assess policies and infrastructure concepts with respect to sustainability. When combined, industrial ecology and engineering yield sound infrastructure design specifications and decision-making support for waste infrastructure. © 2006 Published by Elsevier Inc.

Keywords: Industrial ecology; Waste management; Waste policy; Recycling; Residue grade; Sustainability; Infrastructure development; Roadmap

1. Introduction

While sustainable development is the ultimate goal of EU waste policy, there is no commonly accepted approach to accomplish this objective. In this paper, a combination of industrial ecology
principles with the practice of engineering is investigated to make the concept of sustainable development operational. The operational concept is then applied to the Dutch waste system to evaluate and specify waste infrastructure design for sustainable development, and to test the applicability of such synthesis to support the decision-making on waste infrastructures.

1.1. Waste infrastructure

Infrastructures contain the basic facilities of a system, country, society or organization, which enabling it to function. For countries, infrastructures comprise large-scale technological systems that consist of immovable physical facilities, and deliver an essential public or private service through the storage, conversion and/or transport of certain commodities [1]. The essential service the waste infrastructure delivers concerns the removal, disposal and recovery of municipal solid wastes (MSW). The waste infrastructure is the set of physical facilities necessary/dedicated to perform that function.

Since the 1970s the waste infrastructure has become an increasingly critical infrastructure. Sound waste management is an integral part of environmental protection [2]. Improper disposal of municipal waste can result in unsanitary conditions, which in turn can lead to pollution of the environment and to diseases. Robust, durable infrastructures have been constructed to safely dispose off the waste generated, and minimise impacts on environment and public health. These infrastructures include waste collection systems, a network of transshipment and separation points, and a limited number of disposal options such as landfilling, incineration and composting.

Generally, waste is collected in a multi-stream collection system. Each waste stream is transported via various transshipments and/or pre-treatment nodes that have a buffer function also. To a limited extent also sorting of waste occurs after collection. As illustrated in Fig. 1, final disposal of the remainder, the non-separated waste, is limited to a number of allowable operations, viz. landfill, incineration and composting. The waste infrastructure converts remaining waste into electric power and heat, fertiliser, and ashes usable in road construction and cement production. Final residues must be landfilled. Besides those obtained from separate collection systems, and some scrap metals and electricity, the resources recovered are of relative low quality. Current waste management represents an enormous loss of

![Diagram of waste infrastructure](image)

Fig. 1. A schematic of the Dutch waste infrastructure. Figures indicate material flows involved.
resources both in the form of materials and energy [3]. To prudently manage these resources, restructuring of current waste management practice and infrastructures is required. In addition, the amount of waste that must be processed is increasing, and the sheer quantity of waste is a problem (EEA 1999) for the capacity of waste management infrastructures. Illustrative is the case of the Netherlands. Between 1996 and 1998 the generation of household wastes increased from almost 6.2 million tonnes to over 6.6 million tonnes annually and – in a no-action scenario – the supply of MSW is expected to increase to over 8.5 million tonnes in 2011. This will bring total combustible waste to about 9 to 9.5 Mt/a [4]. The current incineration capacity of 5 to 5.5 Mt/a is not sufficient, and infrastructure must be expanded. The increasing range of environmental measures and policy targets, however, complicates the construction of new infrastructures.

1.2. Dutch waste policy

A crucial question for the Netherlands is how EU regulation affects the infrastructure capacity because of the ongoing European unification. Objectives of the environmental policy are ‘starting points’ for a sound waste policy. Accents in European environmental policy have shifted over time based on new insights. Sustainable development, connecting (among others) the problems of climate control, prudent resource management and economic growth, has become the policy issue. Whereas in the past waste policy focused mainly on management and development of disposal, it must now concentrate on recovery of wastes to meet its new objectives. A single European market for waste disposal is expected around 2005. The ‘free transport of goods’ principle of the EU already applies for wastes intended for recovery. Comparable environmental standards in other surrounding countries are a condition for the Netherlands to also enter a common market for waste disposal.

1.3. Decision-making on infrastructure

Waste management is a complex, politically loaded and emotionally charged issue that is neither well structured nor well understood [5,6]. Decision-making on infrastructure is complex because of the many stakeholders, the fuzzy, often conflicting objectives, perspectives and interests, and the size and ambiguity of the system at large. Improved separate collection and recovery initiatives would mean that less waste has to be disposed off, and that fewer investments in infrastructure may be necessary. The Dutch Waste Management Council (AOO) established a moratorium on incineration capacity to create space for new recovery initiatives and to delay decision-making on infrastructure in anticipation of the different economic settings. However, in spite of separate collection of wastes and large campaigns for waste prevention and reduction, a considerable heterogeneous waste stream is disposed of through landfilling and incineration (e.g. [7]). The municipal waste separation targets were not met, and the foreseen capacity shortage prompts a reconsideration of the moratorium. The expected market introduction, however, may significantly change waste supply in the Netherlands because of competition with other countries.

To prepare the Dutch infrastructure for the expected market situation, extensive stakeholder and environmental impact assessments were carried out. These served as a basis for the Dutch waste management programme (LAP). In the programme increase in wastes quantity is tackled through the stimulation of avoided CO₂, and the early introduction of the common market for combustible waste, and lifting of the ban on expansion of MSW incineration capacity in 2003. The national borders for
waste intended for disposal are opened in 2006. Market introduction, and stimulation of avoided CO₂ – through the replacement of fossil fuels by waste – is expected to yield initiatives for recovery of high calorific waste as a fuel for co-incineration and energy generation. Furthermore, ‘free transport of goods’ principle allows a better match between available infrastructure capacity and waste supply across Europe. Minimum standards for the processing of different types of waste must ensure a high quality of waste processing under the market regime.

This appears to be only one part of the solution. Since a commonly accepted recipe to accomplish sustainable development is not available, the efficacy of the MSW policy and infrastructure is difficult to assess. In theory, a sound policymaking process should provide for thorough assessment, followed by a careful balancing of scientific evidence and policy goals. However, often there are both conceptual and practical difficulties in collecting factual data and linking them in a meaningful way to the impact of policy instruments [8]. Financial incentives to improve separate collection have not been successful as hoped. In the Netherlands, municipalities charge customers for bringing their waste to a collection station, according to weight or classification, a so-called differentiated tariffs (DIFTAR) programme. With the introduction of the DIFTAR system in municipalities, recovery of glass increased. The glass quality decreased, however, due to an increase of heavy, non-glass objects in the glass containers. Another adverse effect was waste tourism by consumers to the next village not participating in the programme. In order to direct changes in the waste infrastructure to a more sustainable practice, the ambiguous concept of sustainable development must be made operational. Particularly in the envisaged market situation where the role of governments changes from executor to director of the waste service, and policy outcomes are harder to predict. To enforce a sustainable development, the waste system, and the concept of sustainable development itself, must be well understood.

2. Industrial ecology

Industrial ecology, the analogy between living and industrial systems, has been suggested as a roadmap to sustainability. Its prescriptive tier [9] provides organising principles for more sustainable practices. Although it is unclear to what extent the analogy is applicable for structuring of industrial systems and infrastructures, some universal organising principles of natural systems can be used as the basis for more sustainable system configurations.

2.1. Ecosystems

Ecosystems are the unit cells of natural organisation. An ecosystem consists of all the plants and animals that live in particular area (biotic part), together with the complex relationship that exist between them and their environment (abiotic part). In ecosystems each individual generates products and wastes, which are directly or indirectly input for activities of other individuals. In a mature ecosystem materials are used in cyclic way: production and recovery are in balance. The analogy implies that waste management and industrial production systems should be complementary. Outputs of the waste infrastructures must be compatible with the input requirements (grades) of the production system. Those materials that cannot be used any longer must be processed into nature compatible substances, both in quantity and composition. Ecosystems are also characterised by cascaded use of energy to maximise the work obtained from the energy source. Configuration of the waste management and production system
should facilitate the exchange of energy between processes and consumer activities either as heat or stored in materials. Finally ecosystems evolve, as opposed to constructed or designed industrial, or infrastructure systems.

2.2. Bioavailability

Current waste management infrastructures and industrial production systems have not developed according to these principles. There are only two long-run fates for waste materials: recycling and reuse, or dissipative losses [10]. The amount of dissipative losses of materials and heat from an economy indicates how sustainable, or rather unsustainable, that economy is [10]. In addition to dissipation, the metaphor of bioavailability can be employed to make the concept of sustainability operational. Similar to plants in our industrial systems, the biological entities form the ‘engine’ of the material cycles, which are mainly fuelled by solar energy. Materials that become biologically unavailable will be lost from the material cycles. The proxy material loss, or rather loss of economical availability of materials, can be used for sustainable development. Waste management covers a large share of the economic loss of materials from production and consumer activities, and can contribute considerably to sustainability. Application of the principles shows that to date, however, the contribution has been limited. Dissipation through waste infrastructure is still considerable, large amounts of waste are incinerated and the bulk of materials dissipate into thin air as carbon dioxide, water, and other emissions. A substantial share of waste is not recovered, but transformed in material mixes with low economical availability. A number of recovery operations produce and involve the use of low-grade construction material. This ignores potential (calorific and) material capital in the waste. Waste management should not only focus on maximising recovery; the produced grades are equally important.

2.3. Infrastructure development

Whereas traditionally wastes infrastructures were designed as reliable, but rigid collection and disposal systems, new infrastructures must be flexible enough to support a continued conversion of wastes into marketable (or process compatible) resources. A combined design according to the principles of ecology, an eco-industrial network, can be expected to be more flexible by analogy with natural ecosystems. In contrast, the opposite is also observed. The ecosystem features – cyclic use of material and cascaded use of energy – require high levels of organisation and interdependence that may partly cancel out the flexibility of such a system [11,12]. Sagar and Frosch [11] for example notice that industrial ecological park ‘Kalundborg seems to have developed locked-in, rigid relationships’ and expect that this will be a ‘problem in the long run since the evolved design of this ecology is based on static optimisation’, which sometimes is ‘difficult or expensive to adapt to new conditions’. Although it is still unclear to what extent Kalundborg has developed locked-in relationships, considering the flexibility of the system configuration seems particularly important when designing systems for long time spans such as waste and other infrastructures.

Ecosystems develop and adapt in response to changes at different rates and system levels. The adaptation of a single organism, or of relationships between organisms and resources yields increasing complex system configurations. In turn, the system configuration can determine the behaviour of the individual. The rate of change is dependent on the dynamics of the surroundings, but also on the role of the organisms in the ecosystem. Integrated complexes, such as Kalundborg, refineries and integrated
petrochemical and metallurgical complexes, generally developed slowly to high levels of integration. In relatively stable situations, e.g. stable demand for metals, and oil-based products, they adapted to changes in regulation and competitive position. Adaptations at plant level, or between plants yielded in increasingly interconnected and interdependent system configurations over time. Besides slow development, these integrated complexes, furthermore, share another interesting characteristic with infrastructures: they provide basic intermediates for other industry, which enable the industrial production system to function. These intermediates are then processed in an ever-changing mix of products by a changing set of processes.

This analogy implies that reduced flexibility is not necessarily a problem for the design of waste infrastructures. Since MSW is considered an extremely difficult stream to directly apply in industrial processes [3], it provides for the constant supply to built infrastructures upon. This would favour an infrastructure that reduces heterogeneity of MSW, and converts it into grades (the quality of raw materials and intermediates) of which the bulk would be economically available to industry. The remainder must at least be compatible with nature, allowing for safe disposal. However, because MSW is heterogeneous, and its composition and quantity change over time, an infrastructure design that performs well under such changing conditions is a challenging task. In the next section, it is investigated how the MSW collection infrastructure design can be optimised according to these principles.

3. Optimisation collection infrastructure for recovery

Application of the above described principles would call for an optimisation of the separation and disposal system using input specifications of plants and compatibility with air, water and soil as boundary conditions. Engineering principles for separation systems (e.g. [13]) teach that at plant level it is not efficient to first mix different streams, and separate them afterwards downstream, which would favour separate collection. Such engineering principles can be extrapolated to a larger system, such as waste management, support the complex decision-making on the waste infrastructure that involves technical considerations, regulations, logistics, economics and public motivation. Engineering practice is providing a convenient way to describe the separation system for primary and secondary materials, as illustrated in Fig. 2.

The figure describes the relationship between grade and recovery. Digre [14] has introduced this relationship for mineral separations, which has, for example, been applied in mineral processing

Fig. 2. Relationship between grade and recovery.
operations at plant level for the recovery of copper ores [15]. Ideally, a separation develops along the arrows to the upper right corner, the situation where the recovery and grade of the process are 100%. From practice we know that this situation cannot be achieved for both parameters at the same time in a single operation; the separation process rather follows the curve. Recycling activities are better understood with this constraint kept in mind. It can be shown that with advanced techniques combined with an effectively organised infrastructure both grade and recovery can be maximised for secondary materials.

3.1. Household waste

The coherence between grade and recovery can best be illustrated by the practice of collecting household waste. First a simplified short historical overview is given. Household waste has been collected in the Netherlands for decades at the curbside and for a period of 30 years after World War II physical separation was not an issue. All the waste from households was collected and was transported to landfill sites. In terms of grade and recovery it means that all the waste is recovered (100%), however, each constituent in the waste has a low grade. Point A in the right lower corner of the curve in Fig. 2 represents this situation. Separation efforts starting from this composition cannot be successful. To escape from the constraint and achieve both a high recovery and grade one has to take the one graph apart into two separate graphs (Fig. 3). The practical equivalent of this split is selective collection of one component effecting a less complex waste. Selective collection starts at B in the right graph and consequently improves the grade of A along the vertical arrow.

A substantial share of waste in the 1950s and 1960s consisted of biodegradable materials; other materials such as ceramics, plastics, paper, metals and glass were present in the waste at a fairly low grade. Valuable materials are recovered and sold to the local scrap metal merchant. In this period hardly any attention was given to hazardous materials. The burden of hazardous materials contained in the waste was passed on to the next generation.

In the 1970s and 1980s the waste gradually becomes more complex, due to an increasing standard of living that also generates more waste per capita. Packaging materials (plastics) are introduced and also hazardous materials are found more frequently in household waste, such as batteries, paint, oil, and electronic equipment. The overall grade or quality of the waste is decreasing caused by more different components each with a lower grade.

3.1.1. Incineration and effects on household waste

In this period incineration of waste is introduced for a number of important reasons, being the volumetric reduction and detoxification of the waste. The bottom ashes are used as a construction
material and emissions are filtered before the combustion gases are introduced into the atmosphere. However, certain components in the waste caused unexpected and undesired contamination of airborne emissions [16] and decrease the quality of the bottom ashes, the filter dust is classified as hazardous material. In order to control the emissions to air, water and soil measures have to be taken both at the source of the waste stream and at the end. At the source products are designed with less environmentally hazardous materials. The waste itself is source separated into concentrated fractions that are processed separately; at the incinerator airborne emissions are cleaned to new standards set up by the European Commission; and bottom ashes are separated and cleaned to soil-compatible material.

For the activity of waste incineration itself the requirement is set up to recover the energy contained in the waste. The input grade has to meet the incinerator specification with regard to calorific value, heavy metals, halogens in order to let the incinerator meet the output requirements for emissions to air, water and soil. These two conditions will transform incinerators into power plants whereas on the other hand power plants will be fuelled increasingly with secondary high calorific materials instead of primary fuels.

3.1.2. Glass collection and the implication for household waste

Concurrent with the above developments for a number of waste materials a selective collection system is set up. One successfully developed programme is glass collection. The activity of glass collection has a number of major consequences for the grade and recovery of both this material and for the remaining household waste. The collection of glass started at a low scale in Rotterdam in the early 1970s. The secondary glass was almost pure as it was obtained from a local production unit and the total recovery at

Fig. 4. “Grade” improvement of household waste caused by the separate selective collection of glass. Glass bottle banks collect the material with a high grade, a more intense collection in time will be at the expense of purity.

Fig. 5. The glass content of household waste has decreased over a period of 30–40 years from 12% to 3.5%, other materials show similar trends [17]. The remaining waste improves in quality to a mixture that allows to be processed technically.
national scale was low. The horizontal arrow in Fig. 4 describes this process. Presently one of the highest recovery rates in Europe is achieved (92% in 1999) through a comprehensive transportation and collection system combined with continuous motivation and information campaign to the consumer.

The grade of glass in household waste in the 1970s was 12% and in the 1980s it was 8%; at present this grade has decreased to 3.5% (Fig. 5 and Table 1).

In fact this decrease of glass in waste improves the quality of household waste; the vertical arrow in Fig. 6 describes this coherence. The composition of waste is getting less complex and develops to a biodegradable mixture, which can be composted, and a combustible mixture (Fig. 6). Not only for glass this sequence of events can be identified, but similar trends can be observed for batteries, electronic waste, small chemical waste (personal care, paint, and oil), paper and biodegradable waste as well. In general, separate collection contributes to the quality of the non-separated household waste.

### 3.1.3. Glass recycling at plant level

Collected glass arrives at the processing plant with a grade of 90% — 95% dependent on the source. At the plant we set the recovery at 100% and the input grade at 95% [19]. The process starts with hand-picking and magnetic separation, which removes the non-glass objects and ferrous metals.

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<td>56</td>
<td>52</td>
<td>53</td>
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<td>20</td>
<td>26</td>
<td>21</td>
<td>25</td>
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<td>0.6</td>
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Table 1 Composition of non-separated household waste from 1940 to 1999 in the Netherlands [18]

Fig. 6. The selective collection of materials other than combustible and compostible substances like glass, chemical waste, Ni–Cd battery cells, lamps, has a positive effect on the “grade” of household waste, it converges into an acceptable input grade to a processing plant for compost, fermentation gas and combustible materials.
This separation process is continued with a number of highly sophisticated separation devices until a grade is reached of less than 100 g/tonne of contamination (metals, ceramic, and plastics) in the glass, the smelter grade (Fig. 7). As a result only a minor part of the glass is lost in the process. The separate collection of glass also effects improvement of the grade of non-separated household wastes at constant recovery: the vertical arrow in Fig. 6.

4. Optimisation for closed material cycles: maximum grade and recovery

Because MSW is heterogeneous, and its composition and quantity change over time, an infrastructure design that obtains both high grades and high recoveries under such changing conditions is a challenging task. Solid waste infrastructures are generally characterized by slow dynamics, or adaptability that result from the scale-of-operations, the related capital-intensity and the size and complexity of infrastructure development projects. In addition, infrastructure decisions have a long-term impact on the scope for future decision-making and limit the scope for timely change. The short historical overview showed that separation of metals and other non-combustible metals would improve the fuel-grade of the remaining fraction. Further development of this capacity does not necessarily jeopardize the infrastructure investments, for example, in expensive waste incinerators. But how well can such a collection and separation system deal with short-term dynamics in waste composition and quantity, and how sustainable is the current processing of the remaining waste?

4.1. Grades of separated resources

Waste in human systems is collected and lumped together. As a result, waste is an aggregate of different products, materials and substances, which as a whole is often to divers to be used by the ‘next user’. Separate collection provides an opportunity to process the household waste fraction effectively. Separate collection of rapidly changing, hazardous or complex commodities, such as electronic equipment, chemical wastes or cars, allows for individual treatment of these streams and provides flexibility to cope with changing composition of these wastes. According to the law of diminishing returns, however, it would require an enormous effort to completely separate waste into resources of high grade at high recoveries. Such a comprehensive programme would generate resistance to the public as illustrated by the DIFTAR experience. To reduce the number of separately collected streams, separate collection systems can be outfitted with a sorting system that removes ‘processable streams’ from waste
intended for final disposal. Metals and waste glass or plastics are easily separable and could in principle be collected in one container. Advances in separation technology can further improve the sorting capacity of waste infrastructures in the medium term.

4.2. Grade of resulting residue

The cascaded set up of the collection and separation system sorting and separate collection of resources from total household waste production also improves grade of remaining non-separated household wastes into a combustible part comprising of paper, cardboard, plastics and textile, a biodegradable part that can be composted, biological wastes, bread, animal and undefined waste, and inerts, such as glass and metals. Metals still contained in the waste are recovered from different screen fractions by magnets and eddy currents. They can also be recovered after incineration. In the filter ash, heavy metals, such as cadmium and zinc, are concentrated. Moreover, screening affects the separation of biodegradable from combustible waste.

The oversize, a combustible plastic, is separated from drink cartons (by electronic sorting) and paper (by pulping and centrifugal separation). The remainder is baled and suitable for dedicated furnaces for optimum recovery of heat. As an alternative this material could also be utilised as fuel for power plants to generate electricity. Paper and cardboard and some textile have relative high calorific values. Secondary plastic grades are often too low to be recycled. However, for most (~80% [20]) of the carbohydrates used as a fuel it is not logic to invest much energy into the recycling of these plastics back into a carbohydrate fuel mixture, and direct incineration may be more energy efficient.

The undersize is treated for the production of compost; however, fermentation is an interesting alternative. For fermentation, the still-present-inert-materials are first removed (sand, concrete, glass, metals, and ceramics) in a wet treatment before combustible gases are recovered from the remaining material through fermentation. The removal of special and small chemical wastes can be a bottleneck in the composting of the undersize. Although the special and small chemical wastes can safely be incinerated, it may pose a problem for composting, particularly in urban regions where separate collection is less successful. The hazardous fraction is concentrated in the compost, and may exceed the concentrations prescribed by law and prevent the downstream use on land. Separate collection systems in the Netherlands have been set up to improve selective collection of special and small chemical wastes [21] and further reduce special and small chemical wastes from non separated waste. A small fraction of special and small chemical wastes is still present in household, but through separation it constitutes a decreasing fraction of the non-separated waste.

A minor amount leaves the process as residue. The quality of the products can be guaranteed due to the combined effort of selective collection and separation [22]. In this way, the separation system can be optimised to produce waste grades suitable for incineration. Moreover, such approach buffers composition changes of the remaining non-separated waste fraction, which in turn may create a favourable climate for investments in waste infrastructure or in initiatives for high calorific waste.

4.3. Sustainability

Ecosystems develop towards increasing complexity and performance, rather being designed. This holds true for industrial systems too: although its individual parts are designed and constructed,
the system as a whole develops organically. It is important to realize that the direction of sustainable development is dependent on initial system configuration, and may change over time. Particularly infrastructures, because of their long lead times, may influence direction. Currently incineration of plastics may appear the most efficient path to exploit their calorific and material value. However, if recycling and separation technologies develop to better produce better grades, oil becomes scarce, or replaced by hydrogen as fuel, for example, cyclic material use may be more preferred. Although waste incineration does not close material cycles, the energy recovery intensifies cascaded use of energy. At the short term, efforts to shift waste from landfilling to incineration appear progressing towards more sustainable system states through reduction of energy dissipation. Particularly in combination with an optimised collection and separation infrastructure, incineration may be the most effective path to recover the remaining non-separated household waste fraction.

5. Concluding remarks

Waste infrastructure is one of the basic facilities of an industrial society that enables it to function. Industrial ecology shows us that only in networks sustainability can be achieved. Sustainability is an emerging system property of the network that cannot be achieved through sound waste management alone. The heterogeneity of MSW waste limits direct application in production processes and as a consequence interrupts the material cycles. Waste infrastructure, therefore, must be designed for the best match of recovered materials with material grades required for production, or alternatively to generate only residues in grades that are compatible with nature. To approach a sustainable development, a preferred result is maximum recovery of waste material at maximum grade of secondary material produced. From industrial practice, however, it is well known that maximum grade and recovery cannot be achieved for both parameters at the same time in a single operation. This is crucial for the proper analysis, design and understanding of recycling activities.

We demonstrated, however, that in a cascaded separation structure for waste infrastructure both grade and recovery can be maximised simultaneously. In such a system changes in waste composition and quantity are manifested as changes in volume of collected streams. Separate collection can deal adequately with these dynamics at limited cost because it comprises ‘wheels’ and logistics only. Further downstream, capacity-related costs are high, for example, for abatement infrastructure such as incinerators or sanitary landfills, and change is limited. The cascaded structure enables control of the residue composition and quantity downstream. Moreover, such approach buffers composition changes in the remaining non-separated waste fraction, which in turn may create a favourable climate for investments in waste infrastructure, or in initiatives for the recovery of high calorific waste as a fuel for co-incineration and energy generation. Thus, it has been shown that the engineering concepts, grade and recovery, provide a simple, yet powerful means to make these principles operational, and support the complex decision-making on sustainable waste infrastructure.

In conclusion, the combination of industrial ecology and engineering provide a roadmap to sustainability. Industrial ecology can be used to operationalise the concept of sustainability. The engineering concepts, grade and recovery, provide a simple yet powerful means to assess policies and infrastructure concepts with respect to the industrial ecology goals.
References

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