Part V

Building Material Disposal

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Summary

The study's aim was to generate life cycle inventory data on the environmental impacts of the generic disposal processes for various common building materials. The study specifies disposal inventories for 36 common building materials. This data is fit to complement inventory data for the production of materials. These inventories are designated to be used for the assessment of buildings in the planning stage. Unlike building material production, the disposal of building materials can only be assessed in regard to a specific building or type of construction. The potential for recycling is influenced by type of construction, procedures in the utilisation of the material and site-specific disposal logistics. Accordingly the inventories of several possible disposal options per material are presented, which can be applied in accordance to the construction at hand. The three options discerned are A) direct recycling, B) disposal via sorting plant and partial recycling, and C) direct final disposal without recycling. The system boundary in the inventory includes expenditures on the building site, like e.g. demolition energies, but also transports, expenditures in a sorting plant and the final disposal of not recycled fractions in an incinerator or landfill. For the latter, the ecoinvent 2000 models (part II and III of this report) are used. In accordance with the ecoinvent 2000 methodology, no bonus or burden compensation is given for recycled material. No partial allocation of burdens from recycling processes to the old and the new products were made. Instead the system boundary cuts off the recycling process itself, but includes sorting plants. Wastes with high recyclable content are thus rewarded by being relieved of the burden of disposal.

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1 Introduction

Ecological assessments of buildings, constructions and building materials are often focussed on the production and use phase. Disposal is often disregarded. In a complete Life Cycle Assessment all relevant processes should be heeded. This study provides LCI data on disposal processes of building materials. It is essentially based on the study (Doka 2000) including some modifications and the use of the new landfill models in ecoinvent 2000.

1.1 Construction waste compositions

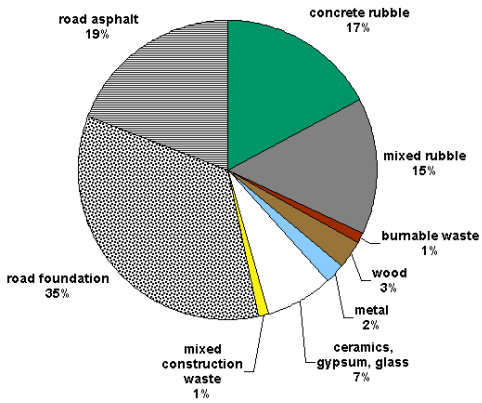
In (BUWAL 2000a) the flows of materials in the Swiss construction industry were analysed. This comprises construction engineering (buildings, German 'Hochbau') and civil engineering (transport and services infrastructure, German 'Tiefbau'). Tab. 1.1 shows the determined waste composition for 1997. The majority of the waste (73%) is essentially mineral material and only 4% is burnable waste. However due to the large masses involved the amount of burnable waste is considerable. Most of the burnable waste is incinerated and burnable construction waste contributes 12 w% to the waste incinerated in municipal solid waste incinerators (BUWAL 2001c). Elemental composition of different materials is detailed in part I.

Tab. 1.1 Total generated construction waste in 1997 (BUWAL 2000a)

Material	Mt/a
concrete rubble	1.90
mixed rubble	1.64
burnable waste	0.136
wood	0.326
metal	0.272
ceramics, gypsum, glass	0.803
mixed construction waste	0.103
road foundation	3.820 [1]
road asphalt	2.12 [2]
total	11.1

1 of which 3.26Mt/a recycled directly on site

2 of which 1.45 Mt/a recycled directly on site



1.2 Construction waste generation and treatment

Information on the mass flows in the Swiss construction industry are given in Fig. 1.1. These figures are estimated based on surveys (BUWAL 2000a) and exclude an approximate flow of 70 Mio t/a of excavated material (BUWAL 2001e). Of the 11 Mio t/a construction waste 4.9 Mio t/a are from construction engineering and 6.2 Mio t/a from civil engineering. Of the generated waste, 4.7 Mio t/a are recycled on-site. These are road materials. Of the remaining 6.4 Mio t/a a share of 47% are recycled and used as secondary materials. The total recycling rate (on-site and MTC) is 69% (7.7 of 11.1 Mio t/a). The potential recycling rate of construction waste is estimated to be 81% (9 Mio t/a).

Note that the *total demand* for building materials (68 Mio t/a) is currently much larger than the potential *recyclate supply* (9 Mio t/a), and recyclate input in construction activities is therefore limited to at most 13%. Larger recyclate input shares are possible if construction activities develop towards sustainability and the material stocks are stabilised.

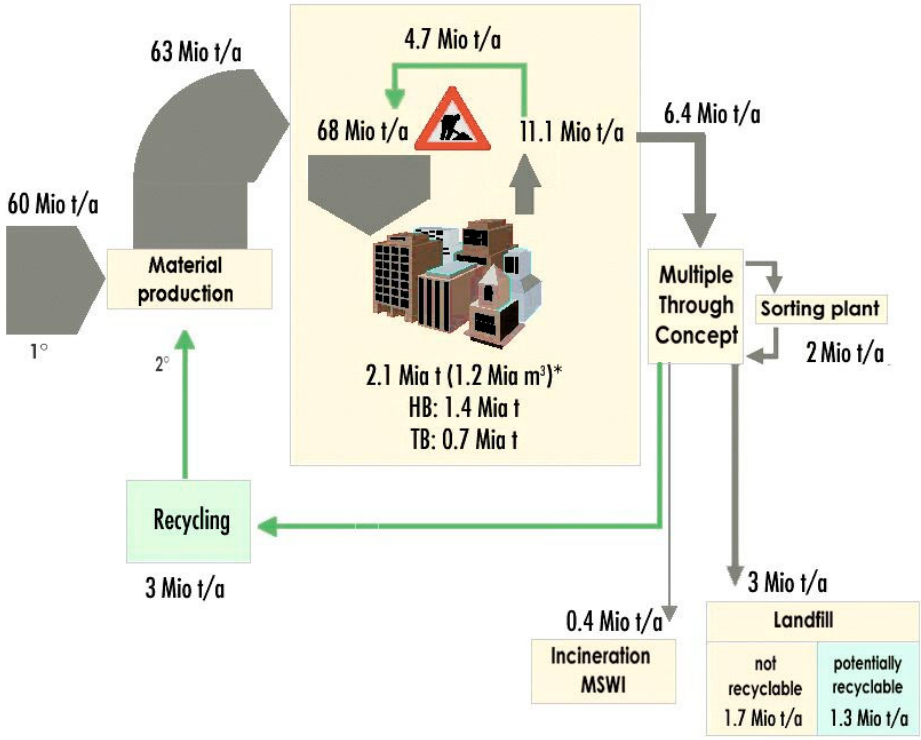


Fig. 1.1 Material flows and stocks in the Swiss construction industry in 1997. Adapted and extended from (Binz 2002).

Mia 1000 million (German 'Milliarde')
* m^3 signifies solid material, not to room space volume
HB construction engineering (German Hochbau)
TB civil engineering (German Tiefbau)

1.3 Sorting plant capacities

Swiss sorting plants processed 18% (2 Mio. t) of all construction waste in 1997 (BUWAL 2000a). These were 52.4 w% mineral material (concrete, brick, ceramics, gypsum, glass), 29.3 w% road materials (foundation and asphalt), 5.0 w% mixed construction waste, 8.0 w% burnable waste, and 5.3 w% metals. In the Swiss building waste recyclers association ARV 36 sorting plant operators are listed in January 2003 (ARV 2003). A sorted annual mass of 2 Mio t/a would then suggest an average throughput of 56'000 t/a per plant.

Annual treatment volumes of three Swiss construction waste sorting plants are cited in (Leuenberger & Spittel 2001:20) and shown in Tab. 1.2. The average treatment flow of those three plants corresponds well with the value of 56'000 t/a derived above.

Tab. 1.2 Data for three Swiss construction waste sorting plants (Leuenberger & Spittel 2001:20)

Mixed rubble sorting plants	annual flow m^3/a	t/a	Transport distance for input km
Recycling-Center Rotholz	38'000	68'400 [1]	13
Beton- und Mischabbruch Riedmatt	30'000	60'000	25
Bauschuttaufbereitung Bubikon	24'150	38'850	15
Arithmetic mean	30'717	55'750	17.7

1 assuming an average density of 1.8 t/m^3

Bilitewski (1993:57) suggests that a stationary sorting plant has a minimal capacity of 100'000 t/a. An average capacity of 200'000 t/a is suggested in (DAFSTB 1996:123). These are figures for Germany. In Germany residential areas tend to be not as dense as in Switzerland which might be a reason that Swiss plants have apparently lower treatment flows.

2 Systems characterisation

2.1 Introduction

The study's aim is to generate data on the environmental burdens of the generic disposal processes for various building materials. These inventories are designated to be used for the assessment of buildings in the planning stage.

Inventorying of generic – i.e. average, site-independent – building materials disposal bears several problems:

- **Constructional restrictions:** Disposal possibilities of materials are often very dependent on the form and the construction the material is used. Separability of a construction – its possibilities of separation – determine if recycling of its composing materials is feasible at all. For example glued or foam-fixed components can be hard to separate and recycle; a solid metal sheet can frequently be recycled, while small metal parts within other materials are usually left in that material and are not recycled.
- **Economical restrictions:** Depending on local circumstances certain recycling or sorting options can either be readily available or economically prohibited. This depends on the relation of costs of sorting facilities, tipping fees on dump sites and transportation costs. In densely built areas the likeliness of a nearby sorting facility together with high tipping fees is probably higher than in rural areas.
- **Applied dismantling methods:** Dismantling or demolition techniques can heavily influence the feasibility of recycling options. For example roof tiles can often be re-used directly, if separated specially before building demolishing starts. On the other hand, indiscriminate demolition transfers these tiles to mixed demolition rubble, which – at best – can be downcycled via sorting plants.
- **Bulk volume effects:** Different lifetimes of materials lead to different points in time of disposal. For example structural concrete usually lasts the whole lifetime of the building – several decades – and is disposed when the whole building is replaced. In contrast short-lived materials like plaster may be replaced several times within the buildings lifetime during renovations. Depending on the size of the building and on the resulting disposal masses, smaller amounts of materials might not be separated due to space, time and economical restrictions. In a bigger building, however, the same material might be separated, since large disposal masses tend to facilitate the logistics of separation and appropriate treatment of several truckloads of material and thus can decrease costs.

2.2 The disposal with the Multiple-Through-Concept MTC

The standard disposal scheme for building waste disposal in Switzerland is the Multiple-Through-Concept MTC (German 'Mehr-Mulden-Konzept' MMK) devised by the Swiss builders association (SBV 1998). The basic idea of the Multiple-Through-Concept is that building wastes should be separated already at the building site and sorted into distinct throughs. The motivation is to increase recycling of waste materials and/or to reduce landfill costs. Four basic types of throughs exist, which are listed in Tab. 2.1. Additionally, all hazardous wastes like paints, solvents or glues must not be sorted into throughs, but disposed separately (SBV 1998).

Tab. 2.1 Basic types of throughs of the Multiple Through Concept MTC (SBV 1998).

No. & label	*Through*	*Waste materials*	*Disposal*
1 green	**Single material** (German 'Einstoffmulde')	One of the following per through: clean excavation material, concrete rubble, tiles and bricks, metal, wood, glass, road foundation, or road asphalt	Recycling or inert material landfill or incineration for wood
2 grey	**Mixed rubble** (German 'Mischabbruch' or 'Bauschutt')	Mixed, inert, mineral building materials (concrete rubble, tiles, bricks, ceramics)	Recycling via sorting plant or inert material landfill
3 red	**Burnable material** (German 'Brennbares')	Burnable wastes (wood, plastics, packaging	MSW incinerator
4 yellow	**Mixed building waste** (German 'Bausperrgut' or 'vermischte Bauabfälle')	all of the above	Sorting plant
–	**–**	Hazardous waste (paints, glues, chemicals...)	Separate disposal, not via throughs

The first priority is to separate single materials and recyclable fractions (thoughs 1 and 2). However, logistical and space restrictions – e.g. during renovations – can prevent the use of several throughs (Mauch et al. 1991:36). If no separation is feasible, the through 4 for mixed building waste can be used, whose contents are treated in a sorting plant. In the sorting plant materials are separated for mineral recycling or for more inexpensive disposal. The disposal scheme for a building depends on the volumes and types of waste materials, sequence and time of dismantling, as well the distance and fees of disposal facilities available at the building site (sorting plants, landfills, MSW incinerator). Swiss law allows the creation of temporal storage sites to increase recycling.

2.3 Intentional limitation of assessed disposal routes

Obviously, it is difficult to devise user-friendly inventories for *generic* disposal of different building materials that heed every possible situation of building locality and construction type. Therefore, I provide data within this study for *a few site-independent disposal routes* that are *most likely to occur* in Switzerland. Up to three disposal routes after demolition are discerned per material, if appropriate. These are:

Option A) Direct recycling

Option B) (Partial) recycling after sorting

Option C) Direct final disposal without recycling (landfilling or incineration)

The applicability of this data to LCAs of buildings or constructions should be checked by experts considering *the building site, the applied construction types and the material lifetimes involved* which all can influence disposal routes. If LCAs of single building materials are made, it should be borne in mind that probably no *single* disposal route applies, but *several*, depending on the building site and the applied construction types, as explained chapter 2.1 'Introduction'.

2.3.1 Further data reduction

In (Doka 2000) over 110 disposal modules are devised for 48 materials. The main reason for this large number of modules is the distinction of waste pathways in the construction phase, in the renovation phase *or* in the dismantling phase, which can all be different. For example no dismantling energies are usually needed for wastes from the construction phase. Also during renovations more mixed wastes are usually created due to space restrictions for MTC throughs.

In the present study the number of modules was reduced.

- No distinction is made anymore between wastes from different building phases.
- For all burnable wastes only direct disposal modules are available. Burnable wastes are sorted out in sorting plants and incinerated. *The environmental burdens of sorting are usually negligible compared to the burdens of incineration*, i.e. burnable wastes to sorting plants can well be approximated with the option C module of direct disposal without recycling (cf. entry *'◆use option C'* in Tab. 3.18 on page 25).
- Materials to direct recycling (option A) can cause exchanges that are inventoried with the building system (dismantling energies, PM emissions). For materials that can be recycled, *but do not cause any of these exchanges* (e.g. PVC window frames), no data modules will be created, since those modules would be empty (cf. entry *'◆no burdens'* Tab. 3.18 on page 25).
- Some material categories were combined and some rare materials deleted.

2.4 Point of time of disposal

Having declared that these inventories are designated to be used for the assessment of buildings *in the planning stage*, it is clear that the time of disposal is not today, but sometime in the future. The exact point of time depends on the *lifetime* of the material. So strictly speaking, various disposal processes *at different points in time* could or even should be inventoried here.

This problem of assessing temporally dissimilar processes is not unique to LCI of building material disposal. A long-lasting process or product has a life cycle that can cover decades or even centuries. For example dams for alpine hydroelectric power production were built over the last 150 years. Strictly, the LCI of hydropower production should heed the concrete and steel production technologies that were used *at the time a dam was built*. Similarly, expenditures for e.g. forestry plantations of wood used today would have to heed the technologies that were used one forestry rotation period (70–100 years) ago. By symmetry, it can be argued that disposal processes that occur in the far future would have to be assessed with the technology that is believed to be applicable at this future point in time. This would introduce the problem of technology development forecasts.

Within the ecoinvent 2000 project these issues of temporal modelling are not addressed. The aim on ecoinvent 2000 is to establish data valid for the reference year 2000. All processes along a life cycle are *inventoried as if they were occurring with current (2000) technology*[1] (Frischknecht et al. 2003a). Accordingly, the current technology and situation in Switzerland is the basis for the building material disposal, and not possible future technologies or situations.

Disposal routes of building materials have been drastically improved during the last few years[2]. While there is still room for improvement (e.g. less downcycling), current disposal routes are following Swiss laws and regulations to a very large extent. In contrast, for 1994 the BUWAL estimated that of all burnable building wastes, 46% were burned or dumped illegally (BUWAL 1996). This number is now believed to be close to zero[3]. From this, it is clear that the disposal inventories created here are

[1] The rationale behind this is, for one, to avoid a debatable forecast of a future technology. On the other hand in LCA it makes sense *not* to heed a future technology with possibly environmentally improved performance. One of the purposes of environmental life cycle assessments is to encourage environmentally efficient technology development. If such *improved technologies* were already included in the assessment, the signal to *motivate such development* would disappear (Steen 1999).

[2] Personal communication of Kaarina Schenk, BUWAL section waste, of April 16, 2002.

[3] Personal communication of Kaarina Schenk, BUWAL section waste, of April 16, 2002.

temporary in the sense that they represent a current state of progress. Coming studies shall adapt this data to the changes in the disposal domain that are likely to occur in the near future.

3 Inventory of building material disposal

3.1 System boundaries

As pointed out in chapter 2.3 'Intentional limitation of assessed disposal routes' on page 5, of the many imaginable disposal options only three are inventoried here:

Option A) Direct recycling

Option B) (Partial) recycling after sorting

Option C) Direct disposal (landfilling or incineration) without any sorting or recycling

The options can be characterised as representing maximal recycling (A), probable recycling (B) and no recycling (C). The system boundaries of the inventory for the three options are shown in Fig. 3.1. The system boundary generally includes expenditures on the building site, like e.g. demolition energies. Subsequent transportation to sorting or disposal facility is also included. This contrasts with all other disposal process modules in ecoinvent 2000, where transport to the disposal facility is *not* included. Expenditures in a sorting plant, incinerator or landfill are inventoried appropriately.

Functional unit

The functional unit for all modules is 'kilogram'. Please note that in ecoinvent 2000 the modules for the *production* of concrete and wood building materials is usually 'm^3' and not 'kilogram'. To inventory disposal modules transformation to kilogram is mandatory. Densities of the disposed materials are given in Tab. 3.20 on page 30.

Allocations

In accordance with the ecoinvent 2000 methodology, no bonus or burden compensation is given for recycled material (Frischknecht et al. 2003a). No partial allocation of burdens from recycling processes to the old (primary) and the new (secondary) products were made. Instead the system boundary cuts off the recycling process itself, but includes sorting plants and the disposal of non-recyclable material. Wastes with high recyclable content are thus relieved of some of the burdens from disposal[4].

[4] Consequently an inventory of recyclate products would be spared the burdens of raw material production, but would include expenditures in a recycling plant.

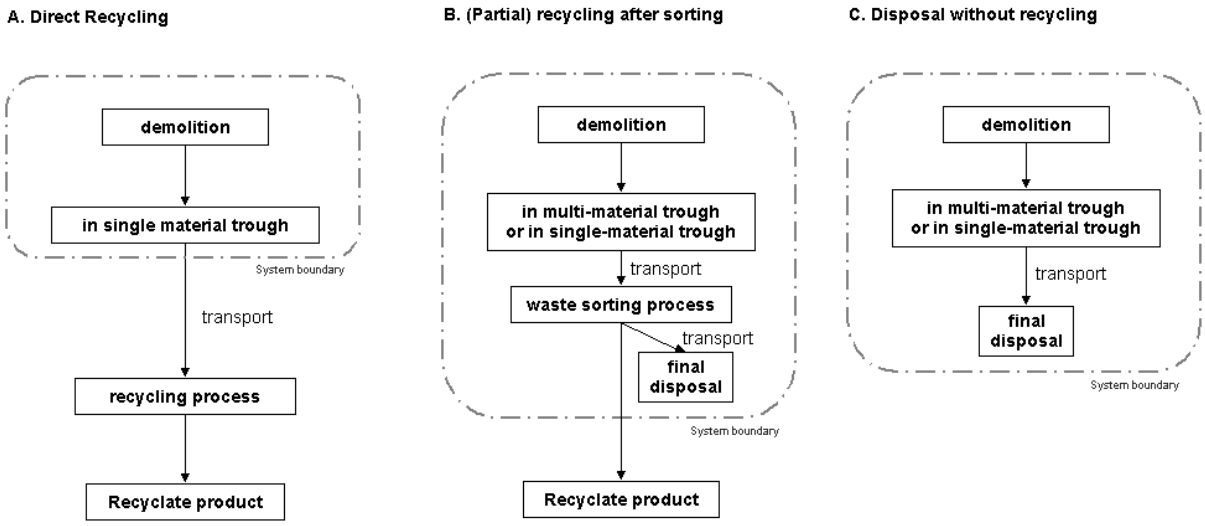


Fig. 3.1 System boundaries of the three types of disposal options. All the processes within the hatched line are included in the inventory of building material disposal. Processes outside the hatched line must be attributed to the recyclate product (cut-off method).

3.1.1 Option A: Direct recycling

The option of direct recycling applies if the building material is separated *at the building site* and is recycled without prior sorting. The material is separated from the original construction, sorted into a single material through and transported off to recycling. Only dismantling burdens (energy, emissions) are inventoried. The used material is regarded as a valuable commodity, the transport to the point of recycling[5] is therefore cut off and assigned to the recyclate consumer. Of the MTC troughs only number 1 (single material) can be used for this option.

The only burdens for direct recycling are dismantling energy consumption and PM emissions during dismantling (see chapter 3.2 'Dismantling process' on page 10). The cut-off attributes all further expenditures (transport, sorting, recycling etc.) to the recyclate consumer and not to the first user of the material.

The disposal modules in case of direct recycling contain at most four exchanges (1 energy + 3 PM). For materials where direct recycling does not cause *any* exchanges for the building system, no modules are created.

3.1.2 Option B: Recycling after sorting

The option of recycling after sorting applies if the building material cannot be separated at the building site, but is mixed with other materials. The material is separated from the original construction, sorted into a MTC waste through and transported off to sorting. Different materials can partly be separated in a sorting plant. The fractions separated in a sorting plant are either recycled or disposed in landfills or incinerators. Consequently, sorting does not automatically mean recycling for all materials. Sorting plants merely separate a recyclable fraction (gravel, bricks etc.) from unwanted materials (plaster, wallpaper, cement etc.). E.g. wall plaster might be part of mixed rubble and go to sorting, but the plaster will be removed to disposal and not recycled.

This option applies e.g. in the case of renovation waste from small scale buildings with little space for the complete Multiple-Through-Concept. In option B the dismantling burdens and a transport to a

[5] This can be either a recycling plant or a building site re-using material.

sorting plant is inventoried. The recycled fraction is regarded as a low-value commodity which is further processed outside the system boundaries. The non-recycled fraction is regarded as a negative-value commodity, i.e. a waste that must be disposed. Accordingly, the final disposal of the non-recycled fraction in a MSWI or landfill is included in the inventory. Of the MTC troughs number 2 (mixed rubble) and 4 (mixed building waste) can be used for this option.

Burnable wastes sorted out in sorting plants are disposed in incinerators. The burden of sorting is usually negligible compared to the burden of incineration. In an effort to reduce the number of data modules the sorting of burnable wastes is not inventoried and the modules for direct disposal (without sorting) shall be used instead.

3.1.3 Option C: Disposal without recycling

In the option disposal without recycling the material cannot be recycled either for lack of quality (mixed, inseparable materials), lack of time or space for detailed dismantling or lack of recyclate receivers. The material is separated from the original construction, sorted into a MTC waste through and directly transported off to final disposal. The dismantling burdens, a transport to the final disposal site and the final disposal in a MSWI or landfill is inventoried. The disposed waste is regarded as a negative-value commodity. Of the MTC troughs number 3 (burnable material, to incineration) can be used for this option. Number 1 (single material, e.g. excavation), and 2 (mixed rubble) can be used for this option, *if they conform to the inert material landfill specifications without sorting*. For the through number 4 (mixed building waste) sorting is compulsory according to Swiss law and its contents cannot be disposed without (partial) recycling (see option B above).

3.2 Dismantling process

3.2.1 Dismantling energy consumption

Data for typical demolition efficiencies are given in Tab. 3.1. The data relates to the daily achievable work load, heeding a degree of utilisation of 50% to 60% and a 8-hour work day. This work load is smaller than the momentary nominal efficiency (DAFSTB 1996:82).

Tab. 3.1 Efficiency of demolition modes in hours per solid volume(DAFSTB 1996:85)

	Reinforced concrete h/m^3	Plain concrete h/m^3	Brick wall h/m^3
1. Dismantling with handheld tools	6 – 15	2 – 10	1 – 4
2. Dismantling with tolls on carrier devices (>5t)	0.25 – 5	0.1 – 2	0.1 – 0.6
3. Dismantling with hydraulic rock chisel (Felsmeissel) on carrier devices (>5t)	0.2 – 1	0.1 – 0.8	0.1 – 0.5
4. Shattering with claw	–	0.1 – 0.5	0.1 – 0.5
5. Shattering with concrete claw (Betonzangen)	0.6 – 6	0.3 – 0.5	0.2
6. Bursting with drop hammer (Fallbirne)	0.1 – 1.5	0.07 – 0.2	0.05 – 0.1
7. Crushing with hydraulic devices	0.3	0.1 – 0.4	0.05 – 0.1
8. Tearing with hydraulic devices #	0.1 – 0.3	0.07 – 0.2	0.05 – 0.1
9. Blasting with explosives	0.4	0.25	0.25
10. Sawing with concrete saws	0.5 – 10	0.4 – 6	3

Selected range

Some information from dismantling practice in Switzerland is available[6]. The upper values of the ranges in Tab. 3.1 are rather rare[7] and the average values are in the vicinity of the lower end of the given range. Dismantling with hydraulic diggers (8. Tearing with hydraulic devices) is common and an average value of approximately 0.2 h/m^3 for reinforced concrete is suggested[8]. Manual dismantling is negligible. The calculation of the inventoried energy demands is shown in Tab. 3.2[9].

Tab. 3.2 Specific diesel consumption for different materials

	unit	Reinforced concrete	Reinforce-ment steel	Plain concrete	Brick wall, gypsum board, cement-fibre slab
Tearing with hydraulic devices 1	h/m3	0.173	–	0.118	0.0707
Diesel consumption 2	MJ/m3	140.85	–	96.22	57.50
Material density	kg/m3	2'300	–	2200	1600
Specific diesel consumption 3	**MJ/kg**	**0.0612**	**0.626 5**	**0.0437**	**0.0359**
Uncertainty 4 (GSD)		131.6%	131.6% 6	130.0%	118.9%

1 Geometric mean of range in row ' 8. Tearing with hydraulic devices' in Tab. 3.1. These values fit also the range of 0.086–0.617 h/m3 and mean value of 0.144 h/m3 for general demolition performance (all materials) given in (EWE 2000) for Swiss demolition works with diggers in 1990.

2 Using 813.2 MJ/h, calculated from 19 kg diesel per hour (Frischknecht et al. 1996:B.55) and a lower heating value of 42.8 MJ/kg for diesel.

3 As 'diesel in building machine'

4 Derived from ranges given in Tab. 3.1.

5 For reinforcement steel alone. Calculated from the difference between plain and reinforced concrete, assuming the difference is caused by 3 w% steel ((0.0612–97%*0.0437)/3%).

6 Adapted from reinforced concrete

It is credible, that the demolition duration per m^3 increases with increasing density of the material. The specific consumption in MJ/kg (and not MJ/m^3) allows to heed the increased demolition energy for more dense materials.

6 Personal communication of Christoph Ospelt, Lenum AG, Switzerland of December 17, 2002.

7 E.g. for a four-story building with an estimated concrete volume of 210 m^3, a demolition rate of 6 h/m^3 (as given as the upper limit for 5. shattering with concrete claw) would lead to a dismantling time of 7 months (!) with one digger and 3.5 months with two diggers, which seems clearly too long for an average case.

8 This leads to a dismantling time of roughly 5 working days for a four-story building with an estimated concrete volume of 210 m^3, which seems to be in the right order of magnitude.

9 The values inventoried here are much lower than the values inventoried in the original study (Doka 2000), where the larger *arithmetic* (not geometric) mean values of '5. Shattering with concrete claw' plus 10% of manual dismantling '1. Dismantling with handheld tools' were used, leading to specific consumption factors of 1.41, 0.34 and 0.22 MJ/kg, respectively.

Fig. 3.2 Dismantling with skid-steer loaders (pictures from Eberhard 2002)

Dismantling energies are only specified for structural materials. Materials in constructions that disintegrate after the structural part is demolished – e.g. mineral wool insulation or paint – are not burdened with dismantling energies (see Tab. 3.20 on page 30).

3.2.2 Dismantling infrastructure

Throughs for waste come in various sizes. A standard building waste through has a nominal volume of 7 m^3 and weighs 820 kg (NMS 2003). No information on load factors or lifetime of throughs is available. Infrastructure for throughs is of minor importance and is neglected. The infrastructure for skid-steer loaders for dismantling is heeded via energy consumption in the module 'diesel, burned in building machine' (Kellenberger et al. 2003).

Fig. 3.3 Standard 7 m^3 through (left) and through transport (right). Pictures from (Hauri Seon 2003)

3.2.3 Dismantling emissions

The emissions associated with energy consumption are already heeded in the generic module 'diesel, burned in building machine' (Kellenberger et al. 2003). There are however other direct emissions from dismantling.

Particulate matter PM

Most particulate mater emissions are discussed in connection with combustion processes. Purely mechanical processes (demolition, crushing, mining) can also lead to fine particles. In Great Britain 4000 tons of PM_{10} were emitted in 1994 from building construction, demolition, renovations, but also highway reconstruction (DOE 1999). It can be assumed that these emissions originate chiefly from mineral building materials. The annual mass of mineral construction waste in the UK can be estimated to be approximately 50 million tons[10]. An approximate emission factor of **80 mg PM_{10} per kilogram mineral construction waste** can be estimated.

Tab. 3.3 Particulate matter profiles for crushing and handling of minerals (CEIDRAS 1999)

PM profile	PM < 10 µm	PM < 2.5 µm	PM < 1 µm
Construction & Demolition #420	**48.93%**	**10.17%**	**3.85%**
Mineral Process Loss #371	50.00%	14.60%	2.00%
Rock Crushers #373	10.00%	3.00%	1.00%

# indicates the profile number in (CEIDRAS 1999)

Size distribution data for particle emissions is given in (CEIDARS 1999). Tab. 3.3 shows some particulate matter profiles for crushing and handling of minerals. The profiles of these mechanical processes show a high fraction of coarse material > 10µm, which is different from the exhaust of diesel engines, where usually less than 10% of PM is > 10µm. Together with the PM_{10} emission factor of 80 mg/kg, the remaining PM species can be calculated (Tab. 3.4). These values are inventoried for all mineral construction materials (concrete, brick, cement, gypsum, plaster). Wood, metal, plastics, paints and glass are assumed to create no such PM emissions during dismantling. The inventoried PM emissions cover emissions during dismantling and further handling in transport and sorting or disposal.

Tab. 3.4 PM emission factors for demolition.

PM category	PM profile	**Emission factors** [4] mg PM/kg material
<2.5µm	10.17% [1]	**16.63**
10µm-2.5µm	38.76% [2]	**63.37**
>10 µm	51.07% [3]	**83.50**

1 from Tab. 3.3
2 =(48.93% – 10.17%) from Tab. 3.3
3 Remainder
4 Note that the sum PM10 emissions factor (16.63+63.37) is 80 µg/kg derived from (DOE 1999).

Tab. 3.5 GSD^2 values for land use exchanges

Exchange	**GSD^2 value**	**Pedigree codes**	**Comment**
Building materials demolition $PM_{<2.5}$	306%	(2,3,3,3,1,5)	Basic uncertainty of 3 [a]
Building materials demolition $PM_{2.5-10}$	207%	(2,3,3,3,1,5)	Basic uncertainty of 2 [a]
Building materials demolition $PM_{>10}$	158%	(2,3,3,3,1,5)	Basic uncertainty of 1.5 [a]

a From one extrapolated PM10 emission factor and generic PM fractions from measurements

[10] Switzerland with 6.9 Million inhabitants in 1994 generated approximately 6 million tons of mineral construction waste per year. For Great Britain with 56.6 million inhabitants a figure of 50 million tons per year can be extrapolated.

Emissions to water

Throughs or piles with construction debris are usually exposed to the weather. Natural precipitation can wash off pollutants from the debris. Sometimes piles are wetted intentionally to prevent dust formation. Experiences with wet sorting plants show that washed off waters contain significant amounts of pollutants in fine fractions (Schachermayer et al. 1998:66). It can be expected that some pollutants are also washed off and emitted in a comparatively less intense washing on site, during transport or intermediate storage. Sorting plants usually feature collector basins. The suspected emissions cannot be further quantified here and are not inventoried.

Transport to sorting plant

If the waste is transported to a sorting plant after dismantling (only in option B) this transport is included in the inventory (see Fig. 3.1 on page 9).

Limited information on transportation distances of three sorting plants is available in (Leuenberger & Spittel 2001:20), cf. Tab. 1.2 on page 2. For this study an average value of 17.7 km per lorry is adopted. With 36 plants over an area of approx. 31'000 km^2 this seems reasonable[11].

3.3 Sorting plants for building waste

Sorting plants separate building waste materials according to desired specifications. This is usually archived by a prior screening/separation and a subsequent crushing/sorting step. A generic scheme of a building waste sorting plant is shown in Fig. 3.5.

The sorting process is designed depending on the desired result. Two chief motivations exist for sorting plants:

- Reduction of landfill costs by sorting out of burnable and metal materials from mineral material.
- Recycling of re-usable fractions (which also saves landfill costs)

Fig. 3.4 Stationary sorting plant RESAG, Berne (RESAG 2002) and manual sorting station (SR 2002)

To obtain recyclable fractions good sorting performance is important, which is not achievable without manual sorting steps (Wrage 1993:262). For building materials from secondary sources following components must be sorted out, since they degrade concrete characteristics: glass, chloride and sulfate

[11] 31'000 km^2 is the area of Switzerland excluding unproductive areas (mainly the Alps, 8810 km^2) and lakes (1700 km^2) (BFS 1999). This area can be taken to be the inhabited area of Switzerland. With 36 plants each plant covers an area of 860 km^2. This area corresponds to a circular area with a catchment radius of 17 km. The mean catchment radius for such an area would be 11 km.

salts (especially gypsum), absorbent and swelling materials. Sorting plants seek to separate the unwanted materials by crushing and subsequent sieving. A majority of unwanted materials is then transferred to a fine fraction. The fine fraction is separated and landfilled. Larger unwanted materials (e.g. bulk metals, wooden poles, windows) can be sorted out prior to crushing. Spinning impact crushers (German 'Prallbrecher') or pulsating jaw crushers (German 'Backenbrecher') are used for crushing. With the less common wet sorting process, generally better recyclate qualities are obtainable, but is more demanding regarding the water cycle and sludge treatment.

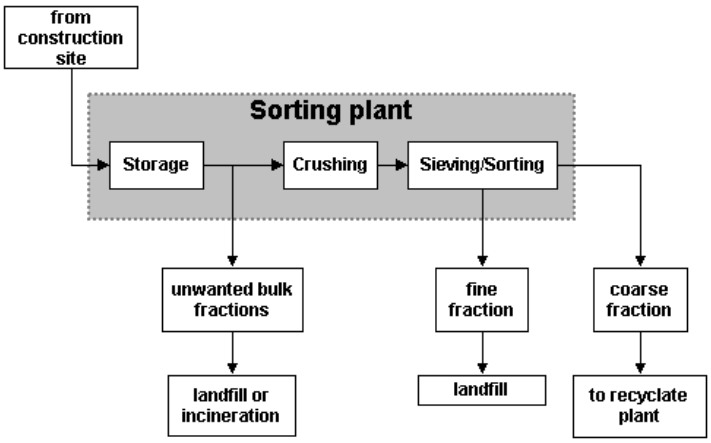
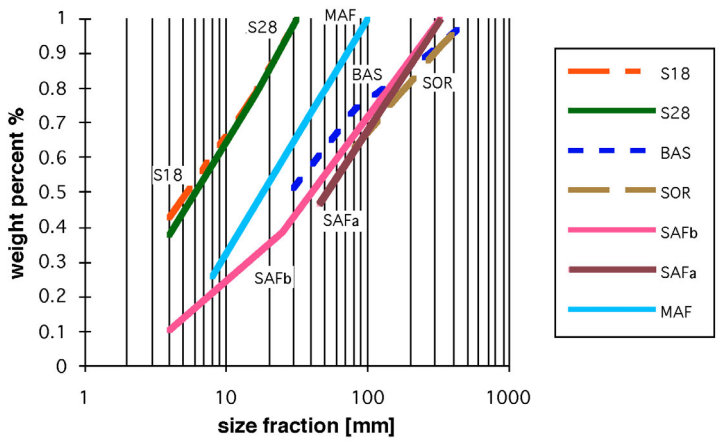


Fig. 3.5 Generic scheme of a building waste sorting plant.

3.3.1 Separated fine fraction

The sorting characteristics of several sorting plants are shown in Fig. 3.6. In this study only dry sorting is considered.



S18	wet sorting plant (Schachermeyer et al. 1998:18)
S28	wet sorting plant (Schachermeyer et al. 1998:18)
BAS	dry sorting plant BASORAG (Schachermeyer et al. 1998:50)
SOR	dry sorting plant SORTAG (Schachermeyer et al. 1998:53)
SAFb	stationary sorting plant, before crusher (Rentz et al. 1997:165/171)
SAFa	stationary sorting plant, after crusher (Rentz et al. 1997:165/171)
MAF	mobile sorting plant (Rentz et al. 1997:171)

Fig. 3.6 Sorting characteristic of several sorting plants

If mixed mineral construction wastes with all waste fractions is sorted (MTC through Nr. 4, German 'Bausperrgut') the fine fraction 0–30 mm cannot be recycled due to pollutants and must be landfilled[12] (Gewiese 1998:86). This corresponds to approximately 40% to 60% of the waste input, according to Fig. 3.6. If mineral construction wastes without other materials are sorted (MTC through Nr. 1 or 2, German 'Bauschutt') only the fine fraction 0–8 mm must be disposed[12]. This corresponds to approximately 20% to 30% of the waste input, according to Fig. 3.6. For this study it is assumed that in the sorting plants an average of 40% of the waste input is transferred to the fine fraction and landfilled. The uncertainty for this figure is estimated to be 122% (GSD), which suggests a 95%-confidence range of 60%-26%.

Tab. 3.6 Distribution of mortar in sorting of concrete (DAFST 1996:148)

Fraction mm	fraction weight of sorted concrete w%	Share of mortar in sorted fraction w%	Mortar in fraction kg mortar/kg concrete	Transfer coefficient for mortar kg/kg mortar	Sum transfer
0-8	30%	98%	0.294	71.29%	71.29%
8-16	32%	18%	0.058	13.97%	85.26%
16-32	38%	16%	0.061	14.74%	100.00%
	100%		0.412	100.00%	

The above transfer coefficient to fine fraction is used for robust materials like gravel or bricks. For more brittle materials like cement, mortar or gypsum other transfer coefficients to fine fraction are applied. Information on distribution of sand and cement (mortar) in concrete sorting is available from (DAFST 1996:148) and shown in Tab. 3.6. The mortar is enriched in the fine fraction 0–8 mm (98 w% compared to the original content of 41.2 w%). 71.29 w% of the mortar is transferred to the fine fraction 0–8 mm, and approximately 98.7 w% to the fraction 0–30 mm. An average value of 85% transfer to the disposed fine fraction is assumed for brittle materials. The remaining 15% enter the recycling as unwanted material in the coarse fraction. The uncertainty for this figure is estimated to be 108% (GSD), which suggests a 95%-confidence range of 100%-72% (the transfer coefficient must not be above 100%).

Tab. 3.7 Applied average transfer coefficients to fine fraction in sorting for different materials

Material	Transfer coefficient to fine fraction (landfilled)	GSD	Remainder
Robust materials (gravel, bricks..)	40%	122%	To recycling
Brittle materials (plaster, mortar...)	85%	108%	To recycling as unwanted material

3.3.2 Disposal of fine fraction

The separated fine fraction from sorting plants usually contains many pollutants and materials which are disturbing for building material recycling (e.g. chlorides, sulfates, shreds of wood and fibres). The practice of Swiss building waste recyclers is to landfill the fine fraction in sanitary landfills[13]. Information from the section waste of the BUWAL also concurs that disposal of fine fraction in

[12] Personal communication with Peter Staub, directing manager of Abbuch- Aushub- und Recycling Verband Schweiz ARV on January 25, 1999.

[13] Personal communication with Peter Staub, directing manager of Abbuch- Aushub- und Recycling Verband Schweiz ARV on January 25, 1999.

sanitary landfills is 'the usual case'[14]. Legally the fine fraction could also be landfilled in less demanding landfills (residual material landfills or inert material landfills), if the waste holder can produce evidence that the material fulfils the requirements set for these types of landfills[15]. For example one of many criteria for inert material landfills is that of 1 kg waste maximally 5 g shall be dissolved in 10 litres of distilled water (TVA 2000:23). Gypsum ($CaSO_4 \cdot 2H_2O$) has a solubility in water of 2.4 g/l. The gypsum content of the fine fraction therefore must not be above 2.4 w% (24g/kg) for not to be rejected as inert waste material[16]. According to (Arendt 2001:154) the gypsum content in the fine fraction from building waste is 3–5%, i.e. above the legal limit for Swiss inert material landfills.

In this study the fine fraction is assumed to be disposed in sanitary landfills, according to the practice of Swiss building waste recyclers and information from BUWAL.

3.3.3 Energy demand in sorting plants

Electricity

An overview of literature values for the electricity demand in sorting plants is given in Tab. 3.8. For this study an average value of 3.7 $kWh_{el.}$ per ton input is assumed. Of that figure 41% are consumed by the crusher alone. The figure is inventoried as low voltage consumption in Switzerland for materials that pass the crusher. The uncertainty of that figure is estimated to be 110% (GSD), which suggests a 95%-confidence range of 3 – 4.5 kWh.

A few materials can be assumed to be sorted out prior to the crusher (like mineral wool, glass panes in burnable frames) or cause no resistance in crushing (paints). For those materials an electricity demand without crusher of 2.2 kWh/t is inventoried. This energy demand is for conveyor belts etc.

Tab. 3.8 Electricity demand for sorting plants

Facility	Source	$kWh_{el.}$ per ton input	GSD
Sorting plant 200 kt/a	DAFSTB 1996:123	2.68	
Impact crusher only	Müller 1998:3	1.5	
Semi-mobile plant 50-120 kt/a	Offermann 1988	2.7 – 7	
Mobile plant 50-100 kt/a	Offermann 1988	3 – 6.2	
Sorting plant incl. crusher	**This study**	**3.7**	**110%**
Sorting plant w/o crusher	**This study**	**2.2**	**110%**

Fuels

For charging and discharging of the sorting facility a skid-steer loader is used. The according module 'skid-steer loader' in the ecoinvent database has the functional unit 'm^3'. To calculate bulk densities (Schüttdichte) from material densities a general factor of 0.9 is used. Per kg displaced material the inverse of the bulk density is inventoried as m^3 moved with skid-steer loader.

[14] Personal communication with Kaarina Schenk, BUWAL section waste, e-mail of March 13, 2001.

[15] Personal communication with Kaarina Schenk, BUWAL section waste, of April 16, 2002.

[16] However, natural gypsum products as part of *unsorted* mineral construction waste ("mineralische Bauabfälle") can be landfilled in inert material landfills without prior chemical analysis (BUWAL 2000b). This recommendation does however not imply that *fine fractions* from construction waste sorting plants can be landfilled as inert material without prior chemical analysis (cf. footnote 15).

Tab. 3.9 Examples of loading volumes for charging and discharging different materials

Material	material density kg/m^3	bulk density kg/m^3	m^3 load per kg displaced material (= 1/ bulk density)
Concrete	2200	1980	0.0005051
Gypsum	1000	900	0.001111
Brick	1600	1440	0.0006944
Glass	2600	2340	0.0004274

Per m^3 skid-steer loader 5.9 MJ diesel are inventoried (value in ecoinvent 2000 from Frischknecht et al. 1996:B.55). For an average material with an approximate bulk density of 2000 kg/m^3, 0.0005 m^3/kg or 2.95 MJ/t are inventoried. This corresponds fairly well with an average value of 3.7 MJ/t for charging and discharging in a sorting plant given in (DAFSTB 1996:123).

Uncertainty for fuel demand is assumed to be equal to electricity demand (GSD = 110%).

3.3.4 Infrastructure for sorting plants

Infrastructure materials

No information on the material demands for the infrastructure of a sorting plant is available. Life-Cycle information from a rock crusher is adopted from (Landfield & Karra 2000). The data displayed in Tab. 3.10 is from a cone crusher (conical crusher) Nordberg model HP400 SX for crushing rocks to a size of <32mm with a capacity of 454 metric tons per hour and an electricity consumption of 0.716 kWh/t.

Tab. 3.10 Infrastructure materials for one rock crusher (Landfield & Karra 2000).

Infrastructure materials	kg per unit
Steel	20'684 [1]
Iron	17'33
Bronze	338
Epoxy resin	80
Aluminum	17
Brass	0.64
miscellaneous [2]	957.4
Total	23'810

1 of which 2874 kg wear and tear parts (Mn-alloy steel)

2 Minor metal parts, e.g. nuts and bolts. Inventoried as low alloyed steel.

Crushing tools deteriorate rapidly and must be replaced several times per year. Such wear and tear parts are shown in Tab. 3.11. The original mass of replaced components during 25 years of operation given in (Landfield & Karra 2000) relate to a full-time operation of 5000 h/a or 2270 kt/a. The inventoried construction waste sorting plant is run at 200 kt/a. The mass of replaced components given in (Landfield & Karra 2000) are therefore reduced in this inventory by a factor 0.0881 (=200/2270). Wear and tear parts of crushers are assumed to be made of manganese alloyed steel (austenitic manganese steel) with approx. 12% manganese and 1.2% carbon (Aqua Alloys 2003, KTS 2003, Symons 2003). Manganese alloyed steel is inventoried as 16.2 w% ferromanganese and 83.8% unalloyed converter steel[17]. The infrastructure module is defined for 50 years, resulting in the use of

[17] Personal communication with Mischa Classen, EMPA Dübendorf, Switzerland, of May 6, 2003. Ferromanganese contains 72% manganese. A share of 16.6% w% ferromanganese results in 12 w% Mn in the alloy (=16.6%/72%).

two complete plants. During 50 years, 10 million tons of waste is processed by the plant. Per kilogram of waste, $1 \cdot 10^{-10}$ plant units are necessary.

Tab. 3.11 Replaced components of rock crusher during 25 years of operation (Landfield & Karra 2000).

Replaced components	Component mass kg	Replacement rate 1/a	Life Cycle masses with 2270 kt/a kg/unit	Life Cycle masses with 200 kt/a kg/unit
Total steel parts	–	–	397'354	35'009
Liner [1]	703	0.9937 [2]	17'464	1'539
Mantle [1]	1089	7	190'575	16'791
Bowl liner [1]	1075	7	188'125	16'575
Torch ring [1]	6.8	7	1'190	104.8
Lubricating oil	568	2	28'400	2'502

1 Assumed to be Mn-alloy steel

2 Not specified in (Landfield & Karra 2000). calculated by difference from a total Life Cycle mass of 397'354 kg given in (Landfield & Karra 2000).

Disposal: All metal parts are assumed to be recycled (cut-off system boundary). Epoxy resin is assumed to be incinerated (plastic to municipal incineration). Lubricating oil is assumed to be incinerated as hazardous waste (waste oil to hazardous waste incineration).

Transport: All materials except epoxy resin and aluminium are transported 600 km by train and 50 km by lorry. Epoxy resin and aluminium are transported 200 km by train and 50 km by lorry. Disposed epoxy is transported 10 km by lorry. Disposed oil is transported 50 km by lorry.

Uncertainty for infrastructure materials: Uncertainty for infrastructure materials is estimated with the Pedigree approach and shown in Tab. 3.12. The uncertainty of transport services is calculated from uncertainty of transport masses and transport distances (cf. part I).

Tab. 3.12 GSD^2 values for infrastructure materials

Exchange	GSD^2 value	Pedigree codes	Comment
infrastructure sorting plant	328%	(1,4,1,1,4,5)	Basic uncertainty of 3; Data from one inventory study for rock crusher (Landfield & Karra 2000)

Energy demand

For heating of a small on-site administrative building a value of 3220 MJ fuel oil per year are adopted from landfills (see part III). With a lifetime of 50 years 161'000 MJ per plant are calculated. Uncertainty for heating fuel demand is assumed to be 120%, due to temperature variation (GSD).

Land use

A typical land occupation of 15'000 m^2 for a 200 kt/a plant is given in Tab. 3.13. The occupied area is usually not completely sealed and is inventoried as 'industrial area'. Original land use type is 'unknown'. Inventoried values are 15'000 m^2 transformed area (from unknown to industrial) and – with an operation time of 50 years – 750'000 m^2a occupation 'industrial area'. Sorting plants are usually well connected, but not close to residential areas, due to noise and dust.

Tab. 3.13 Land occupation and transformation of sorting plants

Sorting plant	capacityt/a	Land occupation m^2	m^2a/kg
Minimal stationary sorting plant (Bilitewski 1993:57)	100	10'000	0.0001
Average stationary sorting plant (DAFSTB 1996:123)	200	15'000	0.000075
This study	200	15'000	**0.000075**

Tab. 3.14 GSD^2 values for land use exchanges

Exchange	**GSD^2 value**	**Pedigree codes**	**Comment**
land transformation sorting plant	214%	(4,5,2,3,1,5)	Basic uncertainty of 2; typical size given for planning data in one source for Germany.
land occupation sorting plant	167%	(4,5,2,3,1,5)	Basic uncertainty of 1.5; typical size given for planning data in one source for Germany. Estimate on operation time

Synopsis sorting plant infrastructure inventory

Tab. 3.15 Life cycle inventory for sorting plant infrastructure per unit

Per unit	Location	InfrastructureProcess	Unit	sorting plant for construction waste	StandardDeviation95%	GeneralComment
Location				CH		
InfrastructureProcess				1		
Unit				unit		
Occupation, industrial area			m2a	15000	167%	(4,5,2,3,1,5) & basic uncertainty of 1.5; typical size given for planning data in one source for Germany. Estimate on operation time
Transformation, from unknown			m2	750000	214%	(4,5,2,3,1,5) & basic uncertainty of 2; typical size given for planning data in one source for Germany.
Transformation, to industrial area			m2	750000	214%	(4,5,2,3,1,5) & basic uncertainty of 2; typical size given for planning data in one source for Germany.
light fuel oil, burned in boiler 10kW, non-modulating	CH	0	MJ	161000	144%	uncertainty estimated from climate variation
ferromanganese, high-coal, 72% Mn, at regional storage	RER	0	kg	12593	328%	(1,4,1,1,4,5) & basic uncertainty of 3; Data from one inventory study for rock crusher (Landfield & Karra 2000)
steel, converter, at plant	RER	0	kg	102623	328%	(1,4,1,1,4,5) & basic uncertainty of 3; Data from one inventory study for rock crusher (Landfield & Karra 2000)
cast iron, at plant	RER	0	kg	3466	328%	(1,4,1,1,4,5) & basic uncertainty of 3; Data from one inventory study for rock crusher (Landfield & Karra 2000)
bronze, at plant	CH	0	kg	676	328%	(1,4,1,1,4,5) & basic uncertainty of 3; Data from one inventory study for rock crusher (Landfield & Karra 2000)
epoxy resin, liquid, at plant	RER	0	kg	160	328%	(1,4,1,1,4,5) & basic uncertainty of 3; Data from one inventory study for rock crusher (Landfield & Karra 2000)
aluminium, production mix, cast alloy, at plant	RER	0	kg	34	328%	(1,4,1,1,4,5) & basic uncertainty of 3; Data from one inventory study for rock crusher (Landfield & Karra 2000)
brass, at plant	CH	0	kg	1.28	328%	(1,4,1,1,4,5) & basic uncertainty of 3; Data from one inventory study for rock crusher (Landfield & Karra 2000)
lubricating oil, at plant	RER	0	kg	5004	328%	(1,4,1,1,4,5) & basic uncertainty of 3; Data from one inventory study for rock crusher (Landfield & Karra 2000)
disposal, used mineral oil, 90% water, to hazardous waste incineration	CH	0	kg	5004	328%	(1,4,1,1,4,5) & basic uncertainty of 3; Data from one inventory study for rock crusher (Landfield & Karra 2000)
disposal, plastics, mixture, 15.3% water, to municipal incineration	CH	0	kg	160	328%	(1,4,1,1,4,5) & basic uncertainty of 3; Data from one inventory study for rock crusher (Landfield & Karra 2000)
transport, freight, rail	RER	0	tkm	74660	233%	uncertainty calculated from uncertainty of transported infrastructure masses and uncertainty of default transport distances
transport, lorry 28t	CH	0	tkm	6480	226%	uncertainty calculated from uncertainty of transported infrastructure masses and uncertainty of default transport distances

3.3.5 Transport to final disposal

The fractions from the sorting plant are either transferred to recycling or transported to disposal facilities (incinerators, landfills). The transport to recycling is not included in the inventories. For transport to disposal facilities the standard distances are applied. These distances are also used for direct disposal without sorting (option C). The uncertainty of the transport service is calculated from

the uncertainty of the transported mass and the uncertainty of the transport distance (see part I 'Uncertainty of transport services').

Tab. 3.16 Standard distances for transport to disposal facilities

Disposal facility	km lorry
Inert material landfill	15
Sanitary landfill	10
Municipal waste incineration	10
Hazardous waste incineration	50

3.4 Inventories of different materials

The inventories are divided into three options (described in chapter 3.1 'System boundaries' on page 8).

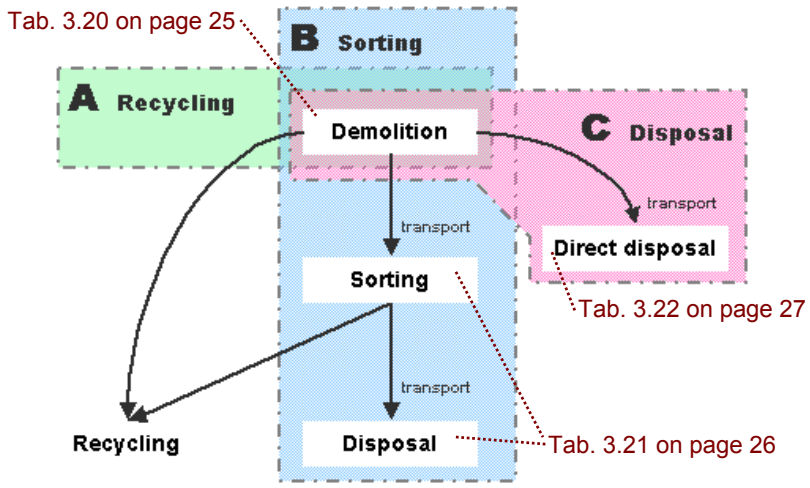


Fig. 3.7 System boundaries and material flows for the three disposal options A, B, C of building materials

A. Direct recycling: The option 'direct recycling' includes only the burdens from demolition for the material (in Tab. 3.20 on page 30). Burdens from recycling are not included. The name of the modules end with '... to recycling'.

B. Sorting: The option 'Sorting' includes the burdens from demolition (in Tab. 3.20 on page 30), from sorting, disposal of unwanted materials and two intermediate transports (all in Tab. 3.21 on page 31). The name of the modules end with '... to sorting plant'.

C. Direct disposal: The option 'Direct Disposal' includes the burdens from demolition (in Tab. 3.20 on page 30), direct disposal and one transport (in Tab. 3.22 on page 32). The name of the modules end with '... to final disposal'.

Please note, that the masses of disposed material and disposal facilities are not necessarily identical in option B and C. The demolition process is shared by all options (Fig. 3.7).

The resulting inventory table for all 36 building materials and all options is very large and very sparse, i.e. contains many zero values. The table is not very readable in print and is not reproduced here. The full table can be viewed in the file 13_Building_demolition1_LCI.xls and 13_Building_demolition2_LCI.xls on the CD-ROM. Here more readable tables of the inventoried exchanges are presented below.

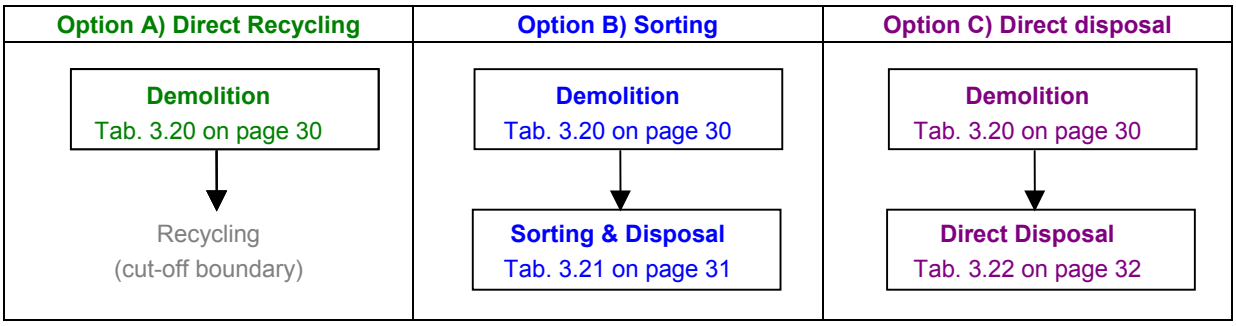


Fig. 3.8 Overview, where life cycle inventories for the three disposal options A, B, C of building materials are documented in this report

How to look up data modules

If you have a certain module and want to check its contents, here is some guidance where you find the descriptions of that module:

1.) Look at the *ending* of the module name and determine, which option it belongs to. This is either of:
   Option A) '... to recycling', or
   Option B) '... to sorting plant', or
   Option C) '... to final disposal'

2) In Fig. 3.8 above, look up the *tables* which document the exchanges for this option.

3) Go to the appropriate tables and look up the exchanges under the *name of the material*. There you find also references to the chapters where those exchanges are discussed in general.

3.4.1 Overview of existing modules

The created modules have a systematic name, combining the material name and the disposal option. All module names begin with "disposal, building, ...". All modules have the unit kilogram, the location CH (Switzerland), and are not flagged as infrastructure processes.

Tab. 3.17 English and German module naming for the example material 'concrete gravel'

Material name	Option A. Direct recycling	Option B. to sorting plant	Option C. to final disposal
concrete gravel	disposal, building, concrete gravel, *to recycling*	disposal, building, concrete gravel, *to sorting plant*	disposal, building, concrete gravel, *to final disposal*
Betonkies	Entsorgung, Gebäude, Betonkies, *ins Recycling*	Entsorgung, Gebäude, Betonkies, *in Sortieranlage*	Entsorgung, Gebäude, Betonkies, *in Beseitigung*

Data modules are created for the options which are feasible for the material under consideration. As explained in chapter 2.3.1 'Further data reduction' on page 5, some modules are omitted, to reduce the number of modules.

- For feasible processes in option A, which create no burden within the building disposal system boundaries are not devised, since those data modules would be empty (see Fig. 3.1 on page 9).
- All burnable wastes to sorting (option B) can be approximated with the direct disposal module (option C) since the burdens from incineration surpass the burdens from sorting.

In Tab. 3.18 a synopsis of all data modules is presented. Missing combinations of options/materials are indicated. All *feasible* options are denoted with a '◆'. For some feasible but missing combinations, explanations or proxy solutions are offered. An exclamation mark '!' denotes materials to sorting

which subsequently are predominantly not recycled. Some material might enter recycling streams as unwanted material, though.

Tab. 3.18 Synopsis of all data modules and combinations of options and materials. See text and comments below.

material name	Option A. Direct recycling	Option B. to sorting plant	Option C. to final disposal
concrete, not reinforced	◆M	◆M	◆M
reinforced concrete	◆M	◆M	◆M
cement (in concrete) and mortar	no recycling	!◆M	◆M
concrete gravel	◆M	◆M	◆M
brick	◆M	◆M	◆M
plaster board, gypsum plaster	◆M	!◆M	◆M
plaster-cardboard sandwich	◆M	!◆M	◆M
reinforced plaster board	◆M	!◆M	◆M
mineral wool	◆M	!◆M	◆M
polystyrene isolation, flame-retardant	◆no burdens	◆use option C	◆M
glass sheet	◆no burdens	◆M	◆M
glass pane (in burnable frame)	◆no burdens	◆M	◆M
reinforcement steel	◆M	◆M	◆M
bulk iron (excluding reinforcement)	◆no burdens	◆M	⁎
waste wood, untreated	◆no burdens	◆use option C	◆M
waste wood, chrome preserved	no recycling	◆use option C	◆M
fibre board	no recycling	◆use option C	◆M
polyurethane foam	no recycling	◆use option C	◆M
paint remains	no recycling	x	◆M
paint on walls	no recycling	!◆M	◆M
paint on wood	no recycling	x	◆M
paint on metal	no recycling	◆M	◆M
emulsion paint remains	no recycling	x	◆M
emulsion paint on walls	no recycling	!◆M	◆M
emulsion paint on wood	no recycling	x	◆M
polyurethane sealing	no recycling	!◆M	◆M
polyvinylchloride products	◆no burdens	◆use option C	◆M
polyethylene/polypropylene products	◆no burdens	◆use option C	◆M
cement-fibre slab	◆M	◆use option C	◆M
mineral plaster	no recycling	!◆M	◆M
plastic plaster	no recycling	!◆M	◆M
PVC sealing sheet	◆no burdens	◆use option C	◆M
PE sealing sheet	◆no burdens	◆use option C	◆M
vapour barrier, flame-retarded	◆no burdens	◆use option C	◆M
bitumen sheet	no recycling	◆use option C	◆M
electric wiring	◆no burdens	◆use option C	◆M

◆	Feasible options
◆M	Feasible options with inventory modules
	Comments for option A (direct recyling):
◆no burdens	Recycling imaginable, but no burdens occur within the system boundaries of building material disposal
no recycling	Specific recycling of this material is unlikely today. Use option C (or option B where applicable)
	Comments for option B (to sorting plant):
◆use option C	Sorting of this burnable material is feasible, but can be approximated by using the module of option C (to final disposal) neglecting the comparatively small burdens from sorting
x	No data module. Sorting not possible. Use option C for this material (final disposal)
!◆	Data module exists, but the majority of the material is *not recycled*, but disposed after sorting
	Comments for option C (to final disposal):
⁎	No data module. All bulk iron can be expected to be recycled (cut-off system boundary to recycling). For reinforcement steel use appropriate module.

3.4.2 Information on inventoried materials

General information on the inventoried building materials is shown in Tab. 3.19. The materials are grouped in the following order: Structural materials, gypsum materials, insulation materials, glass and metal, wood materials, glues and paints, bulk plastic materials, structural composite materials, plaster, plastic sheets and wiring.

The composition refers to shares of material types with dissimilar disposal behaviour. The associated uncertainty is needed in calculation of uncertainty of transportation of waste fractions to disposal facilities after sorting. The uncertainty is derived from the formula GSD= -0.052*log(c)+1, where c is the share in kg/kg.

Tab. 3.19 Density and material composition of inventoried building materials

Material name	Density kg/m^3	Material Composition kg/kg
concrete, not reinforced	2200	1kg inert material (GSD=100%).
reinforced concrete	2300	0.97kg inert material (GSD=100.1%) and 0.03kg steel (GSD=107.9%).
cement (in concrete) and mortar	3150	1kg inert material (GSD=100%).
concrete gravel	2000	1kg inert material (GSD=100%).
brick	1600	1kg inert material (GSD=100%).
plaster board, gypsum plaster	1000	1kg gypsum (GSD=100%).
plaster-cardboard sandwich	1000	0.834kg gypsum (GSD=100.4%) and 0.166kg cardboard (GSD=104.1%)
reinforced plaster board	1000	0.85kg gypsum (GSD=100.4%) and 0.15kg cardboard (GSD=104.3%) [1]
mineral wool	50	1kg inert material (GSD=100%)
polystyrene isolation, flame-retardant	20	1kg flame retarded EPS (GSD=100%)
glass sheet	2500	1kg inert material (GSD=100%)
glass pane (in burnable frame)	2500	1kg inert material (GSD=100%)
reinforcement steel	7900	1kg steel (GSD=100%)
bulk iron (excluding reinforcement)	7900	1kg steel (GSD=100%)
waste wood, untreated	720	1kg untreated wood (GSD=100%)
waste wood, chrome preserved	720	1kg chrome preserved wood (GSD=100%)
fibre board	740	0.925kg untreated wood (GSD=100.2%) and 0.075kg polyurethane (GSD=105.8%)
polyurethane foam	30	1kg polyurethane (GSD=100%)
paint remains	850	1kg paint (GSD=100%)
paint on walls	850	1kg paint (GSD=100%)
paint on wood	850	1kg paint (GSD=100%)
paint on metal	850	1kg paint (GSD=100%)
emulsion paint remains	850	1kg emulsion paint (GSD=100%)
emulsion paint on walls	850	1kg emulsion paint (GSD=100%)
emulsion paint on wood	850	1kg emulsion paint (GSD=100%)
polyurethane sealing	1200	1kg polyurethane (GSD=100%)
polyvinylchloride products	1400	1kg polyvinylchloride (GSD=100%)
polyethylene/polypropylene products	950	1kg polyethylene/polypropylene (GSD=100%)
cement-fibre slab	1200	0.64kg inert material (GSD=101%) and 0.36kg untreated wood (GSD=102.3%)
mineral plaster	2000	1kg inert material (GSD=100%)
plastic plaster	1300	1kg plastic plaster (GSD=100%)
PVC sealing sheet	1200	1kg PVC sealing sheet (GSD=100%)
PE sealing sheet	1000	1kg PE sealing sheet (GSD=100%)
vapour barrier, flame-retarded	1000	1kg flame-retarded vapour barrier (PE) (GSD=100%)
bitumen sheet	1270	1kg bitumen sheet (GSD=100%)
electric wiring	4100	0.615kg cable insulation (GSD=101.1%) and 0.385kg copper (GSD=102.2%)

1 proxy for biomass reinforcement fibres

3.4.3 Burdens from demolition

In Tab. 3.20 the burdens from demolition for each material are presented. Demolition energies are only inventoried for structural materials. Demolition energies and GSD are detailed in Tab. 3.2 on page 11. Particulate matter PM emissions during demolition are constant for each material marked 'yes' in Tab. 3.20 and are detailed (incl. GSD) in Tab. 3.4 on page 13.

For direct recycling (option A) the burdens in Tab. 3.20 are the only burdens that apply. The materials, for which option A modules were created are indicated in Tab. 3.18 on page 25. The general module name structure for these modules is *'disposal, building, NAME, to recycling'*, where NAME is the material name listed in Tab. 3.20. If no burdens are recorded during demolition the option A module is not created to preserve database volume and avoid creating empty modules (entry *'◆no burdens'* in Tab. 3.18). Hence, the absence of a module does not necessarily mean that a material is *not* recyclable. Also no module is created when direct recycling seems not practicable for a material; e.g. plaster and mortars (entry *'no recycling'* in Tab. 3.18).

3.4.4 Burdens from sorting

The varaible burdens from sorting for different materials are shown in Tab. 3.21. All exchanges are inventoried per kilogram waste. Constant burdens that are inventoried additionally are sorting plant infrastructure (cf. chapter 3.3.4 'Infrastructure for sorting plants' on page 18). Together with the burdens from demolition, these burdens are entered in the option B modules (waste to sorting). The materials, for which option B modules were created are indicated in Tab. 3.18 on page 25. The general module name structure for these modules is *'disposal, building, NAME, to sorting'*, where NAME is the material name listed in Tab. 3.20.

The entries under 'Handling' and 'Electric energy' refer to the energy consumption in the sorting plant for charging and discharging (m^3 skid-steer loader) and for overall electricity consumption incl. the crusher. These entries are detailed in chapter 3.3.3 'Energy demand in sorting plants' on page 17.

The entry 'Recycled mass' indicates how much of the waste material is transferred to a recyclable fraction. This material is not necessarily useful or valuable in recycling, i.e. might also represent a disturbing material and might be removed from the recyclate at a later stage.

The entry 'Disposed fractions' indicates the material removed to the fine fraction or other not recycled fractions. The magnitude of the separated fine fraction varies for different materials (robust vs. brittle) and is discussed in chapter 3.3.1 'Separated fine fraction' on page 15. The fine fraction is disposed in a sanitary landfill. The composition of landfilled inert material is approximated with the composition of hydrated cement. The uncertainty of the disposed fractions is calculated from the uncertainty of the input material and the transfer coefficient.

The entry 'Total transport service' gives the sum transport service for transport to the sorting plant (17.7 km) and transport of the disposed fractions from the sorting plant to disposal facilities (cf. chapter 3.3.5 'Transport to final disposal' on page 21). The uncertainty of the transport service is calculated from the uncertainty of the transported mass(es) and the uncertainty of the transport distance using the approximation for addition for lognormal distributions of Wilkinson-Fenton (see comment on uncertainty of standard transport distances in part I). The uncertainty of the transported mass depends on the uncertainty of the material composition and the uncertainty of the transfer coefficients (cf. Tab. 3.7 on page 16).

3.4.5 Burdens from direct disposal

In modules of option C (direct disposal) three burdens are inventoried:

- the demolition burdens (cf. Tab. 3.20 on page 30)
- a transport to the disposal facilities (cf. chapter 3.3.5 'Transport to final disposal' on page 21)
- the burdens from final disposal (landfill or incineration)

The inventoried burdens from transport and final disposal are shown in Tab. 3.22 for different materials. The uncertainty of the disposed fractions is calculated from the uncertainty of the input material.

The materials, for which direct disposal (option C) modules were created are indicated in Tab. 3.18 on page 25 on the right. Mineral wastes to direct disposal are assumed to be collected with other mineral wastes (MTC through 2 or 1, cf. Tab. 2.1 on page 5) and disposed as construction waste in inert material landfill without sorting. If the waste is collected as mixed waste (MTC through 4) it is mandatory to sort the waste and the modules 'to sorting' apply and modules 'to final disposal' shall not be used in this case. This is often the case during renovation.

Waste materials disposed in municipal waste incinerators are assumed to be sorted into the through for burnable material at the building site (polystyrene isolation, wood, fibre board, polyurethane foam, paint on wood, emulsion paint on wood, polyvinylchloride products, polyethylene/polypropylene products, PVC sealing sheet, PE sealing sheet, vapour barrier, bitumen sheet, electric wiring).

Waste materials disposed in hazardous waste incineration are hazardous wastes separated at the building site from new construction and renovation activities (paint remains, emulsion paint remains).

The general module name structure for these modules is *'disposal, building, NAME, to final disposal'*, where NAME is the material name listed in Tab. 3.20.

Tab. 3.20 Burdens from demolition for different building materials. Explanations see chapter 3.4.3 'Burdens from demolition' on page 28.

Material NAME	**Demolition energy** (cf. Tab. 3.2 on page 11) MJ/kg	**PM emissions during demolition** (cf. Tab. 3.4 on page 13)
concrete, not reinforced	0.04374	yes
reinforced concrete	0.06124	yes
cement (in concrete) and mortar	0.04374	yes
concrete gravel	0.04374	yes
brick	0.03594	yes
plaster board, gypsum plaster	0.03594	yes
plaster-cardboard sandwich	0.03594	yes
reinforced plaster board	0.03594	yes
mineral wool	0	yes
polystyrene isolation, flame-retardant	0	–
glass sheet	0	–
glass pane (in burnable frame)	0	–
reinforcement steel	0.6259	–
bulk iron (excluding reinforcement)	0	–
waste wood, untreated	0	–
waste wood, chrome preserved	0	–
fibre board	0	–
polyurethane foam	0	–
paint remains	0	–
paint on walls	0	–
paint on wood	0	–
paint on metal	0	–
emulsion paint remains	0	–
emulsion paint on walls	0	–
emulsion paint on wood	0	–
polyurethane sealing	0	–
polyvinylchloride products	0	–
polyethylene/polypropylene products	0	–
cement-fibre slab	0.03594	yes
mineral plaster	0	yes
plastic plaster	0	yes
PVC sealing sheet	0	–
PE sealing sheet	0	–
vapour barrier, flame-retarded	0	–
bitumen sheet	0	–
electric wiring	0	–

Tab. 3.21 Burdens from sorting of building materials. Explanations see chapter 3.4.4 'Burdens from sorting' on page 28.

Material name	Handling	Electric energy	Recycled mass	Disposed fractions (100% minus recycled mass)	GSD	Total transport service	GSD
	m^3/kg waste	kWh/kg waste	kg/kg waste	kg/kg waste		tkm/kg waste	
concrete, not reinforced	0.0005051	0.0037	0.6	0.4kg 'disposal, inert material, 0% water, to sanitary landfill' [5]	122.5%	0.02178	103.91%
reinforced concrete [5]	0.0004831	0.0037	0.612	0.388kg 'disposal, inert material, 0% water, to sanitary landfill' [5]	122.5%	0.02166	103.81%
cement (in concrete) and mortar	0.0003527	0.0037	0.15	0.85kg 'disposal, inert material, 0% water, to sanitary landfill' [5]	108%	0.02623	102.54%
concrete gravel	0.0005556	0.0037	0.6	0.4kg 'disposal, inert material, 0% water, to sanitary landfill' [5]	122.5%	0.02178	103.91%
brick	0.0006944	0.0037	0.6	0.4kg 'disposal, inert material, 0% water, to sanitary landfill' [5]	122.5%	0.02178	103.91%
plaster board, gypsum plaster	0.001111	0.0037	0.15	0.85kg 'disposal, gypsum, 19.4% water, to sanitary landfill'	108%	0.02623	102.54%
plaster-cardboard sandwich [3]	0.001111	0.0037	0.1251	0.709kg 'disposal, gypsum, 19.4% water, to sanitary landfill' and 0.166kg 'disposal, packaging cardboard, 19.6% water, to municipal incineration'	108% 104.1%	0.02647	102.11%
reinforced plaster board [4]	0.001111	0.0037	0.1275	0.723kg 'disposal, gypsum, 19.4% water, to sanitary landfill' and 0.15kg 'disposal, packaging cardboard, 19.6% water, to sanitary landfill'	108% 104.3%	0.02644	102.15%
mineral wool	0.02222	0.0022 [1]		1kg 'disposal, mineral wool, 0% water, to inert material landfill'	100%	0.0327	100%
glass sheet	0.0004444	0.0037	0.6	0.4kg 'disposal, inert material, 0% water, to sanitary landfill' [5]	122.5%	0.02178	103.91%
glass pane (in burnable frame)	0.0004444	0.0022 [1]		1kg 'disposal, glass, 0% water, to municipal incineration'	100%	0.0277	100%
reinforcement steel	0.0001406	0.0037	1	-		0.0177	100%
bulk iron (excluding reinforcement) [6]	0.0001406	0.0037	1	-		0.0177	100%
paint on walls	0.001307	0.0022 [2]	0.15	0.85kg 'disposal, paint, 0% water, to sanitary landfill'	108%	0.02623	102.54%
paint on metal	0.001307	0.0022 [2]	1 [7]	-		0.0177	100%
emulsion paint on walls	0.001307	0.0022 [2]	0.15	0.85kg 'disposal, emulsion paint, 0% water, to sanitary landfill'	108%	0.02623	102.54%
polyurethane sealing	0.0009259	0.0037	0.15	0.85kg 'disposal, polyurethane, 0.2% water, to sanitary landfill'	108%	0.02623	102.54%
mineral plaster	0.0005556	0.0037	0.15	0.85kg 'disposal, inert material, 0% water, to sanitary landfill' [5]	108%	0.02623	102.54%
plastic plaster	0.0008547	0.0037	0.15	0.85kg 'disposal, plastic plaster, 0% water, to sanitary landfill'	108%	0.02623	102.54%

1 Mineral wool and glass panes in frames are sorted out prior to crushing.

2 Assumed no crushing energy for paints on materials.

3 Cardboard is removed and incinerated.

4 Fibres are combined with gypsum and cannot be removed. Inventoried as cardboard to sanitary landfill.

5 Assuming 3% steel

6 Magnetic separation in sorting plant, to metal recycling.

7 Paint on metal enters metal recycling.

8 Inert material to landfill is inventoried with the composition of cement (cf. part I)

Tab. 3.22 Burdens from direct disposal (without demolition burdens cf. Tab. 3.20). Explanations see chapter 3.4.5 'Burdens from direct disposal' on page 29.

Material name	Final disposal kg/kg waste	GSD	Total transport [3] tkm/kg waste
concrete, not reinforced	1kg 'disposal, inert waste, 5% water, to inert material landfill'	100%	0.015
reinforced concrete	0.97kg 'disposal, inert waste, 5% water, to inert material landfill' and 0.03kg 'disposal, steel, 0% water, to inert material landfill'	100.1% 107.9%	0.015
cement (in concrete) and mortar	1kg 'disposal, inert waste, 5% water, to inert material landfill'	100%	0.015
concrete gravel	1kg 'disposal, inert waste, 5% water, to inert material landfill'	100%	0.015
brick	1kg 'disposal, inert waste, 5% water, to inert material landfill'	100%	0.015
plaster board, gypsum plaster	1kg 'disposal, gypsum, 19.4% water, to inert material landfill'	100%	0.015
plaster-cardboard sandwich	0.834kg 'disposal, gypsum, 19.4% water, to inert material landfill' and 0.166kg 'disposal, packaging cardboard, 19.6% water, to inert material landfill'	100.4% 104.1%	0.015
reinforced plaster board	0.85kg 'disposal, gypsum, 19.4% water, to inert material landfill' and 0.15kg 'disposal, packaging cardboard, 19.6% water, to inert material landfill'	100.4% 104.3%	0.0085
mineral wool	1kg 'disposal, mineral wool, 0% water, to inert material landfill'	100%	0.015
polystyrene isolation, flame-retardant	1kg 'disposal, expanded polystyrene, 5% water, to municipal incineration'	100%	0.01
glass sheet	1kg 'disposal, inert waste, 5% water, to inert material landfill'	100%	0.015
glass pane (in burnable frame)	1kg 'disposal, glass, 0% water, to municipal incineration'	100%	0.01
reinforcement steel	1kg 'disposal, steel, 0% water, to inert material landfill'	100%	0.015
waste wood, untreated	1kg 'disposal, wood untreated, 20% water, to municipal incineration'	100%	0.01
waste wood, chrome preserved	1kg 'disposal, building wood, chrome preserved, 20% water, to municipal incineration'	100%	0.01
fibre board	0.925kg 'disposal, wood untreated, 20% water, to municipal incineration' and 0.075kg 'disposal, polyurethane, 0.2% water, to municipal incineration'	100.2% 105.8%	0.01
polyurethane foam	1kg 'disposal, polyurethane, 0.2% water, to municipal incineration'	100%	0.01
paint remains [1]	1kg 'disposal, paint remains, 0% water, to hazardous waste incineration'	100%	0.05
paint on walls	1kg 'disposal, paint, 0% water, to inert material landfill'	100%	0.015
paint on wood	1kg 'disposal, paint, 0% water, to municipal incineration'	100%	0.01
paint on metal	1kg 'disposal, paint, 0% water, to inert material landfill'	100%	0.015
emulsion paint remains [1]	1kg 'disposal, emulsion paint remains, 0% water, to hazardous waste incineration'	100%	0.05
emulsion paint on walls	1kg 'disposal, emulsion paint, 0% water, to inert material landfill'	100%	0.015
emulsion paint on wood	1kg 'disposal, emulsion paint, 0% water, to municipal incineration'	100%	0.01
polyurethane sealing [2]	1kg 'disposal, polyurethane, 0.2% water, to inert material landfill'	100%	0.015
polyvinylchloride products	1kg 'disposal, polyvinylchloride, 0.2% water, to municipal incineration'	100%	0.01
polyethylene/polypropylene products	1kg 'disposal, polyethylene, 0.4% water, to municipal incineration'	100%	0.01
cement-fibre slab	1kg 'disposal, cement-fibre slab, 0% water, to municipal incineration'	100%	0.01
mineral plaster	1kg 'disposal, inert waste, 5% water, to inert material landfill'	100%	0.015
plastic plaster	1kg 'disposal, plastic plaster, 0% water, to inert material landfill'	100%	0.01
PVC sealing sheet	1kg 'disposal, PVC sealing sheet, 1.64% water, to municipal incineration'	100%	0.01
PE sealing sheet	1kg 'disposal, PE sealing sheet, 4% water, to municipal incineration'	100%	0.01
vapour barrier, flame-retarded	1kg 'disposal, vapour barrier, flame-retarded, 4.5% water, to municipal incineration'	100%	0.01
bitumen sheet	1kg 'disposal, bitumen sheet, 1.5% water, to municipal incineration'	100%	0.01
electric wiring	0.615kg 'disposal, wire plastic, 3.55% water, to municipal incineration' and 0.385kg 'disposal, copper, 0% water, to municipal incineration'	101.1% 102.2%	0.01

1 Only from new construction and renovation

2 Polyurethane sealing is assumed to be landfilled along with the mineral wastes in mixed rubble. If sealings are large enough to be removed and separated as burnable material the direct disposal of polyurethane foam (to municipal incineration) can be applied.

3 GSD =100% for all transport services (1kg is 1kg). Cf. comment on uncertainty of standard transport distances in part I.

3.5 Remark on the disposal of reinforced concrete

The demolition of reinforced concrete usually consumes more energy than the demolition of plain concrete (see Tab. 3.1 on page 10). It can be said that the use of reinforcement increases the demolition energy. The difference in energy consumption is therefore attributable to reinforcement steel alone. This attribution to reinforcement steel was performed in the assignment of demolition energies in Tab. 3.2 on page 11 and in Tab. 3.20 on page 30.

Heed has to be taken in assigning the resulting disposal modules. For example reinforced concrete might be composed of a mass X of steel plus a mass Y of concrete. The use of reinforced concrete can then be inventoried as a mass X of reinforcement steel plus a mass Y of plain concrete[18].

To inventory the disposal of these materials likewise a mass of X of reinforcement steel to disposal plus a mass of Y *plain concrete* to disposal shall be inventoried. I.e. although the considered concrete is *reinforced concrete* the applied disposal module is quite correctly for *plain, un-reinforced concrete*. The additional energy to dismantle reinforced concrete is fully heeded in the disposal of reinforcement steel. It would be double counting to inventory the disposal of *reinforced concrete* here. With the outlined inventory scheme, concrete types with a high mass percentage of reinforcement steel obtain a *larger* demolition energy, which seems suitable[19]. The resulting demolition energies are shown in Tab. 3.23.

Tab. 3.23 Percentage of reinforcement steel and resulting demolition energies.

Percent reinforcement steel	Production and disposal is inventoried as		Resulting demolition energies only (MJ/kg concrete)	Comment (compare to Tab. 3.2 on page 11)
0%	100% plain concrete	0% reinforcement steel	0.0437	Plain concrete
1%	99% plain concrete	1% reinforcement steel	0.0495	
2%	98% plain concrete	2% reinforcement steel	0.0553	
3%	97% plain concrete	3% reinforcement steel	0.0612	Generic default for reinforced concrete
4%	96% plain concrete	4% reinforcement steel	0.0670	
5%	95% plain concrete	5% reinforcement steel	0.0728	

[18] There is no generic *production* module of 'reinforced concrete' in ecoinvent 2000.

[19] It is also possible to inventory the demolition of reinforced concrete as a mass of (X+Y) of 'reinforced concrete'. This module assumes a fixed generic value of 3 w% of reinforcement steel. The resulting demolition energy is therefore a fixed value and would not change with steel content. If X/(X+Y) differs significantly from 3% the demolition energies can be over- or underestimated. This way of inventorying is less precise and shall be avoided.

4 Cumulative Results and Interpretation

4.1 Introduction

Selected LCI results and values for the cumulative energy demand are presented and discussed in this chapter. Please note that only a small part of the about 1000 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. It rather allows to show by examples the contributions of the different life cycle phases, or specific inputs from the technosphere to the selected elementary flows. Please refer to the ecoinvent database for the complete LCIs.

The shown selection is not suitable for a life cycle assessment of the analysed processes and products. Please use the data from the database for your own calculations, also because of possible minor deviations between the presented results and the database due to corrections and changes in background data used as inputs in the dataset of interest.

The ecoinvent database also contains life cycle impact assessment results. Assumptions and interpretations were necessary to match current LCIA methods with the ecoinvent inventory results. They are described in (Frischknecht et al. 2003c). It is strongly advised to read the respective chapters of the implementation report before applying LCIA results.

4.2 Results for concrete disposal

The Tab. 4.1 shows some arbitrary results of the cumulated inventory of the disposal options for concrete. Four datasets were chosen:

- Plain concrete to recycling
- Plain concrete to sorting plant
- Plain concrete to final disposal
- Reinforced concrete to sorting plant

Al results refer to one kilogram of concrete. The results only refer to the disposal and not the production of the materials.

Tab. 4.1 Selected LCI results and the cumulative energy demand for concrete disposal

		Name		disposal, building, concrete, not reinforced, to recycling	disposal, building, concrete, not reinforced, to sorting plant	disposal, building, concrete, not reinforced, to final disposal	disposal, building, concrete, reinforced concrete, to sorting plant
		Location		CH	CH	CH	CH
		Unit		kg	kg	kg	kg
		Infrastructure		0	0	0	0
LCIA results			Unit				
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	0.0591	0.2860	0.3230	0.3050
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	0.0013	0.0334	0.0091	0.0337
	cumulative energy demand	renewable energy resources, water	MJ-Eq	0.0002	0.0113	0.0023	0.0113
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.0001	0.0006	0.0003	0.0006
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	0.0001	0.0013	0.0007	0.0013
LCI results			Unit				
resource	Land occupation	total	m2a	0.0000182	0.00201	0.00161	0.00197
air	Carbon dioxide, fossil	total	kg	0.00383	0.0138	0.0137	0.0151
air	NMVOC	total	kg	0.0000201	0.0000475	0.0000528	0.0000549
air	Nitrogen oxides	total	kg	0.000158	0.000311	0.000335	0.00037
air	Sulphur dioxide	total	kg	0.00000579	0.0000204	0.0000198	0.0000224
air	Particulates, < 2.5 um	total	kg	0.0000327	0.0000458	0.0000481	0.0000519
water	BOD	total	kg	0.0000151	0.0000433	0.0000446	0.0000488
soil	Cadmium	total	kg	2.16E-13	5.65E-11	5.38E-11	5.59E-11
Further LCI results			Unit				
water	Cadmium, ion	total	kg	8.61E-11	0.000000251	7.45E-09	0.000000244
water	Copper, ion	total	kg	1.36E-09	0.00000158	2.68E-08	0.00000154
water	Lead	total	kg	1.05E-09	0.0000119	5.41E-08	0.0000115
water	Zinc, ion	total	kg	0.000000117	0.0000276	0.000000703	0.0000269
air	Particulates, < 10um	total	kg	0.0000964	0.000114	0.000115	0.00012

For the option 'to recycling' (option A, or first dataset) the only inventoried burdens are dismantling energy and emissions of particulates. For the option 'to sorting' (option B, or second dataset) dismantling energy, emissions of particulates, transport to sorting plant, expenditures for sorting, and disposal of residuals (fine fraction) in a sanitary landfill are inventoried. For the option 'to final disposal' (option c, or third dataset) dismantling energy, emissions of particulates, transport to landfill, and disposal in an inert material landfill.

The dismantling energy and emissions of particulates are a common necessity for each option and represent a 'baseline burden'. The more material is recycled the less energy is consumed. The reason for this is that even the landfilling of inert waste consumes e.g. 0.2 MJ of fossil CED (see results of part III). It can't be concluded here if the recycling option as a whole really is less energy consuming than final disposal. To clarify that, one would also have to look at the recycling process itself and the production of new gravel. The pattern of less burdens with increased recycling is also repeated in the air emissions.

Land occupation is largest in option B (sorting plant). This is due to more transport (to sorting plant and to landfill), the occupation of the sorting plant itself, and the fact that a sanitary landfill uses more land per kg waste than the inert material landfill of option C.

The same pattern is found in metal emissions to water. This is because the pollutants from the fine fraction of option B will be released in time from the sanitary landfill, while no waste-specific emissions are inventoried for the inert material landfill of option C.

The particulate air emission shown in Tab. 4.1 is a summation of the two ECOSPOLD exchanges *'Particulates, < 2.5 um'* and *'Particulates, > 2.5 um, and < 10um'*. Thus, it represents the common parameter PM_{10}, i.e. particulates of <10µm aerodynamic cross-section, which are the most hazardous fraction of particulates. During dismantling an emission of 80 mg PM_{10} per kg concrete is inventoried (See section 'Particulate matter PM' on page 13). This emission alone contributes 70 % to 80 % of the cumulated PM_{10} emissions and is therefore dominant. However this value was derived from one single source and was extrapolated to Switzerland. A more detailed investigation of this emission might be important.

The fourth dataset relates to the second dataset. The fourth dataset inventories reinforced to sorting plant, while the second dataset inventories pain, non-reinforced concrete to sorting plant. The energy demand to dismantle reinforced concrete is larger. The increased energy demand for reinforced concrete is also apparent from the CED figures. Decreases compared to the second dataset originate from the fact that 3% of steel are present in reinforced concrete, which reduced the landfilled amount per kg. The CED fossil value for reinforced concrete *to recycling*, i.e. only for dismantling, is 0.082 MJ (not shown), while dismantling of plain concrete consumes 0.059 MJ CED fossil (first dataset).

4.2.1 Energy consumption as an environmental indicator

Within the construction and building community, cumulated energy demand CED is frequently used to make statements about the environmental impact. Equal or similar indicators are 'grey' or embodied energy, and primary energy demand. While for certain environmental aspects of buildings (e.g. space heating) the energy demand might be a simple and useful indicator, it is too crude to point out environmental effects in detail. Energy consumption in disposal processes is usually of minor importance and bears no correlation to the total ecological burden of disposal processes. The common practice of associating energy consumption with environmental burden breaks down for disposal

processes[20]. Since disposal processes can – depending on material – become relevant for the whole life cycle, the notion that energy consumption is a proxy for environmental burden should generally be used with caution in LCA. Other methods are needed to adequately assess the environmental burdens over the life cycle. Authors of CED indicators databases are aware of these shortcomings and also advocate caution.

Associating environmental damage with energy consumption suggests a correlation between the two. The energy consumption of a process plotted against its environmental damage should result in a line or a continuos curve. Such a plot is given in Fig. 4.1. For energy consumption (fossil & nuclear & hydro) and environmental damage expressed with the ecological scarcity or UBP'97-method. The two data sets represent the whole ecoinvent database and the buildings material disposal. Obviously there is no correlation between the two indicators.

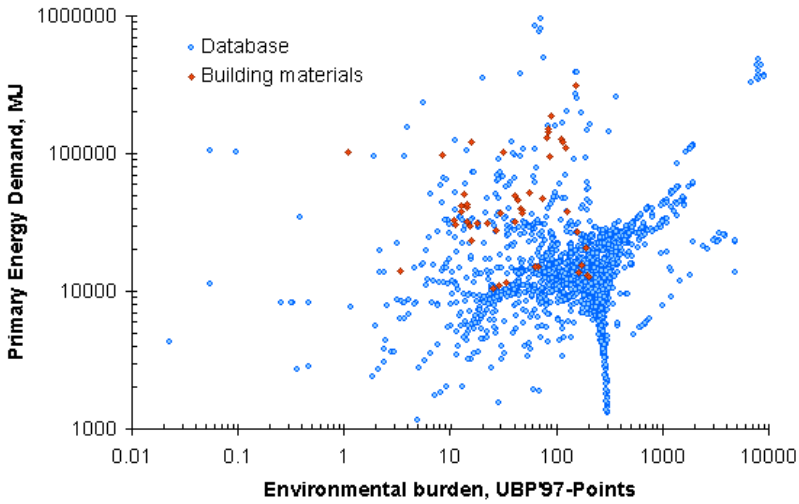


Fig. 4.1 Plot of environmental burden versus energy consumption

One popularly assumed advantage of energy consumption as an 'environmental indicator' is the 'objectivity' of calculation. While the devised unit, usually megajoules, is indeed a defined physical unit, the procedure *how* to calculate Cumulative Energy Demand CED is not unambiguous and requires also several value judgements. One example of ambiguity is the energetic valuation of uranium in the nuclear electricity chain. Another is which energy resources to include. While CED has an apparently objective unit, this helps to hide a definition which is not so objective, and based on value judgements like any other impact assessment method. See (Frischknecht et al. 2003b) for implementation of CED in ecoinvent 2000.

4.2.2 Unsuitable materials in inert material landfills

It was pointed out above that no emissions are assumed in the landfill models of ecoinvent 2000 for inert material landfills (see part III on landfills). It is assumed that landfilled materials are indeed inert and show no or little relevant pollutant potential. However, Swiss legislation tolerates a content of

[20] In general terms and e.g. on a national scale it is often true that a lot of pollutants (especially air pollutants) come from energy consumption (e.g. road and air traffic, space heating). Hence there is some justification in using energy consumption as a proxy for environmental burdens. The reverse is often also true: the processes that are the most polluting often do consume a lot of energy. However for specific processes – like disposal – this simplification can be utterly wrong. There is essentially no point in trying to assess the environmental burdens of disposal by only looking at energy consumption.

maximally 5 w% non-mineral or dissolvable material[21] (TVA 2000:23). The maximally 5% non-mineral material pose a potential threat to the inertness of the landfill, if they are decomposable or soluble substances. For example wall paper, wood shreds or paint remains could initiate microbial activity in the landfill, leading to increased emissions[22]. While these pollution potentials are currently not quantified in the process inventory, it is worthwhile pointing out the waste materials and options that are found to lead to transfers of non-mineral – and therefore unsuitable – material to inert material landfills (see Tab. 4.2). Most instances occur within the option C (direct final disposal, without sorting).

Tab. 4.2 Disposal processes that transfer non-mineral materials to inert material landfills

Disposed building material	**Disposal option** cf. ch. 3.1 on page 8	**Unsuitable material** transferred to inert material landfill
(Emulsion) paint on walls Paint on metal [1]	C. Direct final disposal C. Direct final disposal	(Emulsion) paint Paint
Polyurethane sealing [2]	C. Direct final disposal	Polyurethane
Plaster-cardboard sandwich Reinforced plaster board	C. Direct final disposal C. Direct final disposal	Cardboard Reinforcement fibres (biomass)
Concrete	C. Direct final disposal	Concrete additives and repair polymer reinforcements
Mineral wool [3] Mineral wool	B. Sorting plant C. Direct final disposal	Adhesive in mineral wool Adhesive in mineral wool
Plastic plaster Mineral plaster	C. Direct final disposal C. Direct final disposal	Polymer and additives Plaster additives

1 Rare disposal option as bulk metal is usually sorted out (even without processing in a sorting plant)

2 As small, adherent parts on mineral material

3 Sorted out prior to crushing

4.2.3 Emissions from inert waste materials

No direct waste emissions were assumed for the inert material landfill. However, also inert materials and especially mixed waste building material can contain pollutants. Sources of pollutants can be paints, glues, metal parts, concrete additives etc. In the production of cement there is also a tendency for increased burning of waste fractions to substitute coal. The ashes of these wastes are incorporated into the cement and ultimately will be found in the waste cement product. This can increase pollutant loads of cement. It would be consistent with current methodology to inventory leachate emissions also from inert material landfills.

As a coarse estimate of the relevance of emissions from such 'inert materials' the process module 'hydrated cement to residual material landfill' could be used. The average trace contents in hydrated cement are heeded in that module. Residual material landfill development predicts an extended carbonate phase of more than 60'000 years; i.e. no drop of pH in the modelled time period. This behaviour is also likely for inert material landfills. So the chemical behaviour of residual material landfills is not identical, but probably comparable that of inert material landfills[23].

In Tab. 4.3 a comparison is made between the following landfilling options:

[21] Mineral or 'rock-like' material is described as silicates, carbonates, aluminates. Dissolvable content is tested with distilled water with a solid-to-water ratio of 0.1.

[22] An accidental spreading of paper production sludges on an inert material landfill and the subsequent anaerobic conditions and increases in emissions are described in (Grauwiler 1992).

[23] This statement relates to the chemical behaviour of elements in the landfill, as expressed by transfer coefficients. Of course the pollutant content per kilogram waste is higher in residual landfills.

- Inert material to inert material landfill (no direct emissions)
- Inert material to residual material landfill (leachate emissions, but no pH drop in 60'000 years)
- Inert material to sanitary landfill (leachate emissions and pH drop after 4'500 years)

For the composition of inert materials a current composition of cement is applied in the latter two datasets. The second dataset is used for landfilling of *solidifying cement* for residual waste materials. The second dataset is used for landfilling of *fine fractions* from mineral building materials like brick or concrete. Here also the composition of hydrated cement is used as a typical composition.

Tab. 4.3 Selected LCI results and the cumulative energy demand for landfilling of inert material

		Name		disposal, inert waste, 5% water, to inert material landfill	disposal, cement, hydrated, 0% water, to residual material landfill	disposal, inert material, 0% water, to sanitary landfill
		Location		CH	CH	CH
		Unit		kg	kg	kg
		Infrastructure		0	0	0
LCIA results			Unit			
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	0.2030	0.3190	0.3180
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	0.0059	0.0099	0.0187
	cumulative energy demand	renewable energy resources, water	MJ-Eq	0.0016	0.0027	0.0058
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.0002	0.0003	0.0004
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	0.0004	0.0006	0.0010
LCI results			Unit			
resource	Land occupation	total	m2a	0.00154	0.00602	0.00452
air	Carbon dioxide, fossil	total	kg	0.00679	0.0089	0.0117
air	NMVOC	total	kg	0.0000269	0.0000356	0.0000436
air	Nitrogen oxides	total	kg	0.000149	0.000169	0.000249
air	Sulphur dioxide	total	kg	0.0000105	0.0000154	0.0000198
air	Particulates, < 2.5 um	total	kg	0.0000138	0.0000155	0.0000239
water	BOD	total	kg	0.0000208	0.0000253	0.000035
soil	Cadmium	total	kg	2.56E-11	2.93E-11	3.81E-11
Further LCI results			Unit			
water	Cadmium, ion	total	kg	3.59E-09	8.31E-09	0.000000612
water	Copper, ion	total	kg	0.000000016	0.000000173	0.0000039
water	Lead	total	kg	2.64E-08	0.000000184	0.0000294
water	Zinc, ion	total	kg	0.000000372	0.00000149	0.0000674

The effect of inclusion of leachate emissions are obvious for the metal emissions to water at the bottom of Tab. 4.3. Compared to a inert material landfill there is however also an increase in infrastructure and process energy burden for the residual and sanitary landfill, as can be seen in the cumulative energy demand CED and air emissions. This increase from background processes is up to a factor 2 for residual landfills, and a factor 2 to 4 for sanitary landfills. The increase in water emissions is a factor 2 to 11 for residual landfills, and a factor 170 to 1'100 for sanitary landfills, and originates mainly from the waste itself and not from background processes. Due to a large acid buffer capacity and no pH drop, the retention behaviour of residual landfills is better than that of sanitary landfills. This accounts for the larger leachate emissions from the sanitary landfill.

For the 'inert' materials the inclusion of leachate emissions seems relevant. However the pollutant loads per kg waste to residual landfill are 3 to 4 orders of magnitude lower for inert materials than the pollutant loads of 'typical' residual material wastes like average incineration residues or steel slags (given in result section of part III on landfills). So, while for the results of landfilling of inert waste *per se* the inclusion of leachate emissions is relevant, they probably will not be so relevant when compared to other materials. I.e. the burden from inert materials will still be significantly lower, than from other materials.

4.2.4 Disposal of gypsum products

The issue of gypsum disposal in sanitary landfills has led to some debate after the publication of (Doka 2000). Also some misunderstandings in the perception of the results of that study occurred. The

issue is discussed in an extended manner in the appendix (chapter 6.1 'Gypsum from building materials in sanitary landfills' on page 42).

5 Conclusions

The disposal of building materials is a difficult topic to address within the framework of life cycle assessment. While for the *production* of materials generic inventories of the industrial processes involved are well feasible, the *disposal paths* depend heavily on many circumstances which cannot be well resolved in a generic manner. Disposal options depend e.g. on construction assembly of the material, i.e. which materials are combined in what way in the considered construction. This influences feasibility of recycling options. Also renovation techniques can influence the disposal fate. The choice between discarding and recycling depends on many factors like local distances to recycling or disposal plants and transport costs, disposal fees, and recycling fees. The special topic of contaminated building infrastructure and special dismantling – like e.g. for asbestos – was not heeded in this study , but can financially burden and complicate disposal paths further. A special circumstance is that building material disposal will be usually performed *decades* after a building has been built. As LCA is typically used in the planning stage to decide for less burdening products or constructions, the stakeholders that will be confronted with disposal choices for the chosen constructions will usually not be present when the LCA is performed. So there might be an information transmission gap between those in charge for *construction* and those in charge for the *dismantling*[24]. The information transmission gap is also increased by the common urgency in building processes, i.e. what is *planned* might not be exactly what is *actually built*, due to lack of time. All these effects make the prediction of the disposal pathways for a single material difficult.

So in general there won't be a single disposal option for a specific material, but several possible options. In this study an attempt was made to limit the number of possible options to three main possibilities:

Option A) Direct recycling (where possible)

Option B) (Partial) recycling after sorting in a sorting plant

Option C) Direct final disposal without recycling (landfilling or incineration)

In decreasing order, these options make use of the waste material by delivering them to a recycling process producing secondary building materials. Incineration is not considered to be recycling. All options include the burdens from dismantling.

The found differences in results justify the splitting up into several options per material. In general less burdens are created with more recycling of materials. However, the sorting of building waste produces a fine fraction which is landfilled and counteracts the beneficial effect of recycling.

The important notion of these results is that each option has a justification under certain circumstances, and the application of a certain dataset with an application must be checked against these circumstances (construction, local disposal possibilities etc.). So in general, there won't be *the* disposal of e.g. concrete, but only a possible disposal of concrete within a certain construction type etc.[25].

In the future the application of these datasets has to be observed. Criticism and suggestions – if any – have to be collected, transformed into practicable frameworks, and incorporated into future updates.

[24] Such circumstances can also occur in other areas of LCA, such as recultivation processes for open cast mining

[25] Such implementation of building materials disposal was performed by the Zürich municipal agency for construction engineering (Amt für Hochbauten Zürich) in December 2003. This was a pre-study of a possible update of the 1995 SIA publication of ecological assessments for constructions (SIA 1995).

Abbreviations

a	annum = year, used in expressions like "kg/a" for "kilogram per year".
EPS	expanded polystyrene (insulation)
GSD	also SDg, Geometric Standard Deviation. Uncertainty measure for lognormally distributed values.
MSWI	Municipal Solid Waste Incinerator (Swiss expression: KVA Kehrichtverbrennungsanlage, German expression: MVA Müllverbrennungsanlage)
MTC	Multiple-Through-Concept (German 'Mehr-Mulden-Konzept' MMK). Concept of sorting building wastes into distinct throughs already at the building site (SBV 1998). Cf. chapter 2.2 'The disposal with the Multiple-Through-Concept MTC' on page 4f.
PM	Particulate matter. Fine solid matter as air emission. Characterised by the aerodynamic diameter usually given in micrometers, i.e. $PM_{2.5}$ for particles with diameter of < 2.5 µm, PM_{10} for particles with diameter of < 10 µm. See also TSP.
TSP	Total suspended particles. All fine solid matter as air emission. See also PM.
TVA	Technische Verordnung über Abfälle. Swiss waste ordinance (TVA 2000)

Glossary of terms

Civil engineering	construction, servicing and demolition of transport and services infrastructure, German 'Tiefbau'
Construction engineering	erection, servicing and demolition of buildings, German 'Hochbau'
Downcycling	Re-processing of waste material to new products with inferior quality. In contrast with → 'Recycling'.
Mixed building waste	or mixed construction waste. Construction waste that not only contains mineral, inert wastes (→ mixed rubble) but also contains burnable waste like wood, plastics or packaging. MTC through No. 4. German: 'Bausperrgut' or (terminology in the Swiss waste ordinance TVA) 'vermischte Bauabfälle'.
Mixed rubble	Rubble is mostly mineral construction waste like concrete, tile, brick, ceramic or gypsum waste without burnable waste. MTC through No. 2. German: 'Mischabbruch' or 'Bauschutt'.
Recyclate	'(effectively) recycled material'. Useful output product of a recycling process.
Recycling	Strictly, 'Recycling' means the re-processing of a waste product to a new product *with identical quality* (e.g. waste PET bottle to new PET bottle). However, re-processing of a waste product often leads to products with *inferior* qualities (e.g. waste paper to recycling paper with shorter fibres). Recycling with loss of quality is called 'Downcycling'. Within this report the term 'Recycling' is used non-exclusively for 'Recycling' *and* 'Downcycling'.

6 Appendices

6.1 Gypsum from building materials in sanitary landfills

The issue of gypsum disposal in sanitary landfill has led to some debate after the publication of (Doka 2000). Also some misunderstandings in the perception of the results of that study occurred. The issue is therefore presented here in an extended manner.

What is regarded here?

Gypsum can be transferred to a sanitary landfill as component of the disposed fine fraction from sorting plants for construction waste (see chapter 3.1.2 'Option B: Recycling after sorting' on page 9). *Other disposal fates of gypsum are possible* (direct recycling, landfilling without sorting) and are covered in the report (see chapter 3.1 'System boundaries' on page 8). This section deals *only and exclusively* with gypsum disposed via construction waste sorting.

What is happening?

Gypsum (calcium sulfate dihydrate $CaSO_4 \cdot 2H_2O$) is a mineral material with exceptional properties regarding indoor air quality and is generally regarded as environmentally favourable due to its comparatively low manufacturing energy and potential recyclability. However, if gypsum (as part of fine fraction from construction waste sorting) enters a sanitary landfill, unexpected reactions can happen. Gypsum is moderately soluble in water (2.6 g/l) and is dissolved into the landfill leachate[26]. In the anaerobic and biologically active environment of a sanitary landfill, sulfate-reducing bacteria can convert the sulfate of gypsum (SO_4) to sulfide (S^{2-}). The sulfide has several fates in the landfill: sulfide can be re-precipitated with metal cations to a solid metal sulfide, it can be leached from the landfill as a dissolved sulfide anion, or it can be transferred to the gas phase of the landfill as dihydrogen sulfide (H_2S) and become part of the landfill gas. In the latter case the H_2S is subsequently oxidised to sulfur dioxide SO_2 either by incineration or flaring of landfill gas or by atmospheric oxidation. SO_2 is a serious pollutant which contributes to acidification and secondary particle formation (winter smog). The formation and emission of H_2S has been reported in landfills of USA, Canada, Switzerland[27], Germany and Austria, in some cases leading to complaints of nearby residents due to the accompanying characteristic smell of rotten eggs[28] (Batten 1998, DEQ 1998, UFL 1998, Baier 2001, FES 1996, Weihs 1996, Reinhart & Townsend 2003). In studies as early as 1986 gypsum has been identified as the single most important cause for landfill emissions of H_2S (Johnson 1986, UMBW 1988, Fairweather & Barlaz 1998, Dunleavy 1997).

Fate of sulfur in reactive sanitary landfills

These incidents show that formation and release of H_2S from sanitary landfills is observed in the field and a real possibility. H_2S formation occurs only in landfills that are – by design or by accident – biologically active, i.e. contain degradable carbon that triggers some microbial activity.

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[26] Gypsum boards are sometimes manufactured with silicone additives (polymethyl hydrogen siloxan) to improve stability against water during use. This can hinder gypsum dissolution in water. Tests by the author with samples of gypsum board waste have shown that gypsum fragments (<5mm) are dissolved in water within a matter of days.

[27] Personal communication with Peter Oester, specialist in landfill gas measurements, Oester Messtechnik (www.deponiegas.ch), Frutigen BE, Switzerland January 27, 2003.

[28] H_2S has an odour threshold of 0.43µg/m^3.

In the former ETH sanitary landfill models, a significant fraction of the sulfur in a decomposable waste is emitted to air[29] (Zimmermann et al. 1996, Doka 2000). Many parameters influence the H_2S formation and emission to air:

1. The **decomposition rate** of the waste determines, if a waste matrix is broken up and its contents metabolised. If the waste is not decomposed during the first decades in which extensive biological activity occurs, no transfer of sulfur to the gas phase is likely.
2. A **biologically active environment** with anaerobic conditions is necessary. Biological activity is mainly triggered by the presence of decomposable carbon. Anaerobic conditions are supported by bad drainage conditions and large water content.
3. Sulfide can enter the **aquatic biosphere** without emissions to air when it is directly leached from the landfill.
4. Even if sulfide is formed, it can be **re-precipitated** with metal cations as solid metal sulfides and remain within the landfill body. This effectively immobilises the sulfur within the landfill. The metal sulfides are stable until aerobic conditions are established, which occurs well after the active phase of the landfill is over. Sulfides are then washed out with leachate as sulfate. Given the abundance of metals in landfills, iron is the most important reaction partner in precipitation of sulfide[30].

Precipitation has not been considered in the former landfill models of ETH (Zimmermann et al. 1996, Hellweg 2000, Doka 2000). In those models the decomposed waste material is *completely* emitted *either* to water (as sulfide/sulfate) *or* to air (as H_2S/SO_2). In the landfill models of the present study precipitation was heeded (cf. Tab. A. 1). The actual occurring precipitation is estimated based on comparisons of data on waste composition, waste degradation and leachate concentrations *measured in the field* (cf. part III). Precipitation can indeed be observed to a certain extent. For gypsum a complete decomposition within the first century after waste placement is assumed, based on the good solubility of gypsum products.

[29] This effect has led to a surprising result in case of the disposal option 'building waste to sorting plant' in (Doka 2000). In this option – and only this option –, gypsum in mixed rubble is sorted, *partially* transferred to the fine fraction and the fine fraction is landfilled in a sanitary landfill. Only under these circumstances the resulting H_2S generation leads to large environmental impacts for disposal of gypsum from acidification which even surpass the environmental loads of the *production* of gypsum boards (production based on Weibel & Stritz 1995).

[30] I.e. as iron sulfide FeS or pyrite FeS_2. Thermodynamic calculations in (Lothenbach 2001:10) calculated that the majority of sulfur is precipitated with iron and that only 0.00001 w%–0.0002 w% of the sulfur is present as gaseous H_2S. Yet thermodynamic calculations are not able to model *media dynamics*, which would be necessary to model gas emission rates. Nor are thermodynamic calculations able to predict microbially active environments. That such calculations are not necessarily conclusive in a reactive landfill context is also indicated by the observation that the measured concentrations of sulfide and metals like iron, copper, lead in sanitary landfill leachate (cf. appendix of part III) exceed by far the solubility of the corresponding metal sulfide (2.7 nanograms/l). However, metals in leachate might also be adsorbed to particles and evade precipitation (Personal communication with Annette Johnson, EAWAG Dübendorf, of February 20, 2001). If this were the case, the measured concentration levels would suggest that the *majority* of metals are indeed adsorbed and not dissolved.

Tab. A. 1 Factors influencing the release of sulfur to air from gypsum in a sanitary landfill

as weight-percent w%	Doka 2000	This study
Gypsum decomposition	100% (over 150a)	100% (over 100a)
re-precipitation rate of S (as sulfide)	none assumed	56.2% [1]
released share	100%	43.8%
S transfer to gas phase (as H_2S)	35.8%	14.9%
% sulfur emitted to air	35.8%	6.5%

1 100% minus the release factor r% of sulfur of 43.8% (cf. appendix of part III). This release factor is based on measured leachate concentrations from sanitary landfills.

An input of sulfate to the landfill is also the application of reverse osmosis leachate treatment[31]. Leachate is acidified with sulfuric acid H_2SO_4. The treatment residue, which contains sulfate is returned to the landfill. However, reverse osmosis is not common in landfills and is not considered here.

Recent changes regarding less reactive waste composition

A biologically active, anaerobic environment is a prerequisite for H_2S formation in landfills. Such conditions are maintained by degradable wastes. The amount of degradable carbon in Swiss sanitary landfills has decreased since 2000, when landfilling of burnable wastes was banned. However some municipal landfills still receive reactive wastes which are unsuitable for incineration (e.g. road sweeping waste) and continue to have gas collection systems (TVA 2000). Peter Oester, a Swiss expert in landfill gas monitoring, actually observes an *increase* of H_2S concentration in landfill gas in recent years due to increasing amounts of construction waste fractions[32]. For example in the landfill Türliacher/Jaberg BE (a sanitary landfill with 275'000 t total capacity) an increase of H_2S from approx. 100 mg/m^3 to 1000 mg/m^3 in the landfill gas was observed. This landfill deposited a mass of 8775 t of sorted building waste and 14'554 t of burnable waste (mainly MSW) in 2000 (BUWAL 2001d). In the landfill Tambrig ZH (a sanitary landfill with 230'000 t total capacity) very high concentrations of H_2S of up to 8000 mg/m^3 are familiar. This latter landfill deposited *exclusively* a mass of 18'204 t sorted building waste in 2000 (BUWAL 2001d). In the closed landfill Lindenstock municipal waste was landfilled with gypsum from chemical industry leading to initial H_2S concentrations of 20'000–30'000 mg/m^3 which after 10 years decreased to a current level of 800 mg/m^3.

Fine fraction from construction waste sorting contains degradable carbon in moderate amounts in the form of shreds from wallpaper, wood splinters, biomass reinforcement fibres or cardboard shreds of gypsum boards. Gypsum wallboard, consisting of gypsum and paper, was found to be able to produce high H_2S concentrations *by itself* – provided water content is high enough (Reinhart & Townsend 2003:4)[33]. The fine fraction therefore adds to the reactive potential of the landfill.

[31] Personal communication with Peter Oester, specialist in landfill gas measurements, Oester Messtechnik (www.deponiegas.ch), Frutigen BE, Switzerland January 27, 2003.

[32] Personal communication with Peter Oester, specialist in landfill gas measurements, Oester Messtechnik (www.deponiegas.ch), Frutigen BE, Switzerland January 27, 2003.

[33] Reinhart & Townsend (2003:4) write *"Other results of interest included the fact that gypsum drywall alone (i.e. without another source of organic matter) was sufficient to result in high H_2S concentrations and the fact that concrete played a major role in the migration of the gas."*.

Validation of the model transfer coefficient

Under the circumstances of currently reduced landfill gas production is the model transfer coefficient of sulfur to gas in Tab. A. 1 still valid? In the following a validation is attempted, based on current measurements in Swiss landfills. The reduced landfill gas production is estimated in Tab. A. 2.

Tab. A. 2 Estimate of total gas production in a sanitary landfill with construction waste

Specific landfill gas production in sanitary landfills [1]	Nm^3/t waste	150 – 300
Observed reduction in specific landfill gas production in sanitary landfills with construction waste 1990–2002 [2]	–	30 – 90%
Estimated current specific landfill gas production	Nm^3/t waste	15 – 210

1 Range given by (Oester 2001)

2 Based on information from Swiss landfills provided by Peter Oester, Frutigen BE, Switzerland March 13, 2003.

With current, measured sulfur concentrations observed in the gas of construction waste landfills, the emitted sulfur amount to air can be estimated (output). To obtain a transfer coefficient, the sulfur *input* must be known too. It is assumed here that the sulfur amount in waste is dominated by sulfate from gypsum waste, i.e. other sulfur sources are neglected. The gypsum content in sorted construction waste (including the fine fraction) is estimated to be 2%, leading to a sulfur content of 3800 mg S per kg of landfilled waste (see Tab. A. 3).

The estimated range of sulfur transfer to landfill gas in Tab. A. 3 (1–14%) matches well the generic sulfur transfer coefficient used in the landfill model in Tab. A. 1 on page 44 (6.5%). While these findings are not a decisive proof, they encourage confidence in the present model. These findings are also remarkable, because the present model transfer coefficient in Tab. A. 1 was obtained in a *generic* fashion, and not specifically with gypsum in mind[34].

Tab. A. 3 Estimate of a sulfur transfer coefficient to landfill gas in a landfill with construction waste

For landfill with construction waste		
H_2S-sulfur in landfill gas (as S) [1]	mg S/Nm^3	2600
Specific landfill gas production per kg waste [2]	Nm^3/kg	0.015 – 0.21
Sulfur to air per kg construction waste	**mg S/kg**	**39 – 546(output)**
Gypsum content in sorted construction waste [3]		2 w%
Sulfate content in sorted construction waste as S	**mg S /kg**	**3800 (input)**
Sulfur transfer coefficient to landfill gas		**1%–14%**

1 Geometric mean of 4 measurements 2000-2002 for landfill compartments with building waste

2 From Tab. A. 2.

3 Assumption based on building composition and building waste masses.

The transfer coefficient used in the current model is over five times lower than in the original study (Doka 2000, cf. Tab. A. 1), but still large enough to make this specific type of disposal of gypsum (via fine fraction) an important or even dominant impact in the total life-cycle of a gypsum product disposed in that way (depending on the chosen impact assessment method)[35].

[34] I.e. the same sulfur transfer coefficient would be applied in the model to *any* sulfur-bearing waste with 100% degradability in 100 years.

[35] This remark is true if the same reference inventory for gypsum board *production* is used as in (Doka 2000). The reference there was from (Weibel & Stritz 1995). The new ecoinvent 2000 inventory for gypsum boards was not yet available for a similar calculation at the time this text was finished (August 2003). The ecoinvent 2000 inventory for gypsum boards is published in 2004 in version 1.1. Preliminary data for gypsum *from mine* suggest, however, that the burdens for gypsum →

production were *underestimated* in (Weibel & Stritz 1995) by a factor 19 to 65, depending on the LCIA method. In (Doka 2000:110) the relative ratios of 'burden from disposal' vs. 'burden from production' were calculated for Eco-indicator'95+ and UBP'97. The disposal of gypsum boards via sorting plant was there found to be 64–86 times more burdening than the board production. With the current landfill model the burden from disposal can be expected to drop by a factor 5.5 (35.8%/6.5% from Tab. A. 1). The burden *from production* can be expected to *rise* by a yet unknown factor but *possibly* a factor 65 or even larger. With this new data the ratio of gypsum disposal *via sorting plant* vs. gypsum production can be expected to attain a value lower than 12–16, but more likely a value in the broad neighbourhood of unity.

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