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Influence of different factors in the life cycle assessment of mixed municipal solid waste management systems – a comparison of case studies in Finland and China

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Abstract

The life cycle assessment (LCA) of municipal solid waste (MSW) management systems is typically rather arduous due to extensive data acquisition needed to calculate the direct and avoided emissions of the systems. A possibility to diminish the workload of the LCA studies is to utilise default or generic data instead of direct and case-specific data. However, it is crucial to know when this is justified. Direct and case-specific data should be applied at least to the key processes and parameters which have the strongest influence on the total results, whereas default data can be applied to the processes and parameters which have only a minor influence on the total results.

Mixed MSW management systems in the South Karelia region, Finland, and the city of Hangzhou, China, were compared in this study in terms of the influence of different factors on the LCA results of the systems. The comparison focused particularly on the influence of individual parameters on the global warming, acidification and eutrophication potentials of the LCA studies. According to the study, parameters directly related to the generation and collection of landfill gas, the energy and fossil carbon content of mixed MSW, energy production efficiencies, as well as the nitrogen oxide and sulfur dioxide emissions of incineration had the highest influence on the total results in both case studies, and therefore direct, case-specific data should be applied particularly to them. The use of machinery in landfilling, the electricity and chemical consumption in leachate treatment, the transportation of auxiliary materials (e.g. chemicals and incineration residues) as well as the electricity consumption and the use of machinery in bottom and boiler ash treatment had instead only a minor influence on the total results. Default or generic data could be applied to them to diminish the workload of the LCA studies. It is worth mentioning that the findings of the study apply merely to these particular case studies. Further research and corresponding comparisons are required to draw more profound and general conclusions.

Keywords
Life cycle assessment, municipal solid waste, sensitivity, landfilling, incineration

1. Introduction

Waste is a worldwide issue. Particularly due to population growth and urbanisation in developing countries, the generation of municipal solid waste (MSW) has increased significantly over the past decades. For instance, the global MSW generation rate is expected to double by 2025 from the generation rate in 2012 (World Bank, 2012). Alongside the increase in MSW generation, the environmental impacts of MSW have been more comprehensively identified globally. The growing awareness of the negative environmental impacts of MSW has increased the use of life cycle assessment (LCA) methodology in the MSW management sector. By means of LCA, the potential environmental impacts of MSW management systems can be evaluated (EN ISO 14040, 2006; EN ISO 14044, 2006). LCA enables taking into account both direct (i.e. emissions from treatment processes) and avoided (i.e. emissions avoided due to energy or material substitution) emissions of MSW management processes (Ekvall et al., 2007). Laurent et al. (2014) conducted a comprehensive review of the application of LCA to MSW management systems. According to the study, LCA was first conducted on MSW management systems in the 1990s, and currently it is a widely used method in the assessment of the environmental impacts of MSW management systems. The LCA of MSW management systems has been primarily applied in high income countries, particularly in Europe. It has also gained popularity in lower income countries during the past decade due to increased MSW generation and urbanisation. For instance, several MSW LCA studies have been conducted in China in recent years.

LCA studies of MSW management systems are typically highly case-specific, depending on the objective of the study and local conditions and features. Nevertheless, the purpose of most LCA studies is the comparison of different treatment and management options for MSW. For instance, De Feo and Malvano (2009) assessed the environmental impacts of 12 different management options for MSW in a region in South Italy to select the best MSW management system for the region. LCA has also been used to compare different source separation and collection systems: for instance, Larsen et al. (2010) assessed five scenarios with alternative collection systems for recyclables by means of LCA, and Rigamonti et al. (2009a) utilised LCA in the optimisation of collection systems for recyclables. Additionally, LCA has widely been used as a decision support tool for policy making in the field of MSW management. For instance, Turner et al. (2016) and Lazarevic et al. (2012) introduced different approaches to how the LCA of MSW management systems can be utilised as a decision support tool.

The intricacy of MSW management systems poses challenges for LCA studies. Of the main phases of LCA (i.e. goal and scope definition, inventory analysis, impact assessment and interpretation) (ISO 14040, 2006), particularly inventory analysis is highly time and resource-consuming due to the comprehensive data acquisition needed to calculate the direct and avoided emissions of the system. Various approaches have been developed to facilitate and simplify LCA (e.g. Fleischer et al., 2001). A simple and straightforward way to diminish the workload of MSW LCA studies is to use default or generic data (i.e. secondary data) instead of direct and case-specific data (i.e. primary data) in inventory analysis. In order to do that without reducing the reliability of the results, it is important to know the influence of an individual parameter on the total results. Therefore, the following straightforward rule of thumb should be retained: one can apply default or generic data to parameters with a minor influence on the total results while simultaneously applying direct and case-specific data to other parameters in order to maintain the reliability of the LCA study.

The influence of an individual parameter on the total results can be identified by sensitivity analysis, which assesses the effect of input parameters' changes on the total results. The more sensitive the result is to a given parameter, the more case-specific and reliable the data concerning the parameter should be. Direct data should be used at least concerning the key parameters which have the highest influence on the overall environmental performance of MSW management systems. Regarding the LCA of MSW management systems, the key processes and parameters have been rather well recognised in literature (see Table 1). The environmental impacts of surrounding systems, e.g. electricity and heat production, often override the environmental impacts of the MSW management system itself (Ekvall et al., 2007). Parameters related to energy and material recovery and substitution (e.g. electricity and heat production efficiencies, material recovery efficiency) are therefore particularly important in MSW LCA studies. While previous research has particularly focused on the key processes and parameters of MSW management LCA studies, little research has been conducted to identify the processes and parameters which have only a minor influence on the total results. Nevertheless, they are crucial in terms of the above-mentioned simplification possibility, i.e. using default or generic data instead of direct and case-specific data.

Table 1

Typical key factors in the LCA of MSW management systems presented in literature (literature studies particularly focusing on the subject are listed as references).

MSW management phase	Key factor	Reference
MSW generation	Waste composition	Slagstad and Brattebø, 2013
	Source-separation efficiency	Rigamonti et al., 2009b
Landfilling	Collection of landfill gas (LFG) and leachate	Manfredi and Christensen, 2009
Incineration	Energy recovery and substitution	Burnley et al., 2015
Recycling	Material recovery and substitution	Rigamonti et al., 2009b

Two different case studies are compared in this study: the South Karelia region in Finland and Hangzhou city in China (see Fig. 1). South Karelia is a region in South-East Finland, and it consists of nine municipalities. Hangzhou is the capital city of the Zhejiang Province in Eastern China. In both case studies, mixed MSW (i.e. the remaining part of MSW after the source separation of different waste fractions) management system of the area is investigated by means of LCA. The case studies have been initially reported by Hupponen et al. (2015) and Havukainen et al. (2017). The comparison of the case studies focuses particularly on different input parameters used in the LCA of the mixed MSW management systems. The objective of the study is to determine the most and least important (i.e. sensitive) input parameters of the case studies in order to identify possibilities to simplify their LCA by using default or generic data instead of direct and case-specific data.

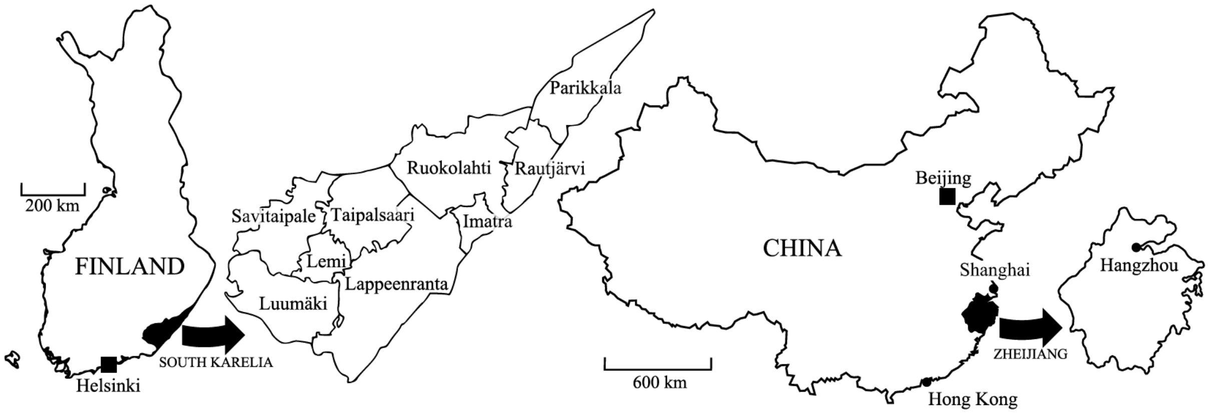


Fig. 1. Case study areas.

The research questions are the following:

- What are the key factors, i.e. processes and input parameters, in the case LCA studies on South Karelia, Finland, and Hangzhou, China?
- Which factors have instead only a minor influence on the total results in the case areas?
- How could the LCA of the case studies be simplified by using default or generic data instead of case-specific, direct data?

2. Materials and methods

2.1 Description of the case areas

The South Karelia region in Finland and Hangzhou city in China were selected as the case areas for the study to analyse both high income and lower income countries' mixed MSW management systems (see Supplementary material A for further information). They represent distinctly different areas (e.g. population, geographical location, income level) and mixed MSW management systems, however with some similarities, which enable the comparison between them. For instance, incineration is a treatment method for mixed MSW in both areas. Since the case studies differ from each other in many respects, the similarities between them can be an indication of a more extensive phenomenon. In other words, if the influence of a given parameter on the total results is similar in both case studies, the same phenomenon can be valid in other mixed MSW management systems, too.

Key data (i.e. population, MSW generation rate, the composition of mixed MSW and collection system) concerning the case areas' MSW management systems are presented in Fig. 2. In South Karelia, all mixed MSW generated in the region was landfilled until 2013. The incineration of mixed MSW started in 2013 and has increased in stages. Currently, all mixed MSW generated in the region is incinerated. Since there is no waste incineration plant in the region, mixed MSW is transported to a waste incineration plant in Riihimäki which is located approximately 220 km from the region. (Etelä-Karjalan Jätehuolto Oy, 2016.) In Hangzhou, incineration and landfilling are the main treatment methods for mixed MSW. In 2013, 58% of mixed MSW was landfilled and the rest incinerated. At present, there are two landfills and four incineration plants in Hangzhou. (Havukainen et al., 2017.)

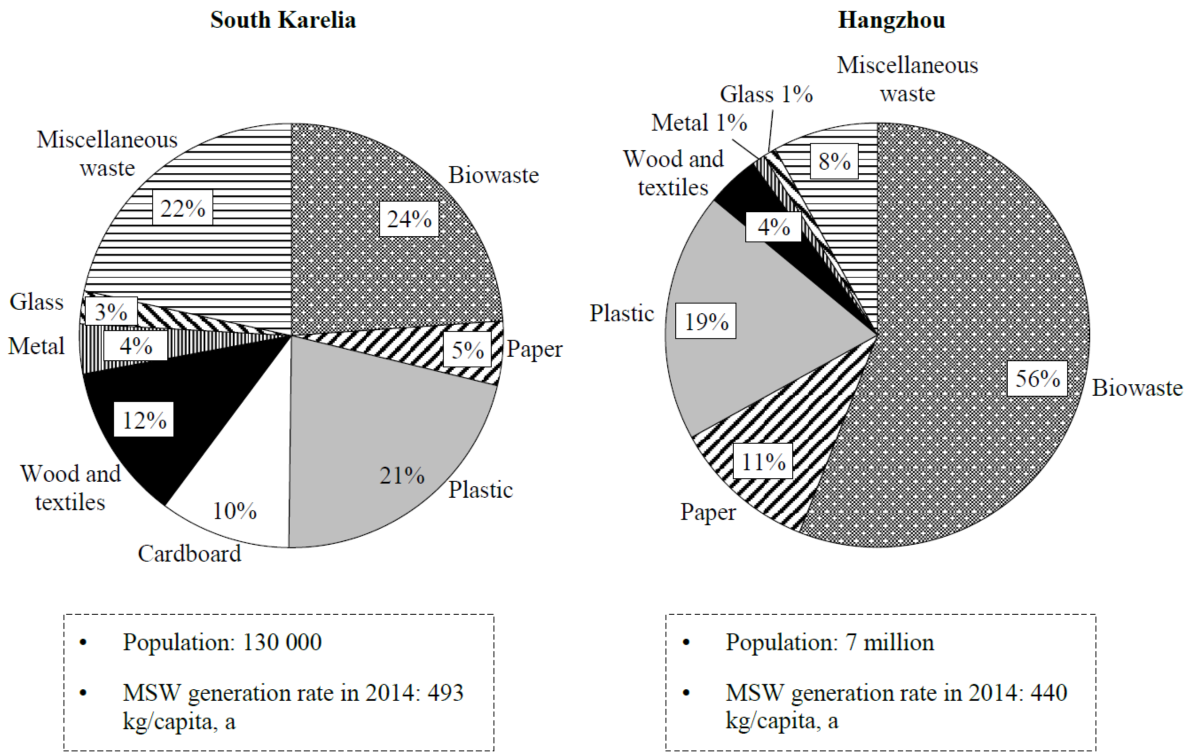


Fig. 2. Key data of the case areas' MSW management systems (Horttanainen et al., 2013; Regional Council of South Karelia, 2016; Lappeenranta, 2016; Eurostat, 2016; Havukainen et al., 2016; Dong et al., 2013).

2.2 Life cycle assessment

As mentioned previously, the case studies have been initially reported by Hupponen et al. (2015) and Havukainen et al. (2017) in peer-reviewed literature. Thus, the validity of the case studies has already been checked. However, the South Karelia case study (Hupponen et al., 2015) was significantly modified in this study to enable the comparison between them (see Chapter 2.3.1 for further information). The LCAs of both cases, South Karelia and Hangzhou, were carried out according to the ISO standards 14040 and 14044 (ISO 14040, 2006; ISO 14044, 2006). The GaBi 6.0 LCA modelling software was used in both studies (Thinkstep, 2016). CML 2001 – November 2010 was used for impact assessment in the South Karelia case study, and CML 2010 – April 2013 was used in the Hangzhou case study. These particular versions of CML were used in this study since they were also applied by Hupponen et al. (2015) and Havukainen et al. (2017). The impact categories were the global warming potential (GWP) for a 100 year time span, acidification potential (AP) and eutrophication potential (EP) in both studies. According to a review by Cleary (2009), these impact categories have been most commonly applied in the LCA of MSW management systems. The functional unit of the LCA studies was the same in both studies, i.e. the treatment of mixed MSW generated in the areas during a year: 22 500 t in the South Karelia study (Etelä-Karjalan Jätehuolto Oy, 2013; Statistics Finland, 2016) and 3 086 kt in the Hangzhou study (Havukainen et al., 2017).

2.3 Scenarios and calculation principles

2.3.1 South Karelia

The scenarios of the South Karelia case study are the same as in a study by Hupponen et al. (2015), i.e. the regional mixed MSW management situation in 2012 is assessed (see Fig. 3). There are two main scenarios: landfilling (Scenario 0) and incineration (Scenario 1). Additionally, there are three different sub-scenarios in the incineration scenario: Riihimäki (Scenario 1.1; the situation in 2012, i.e. without plastic and bio refineries which currently operate in the plant), Kotka (Scenario 1.2) and Leppävirta (Scenario 1.3), which are cities rather close to South Karelia and represent different treatment options for mixed MSW generated in South Karelia. The sub-scenarios are rather different from each other. First of all, the incineration scenarios have different transportation distances: 220 km (Scenario 1.1), 120 km (Scenario 1.2) and 210 km (Scenario 1.1). Another distinct difference between the scenarios is the incineration technology. Mixed MSW is incinerated in a grate furnace in Scenarios 1.1 and 1.2, whereas in Scenario 1.3, refuse-derived fuel (RDF) is produced from mixed MSW and incinerated in a fluidised bed boiler. Additionally, the substituted heat production differs between the scenarios. In Scenarios 1.1 and 1.2, the produced district heat substitutes heat produced by natural gas, whereas produced heat substitutes biofuels (72% of the heat production), plastic waste (19%), heavy fuel oil (7%) and coal (2%) in Scenario 1.3.

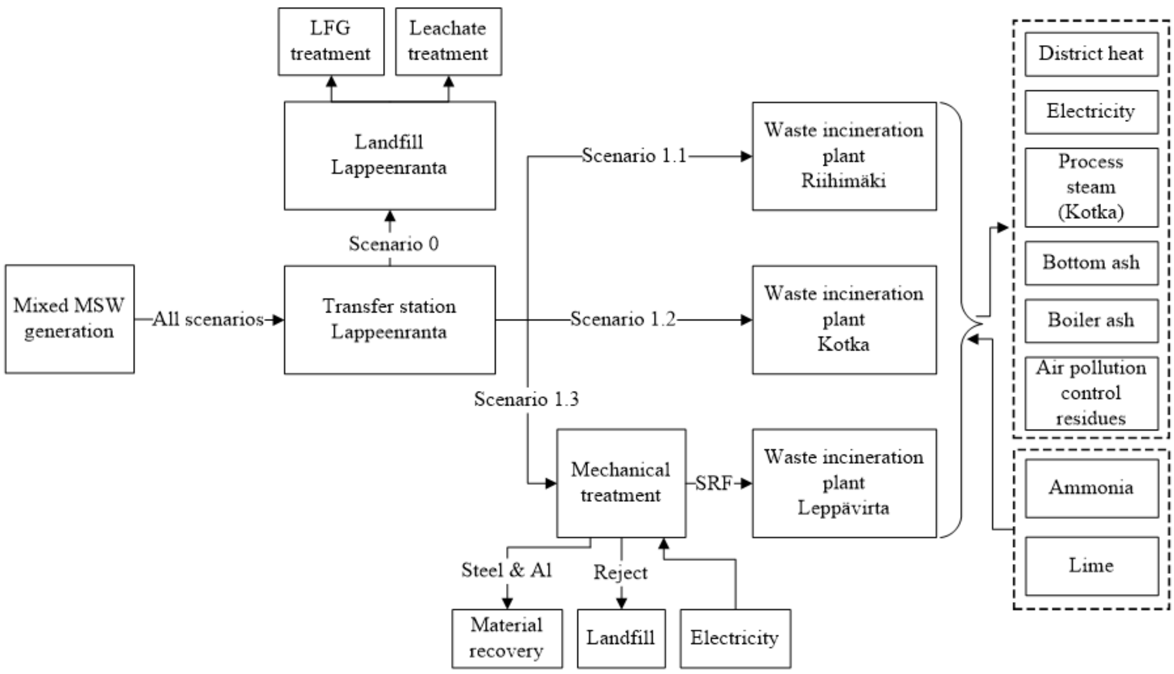
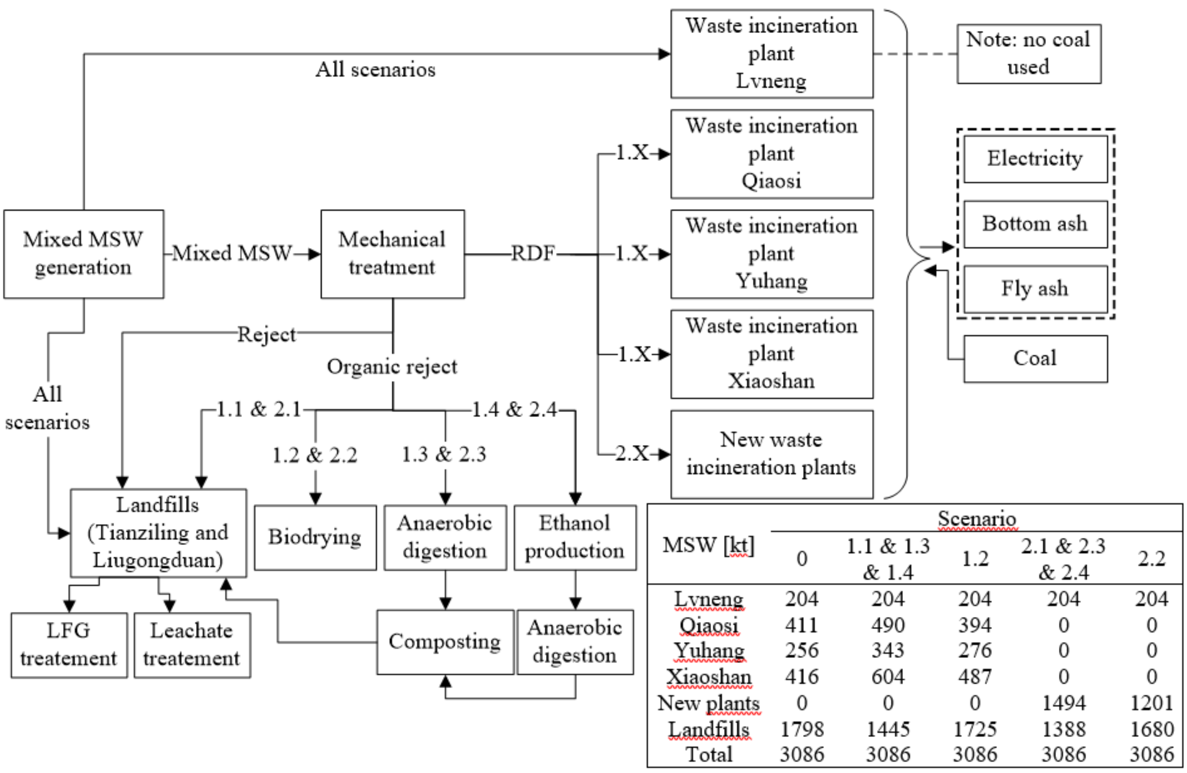


Fig. 3. Mixed MSW management scenarios in the South Karelia case study.

Hupponen et al. (2015) assessed the GWP of the management of mixed MSW from regional collection points (approximately 3 100 $t_{mixed\ MSW}$/a). In this study, the mixed MSW management of the entire region is assessed instead of mere regional collection points. Additionally, the AP and EP of the mixed MSW management is assessed in this study in addition to GWP. The GWPs of the management scenarios have been calculated similarly as in a study conducted by Hupponen et al. (2015). The data used to calculate the APs and EPs of the scenarios are presented in Supplementary material B. The environmental impacts of capital goods (e.g. trucks, buildings, equipment, etc.) were not taken into account in the study, although according a recent study by Brogaard and Christensen (2016), the capital goods of waste management systems can have a significant influence on the total results. This results from the system boundaries of the case study initially defined by Hupponen et al. (2015).

2.3.2 Hangzhou

The scenarios of the Hangzhou case study are the same as in a study by Havukainen et al. (2017). There are three main scenarios in the Hangzhou LCA study (see Fig. 4): the actual mixed MSW management situation in 2013 (Scenario 0), the production and incineration of RDF at three incineration plants (Qiaosi, Yuhang and Xiaoshan) to replace MSW and coal co-incineration (Scenario 1), and the production and incineration of RDF at new plants with a higher electricity production efficiency (Scenario 2). Additionally, there are four different treatment options for the organic reject generated from mechanical treatment in the LCA study (i.e. four different sub-scenarios): landfill (Scenarios 1.1 and 2.1), biodrying (Scenarios 1.2 and 2.2), anaerobic digestion (Scenarios 1.3 and 2.3) and ethanol production (Scenarios 1.4 and 2.4). As in the South Karelia study, the environmental impacts of capital goods were not taken into account in this study, either, due to the initial system boundaries of the study.



MSW [kt]	Scenario 0	1.1 & 1.3 & 1.4	1.2	2.1 & 2.3 & 2.4	2.2
Lvneng	204	204	204	204	204
Qiaosi	411	490	394	0	0
Yuhang	256	343	276	0	0
Xiaoshan	416	604	487	0	0
New plants	0	0	0	1494	1201
Landfills	1798	1445	1725	1388	1680
Total	3086	3086	3086	3086	3086

Fig. 4. Mixed MSW management scenarios in the Hangzhou case study.

2.4 Comparison of the case studies

2.4.1 Contribution analysis

Contribution analysis is a commonly used method to present the results of LCA studies (Heijungs and Kleijn, 2001). In addition to presenting the results, it is a sensitivity analysis method even though not always identified as one (Clavreul et al., 2012). In contribution analysis, the total LCA result is decomposed into individual process contributions, i.e. the net result, either positive or negative, is presented as a sum of direct and avoided emissions of individual processes. The positive and negative impacts of individual processes are typically separately presented in contribution analysis in order to identify where direct and avoided emissions result from. Therefore, the most and least important processes can be identified through a contribution analysis.

2.4.2 Perturbation analysis

The influence of an individual parameter on the total result can be determined by means of a perturbation analysis, where input parameters are individually varied and the total result is calculated for each variation (Heijungs and Kleijn, 2001). The influence of each variation on the total result can be determined by the following equation:

$$\mathrm{SR} = \frac{\frac{\Delta \mathrm{result}}{\mathrm{initial\ result}}}{\frac{\Delta \mathrm{parameter}}{\mathrm{initial\ parameter}}} \tag{1}$$

where SR is the sensitivity ratio. As presented in the equation, SR is determined by proportioning the relative change of the total result to the relative change of an individual parameter. (Clavreul et al., 2012.) Thus, the change of a parameter results in an SR-fold change in the total result. For instance, if a parameter has an SR of 5, then a 20% increase in the parameter's value results in a 100% increase in the total result. If the SR of a parameter were negative, the total result would decrease when increasing the value of a parameter. Therefore, the sign of an SR indicates what kind of influence a parameter has on the total result: parallel or reverse. By determining the SRs for the input parameters, the most and least important parameters of the LCA study can be identified. According to Heijungs and Kleijn (2001), parameters with SRs (as absolute values) higher than 0.8 are important. When the absolute value of an SR is higher than 1.0, the parameter can be regarded as particularly important. If the SR of a parameter is less than 0.2, the parameter's influence on the total result is rather minor. These definitions are however only approximate since the magnitude of an SR is highly dependent on the impact category. Therefore, different impact categories' SRs should not be compared with each other, and the sensitivity of parameters should be evaluated within an impact category (Bisinella et al., 2016).

It is worth to mention and emphasise that the South Karelia and Hangzhou case studies present actual mixed MSW management systems. Thus, they include case-specific, direct data derived from different operators in the case areas. In previous literature, perturbation analysis has been conducted in hypothetical MSW LCA studies

(Clavreul et al., 2012; Bisinella et al., 2016). Various parameters were tested in the South Karelia and Hangzhou case studies. Approximately 50% of them were applied in both case studies. The list of the tested parameters is presented in Supplementary material C.

3. Results and discussion

3.1 Contribution analysis

3.1.1 South Karelia

The GWPs, APs and EPs of the mixed MSW management scenarios in the South Karelia region are presented in Supplementary material D. According to the results, incineration (Scenarios 1.1, 1.2 and 1.3) is better option than landfilling (Scenario 0) in all impact categories. Heat substitution made a significant contribution to the results. In Scenario 1.3, the substituted heat is produced mainly by biofuels, whereas substituted heat is produced by natural gas in Scenarios 1.1 and 1.2. Therefore, due to the higher amount of avoided emissions resulting from substituting heat produced by natural gas, Scenarios 1.1 and 1.2 had negative GWPs. The GWP of Scenario 1.3 was instead positive due to the lower amount of avoided emissions from substituting heat produced by biofuels. On the other hand, Scenario 1.3 had the lowest AP and EP mainly due to avoided emissions resulting from heat substitution and a higher electricity production efficiency.

The collection and transportation of mixed MSW accounted for a larger proportion of the direct emissions in the AP and EP impact categories than in GWP (see Table 2 presenting the main processes' contributions to the direct and avoided emissions). Landfilling made a similar contribution to the total results in all impact categories: it accounted for the vast majority of the direct emissions. The incineration of mixed MSW accounted for a larger proportion of the direct emissions regarding GWP than the other impact categories. The treatment of boiler ash, air pollution control (APC) residues and metals generated relatively more emissions concerning AP and EP than GWP. The treatment of bottom ash and the use of chemicals in incineration made a minor contribution to the direct emissions in all impact categories. As for the avoided emissions of Scenarios 1.1–1.3, the most noteworthy difference between the scenarios is that metal substitution accounted for less emissions concerning EP compared to GWP and AP, whereas the proportion of energy (i.e. electricity, heat and process steam) substitution of the avoided emissions was similar between the impact categories, i.e. it accounted for the vast majority of the avoided emissions. Gravel substitution made only a minor contribution to the total results in all impact categories.

Table 2

The contributions (%) of treatment processes to the total direct and avoided emissions in the South Karelia case study.

Impact category	GWP				AP				EP			
Scenario	0	1.1	1.2	1.3	0	1.1	1.2	1.3	0	1.1	1.2	1.3
Direct emissions												
Transportation of mixed MSW	1.8	2.2	1.6	2.0	4.4	11.9	10.0	9.4	6.4	12.3	9.7	13.5
Landfill emissions	98.2	0.0	0.0	0.0	95.6	0.0	0.0	0.0	93.6	0.0	0.0	0.0
Incineration	0.0	93.3	93.8	90.8	0.0	75.4	74.4	68.1	0.0	78.2	79.1	66.7
Bottom ash treatment	0.0	0.1	0.1	0.0	0.0	0.5	0.8	0.0	0.0	0.4	0.8	0.0
Boiler ash treatment	0.0	1.2	1.2	4.4	0.0	5.4	6.0	16.9	0.0	3.0	3.1	12.8
Pretreatment of metals	0.0	1.8	1.9	1.7	0.0	6.0	7.2	5.0	0.0	4.4	4.9	5.1
Use of chemicals in incineration	0.0	1.4	1.5	1.0	0.0	0.8	1.6	0.6	0.0	1.6	2.5	1.9
Avoided emissions												
Electricity substitution	0.0	21.0	15.5	60.3	0.0	51.7	42.8	55.4	0.0	38.8	30.1	52.6
Heat substitution	0.0	68.9	28.9	27.4	0.0	38.4	18.1	40.1	0.0	59.0	26.0	46.3
Steam substitution	0.0	0.0	46.4	0.0	0.0	0.0	29.0	0.0	0.0	0.0	41.8	0.0
Metal substitution	0.0	10.0	9.1	12.3	0.0	9.7	10.0	4.5	0.0	2.0	1.9	1.1
Gravel substitution	0.0	0.1	0.1	0.0	0.0	0.1	0.1	0.0	0.0	0.2	0.2	0.0

3.1.2 Hangzhou

The GWPs, APs and EPs of the mixed MSW management scenarios in Hangzhou are presented in Supplementary material E. Scenarios 0 and 1.1 had the highest GWPs, whereas Scenarios 1.1 and 1.2 had the highest APs and EPs. Scenarios 2.3 and 2.4 had the lowest emissions in all impact categories. It is noteworthy that the GWPs of the scenarios were positive. The APs and EPs were instead negative with the exception of the EPs of Scenarios 1.1 and 1.2. The negative APs and EPs resulted from electricity substitution.

The transportation of mixed MSW contributed relatively more to the total APs and EPs of the scenarios compared to the GWPs of the scenarios, as in the South Karelia case study (see Table 3 where the direct and avoided emissions of the main processes are presented). Landfilling accounted for a significantly lower proportion of the direct emissions concerning AP than EP and GWP. Incineration generated relatively more emissions regarding AP compared to the other impact categories. Bottom ash treatment also accounted for a larger proportion of the direct emissions concerning AP and EP than GWP. It is noteworthy that bottom ash treatment made a more significant contribution to the total results in the Hangzhou case study compared to the South Karelia case study. Boiler ash treatment made only a minor contribution to the direct emissions in all impact categories. The treatment of organic reject made a similar contribution to direct emissions in all impact categories. Mechanical treatment to produce RDF made a greater contribution to the direct emissions concerning AP and EP than GWP due to electricity consumption. The division of the avoided emissions was rather similar in all impact categories: electricity substitution generated most of the avoided emissions, whereas metal recycling did not yield a significant amount of avoided emissions. The contribution of electricity substitution from the combustion of LFG and the energy substitution from organic reject to the avoided emissions was noteworthy in all impact categories.

Table 3

The average contributions (%) of treatment processes to the total direct and avoided emissions in the Hangzhou case study.

Impact category	GWP			AP			EP		
Scenario	0	1.1–1.4	2.1–2.4	0	1.1–1.4	2.1–2.4	0	1.1–1.4	2.1–2.4
Direct emissions									
Transportation of mixed MSW	1.0	1.0	1.0	18.7	9.5	8.4	12.8	9.9	9.0
Landfill emissions	65.9	57.1	55.5	1.2	0.6	0.5	47.8	33.9	31.6
Incineration	31.4	31.2	32.3	67.9	31.0	34.0	34.3	23.3	26.4
Bottom ash treatment	1.6	0.9	0.9	11.2	3.3	3.1	4.5	2.1	2.0
Boiler ash treatment	0.1	0.0	0.0	1.0	0.2	0.2	0.6	0.2	0.2
Organic reject treatment	0.0	5.0	5.3	0.0	5.3	5.2	0.0	4.8	4.9
RDF production	0.0	4.7	4.9	0.0	50.1	48.6	0.0	25.9	26.0
Avoided emissions									
Electricity substitution of incineration	76.1	61.2	73.0	76.3	64.1	75.5	76.7	65.2	76.3
Electricity substitution of LFG combustion	22.7	18.9	12.5	22.7	19.7	12.9	22.9	20.1	13.1
Energy substitution of organic reject treatment	0.0	15.0	11.0	0.0	13.3	9.6	0.0	13.7	9.9
Metal substitution	1.3	4.9	3.5	0.9	2.9	2.0	0.4	1.0	0.7

3.2 Perturbation analyses

3.2.1 South Karelia

The most important, i.e. sensitive, parameters concerning the GWP, AP and EP of landfilling in the South Karelia case study are presented in Fig. 5. As can be seen, due to the dependency of an SR on an impact category, the most important parameters vary significantly between the impact categories. When it comes to the least important parameters, certain ones stood out in all impact categories. The electricity and chemical consumption of leachate treatment had only a minor influence on the total results in all impact categories (SRs<0.01). Additionally, the NH_3 emissions of landfilling had only a minor influence on the AP and EP of landfilling (SRs<0.007). Otherwise, there were no distinct similarities between the impact categories in terms of the least important parameters.

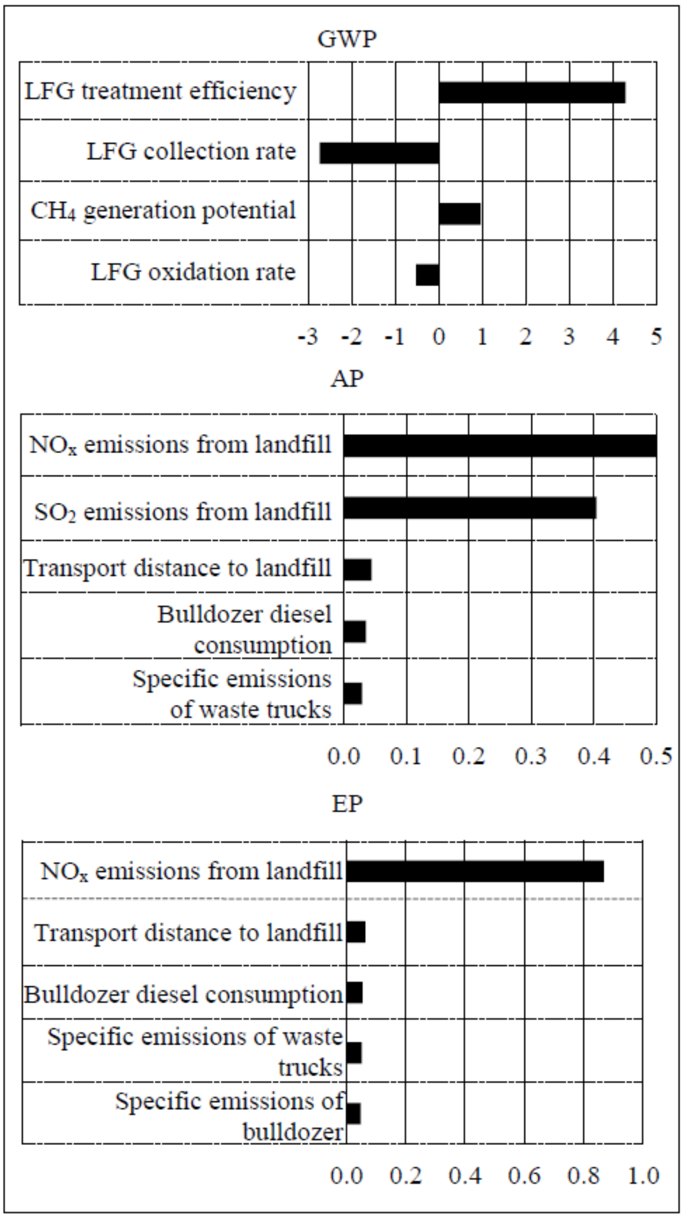


Fig. 5. The most important parameters and their SRs regarding landfilling in the South Karelia case study.

The most important parameters concerning the GWPs, APs and EPs of the incineration scenarios (1.1–1.3) are presented in Fig. 6. Among the least important parameters, particularly those related to the transportation of auxiliary materials (i.e. other materials than waste) stood out in all impact categories (SRs<0.01). Furthermore, certain parameters regarding bottom ash treatment, metal recycling as well as the treatment of boiler ash and APC residues had only a minor influence on the total results in all impact categories. These parameters concerned the electricity consumption in the treatment of boiler ash and APC residues, the use of machinery (i.e. wheel loaders) in bottom ash treatment and the pretreatment of metals for recycling (SRs<0.01).

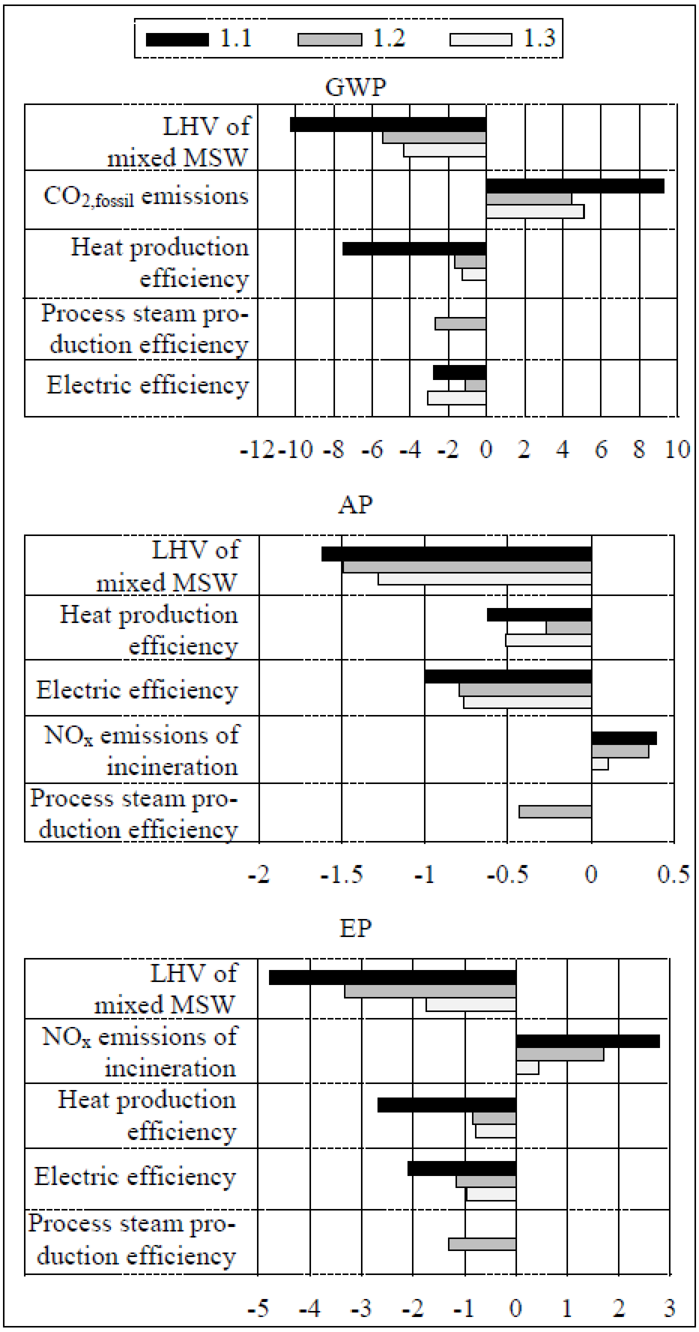


Fig. 6. The most important parameters and their SRs regarding incineration (Scenarios 1.1–1.3) in the South Karelia case study.

3.2.2 Hangzhou

The most important parameters regarding landfilling (Tianziling and Liugongduan landfills) in the Hangzhou case study are presented in Fig. 7. With regard to the least important parameters, the electricity consumption of leachate treatment had only a minor influence on the total results regarding all impact categories (SRs<0.02), as in the South Karelia case study. Parameters concerning the use of bulldozers in landfilling (i.e. diesel consumption and emissions generated during use) had only a minor influence on the total results in all impact categories (SRs<0.02).

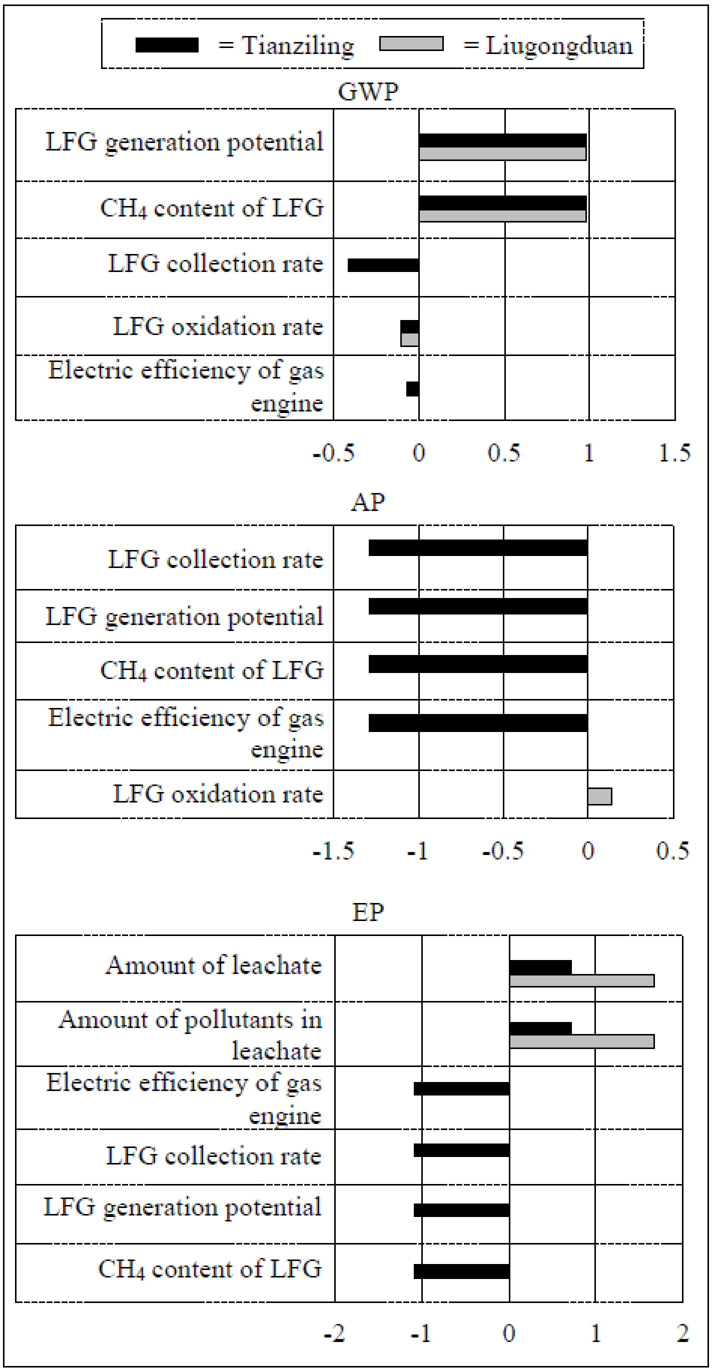


Fig. 7. The most important parameters and their SRs regarding landfilling in the Hangzhou case study.

The most important parameters regarding the GWPs, APs and EPs of the incineration of mixed MSW in the Hangzhou case study are presented in Fig. 8. The transportation of auxiliary materials proved to have only a minor influence on the total results in all impact categories (SRs<0.01), as in the South Karelia case study. Additionally, certain parameters concerning the treatment of boiler ash and metal recycling were among the least important parameters. These parameters concerned the share of aluminium and steel in bottom ash, the amount and water content of boiler ash, and the cement consumption of boiler ash treatment (SRs<0.02).

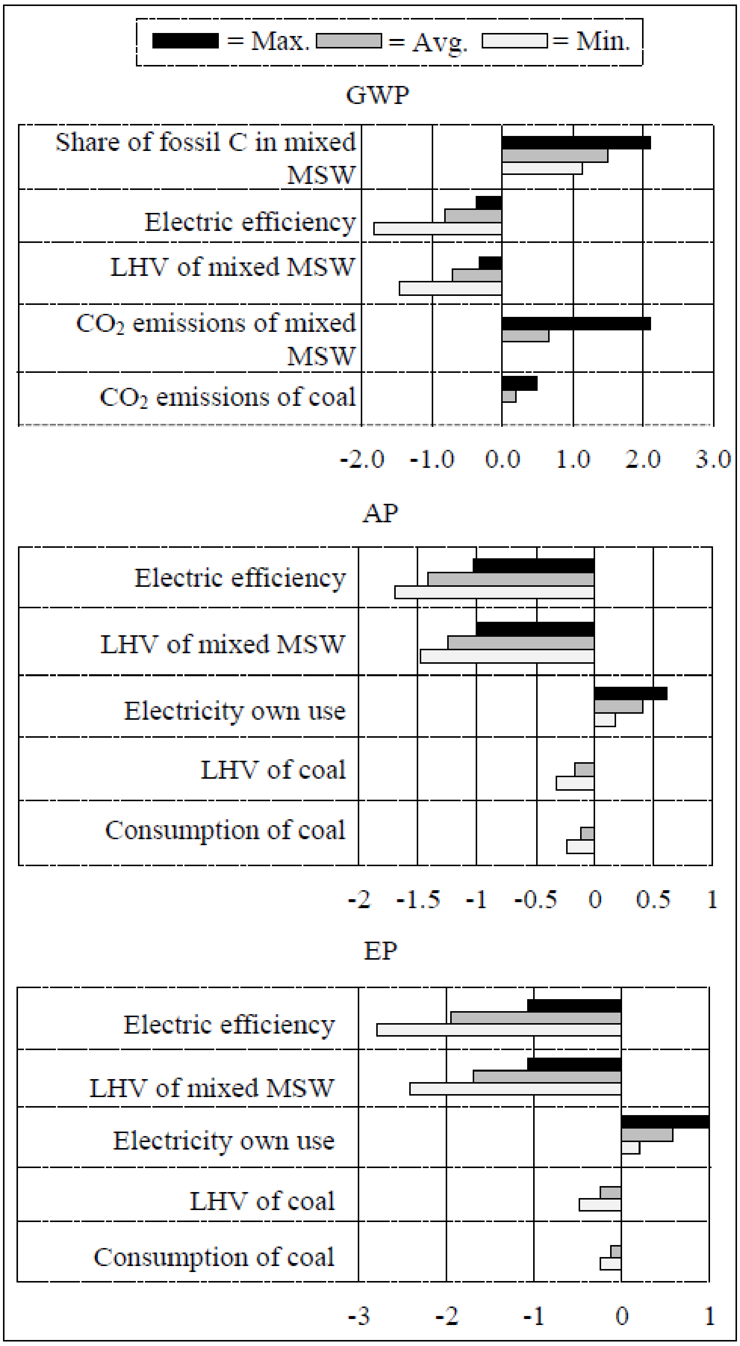


Fig. 8. The most important parameters and their SRs regarding incineration in the Hangzhou case study.

3.2.3 Comparison of the case studies

The case studies are compared to each other in terms of the SRs of the parameters that were applied in both studies. These parameters' mean values and coefficients of variation (CV) are presented in Table 4. The mean values and CVs were calculated from the parameters' SRs in the different scenarios of each case study, i.e. case by case. Furthermore, the Mann-Whitney U test on a 95% confidence level test was applied to identify significant differences among the case studies (see Supplementary material F where the results of the test are presented) (Brunner and Puri, 1996). A simple guideline when interpreting the results of the test: the smaller the *p*-value is, the more significant the difference among the case studies is. The range of *p*-values is 0-1 (*p*-value less than 0.05 indicates a significant difference). The analysis was carried out with SPSS Statistics Version 23.

Table 4

Comparison of the SRs of the parameters that were applied in both studies.

Parameter	SRs' mean values and CVs (in brackets)					
	GWP		AP		EP	
	South Karelia	Hangzhou	South Karelia	Hangzhou	South Karelia	Hangzhou
Landfilling						
LFG collection rate	-2.73 (-)	-0.42 (-)	-	-1.29 (-)	-	-1.07 (-)
LFG oxidation rate	-0.52 (-)	-0.11 (0.1%)	-	0.14 (-)	-	0.12 (-)
LFG generation potential	0.97 (-)	0.98 (0.1%)	-	-1.29 (-)	-	-1.07 (-)
Bulldozer diesel consumption	0.01 (-)	0.001 (18%)	0.04 (-)	0.01 (40%)	0.05 (-)	0.01 (40%)
Bulldozer emissions	0.01 (-)	0.001 (18%)	0.03 (-)	0.01 (40%)	0.05 (-)	0.01 (40%)
Amount of leachate	-	-	-	-	0.001 (-)	1.19 (40%)
Amount of pollutants in leachate	-	-	-	-	0.001 (-)	1.19 (40%)
Electricity consumption of leachate treatment	0.003 (-)	0.001 (18%)	0.01 (-)	0.02 (40%)	0.005 (-)	0.01 (40%)
Incineration						
Electric efficiency of incineration	-2.30 (37%)	-0.82 (64%)	-0.85 (12%)	-1.42 (17%)	-1.41 (35%)	-1.95 (32%)
LHV of mixed MSW	-6.70 (38%)	-0.71 (58%)	-1.46 (9%)	-1.25 (16%)	-3.28 (38%)	-1.70 (30%)
$CO_{2,fossil}$ emissions of incineration	6.29 (33%)	2.16 (25%)	-	-	-	-
NO_x emissions of incineration	-	-	0.28 (45%)	0.20 (58%)	1.64 (58%)	0.63 (65%)
SO_2 emissions of incineration	-	-	0.05 (50%)	0.09 (57%)	-	-
HCl emissions of incineration	-	-	0.01 (44%)	0.01 (60%)	-	-
Electricity own use in incineration	0.30 (32%)	0.19 (23%)	0.12 (35%)	0.41 (43%)	0.21 (49%)	0.58 (53%)
Cement consumption for residue treatment	0.12 (57%)	0.07 (50%)	0.03 (21%)	0.05 (62%)	0.07 (18%)	0.09 (69%)
Amount of residues (i.e. flue gas residues)	0.14 (56%)	0.01 (61%)	0.04 (20%)	0.01 (72%)	0.09 (20%)	0.02 (81%)
Metal recycling						
Proportion of aluminium in bottom ash	-0.41 (35%)	-0.01 (23%)	-0.12 (2%)	-0.02 (40%)	-0.02 (20%)	-0.01 (53%)
Proportion of steel in bottom ash	-0.26 (35%)	-0.002 (25%)	0.01 (0.2%)	-0.001 (40%)	0.08 (19%)	-0.0003 (52%)
Transportation						
Transportation distance of mixed MSW	0.10 (69%)	0.02 (28%)	0.04 (34%)	0.03 (47%)	0.17 (72%)	0.10 (59%)
Transportation distance of residues	0.002 (85%)	0.002 (70%)	0.001 (73%)	0.005 (80%)	0.004 (80%)	0.01 (86%)
Transportation distance of cement	0.001 (72%)	0.001 (63%)	0.0003 (44%)	0.002 (74%)	0.001 (39%)	0.01 (81%)

The parameters concerning landfilling could not be analysed by the Mann-Whitney U test due to lack of data: the South Karelia case study included one landfilling scenario and the Hangzhou case study included two.

Therefore, these parameters' SRs among the case studies are compared solely based on the data presented in Table 4. As can be seen, among the parameters related to landfilling, the collection rate of LFG was considerably more sensitive in the South Karelia case study than in the Hangzhou case study with regard to GWP. The collection rate of LFG was 75% in the South Karelia case study, whereas it was 25% in the Hangzhou case study. Based on this, the higher the collection rate is, the more sensitive it is. The collection rate of LFG also had an influence on the total AP and EP in the Hangzhou case study due to the electricity production from LFG. The oxidation rate of LFG was also more sensitive in the South Karelia case study in terms of GWP. The oxidation rate was approximately four times higher in the South Karelia case study, which indicates the same phenomenon as the collection rate of LFG. The LFG generation potential was equally sensitive concerning the GWPs of both case studies. In the Hangzhou case study, it also had an effect on the total APs and EPs due to electricity substitution. In terms of the parameters concerning the use of bulldozers, the parameters were more sensitive with regard to GWP in the South Karelia case study than in the Hangzhou case study. However, such distinct differences were not identified in the other two impact categories. The influence of parameters concerning the generation of leachate and the concentration of pollutants in it differed between the case studies due to the higher concentration of pollutants in leachate in the Hangzhou case study.

As for the parameters concerning the incineration of mixed MSW, it can be seen that the electric efficiency of incineration was more sensitive regarding the GWP in the South Karelia study due to a higher energy production rate, which correspondingly results from the higher energy content of mixed MSW in South Karelia (the *p*-value of the Mann-Whitney U test was 0.071 → a rather significant difference among the case studies). The parameter was more sensitive regarding the AP in the Hangzhou case study (*p*-value 0.036 → a significant difference). In terms of EP, there was no distinct difference between the case studies (*p*-value 0.393). Concerning GWP, the LHV of mixed MSW was substantially more sensitive in the South Karelia case study (*p*-value 0.036). The parameter itself was also substantially higher in the South Karelia study. This again indicates the correlation between parameter's value and sensitivity: the higher the LHV of mixed MSW is, the more sensitive it is. There were no such distinct differences between the case studies in terms of the parameter in the AP and EP impact categories (*p*-values 0.143 and 0.250). As did the LHV, the $CO_{2,fossil}$ emissions of incineration was significantly more sensitive regarding GWP in the South Karelia case study (*p*-value 0.036): its SR was multiple times higher than in the Hangzhou case study due to the higher fossil carbon content in the mixed MSW. There were no distinct and noteworthy differences between the case studies regarding the SRs of NO_x (*p*-values 0.393 and 0.250 in the AP and EP impact categories), SO_2 (*p*-value 0.571 in the AP impact category) and HCl (*p*-value 0.114 in the AP impact category) emissions. The electricity own use in incineration was more sensitive in terms of AP in the Hangzhou case study (*p*-value 0.036). In terms of the other impact categories, the sensitivity of the parameter did not vary significantly among the case studies. The SRs of cement consumption in residue treatment did not vary substantially between the case studies (*p*-values 0.571, 0.571 and 0.786 in terms of GWP, AP and EP). The SRs of the amount of residues varied significantly between the case studies (*p*-values 0.036 in all impact categories).

Parameters concerning metal recycling had rather a minor influence on the total results in both case studies, and their SRs did not vary significantly between the studies (*p*-values 0.095 in all impact categories). However, as can be noticed in Table 4, parameters concerning metal (i.e. aluminium and steel) recycling were more sensitive in the South Karelia case study, particularly in terms of GWP. Parameters regarding transportation were similar from their sensitivity point of view in both case studies with one exception. The transportation of mixed MSW was significantly more sensitive in South Karelia case study in terms of GWP (*p*-value 0.036).

3.3 Factors influencing the LCA of the case studies

The contribution analyses of the case studies demonstrated how critical energy substitution was in the case studies. In the South Karelia case study, heat substitution had a remarkably strong influence on the total results, and it determined the order of the incineration scenarios in all impact categories. Electricity substitution also had a major influence on the total results. In the Hangzhou case study, the influence of energy recovery and substitution was not as obvious due to only electricity recovery from mixed MSW. Nevertheless, energy recovery and substitution was evidently the most critical individual process influencing the total results of both case studies. It is therefore highly recommendable to use case-specific and direct data regarding parameters concerning energy recovery and substitution (e.g. energy content of mixed MSW, energy production efficiencies, etc.).

The perturbation analyses of the case studies demonstrated that the most critical parameters concerning landfilling were directly related to LFG (i.e. generation potential, collection rate, treatment efficiency) and leachate (i.e. generation potential, concentration of pollutants), even though there were some inconsistencies between the case studies, as presented in Table 4. The LHV of the mixed MSW, $CO_{2,fossil}$ emissions of incineration, and energy production efficiencies were clearly the most critical ones of the parameters related to incineration in the case studies. Additionally, the NO_x and SO_2 emissions of incineration had a notable influence on the total results. In terms of metal recycling, the most important parameters were related to the recoverable amount of metal in mixed MSW, or rather in bottom ash. Of the transportation-related parameters, parameters concerning the transportation of mixed MSW had the strongest influence on the total results.

As presented in Table 4 and previously discussed, parameters with only a minor influence on the total results were identified in all the main mixed MSW management phases: transportation, landfilling and incineration. In terms of the least important parameters concerning landfilling, the use of a bulldozer in landfilling, and the electricity and chemical consumption in leachate treatment had a fairly minor influence on the total results. Certain parameters related to bottom and boiler ash treatment were the least important ones related to incineration. For instance, the electricity consumption during the treatment did not have a notable influence on the total results. Additionally, the transportation of auxiliary materials had a rather minor influence on the total results, regardless of the impact categories.

The perturbation analyses of the case studies also demonstrated how the magnitude of an SR is dependent on the value of a parameter. With regard to certain parameters (e.g. the LHV of mixed MSW and the collection rate of LFG), the correlation between the magnitude of an SR and the value of a parameter was the following: the higher the value of a given parameter is, the more sensitive the parameter is.

A possibility to simplify the LCA of the case studies is to apply default or generic data instead of direct, case-specific data. Default data should be applied with caution, i.e. to parameters which have only a minor influence on the total results. The exclusion of certain processes (e.g. the transportation of auxiliary materials) from the assessment is also a possibility to simplify the LCA of the case studies. However, it requires particular caution. Possibilities to simplify the LCA of the South Karelia and the Hangzhou case studies are presented in Table 5.

Table 5

Possibilities to simplify (i.e. apply default or generic data instead of case-specific, direct data) the LCA of the South Karelia and Hangzhou case studies.

	Simplification possibility
Landfilling	– Electricity and chemical consumption in leachate treatment – The use of machinery in landfilling (i.e. the diesel consumption of a bulldozer)
Incineration	– The treatment of boiler ash and APC residues: electricity consumption, the use of machinery (i.e. the diesel consumption of a wheel loader) – Bottom ash treatment and metal recycling: the use of machinery in bottom ash treatment, the pretreatment of metals for recycling (i.e. the use of machinery and electricity consumption)
Transportation	– The transportation of auxiliary materials, such as chemicals, APC residues, boiler and bottom ash (i.e. diesel consumption and transportation distances)

The possibilities to simplify the LCA of the South Karelia and Hangzhou case studies were identified and discussed in this study. However, one should identify the limitations of the study. First of all, only three impact categories were assessed in the case studies. Therefore, the simplification possibilities concern only the GWP, AP and EP impact categories. Secondly, only two different case studies were compared in this study. The findings of the study apply solely to the case studies, and more case studies are required in order to draw more extensive and general conclusions. Thirdly, it should be noticed that the study focused on individual parameters and their sensitivity, and the identified simplification possibilities concerned merely them. In other words, this study did not concern process, modelling or scenario uncertainties, although they can also have a strong influence on the overall uncertainty of LCA studies (Clavreul et al., 2012). This is due to the fact that parameter sensitivity can be computationally quantified (i.e. by determining SRs), and thus utilised in the comparison of different case studies. Fourthly, it is worth noting that the differences between the LCAs of the case studies (e.g. system boundaries, modelling principles, etc.) can influence the magnitude of SRs. Therefore, the most and least important parameters were identified case by case based on the ranking of the SRs rather than focusing merely on the magnitude of SRs. For instance, although the SR of a parameter would vary notably (e.g. 1.5 and 2.5) between the case studies, if the parameter were among the most important parameters in both studies based on the case-specific ranking of SRs, the parameter would be identified as an important one, and vice versa. Regardless of the limitations of the study, the study introduces a novel perspective to the LCA of MSW management systems. When default or generic data is enough instead of direct, case-specific data? It is not easy to draw the line between them. However, the study presents examples on how the particular case studies could be simplified in this manner. It should be acknowledged that the simplification possibilities presented in this study are rather conservative due to the above-mentioned limitations. Therefore, they may well be applicable in other case studies, too.

4. Conclusions

Mixed MSW management systems in the South Karelia region, Finland and the city of Hangzhou in China were compared in this study in order to find out the similarities and differences between the case studies in terms of the influence of different factors on the total results of the LCA studies. The comparison of the case studies focused particularly on the influence of various input parameters on the total results, i.e. the GWPs, APs and EPs of the systems. After the comparison, possibilities to simplify and thus diminish the workload of the case studies were discussed and introduced in the study.

Even though there were differences in the influence of individual parameters on the total results of the case studies, certain factors stood out. Energy recovery and substitution were the most critical individual processes influencing the results of the case studies. In terms of individual input parameters, those directly related to the generation and collection of LFG, the energy and fossil carbon content of mixed MSW, energy production efficiencies, as well as the NO_x and SO_2 emissions of incineration had a significant influence on the total results in both case studies. Therefore, direct and case-specific data should be particularly applied to these parameters. Parameters related to the use of machinery in landfilling, the electricity and chemical consumption in leachate treatment and the transportation of auxiliary materials were not that crucial regarding the total results of the case studies. Additionally, certain parameters related to boiler and bottom ash treatment had a minor influence on the total results. To diminish the workload of the LCA of the case studies, default or generic data could be applied to these parameters instead of case-specific, direct data. It is worth noting that the findings of the study apply only to these particular case studies. Therefore, to draw more general conclusions, further research on the subject is required.

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