Life cycle inventory of the pneumatic waste collection system in a dense urban area

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Summary

Pneumatic waste collection is a novel waste collection method. Its potential to increase safety and hygienic levels and reduce traffic flow makes the pneumatic waste collection an interesting choice when planning new solutions for the waste collection in dense urban areas. In this case study, the environmental loads (GHG, NO_x and SO_x) of hypothetical pneumatic system installed in Punavuori area, Helsinki, Finland, are calculated and the results are compared to those of the prevailing conventional vehicle operated waste collection system. Life cycle inventory (LCI) is used as a tool to evaluate the environmental loads of the relevant life cycle phases. A marginal analysis is performed by determining the environmental loads of the pneumatic waste collection first for a smaller area and then gradually expanding the analysis to cover a larger area. Also, the number of waste fractions collected varies in the different stages of the analysis. In the results, the loads formed in the whole case area in both waste collection systems are combined. According to the analysis, replacing the prevailing waste collection with pneumatic system would generate more air emissions. The electricity consumption and the origin of energy have a significant effect on the results, but decisive are the emissions from manufacturing the system components. On the local level emissions nonetheless diminish, since collection traffic reduces.

Keywords: pneumatic waste collection, life cycle inventory (LCI), marginal analysis

1. Introduction

Pneumatic waste collection system has been suggested as a high-tech solution which has a potential to increase the hygienic and safety level of waste collection. Such a system reduces the need for vehicle transportation in collection areas, thus reducing noise and congestion effects and potentially saving space [1]. Pneumatic waste collection has also been proposed as a means to enhance source separation [2]. By pneumatic waste collection it is possible to collect around 80 % of municipal solid waste. The system is not suited for large items, hazardous waste, waste electric equipment nor liquid waste. [3]

In a stationary pneumatic waste collection system, waste collection points are located according to case specific needs. The collection points comprise one or several waste inlets, depending on application technique and the number of waste fractions collected. Waste is transported in underground pipelines through the use of vacuum to waste terminal. There, each fraction is diverted to its own container. Full containers are transported to final processing and disposal sites.

In Finland, constructing and designing pneumatic waste collection systems has focused on new urban areas. However, it is also possible to implement pneumatic waste systems in a smaller scale in buildings being renovated or partially rebuilt or in existing dense urban areas. In such areas, conventional vehicle based waste collection is often challenging due to, for example, varying topographies and limited space for waste transportation vehicles. Waste containers may also be placed impractically due to lack of proper placing spaces. The use of pneumatic waste collection in these areas could provide a competitive alternative to conventional waste collection. However, installing pneumatic waste collection system into existing infrastructure is challenging. For example, it can be difficult to integrate new pipelines with existing under- and overground structures. Also, for residents the average distance to the nearest waste collection point may lengthen if there are fewer points for pneumatic waste collection relative to traditional containers.

This case study analyses the hypothetic application of pneumatic waste collection system in the densely built and populated district of Punavuori in central Helsinki and its environmental loads. Additionally, we have evaluated the relevant environmental effects of the prevailing conventional vehicle operated waste collection system in order to compare the loads of alternative collection systems.

2. Methodology

2.1 Life cycle inventory

Life cycle inventory (LCI) was used as a tool to analyse and to compare the emissions of both waste collection systems studied. According to ISO 14040, LCI “involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system” [4]. Thus, LCI identifies and quantifies the energy and material flows entering and leaving a given system, such as energy, waste and emissions. Ideally, the social effects such as noise and congestion effects should be included in the life cycle assessment. However, because of the difficulty of quantifying social aspects, in this study these effects are discussed qualitatively. The economic aspects of the pneumatic waste collection system in the same area are reported in another paper [5].

The first phase of LCI is the definition of the relevant life cycle phases and the functional unit (FU) per which the results are presented. The functional unit of this study was the annual waste generation in the case area (loads /a). Additionally, results per ton of waste are presented. The environmental loads included in LCI were the air emissions of green house gases (GHG), nitrogen oxides (NO_x) and sulphur oxides (SO_x). The CO_2, CH_4, and N_2O emissions were converted into commensurable CO_2 equivalents by using the GWP factors (Global Warming Potential) 1, 25 and 298, respectively (for 100 years’ time period) [6]. The calculation covers all the emissions during the life cycle of the system separately for each compound, which are finally summed.

2.2 Boundaries of the LCI

The following life cycle phases of pneumatic waste collection system were defined as relevant:

1. Manufacturing of pipelines and waste collection points and the production of their raw materials (steel, plastic, concrete)
2. The building of the waste terminal and the related components as well as production of their raw materials, transportation of construction materials to building site
3. The installation of pipelines (excavation and re-asphaltation)
4. The system’s use of energy
5. The transportation of waste containers to waste treatment centre and the production of the required diesel fuel

For the conventional vehicle operated waste collection, the following life cycle phases were defined as relevant:

1. Manufacturing of waste containers (plastic)
2. Collection and transportation of waste from the collection area to waste treatment centre and the production of the required diesel fuel

The transportation of system components to case area, the manufacturing of machinery for earth construction purposes, and the end of life cycle of system components after their service life were not included in the study. As a whole, these life cycle phases were evaluated as minor. The number of transportation vehicles in pneumatic waste collection was assessed as roughly equal to the vehicle number in the conventional system. Also, the treatment and disposal of the collected waste is defined out of the scope of this study because the utilization and treatment of waste does not influence the collection phase.

2.3 Description of the case area

Punavuori area in central Helsinki was chosen to represent a densely built and populated district in Finland. The case area contains 11 city blocks. It is a typical example of a city area where conventional vehicle operated waste collection is often challenging, due to varying topographies and limited space for waste transportation vehicles and containers. Table 1 shows basic data on the case area and the annual waste generation.

Table 1 Source data including population, buildings and waste generation on the case area.

Basic data	Number	Data source
Population	5 095	[7]
Buildings	98	[7]
Apartments	3 911	[7]
Number of inhabitants per apartment	1.3	
Waste generation	t/a	Data source
Mixed refuse	1 055	[7]
Organic waste	155	[7]
Paper	662	estimated value
Cardboard	64	estimated value
total	1 936	

2.4 Modelling of the waste collection systems

A hypothetical pneumatic waste collection system suitable for the case area was modelled with the help of system suppliers. Additionally, the evaluation of the relevant environmental effects of the prevailing conventional vehicle operated waste collection system was performed by using a time-based model [8]. The environmental data were collected from the case study area whenever possible, otherwise earlier studies and other data were used. All relevant life cycle phases, their useful lifes, materials or processes and the data sources are listed in Table 2. The basic characteristics of the modelled pneumatic collection system are presented in Table 3. A detailed description of the life cycle phases included in LCI for both systems is provided in chapters 2.4.1-2.4.4.

Table 2 Source data of different life cycle phases in both systems.

Pneumatic system	Useful life (yrs)	Material or process	Data source
Waste terminal, building	35	materials, building, transporting	[9]
Waste terminal, equipment	20	steel	[10]
Pipes	35	steel	[10]
Pipe installation		machines used, asphalting	[11], [12]
Collection points	25	steel, HDPE plastic, technical space	[10], [13], [14] *
Electricity consumption		average electricity production	[15]
Transportations		transporting, diesel production	[16], [17]
Vehicle based collection			
Waste containers	13,5	HDPE plastic	[13], [14]
Transportations		transporting, diesel production	[18], [17]

* Loads of technical space calculated based on loads generated in building the waste terminal, by scaling down the building. Primary structures and the transportation of materials were not included.

The comparison of the results on pneumatic waste collection with those of the conventional waste collection system using waste containers was made by means of marginal analysis. This way it was possible to analyse the feasibility of pneumatic waste collection system installed, compared to vehicle based collection. In the marginal analysis, both systems were assumed to cover four municipal solid waste fractions: mixed refuse, organic waste, paper and cardboard. At the first stage of the analysis, only mixed refuse was expected to be collected with pneumatic waste collection, whereas the other residues were supposed to be collected conventionally. At the following stages, the examination was extended one fraction by one (in the order: organic waste, paper and cardboard) so that at the final stage pneumatic waste collection covered all four waste fractions. The size of the waste terminal and the number of waste inlets in each collection point was also supposed to grow alongside with fractions added to pneumatic collection. The environmental loads of the pneumatic waste collection were first calculated for a small area and then gradually expanded the analysis to cover two larger areas. In the results, the loads formed in the case area in both waste collection systems were combined. Detailed information on the analysis is presented in Figure 1 and in Table 3.

Table 3 The proceeding of the marginal analysis and the data collected from systems. VB: vehicle based, PC: pneumatically collected, M: mixed refuse, O: organic waste, P: paper, C: cardboard.

Ground state	VB collection	Area 1	PC fractions	Area 2	PC fractions	Area 3	PC fractions
Step 1	M+O+P+C	Step 2	M	Step 6	M	Step 10	M
		Step 3	M+O	Step 7	M+O	Step 11	M+O
		Step 4	M+O+P	Step 8	M+O+P	Step 12	M+O+P
		Step 5	M+O+P+C	Step 9	M+O+P+C	Step 13	M+O+P+C
Pneumatic system		Area 1		Area 2		Area 3	
Blocks included		4-8		1-8		1-11	
Main pipe line length (m)		584		1 064		1 626	
Feeder pipe line length (m)		920		1 360		1 920	
Total pipe length (m)		1 504		2 424		3 546	
Number of collection points		23		34		48	
Number of waste terminals		1		1		1	
Vehicle based collection							
Blocks included		1-3, 9-11		9-11		-	
Number of collection points [7]		50		69		88	

2.4.1 Waste terminal

The waste terminal is a semi-warm hall building, constructed from prefabricated reinforced concrete and situated in an underground parking space. The hypothetical location of the terminal is presented in Figure 1. The waste terminal consists of sorting equipment, waste containers for different fractions, baling presses and suction devices. The size of the terminal collecting one waste fraction was assumed to be 200 m^2, two fractions 267 m^2, three fractions 334 m^2 and four fractions 400 m^2 [19].

2.4.2 Pipes and collection points

Pipes for main and feeder lines are typically manufactured from non-alloyed PE-coated pressure vessel steel. One collection point consists of one or more waste inlets according to the amount of fractions collected or the technology used. In Finland, one collection point serves typically 100 – 150 inhabitants [2]. In many other countries, though, 200 – 300 inhabitants per one point are common due to higher population densities [19]. In this study it was assumed that one collection point is sufficient to cover the waste production of approximately 125 persons. This means that there is significantly smaller number of collection points (ca. 50 % less) than in the prevailing vehicle based collection (Table 3). One collection point was supposed to consist of the number of waste inlets needed on each stage of the study (Table 3).

Fig. 1 Case-area in Punavuori. Numbers from 1 to 11 present the blocks covered by the pneumatic system. Red lines represent the modelled main pipe lines and the blue box the approximate placing of the waste terminal. Feeder pipe lines are not marked in the picture.

2.4.3 Operation, maintenance and transportations

Pneumatic waste collection requires electricity for operation, heating for waste terminal, basic maintenance and temporary reparations. The transfer of waste from inlets to the waste terminal is done by the means of air flow. The quantity of electricity needed depends on the amount of the waste generated and thus the filling rate of the waste inlet. This determines the amount of suctions needed per day. Also the degree of filling or one-cycle suction influences the electricity consumption. The smaller the filling rate is the more it consumes energy per waste ton conveyed [20]. At the same time, the number of collection points influences indirectly electricity consumption [19].

The transportation of waste from the terminal to further treatment or final disposal is typically done by truck, taking one container at a time. The energy consumption is smaller than in ordinary vehicle based waste collection, because the actual waste collection drive is not required. Also the amount of waste transported per time is usually greater than in ordinary waste transportation vehicles. Mixed refuse, paper and cardboard containers at the waste terminal were supposed to be emptied as soon as they were filled, and because of hygienic issues, the containers for organic waste in every three weeks regardless of the waste accumulation.

Measured values of the energy consumption were not available, so the calculations were based on approximate values compiled from the system suppliers. Fluctuation among different electricity consumption estimates was significant (50–356 kWh/waste ton). The annual electricity consumption estimate used in the calculations was 184 000 kWh and the electricity consumption emptying one single waste inlet by air suction was calculated according to this value. The number of waste suction times needed was determined based on the amount of waste accumulation in one collection point and the one inlet's storage capacity. The outcome of this calculation was that mixed refuse is collected twice a day and the other fractions once a day.

From the environmental loads of the systems operation, only electricity consumption and transportations (including diesel fuel production) were taken into consideration. Loads caused by maintenance work, reparations and heating the terminal were evaluated as minor.

2.4.4 Conventional vehicle operated waste collection

Currently, the vehicle operated waste collection, where waste is collected to plastic containers is used in the case area. Approximately 60 persons use one collection point. Waste containers in Punavuori are emptied by rear loading waste transportation vehicles [8]. Waste collection drive differs from the transportation of waste to treatment or disposal sites (more accelerations and stopovers) and thus produces different amount of emissions. Fuel consumption and exhaust fume emissions were modelled [18] on the basis of timing experiments made in the case area [8].

3. Results

3.1 Environmental loads of the pneumatic waste collection

The origin of emissions formed in pneumatic waste collection and vehicle operated waste collection is easier to understand when total loads are divided into each system's life cycle phases. Figure 2 presents the annual total emissions of waste collection in the case area and emission shares of each life cycle phase within the two systems. The total amount of GHG and SO_x formed is higher in the pneumatic waste collection than in the vehicle based collection (steps 1 and 13). The most significant single loading phase is the electricity needed in pneumatic waste collection. However, regarding the NO_x emissions the overall situation is opposite. Thus the total amount of GHG and SO_x emissions increases, whereas the NO_x emissions decrease, when the area studied is extended. Reduced NO_x emissions result from the descending rate of vehicle based collection.

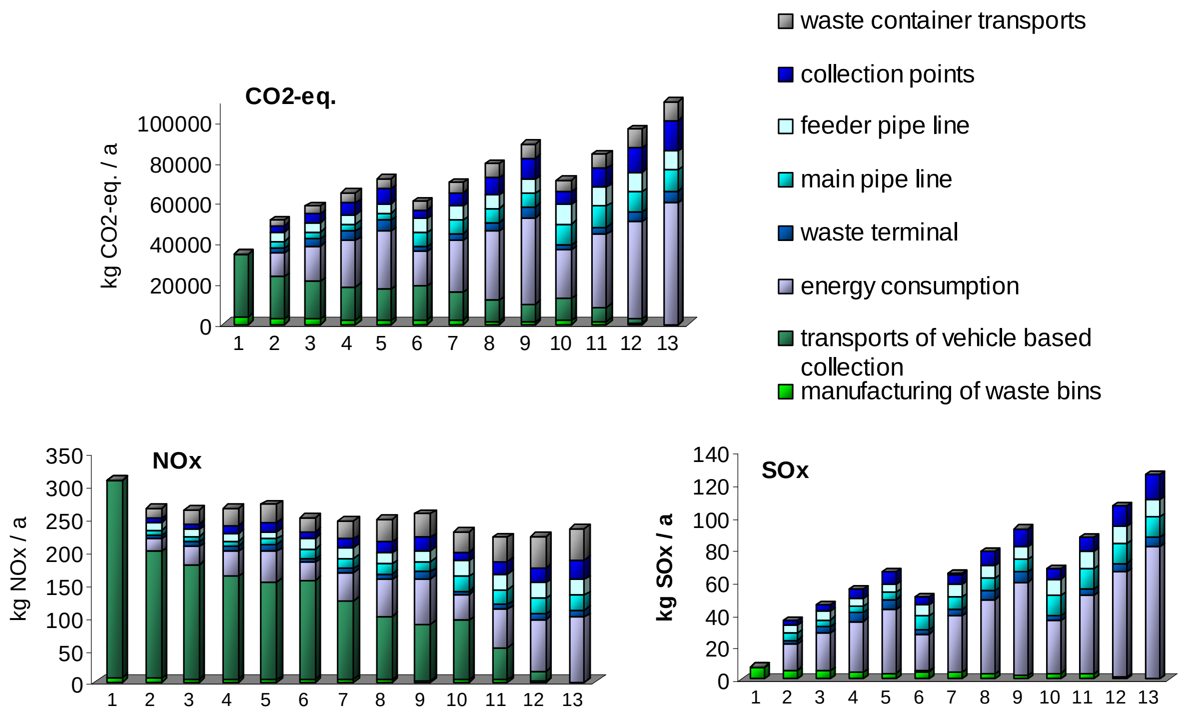

Fig. 2 Air emissions in both systems studied at every life cycle phase (in kg/a). The loads were calculated for three extended areas in 13 different steps (see also Table 3).

However, there are some uncertainties related to the evaluation of the loads caused by the electricity usage. The presented calculations do not take cognizance of how the properties of waste influence the energy consumption. Though, it is presumable that the suction of lighter fractions does not consume energy as much as heavier fractions do [2]. Furthermore, the approximate values compiled from the system suppliers did not emerge the supposed operation mode of the system. Each waste inlet may have sensors which indicate when the inlet is full after which the inlet is emptied. An alternative control mode is a scheduled collection [21]. Scheduled collection increases the energy consumption per waste ton for fractions with low accumulation rate (in this case organic waste and cardboard). In this study, it was assumed that the collection is scheduled.

The single most important cause of GHG and NO_x emissions in the vehicle based collection is the collection and transportation of waste. The NO_x emission from the transportations is so high that it leads the vehicle based collection to be the weaker of the two alternatives examined. The formation of SO_x emissions in vehicle based collection is negligible, because the emission levels of modern waste transportation vehicles are low.

The share of transportations in SO_x emissions is insignificant also in pneumatic collection. NO_x emissions caused from the container transportation are quite remarkable in this system also. Though, the transportation of containers from the waste terminal in the pneumatic system generates only sixth of the NO_x emissions compared to the vehicle based collection. This results from the avoided collection traffic in pneumatic waste collection system. Also GHG emissions are two thirds lower in transports related to the pneumatic system, than in waste transported conventionally.

The overall air emissions for pneumatic collection (in step 13) and vehicle based collection (in step 1) in different emission categories calculated per waste ton are presented in Figure 3. The results are similar to those calculated per annum; the GHG and SO_x emissions are higher in pneumatic collection and lower in the category of NO_x than in vehicle based collection.

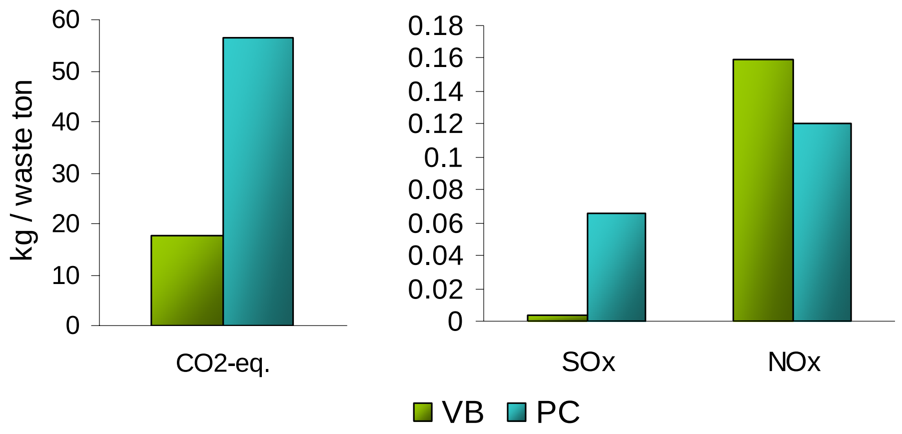

Fig. 3 Results for different emission components in the vehicle based waste collection and pneumatic waste collection, calculated per waste tonnage. VB: vehicle based collection, PC: pneumatic collection.

3.2 Sensitivity analysis for CO_2

As mentioned earlier in the chapter 2.4.3, the variation among different electricity consumption estimates was significant. The energy consumption in the case area was supposed to be 95 kWh/waste ton. The value was an average of one system supplier's wider estimate 70-120 kWh/waste ton. Therefore a sensitivity analysis was made also from these approximations to investigate the effect of varying electricity consumption on the final results.

The emissions related to electricity consumption depend on the production method and emission factor of the electricity. The calculations in this study are based on the emission factors of the average Finnish electricity production in 2004 [15]. The emission factor of average electricity production may alternate annually, depending on, for example, the amount on renewable energy used and the climatic circumstances. On this account, the evaluation of the effect of changing CO_2 emission factor was accomplished. The CO_2 emission factor used in the base case calculations was 292 g/kWh. In the sensitivity analysis an alternative emission factor used was 212 g/kWh, which is the mean value based on the monthly electricity production data published from the year

2010 [22].

The difference in electricity consumption in the CO_2 emissions for the two extremes (highest electricity consumption + highest emission factor vs. lowest electricity consumption + lowest emission factor) is over twofold. It is noticeable though, that the results from other emission compounds might not be similar to these results. That is, the electricity produced in the year 2010 might not be environmentally friendlier in all emission classes.

Changing the emission factor and electricity consumption estimate has also influence on the relative shares of the loads caused by the electricity consumption and by other system components. If the electricity used would be totally from renewable sources, the CO_2 emissions of the whole system would be reduced from 51 to 24 kg/waste ton. Nevertheless, the GHG emissions would still be higher in pneumatic collection than in vehicle based collection, because of the effects from the stationary components the system needs.

Figure 4 demonstrates the effect of emission factor and electricity consumption estimate on the CO_2 emissions of the whole system. With the lowest energy consumption value and the lower emission factor the emissions varied between 18 kg (step 1) and 39 kg (step 13) per waste ton. With the highest energy consumption value and the higher emission factor the variation between different steps is higher (18-59 kg/waste ton).

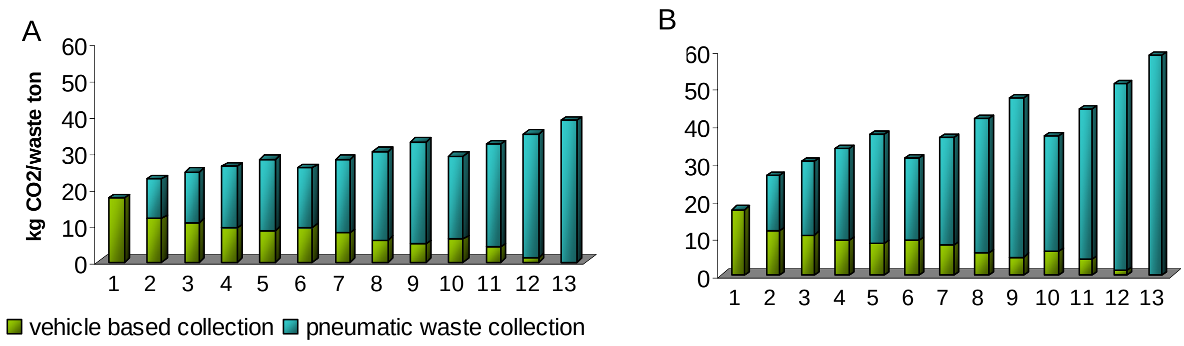

Fig. 4 The effect for changing the CO_2 emission factor of electricity production and electricity consumption estimate in 13 different steps investigated. A: emission factor 212 g/kWh, energy consumption 70 kWh/waste ton, B: emission factor 292 g/kWh, energy consumption 120 kWh/waste ton.

To conclude, in order to improve the reliability of results, it would be crucial to have a realistic estimate of the energy consumption. Also, the choice of emission factor for electricity has a significant effect on the results.

4. Conclusions

According to the analysis, replacing the prevailing waste collection with pneumatic waste collection would generate more air emissions. The emissions are associated with the high electricity consumption of the system and the manufacturing of system components. On the local level, namely at the waste collection area, the emissions nonetheless diminish, since collection traffic reduces. This implies better air quality at the collection area but at the same time the transfer of emissions to areas where the system components are manufactured or the electricity is produced.

For the pneumatic waste collection system covering the whole case area, the total NO_x emissions are 24 % smaller compared to the situation where conventional vehicle operated waste collection is implemented on the same area. However, SO_x emissions in pneumatic collection system are 17 times higher than those of conventional collection. The GHG emissions are increased threefold. The emissions from vehicle transportation are expectedly reduced.

The assumptions on the electricity consumption and the origin of energy have a significant effect on the results. If the electricity used in the pneumatic collection was assumed fully renewable, the GHG emissions due to electricity use would be eliminated. However, even in this extreme case the total GHG emissions of the pneumatic collection system would be larger than those of conventional collection system due to emissions associated with the manufacturing of system component.

There are, however, other aspects that favour the installation of pneumatic systems in already built residential areas. These factors include the positive effects arising from reduced vehicle transportation, such as less congestion and noise, the general improvement in hygienic conditions, reduction in contamination, odour, and pests, and possible positive effects on both residential and occupational safety. An interesting question is, how the system affects residents' eagerness to recycle would develop, as the user comfort of waste collection improves as a result of the aforementioned reasons, but at the same time the average distance to the nearest waste collection point increases. Additionally, a question to ponder is, whether there is any effect on waste reduction, if the system can be equipped with technology that measures the generated waste volumes on the household level. However, these effects remained outside of the scope of the quantitative evaluation, mainly due to lacking data or the difficulty of measuring such effects.

At the same time, it should be kept in mind, that also other solutions can improve waste collection in dense urban areas. Multi-chamber trucks have been suggested to reduce the need for vehicle transportation in collection areas, the use of alternative fuels (natural gas, biodiesel, biogas) may decrease emission loads, and twin-engined vehicles are devised to diminish the noise effects caused from vehicle collection. Also the installation of deep collection containers reduces the need for collection traffic. Progress in the pneumatic system can also be expected.

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