Energetic model of hydraulic system of refuse collection vehicle based on simulation and experimental data

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Abstract. This paper presents an energetic model of hydraulic system of a refuse collection vehicle. First, benefits resulting from implementation of an energetic model in the industry and operation of a Refuse Collection Vehicle are briefly explained. Then, components of the energy consumption in hydraulic circuits of compactor and lifting device are described and combined into a comprehensive model that can be evaluated using basic measurement equipment. Efficiency of individual components determined through measurement and simulation is also presented. Finally, potential application of the model and conclusions resulting from the carried out analysis are presented.

1. Introduction

Collection of the municipal solid waste is probably the most complicated and resource consuming component of the solid waste management. Refuse collection vehicles (RCV's) are essential to tackle this objective. They have to operate regardless of weather, traffic density and condition of the infrastructure to provide a key utility service, which is often rated as one of the top three priorities faced by the developing country cities [1]. Due to the nature of this task - frequent stops and continuous low speed maneuvering, fuel consumption of RCV's can be as high as 218 dm^3/100 km during collection trips and 40 dm^3/100 km during transfer of waste with the daytrip average of 79.5 dm^3/100 km [2]. In spite of ever increasing number of studies of the RCV's operation [3-10] there is still no comprehensive energetic model of a RCV which would allow to quantitatively assess the performance of particular components of the system and provide a reliable information to the customers. Creation of such a model could also direct the development effort of the RCV's manufacturers to the areas with the greatest potential for improvements. The aim of this paper is to lay out a part of an energetic model that describes hydraulic system of a rear-loader RCV, present its constituents and suggest a feasible approach to its implementation in the industry.

2. Components of RCV

Main components of RCV's are: body, ejector plate, tailgate, sweep and slide compactor, lifting device and bin catcher (Figure 1). They are typically driven by a double chamber hydraulic pump. Compactor consists of a carriage plate (1), which is mounted on the rails in the tailgate (2) and the packer plate (3), which is connected via hinges to the carriage plate. Both carriage plate and packer plate are driven by hydraulic cylinders and realise a four stage motion sequence.
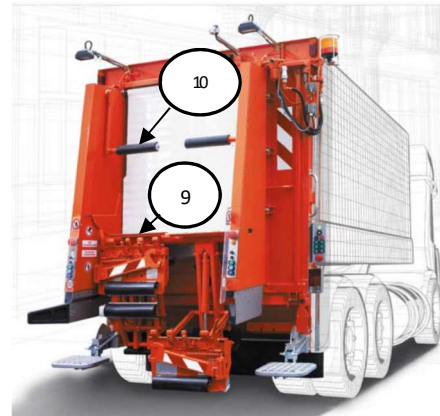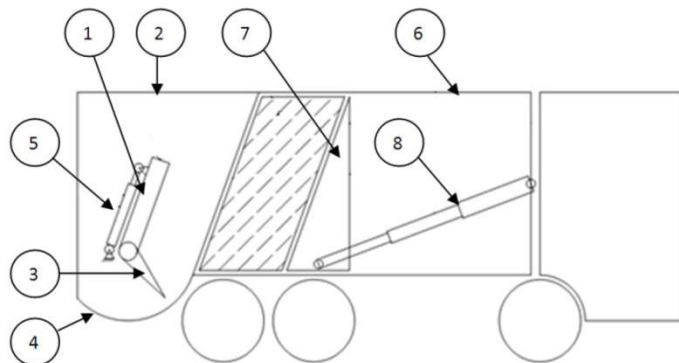
Figure 1. RCV with sweep and slide compactor; 1 - carriage plate, 2 - tailgate, 3 - packer plate, 4 - hopper, 5 - hydraulic cylinder, 6 - body, 7 – ejector plate, 8 - hydraulic telescopic cylinder, 9 - lifter, 10 - bin catcher

3. Compactor's circuit

3.1. Operation of a sweep and slide compaction mechanism

In the beginning of the compaction cycle (Figure 2) the packer plate opens (4-1) and then the carriage plate moves downwards (1-2). Then the packer plate pivots to shovel the garbage out of the hopper (2-3). In the final stage the carriage plate slides upwards compressing the garbage and loading it into the body (3-4). Inside the body an ejector plate is installed. It is driven along the rails by a hydraulic telescopic cylinder (8, Figure 1). When the garbage truck is empty the wall is positioned in its most rear position (telescopic cylinder fully extended). During the loading cycle minimal pressure needed to retract the telescopic cylinder is adjusted by a pressure control valve. This generates an additional reaction force, which increases the compaction force. As more waste is being loaded, the ejector plate slides towards the driver's cab the so the resistance force is provided constantly throughout the entire vehicle's loading cycle. When the tailgate is opened the ejector plate is also used to empty the body.

Figure 2. Operation stages of a compaction mechanism

3.2. Energy consumption components

Energy supplied by the pump to the compactor's circuit consists of:

$$E_{p1} = E_{\Delta p1} + E_{sc} \tag{1}$$

where:

E_{p1}– total hydraulic energy supplied to the compactor's hydraulic circuit (generated in the larger chamber of the pump)

$E_{\Delta p1}$– energy lost due to the pressure drop in the hydraulic system

E_{sc}– hydraulic energy supplied to the compactor's actuators

Hydraulic efficiency at which the power is delivered to the compactor through the hydraulic system can be defined as:

$$\eta_{hc} = \frac{E_{sc}}{E_{p1}} * 100\% \tag{2}$$

and it can be calculated from:

$$E_i = \int Q_i \, p_i \, dt \tag{3}$$

Where:

$i = 1$, SC, etc., depending on calculated value E

Q_1, p_1 – flow rate and pressure measured at the pump's outlet

Q_{sc}, p_{sc} – flow rate and average value of pressure in the actuators

This allows to measure η_{hc} of a RCV equipped with fixed displacement pump using pressure sensors measuring p_1 and p_{sc}. p_{sc} should be measured directly at the actuator's inlet ports but the its value can be approximated through installation of a sensor in another location that is possibly close to both actuators. Q_1 is equal to Q_{sl} and it can be approximated based on the pump's size, PTO's speed (or engine speed) and p_1. In case of a variable displacement pump use of additional measurement apparatus is required.

Hydraulic energy supplied to the compactor's actuators - E_{sc} consists of:

$$E_{sc} = E_{c1} + E_{c2} + E_{c3} + E_{c4} \tag{4}$$

Where:

E_{c1} – energy used to open the packer plate (Figure 2; 4-1)

E_{c2} – energy used to lower the carriage plate(Figure 2, 1-2)

E_{c3} – energy used to close the packer plate (Figure 2, 2-3)

E_{c4} – energy used to lift the carriage plate (Figure 2, 3-4)

E_{c1}, E_{c2}, E_{c3} and E_{c4} could be further separated by subtraction of the energy loss in the compactor mechanism but it is not applicable to a real RCV due to the cost and complication of measurement of the active force in the cylinders using tensometric pins.

Definition of an explicit formula describing the efficiency of the compactor itself (η_c) is problematic due to several reasons. During the compaction process useful work is equal to the portion of energy that contributes to increase of the waste density through deformation. Calculating this value requires separating this portion of energy from energy lost due to friction of waste against the walls, energy used to transport the waste within the body of a RCV and the aforementioned energy loss in the compactor mechanism. One possible practical solution would be definition of the cycle efficiency of the compactor as:

$$\eta_c = \frac{E_{c4}}{E_{sc}} * 100\% \tag{5}$$

Because only during lifting of the carriage plate compaction occurs for the analyzed system (Figure 1) and each of the functions is realized separately in a cycle. However, this value still does not take into account the density of waste before and after compaction. This is why a new performance measure – a Compaction Curve was suggested. This curve presents density of the waste after compaction [kg/m^3] as a function of compaction effort per cubic meter (E_{c4} divided by the volume of the compacted waste) [MJ/m^3].
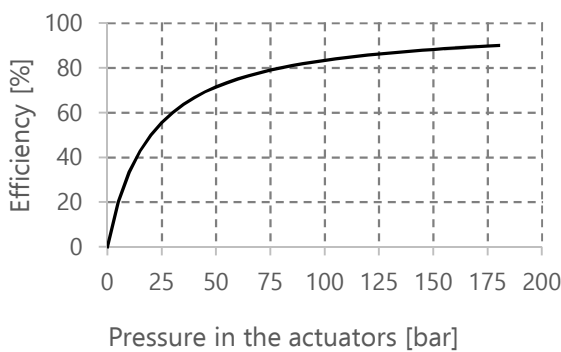
3.3. Efficiency

3.3.1. Hydraulic System

Efficiency of the compactor's hydraulic system can be estimated based on the pressure drop between the pump's outlet and the compactor's actuators inlet. Measurements performed on a single RCV showed a steady pressure drop of approximately 20 bar in the entire range of tested loads. Efficiency of the compactor's circuit (5) as a function of the actuator load is presented on Figure 3.

### 3.3.2. Compactor efficiency and Compaction Curve

So far the compactor efficiency (η_c) has not been investigated, but exploitation data from two RCVs that were equipped with different compactors delivered the results necessary for creation of a compaction curve:

- Sum of E_{c4} from compactor cycles needed to load the body of a RCV
- Volume of waste collected
- Mass of waste collected

Resulting compaction curves are shown on Figure 4. It shows that compactor installed in truck FF0355 is more efficient because it will achieve greater compression ratio (compacted waste density over bulk waste density) for the same energy consumption per cubic meter of compacted waste.

Figure 3. Relationship between efficiency of the compactor's hydraulic system and load
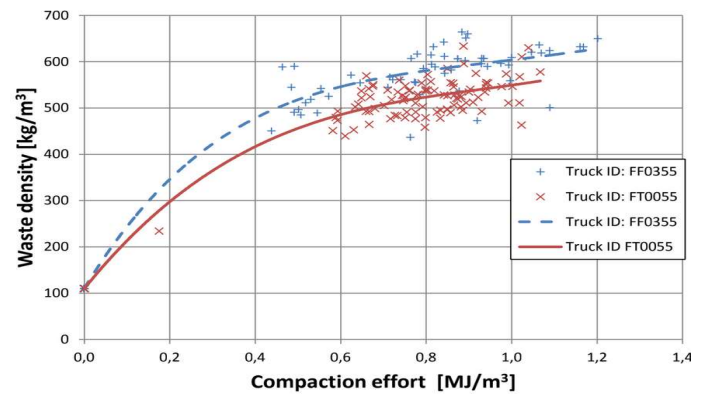

Figure 4. Compaction curves for two different compaction mechanisms

4. Lifter's circuit

4.1. Operation of a lifting device

Lifting devices have to grab a container at its pick-up height and move it along a trajectory that assures that all of the waste is emptied into the hopper. They also have to be equipped with a standard interface for attaching to the containers. Lifter movement is shown in **Figure 1**Figure 5.
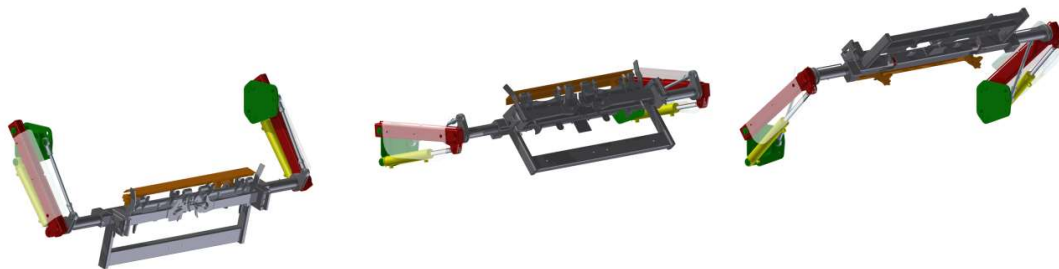
Figure 5. Operation of a lifting device

4.2. Energy consumption components

Hydraulic energy supplied by the pump to the lifter's hydraulic system consists of:

$$E_{p2} = E_{\Delta p2} + E_{sl} \tag{6}$$

Where:

E_{p2}– total hydraulic energy supplied to the lifter's circuit (generated in the smaller chamber of the pump)

$E_{\Delta p2}$– energy lost due to the pressure drop in the system

E_{sl}– hydraulic energy supplied to the lifter's actuators

Hydraulic efficiency at which the power is delivered to the lifting device in the hydraulic system can be defined as:

$$\eta_{hs} = \frac{E_{sl}}{E_{p2}} * 100\% \tag{7}$$

and it can be calculated from equation (3).

This allows to measure η_{hs} of a RCV equipped with double chamber, fixed displacement pump using pressure sensors measuring p_2 and p_{sl}. Q_2 can be approximated based on the pump's size and PTO's speed, whereas Q_{sl} can be calculated based on the actuator's dimensions and cycle time. However, under the assumption that all of the oil in the lifter's circuit is used to drive the actuators, the formula can be simplified to:

$$\eta_{hs} = \frac{p_{sl}}{p_{p2}} * 100\% \tag{8}$$

This assumption is only true for full speed operation in systems with low excess oil flow. In case of a variable displacement pump use of additional measurement apparatus is required.

Hydraulic energy supplied to the lifter's actuators - E_{sl} consists of:

$$E_{sl} = E_{loss} + E_l + E_c + E_w \tag{9}$$

where:

E_{loss}– overall energy loss in the lifting device
E_l– energy used to drive the lifting device
E_c– energy used to move the container along its trajectory
E_w– energy used to move the waste along its trajectory
E_l, E_c and E_w can be obtained through multi body simulation conducted on an exact model of a lifting device loaded with container and waste, operating in a gravity field:

$$E = \sum_{i=1}^{n} (F_i + F_{i-1}) * \frac{x_i - x_{i-1}}{2} \tag{10}$$

where:

F– driving force
x – position of a linear actuator
Energy loss consists of:

$$E_{loss} = E_a + E_{fr} + E_e \tag{11}$$

E_a– energy lost in the actuators
E_{fr} – energy lost due to friction in the joints
E_e– excess energy required to assure continuous, smooth operation at the desired speed

Measurement of the exact values of E_a, E_{fr} has limited application during real operation of a RCV because it requires a complex measuring apparatus. Determination of E_a requires installing expensive tensometric pins in the actuators or carrying out comprehensive tests on test benches. Magnitude of E_{fr} can be estimated by including friction in the joints in the multi body simulation but the results can be misleading because most of the lifting devices are over-constrained and increase of values of the reaction forces can occur due to manufacturing inaccuracies.

Component E_e is only present, when the oil flow in the lifter's circuit would make its movement faster than it is allowed by the safety regulations. In such case, excess flow has to be returned to the tank at the lifter's operation pressure.

Evaluation of the efficiency of the lifting mechanism depends on the definition of the useful work. The aim of the emptying process is to deliver the waste to the hopper (a cavity in RCV's tailgate where

the waste is stored before compaction) which means, that a theoretical efficiency (η_{th}) of a lifting mechanism can be described as:

$$\eta_{th} = \frac{E_w}{E_{sl}} * 100\% \tag{12}$$

However, since none of the commonly used solutions empties the containers without lifting them, real efficiency (η_r) of the lifting mechanism should also be considered:

$$\eta_r = \frac{E_c + E_w}{E_{sl}} * 100\% \tag{13}$$

4.3. Efficiency

4.3.1. Hydraulic System

Efficiency of the hydraulic system (δ) can be estimated based on the pressure drop between the pump's outlet and the lifter's actuator. Measurements performed on a single RCV showed a steady pressure drop of approximately 50 bar in the entire range of tested loads (Figure 6) [11].
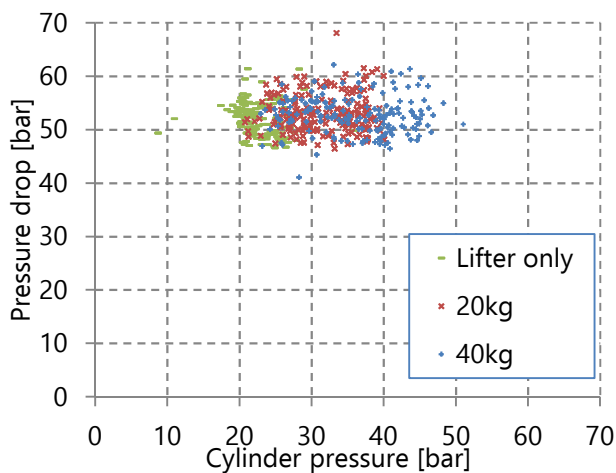
Figure 6. Pressure drop in the hydraulic system of SK350 lifter [11]
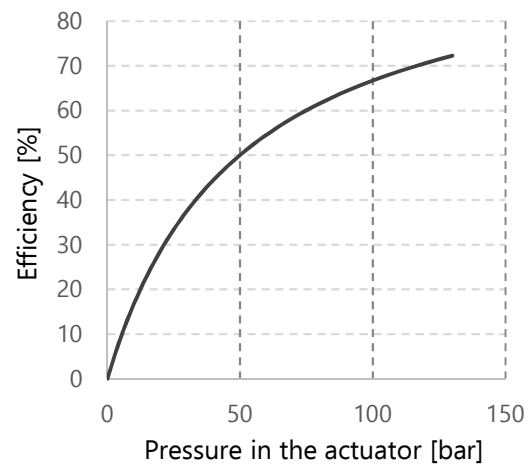
Figure 7. Relationship between efficiency (7) of the SK350 lifter hydraulic system and load

An approximated relationship between hydraulic cylinder load and efficiency of the hydraulic system resulting from this pressure drop is presented on Figure 7.

4.3.2. Lifting Device

Since the operation of the lifting device depends on numerous factors such as:
- type of the lifting device
- type of waste container
- mass of waste
- centre of gravity of waste

analysis was carried out for the following cases:
- two lifter types: SK350 and DELTA (**Figure 8**)
- two frequently used containers compliant with EN 840: 240L and 1100L with a flat lid)
- centre of gravity of waste located in 1/3 of the container's height
- four fractions of the solid waste: plastic, dry, mixed, glass
- mass of waste used in the simulation equal to mean, median, 1st and 3rd percentile of each fraction (

- Operation of both lifting devices for all of the described cases was carried out to obtain the theoretical energy consumption of a lifter operating without friction and resistance forces. The simulations were then adjusted according to internal simulation guidelines to determine the real energy consumption by including friction in the joints and resistance force of the actuators. Procedure that leads to accurate simulation of real operation of SK350 and DELTA lifters is described in detail in another study [11].

Figure 11 shows the real energy consumption of both lifting devices. Energy consumption of DELTA lifter is significantly higher than SK350 lifter, due to its higher mass.

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Selected lifter and container types are very popular what makes them an interesting target for this study. Position of centre of gravity of waste was selected arbitrarily due to lack of statistical data. Waste was simulated as a solid block with a constant cross-section and uniform density and height equal to 2/3 of the container's height. Selection of this value has significant influence on results, what is shown on **Figure 9Figure 1**, which shows relationship between location of the centre of gravity of waste and energy required to lift the 240L filled with 96 kg of waste (with and without bin).

The mass values are based on a statistical analysis of data from a RCV equipped with RFID containers identification and lifter with a weighing system. Result of this analysis are presented in Table 1 and on Figure 10. It should be noticed that the mass of waste is significantly lower than the maximal load for both of the considered bins. The difference is especially visible for plastic and dry waste.
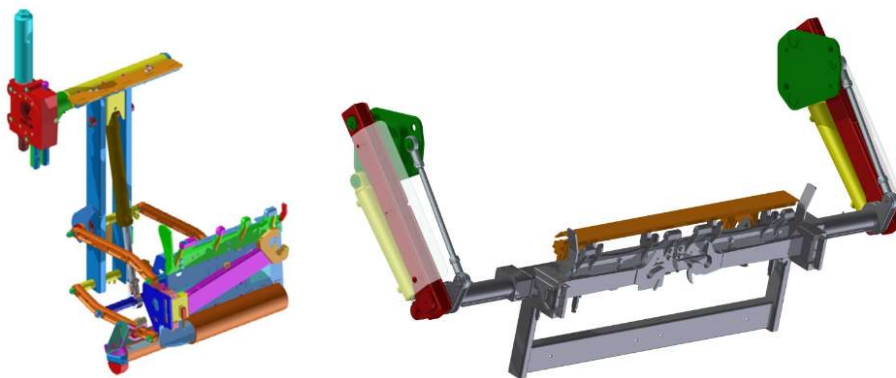

Figure 8. DELTA lifter (left, one of two independent units); SK350 lifter (right)

Table 1. Masses of waste used in the simulation

|	Fraction	Samples	Bin mass [kg]	Max load [kg]	Weight [kg]			
					Mean	1st quartile	median	3rd quartile
240L	Plastic	37			7,3	4	6	10
	Dry	1541	14,4	96	13,4	6	10	18
	Mixed	5436			23,2	15	21	28
	Glass	1497			30,9	18	28	42
1100L	Plastic	273			25,7	15	25	35
	Dry	13972	56	440	43,9	20	35	55
	Mixed	57500			79,2	45	70	100
	Glass	573			117	55	90	160
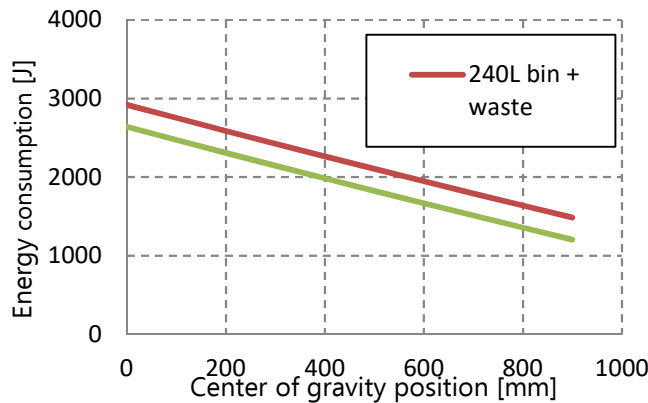
Figure 9. Relationship between energy consumption and height of the centre of gravity of waste
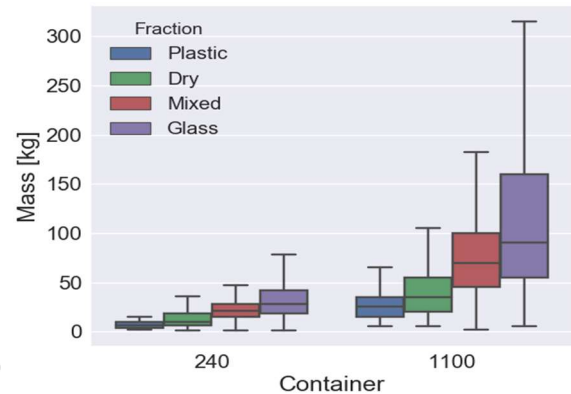
Figure 10. Mass of waste depending on the fraction and container type

Operation of both lifting devices for all of the described cases was carried out to obtain the theoretical energy consumption of a lifter operating without friction and resistance forces. The simulations were then adjusted according to internal simulation guidelines to determine the real energy consumption by including friction in the joints and resistance force of the actuators. Procedure that leads to accurate simulation of real operation of SK350 and DELTA lifters is described in detail in another study [11].

Figure 11 shows the real energy consumption of both lifting devices. Energy consumption of DELTA lifter is significantly higher than SK350 lifter, due to its higher mass.
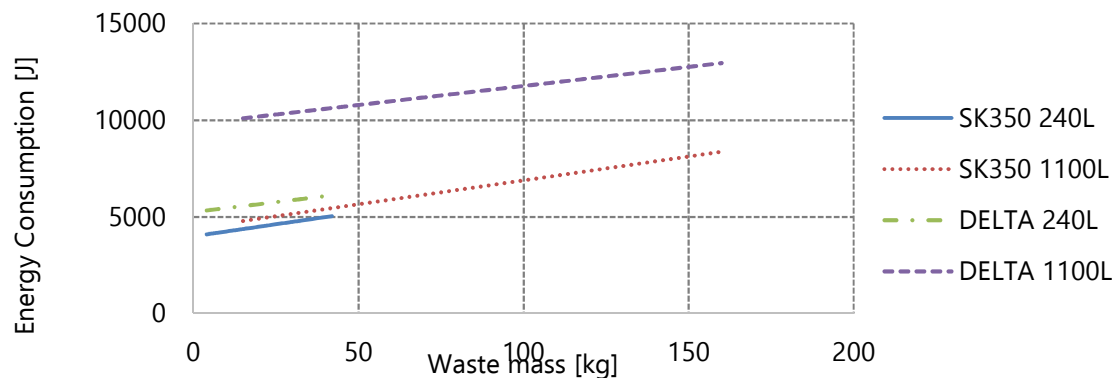

**Figure 11.** Total energy consumption of SK350 and DELTA lifting devices

Figure 12 shows relationship between theoretical (η_{th}) and real (η_r) efficiency of SK350 and DELTA lifting devices. Since the energy required to lift the components of the mechanism is constant the efficiency increases with the mass of waste. Significant difference between theoretical and real efficiency shows that for the tested mass range energy required to lift the waste container is a significant component of the total energy consumption. Moreover, large disproportion between maximal load of the containers and the real load, especially for plastic and dry waste shows that both containers and lifting devices are over-dimensioned for the performed task. This results in a relatively low efficiency, compared to operation with maximal load.

Figure 13 shows theoretical efficiency of the tested lifters for the characteristic masses of waste. Application of specialized lifting devices and containers optimized for lighter fractions of waste could significantly increase efficiency of the process.
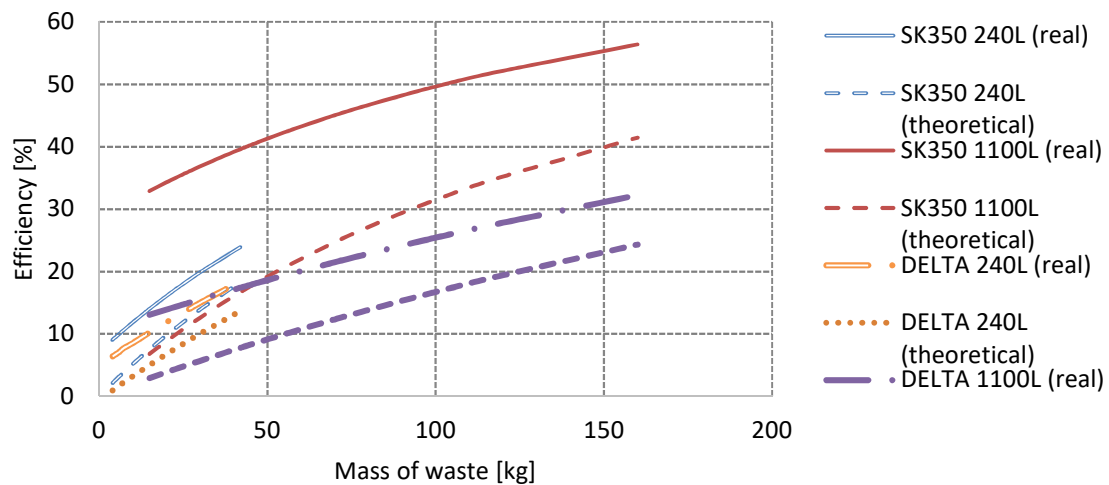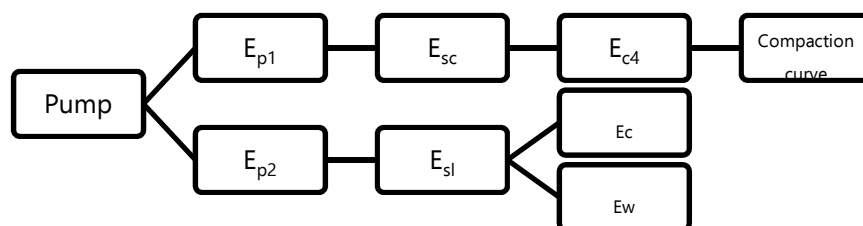
Figure 12. Relationship between real and theoretical efficiencies of SK350 and DELTA lifters and mass of waste
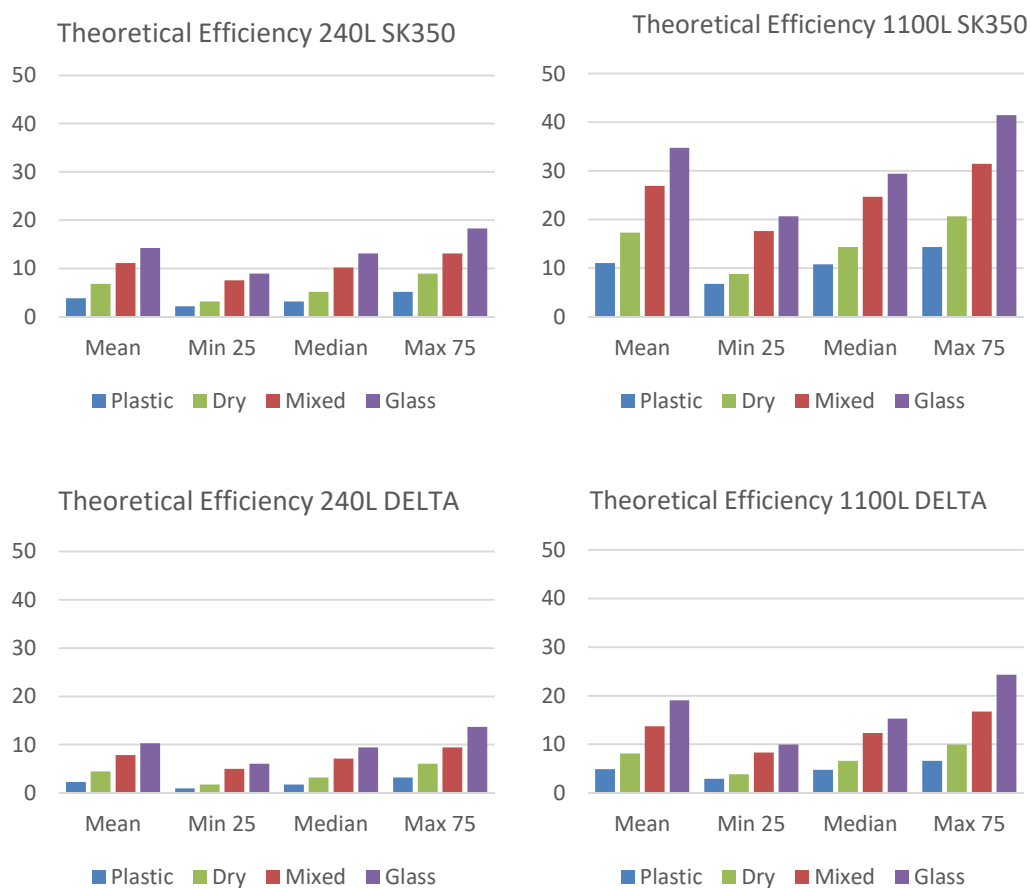
Figure 13. Theoretical efficiency of SK350 and DELTA lifters for characteristic masses of waste

Summary

Figure 14. Energetic model of the hydraulic system of a RCV

Figure 14 lays out the energetic model of the hydraulic system of a refuse collection vehicle. Energy consumption at each stage of the process can be calculated based on values that are possible to measure without disrupting RCV's daily operation. Then it is also possible to determine the energy losses even if they cannot be measured explicitly. Analysis of efficiency of energy transfer between its constituents can indicate the components with the highest potential for improvements and enables to compare various existing solutions.

Results of the presented analysis already shows that waste segregation introduced substantial differences between specific weights of various types of waste and it might be beneficial to optimize the performance (and consequently mass) of lifting devices and containers for specific fractions.

In the future presented energetic model of the hydraulic system of a RCV could be further developed by adding the relationship between pump and combustion engine. This comprehensive model should by then tested by applying it to several different RCV's to model their operation and compare fuel consumption in various conditions. Future studies could also focus on verification of durability requirements of waste containers and lifting devices that take waste segregation into account and verify applicability of fraction specific approach in waste collection.

Acknowledgements

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