AN INNOVATIVE, ECOLOGICAL SYSTEM FOR IN-HOUSE RECYCLING OF MUNICIPAL SOLID WASTE (PAPER, PLASTIC AND METAL PACKAGING WASTE)

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1. Introduction

According to the targets set by the Waste Framework Directive (2008/98/EC) and national legislation, source separation of Municipal Solid Waste (MSW) must be set up by 2015. More particularly, subject to Article 27 of the Law 4042/20121, by 2015 separate collection shall be set up for at least the following: paper, metal, plastic and glass. Separate collection of Municipal Solid Waste is not only a target set by the Waste Framework Directive (2008/98/EC), but also a need increasingly considered when addressing resource efficiency issues. The European policies recognize that, for reducing our dependence on raw material imports as well as for minimizing the environmental impact related to waste management and material use, it is of paramount importance to develop new technologies that aim at better waste sorting and separation at source.

The Recycling@Home prototype unit that is described within this work, aims at separating six (6) different waste channels, so as to achieve high purity end-products at the point of waste generation, that is at household level. More particularly, the pilot unit can receive and treat the following waste streams:

(a) Ferrous containers (e.g. tin cans);

(b) Aluminium cans;

(c) High Density Polyethylene containers (e.g. detergent bottles);

(d) Polyethylene containers (e.g. plastic water bottles);

(e) Drink cardboard boxes (e.g. milk containers) and

(f) high quality paper.

The methodology followed for designing the prototype Recycling@Home unit, involved simulation of the compression process of selected waste streams, experimental validation of the results and sensitivity analysis for predicting the operating performance of the unit in terms of energy and compressive load requirements are also presented. What is more, the sensitivity analysis plots were used for determining the characteristics (e.g. waste channels volume, compressive load requirements of the compression piston etc.) of the prototype system and for the final design of the system.

2. Methodology

The design stage involved the following steps: (a) Determination of the main components; (b) Development of a simulation tool for the compression of specific packaging waste; (c) Sensitivity analysis for predicting the performance of the pilot system and thus minimize discrepancies between the design stage estimates and actual performance; (d) Experimental validation of the simulation results; and (e) Final design of the prototype Recycling@Home system.

3. Numerical modelling

In order to model the axial compression and the collapse of the waste items, numerical modeling based on Finite Element Method (FEM) was employed. The Finite Element Method is a method used to solve engineering problems through numerical analysis. The process relies on the use of fundamental equations related to material behavior and established mathematical approaches to iteratively solving the equations to determine state variables such as stress, strain, strain rate and temperature related to a given deformation problem. Decreasing costs associated with computer hardware and the increased availability of software and increasing costs associated with (repeated) experimental works/procedures are driving forces for use of FEM in industrial practice. The role of FEM in the manufacturing process for both design and process and product optimization has been increasingly important, while proper use of FEM can result in lower turnaround times from design to product. Commercial and in-house/selfprogrammed versions of FEM code are used to solve a large number of engineering related problems.

The explicit FE Code LS-DYNA was used to simulate the collapse mechanism.

4. Experimental set-up

Thin-walled aluminium, tin-plate, PET, HDPE and TETRAPAK bottles/cans were axially compressed between two parallel steel platens in a fully automated INSTRON 4482 Universal Testing Machine of 100 kN loading capacity (see also Figure 1), in “dry” boundary conditions. The top end (or bottleneck) was always placed in contact with the upper moving platen, while the lower end was always placed in contact with the down stationary platen.

Figure 1:: Experimental equipment/set-up, laboratory of Manufacturing Technology, School of Mechanical Engineering, National Technical University of Athens

Typical household waste synthesis used

For conducting the sensitivity analyses a typical 4-member family was considered. According to the most recent data provided by Eurostat (**code**: tsdpc240), in Greece each person generates around 496kg of municipal solid waste per year which corresponds to 1.36 kg/capita/day (2011 data). Thus, a 4-member family would generate approximately 5.43 kg of household waste per day.

These figures were used for assuming the packaging waste that is generated daily in a typical household. For translating the mass quantity into waste items the following typical packaging waste were used (see also Figure 2 and Table 1).

Figure 2: Recyclable household waste (bottles/cans) simulated and tested

Table 1: Dimensions and weigh of typical packaging waste used for the design study

Packaging Waste	Maximum external dimensions [mm]			Wall thickness, t [mm]	Volume, V [lt]	Weight (g)
	Height, H (mm)	Length, L (mm)	Width, W (mm)			
Aluminium can	115.4	Ø 66.1	Ø 66.1	0.10 ÷ 1.16	0.33	12.4
HDPE bottle	261.2	Ø 74.5	Ø 74.5	0.43 ÷ 3.45	0.75	43
PET bottle	210	Ø 65.3	Ø 65.3	0.14 ÷ 1.5	0.5	13.5
Drink Cardboard bottle	244.1	65	60	0.6 ÷ 4.2	1	38
Tin-plate can	109	Ø 73.3	Ø 73.3	0.17 ÷ 1.15	0.4	41.9

According to the typical household waste presented in the table above, it can be assumed the following household waste profile for one day (see also Figure 3):

Table 2: Typical household waste synthesis (4-member family)

Packaging Waste	Number of waste items produced daily
Aluminium can	3
HDPE bottle	4
PET bottle	16
TETRAPAK can	11
Tin-plate can	4
Total	38 items

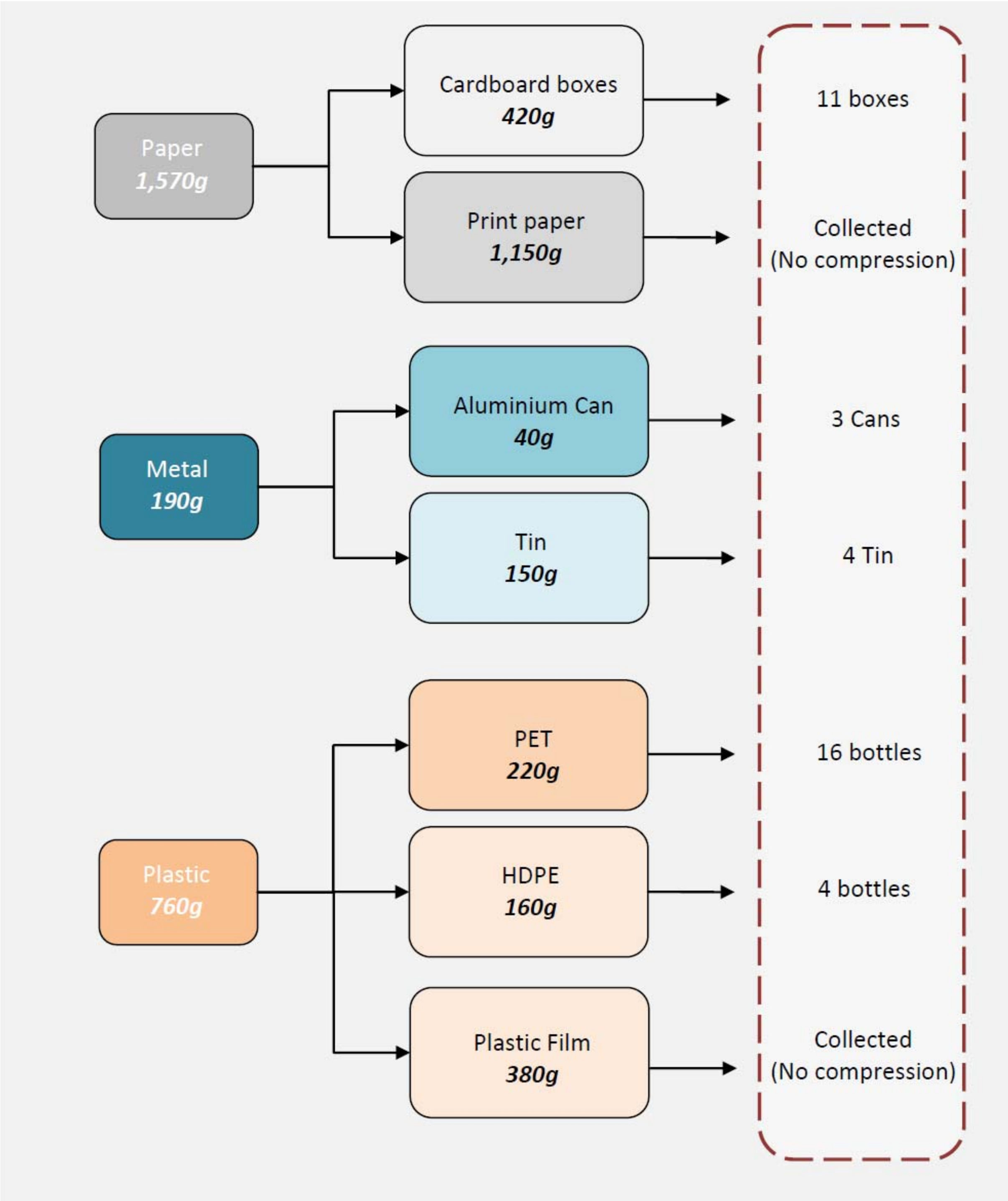

Figure 3: Typical packaging waste generated by a typical household

5. Experimental results

The experimental results are given in the following figures, as follows:

- Figure 4: Experimental terminal views of tin-plate can axial collapse: isometric view (upper left), side view (upper right), bottom view (bottom left) and top view (bottom right)
- Figure 5: FEM analysis and experimental progressive views of tin-plate can axial collapse
- Figure 6 Experimental terminal views of aluminium can axial collapse: side views (top figures), top view (bottom left) and bottom view (bottom right)
- Figure 7 FEM analysis progressive views of aluminium can axial collapse
- Figure :8 Experimental terminal views of HDPE bottle axial collapse (1-4: side views, 5: top view, 6: bottom view)
- Figure 9 FEM Analysis and Experimental progressive views of HDPE bottle axial collapse
- Figure 10 Experimental terminal views of PET bottle axial collapse (1-2: side views, 3: top view, 4: bottom view)
- Figure 11 FEM Analysis and experimental progressive views of PET bottle axial collapse
- Figure 12: Experimental terminal views of TETRAPAK can axial collapse (1-4: side views, 5: top view, 6: bottom view)
- Figure 13 FEM Analysis and experimental progressive views of drink cardboard box axial collapse

Figure 4: Experimental terminal views of tin-plate can axial collapse: isometric view (upper left), side view (upper right), bottom view (bottom left) and top view (bottom right)

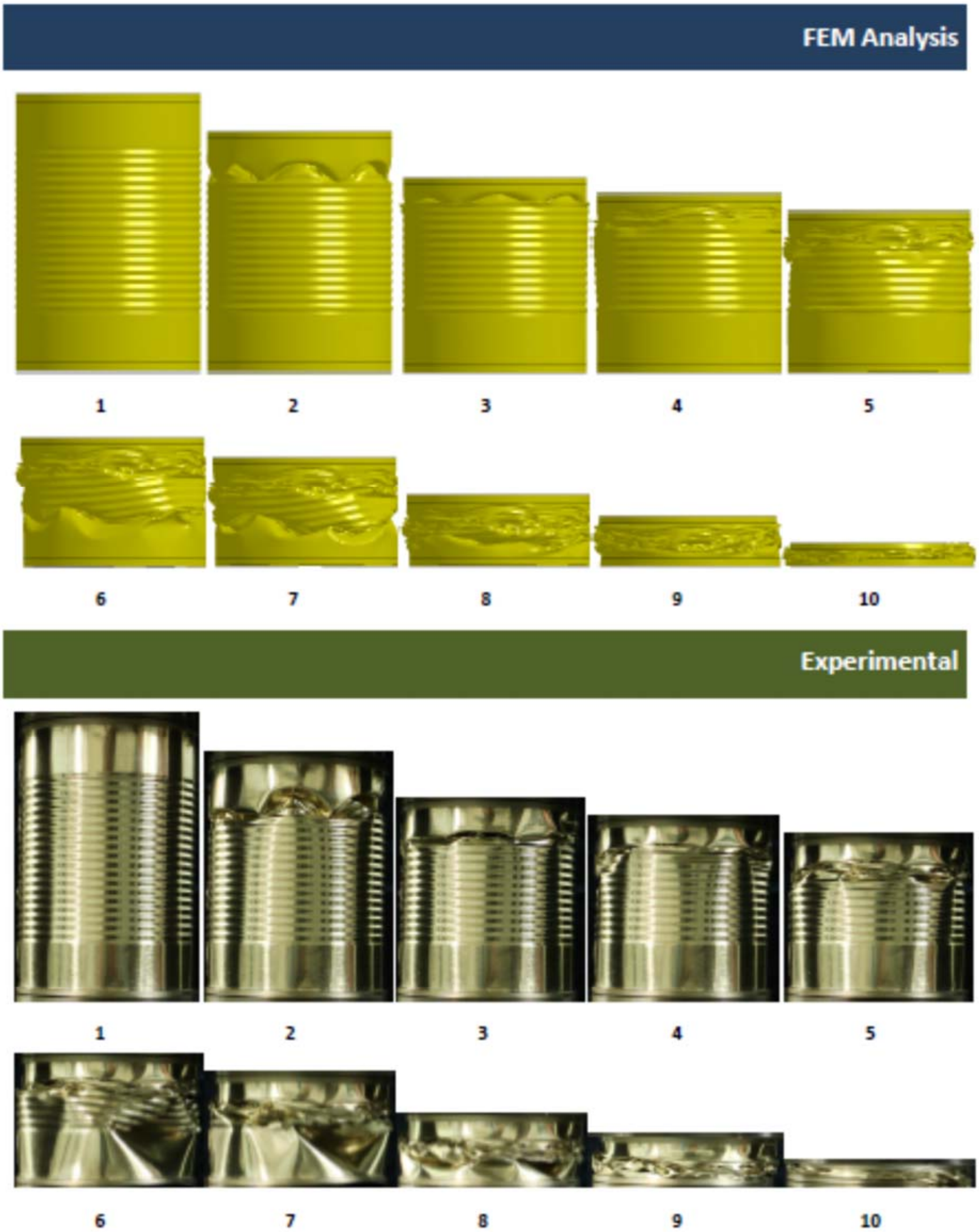

Figure 5: FEM analysis and experimental progressive views of tin-plate can axial collapse

Figure 6 Experimental terminal views of aluminium can axial collapse: side views (top figures), top view (bottom left) and bottom view (bottom right)

Figure 7 FEM analysis progressive views of aluminium can axial collapse

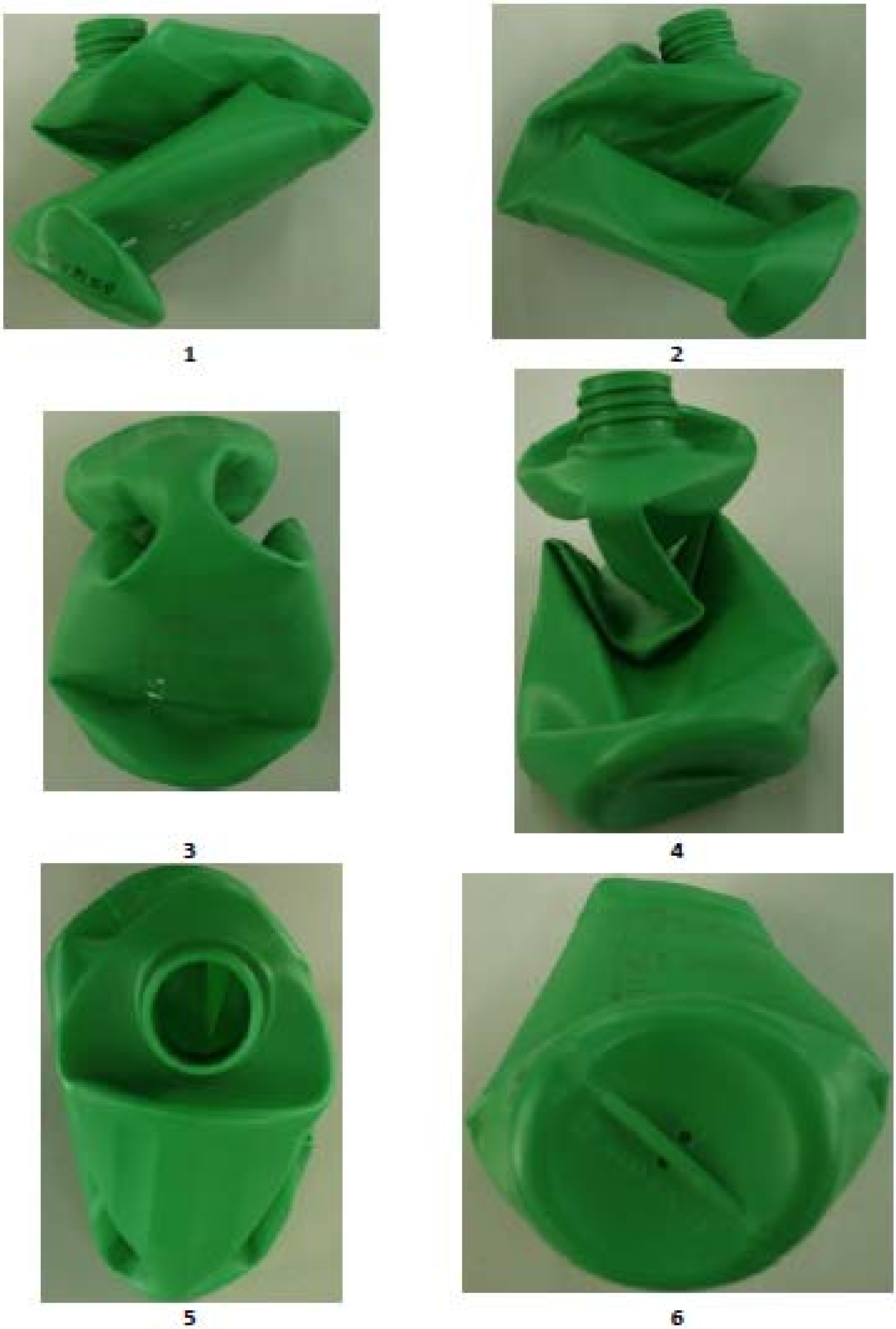

Figure :8 Experimental terminal views of HDPE bottle axial collapse (1-4: side views, 5: top view, 6: bottom view)

Figure 9 FEM Analysis and Experimental progressive views of HDPE bottle axial collapse

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Figure 10 Experimental terminal views of PET bottle axial collapse (1-2: side views, 3: top view, 4: bottom view)

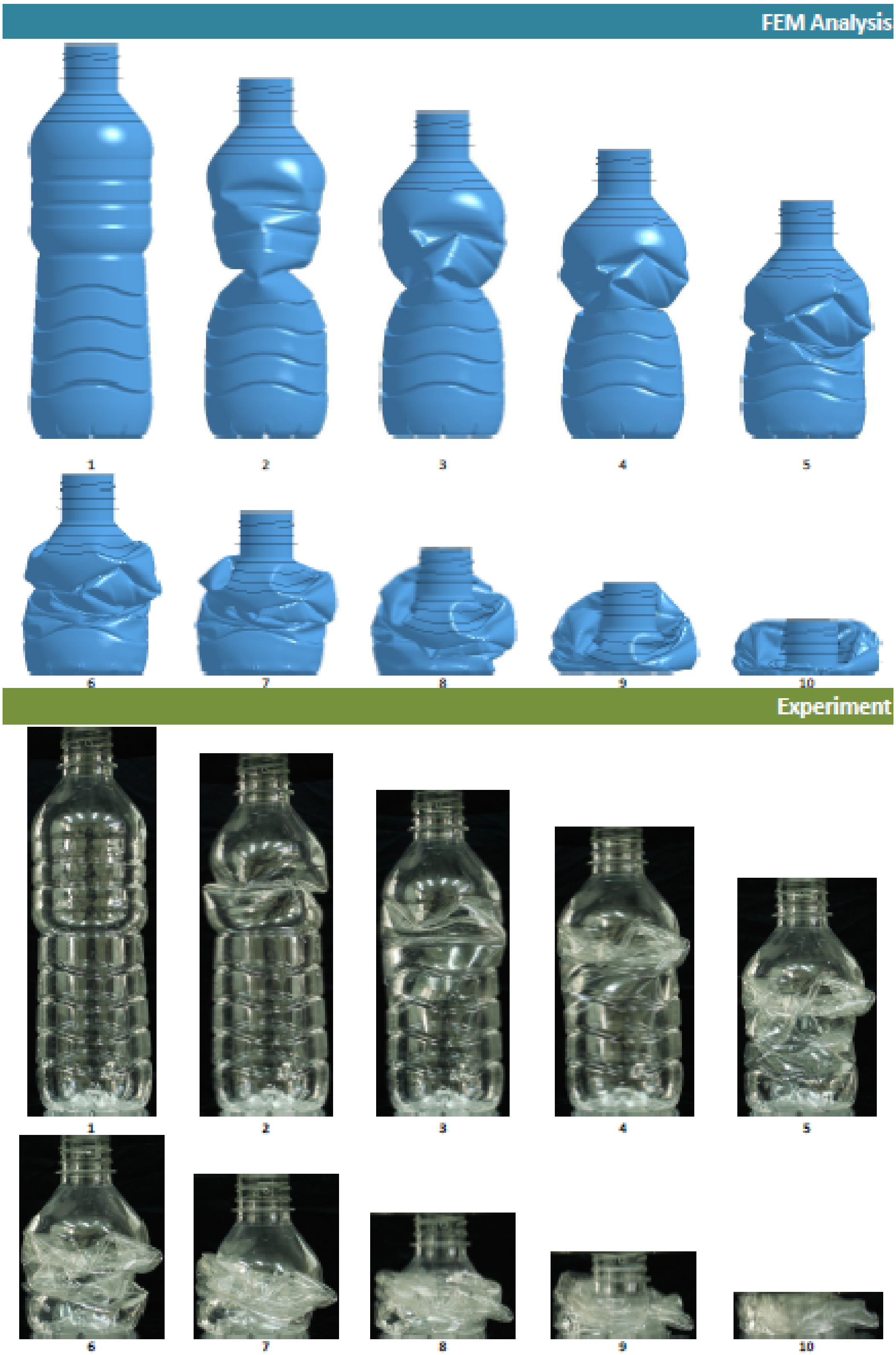

Figure 11 FEM Analysis and experimental progressive views of PET bottle axial collapse

Figure 12: Experimental terminal views of TETRAPAK can axial collapse (1-4: side views, 5: top view, 6: bottom view)

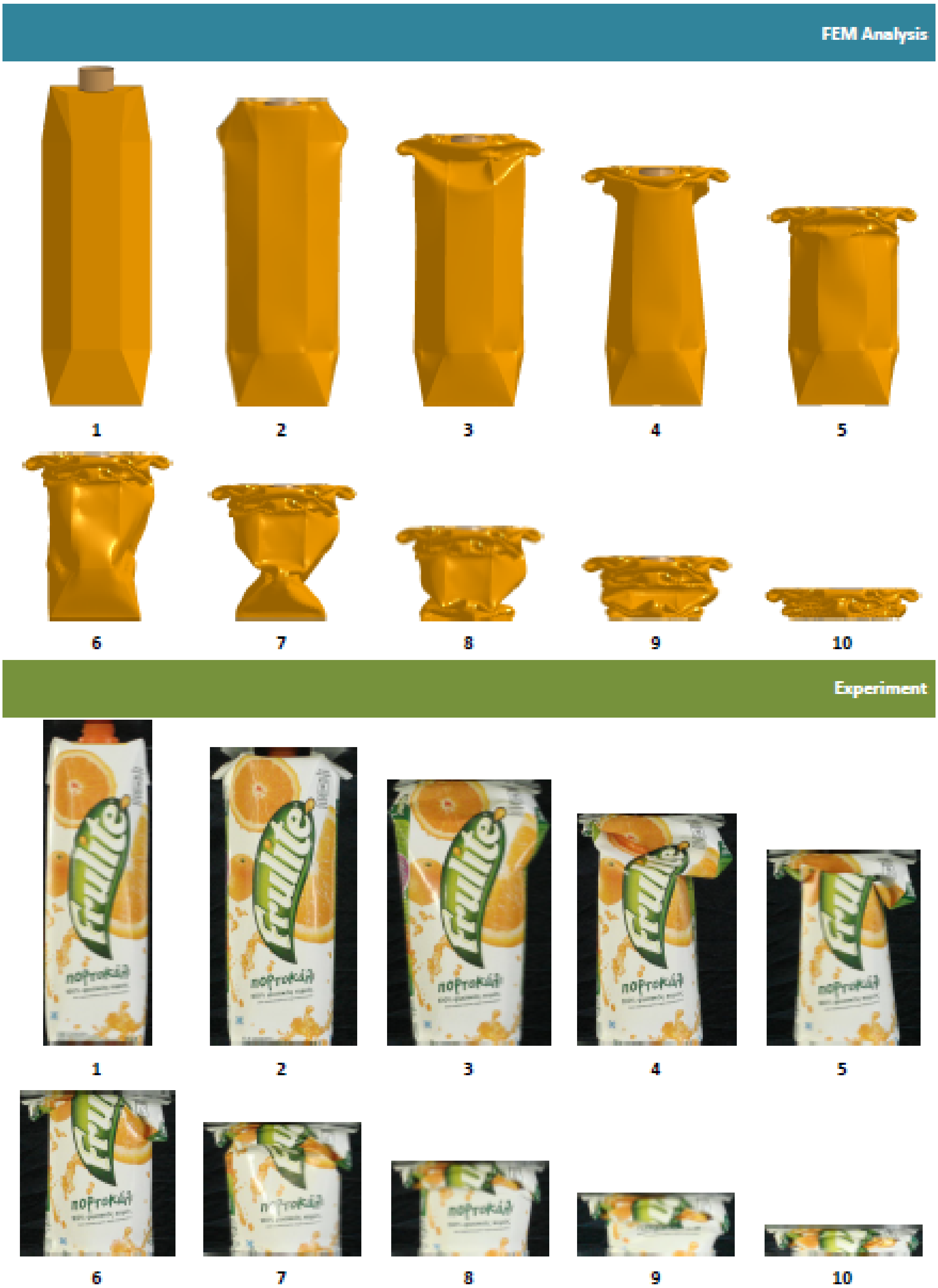

Figure 13 FEM Analysis and experimental progressive views of drink cardboard box axial collapse

Table 3: Total energy requirements of the prototype system (daily basis)

Item	Number	Compression ratio	Compressive Load (kg)	Energy per item (J)	Total energy (Wh)
Tin can	4	12	2,400	368.5	0.4Wh
Aluminium can	3	22	900	84.37	0.07Wh
HDPE bottle	4	8.4	100	54.91	0.06Wh
PET bottle	16	7.55	130	17.52	0.08Wh
Tetrapak	11	17.4	422	97.42	0.3 Wh
				Total	0.91 Wh

The compression ratio presented in the table is given by the following formula:

$$Compression\ Ratio = \frac{h}{h - x}$$

In the following figure the example of aluminium can is given on how the compression ratio is used within this work.

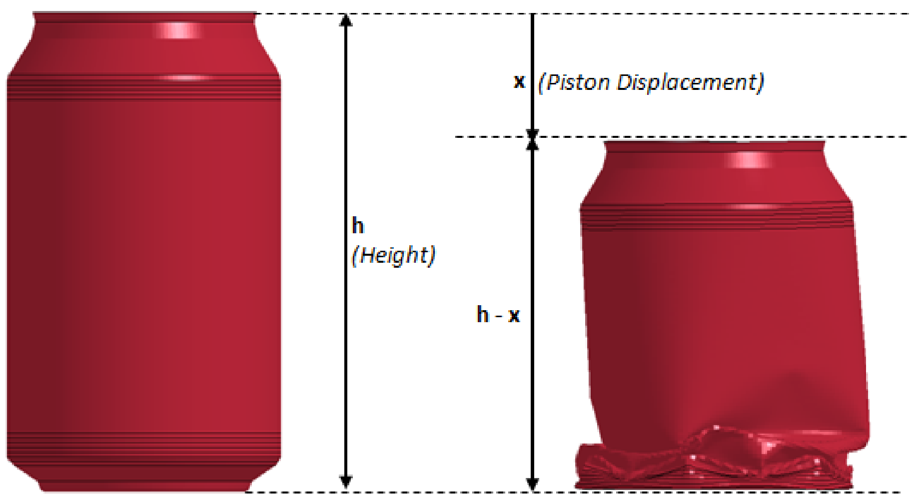

Figure 14: Compression ratio and piston displacement, example of aluminium can

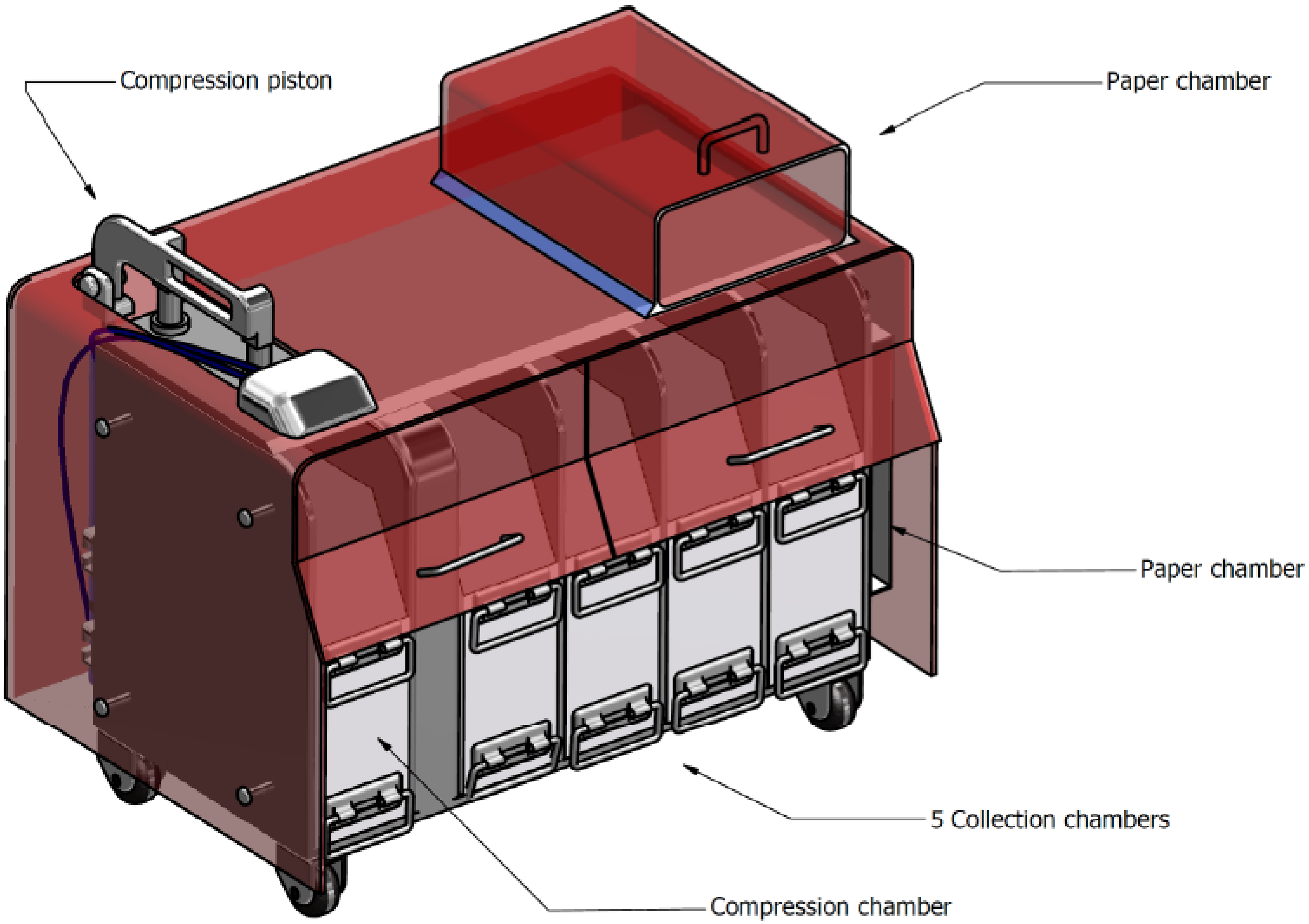

Figure 15: Engineering drawing of the prototype system