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A novel design on polymeric material recycling technology

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ABSTRACT. The necessity for recycling of wastes has increased nowadays and there are various solutions according to the types of wastes which are presented accordingly. By observing these solutions, the recycling system from the waste collection and separation system of the long-term disappearing of polymer waste to the additive manufacturing design stage has been indicated. Waste collection and separation systems have been reviewed and systems to be used effectively in the systematic way have been exemplified. Among four different separating systems which are with rotating, rail and fixed containers, fixed container four-sorting waste separation systems were chosen and developed as a mechatronic system design. The mechatronic system design is very prominent in order to create efficient and economical mechanisms in fixed-container four-sorting waste separation collection system (FCWS) applications. In addition, physical mechatronic system design (MSD), mechanical design, material selection, electrical electronic design sub-heading and cost analysis were made. In this study, the necessity and importance of the waste separation plants are revealed.

Keywords: Mechatronic system design; recycling; waste separation; polymer.

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Introduction

The widespread cost effective polymeric materials of the additive manufacturing technology (Zander, 2019) are becoming one of the major source of the novel functional waste recycling system designs (Sanchez, Boudaoud, Camargo, & Pearce, 2020). Excessive amount of waste causes the greenhouse effect to increase with the formation of some gases and causes global warming. Since the waste are environmentally dangerous than ever, the waste collection is required. The main measures such as the separation of wastes are imperative in order to prevent this situation from becoming worse. Thus, the waste management concept has been developed by many administrations (Taherzadeh, Bolton, Wong, & Pandey, 2019). Waste management is defined as the collection, transportation, processing, recovery, disposal, and inspection activities of the wastes to minimize environmental pollution (Kayakutlu, Daim, Kunt, Altay, & Suharto, 2017). These types of wastes are collected in factories and their recycling processes are completed via separated operations (Al-Salem, Lettieri, & Baeyens, 2009).

Wide variety of undesired waste polymers can be made useful via recycling systems (Maris et al., 2018). Rather than treating waste materials, their potential use and industrial applications (Dilibal, Sahin, & Celik, 2018) through waste-energy technologies can be considered (Yi, Jang, & An, 2018). Raw material recycling, which covers a range of technologies that can be multi-layered and composite plastics (Eriksen & Astrup, 2019), low-quality, poorly separated plastic piles, and attractive recovery solutions for food and soil-contaminated plastic wastes, aims to turn these plastics and some other materials into basic chemicals (Diaz, Golueke, Savage, & Eggerth, 2020). These products are also used as raw materials for various sub-processes or for fuel production (Garforth, Ali, Hernández-Martínez, & Akah, 2004). Although raw material recycling is one of the most difficult methods for recycling plastics, various technologies have been successfully exhibited and continue to be developed for this purpose (Kaminsky, Predel, & Sadiki, 2004).

The amount of waste generated per person is increased globally (Jouhara et al., 2017). The high concentration of metal in new wastes, the source of waste and the continuity of new scrap formation are among the advantages of new wastes (Zhang, Ding, Liu, & Chang, 2017). Recycled paper is an integral part of paper production, and an increase of 20% is expected in Europe for recycling in the coming years (Pivnenko, Eriksson, & Astrup, 2015). Recycled paper, an important global trade product, is used by volume as the most important raw material for the paper and cardboard industry (Ervasti, Miranda, & Kauranen, 2016). Energy efficiency of buildings (Kim & Yu, 2018) and recycling in office environments (Price & Pitt, 2012) are research areas in the field of indoor and built environment.

The recycling of recyclable wastes with other wastes and collecting them in the waste collection sites makes it difficult to separate from each other. It is necessary to undergo various technological processes for this separation process. This leads to an inability to obtain high quality recycled materials, often due to the increased cost of non-clean waste. As the sorting and separation are the most vital steps in recycling, managing better separation at source has become an important task (Idumah & Nwuzor, 2019). This reveals the need to separate waste at the source. The separation of the waste at the source is not widely used. Thus, a technological waste separation system is required. Waste collection and sorting systems can be classified into four different systems based on the number of sorter in the literature. These are one-sorter, two-sorter, three-sorter, and four-sorter. One-sorter, two-sorter, and three-sorter systems are shown in Figure 1.

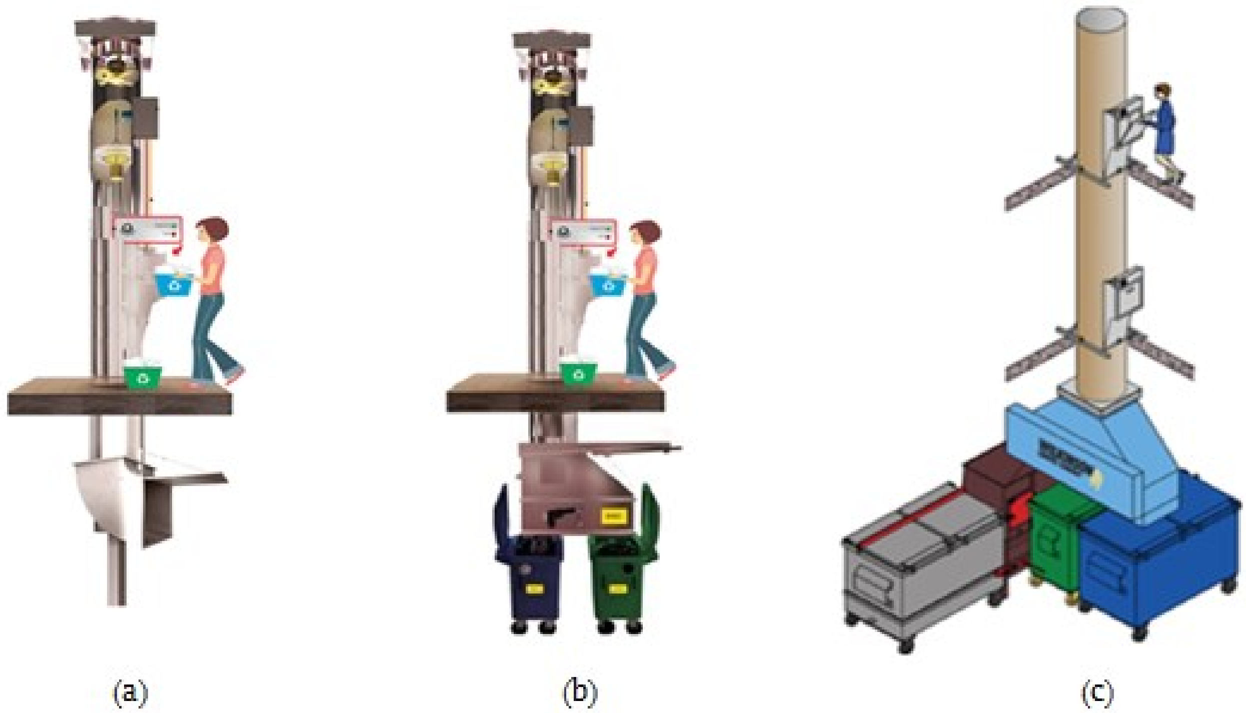


Figure 1. Types of waste collection and sorting system with a) one-sorter b) two-sorter c) three-sorter (Waste Conveyance System, 2018).

Due to the smaller space requirement, the waste collection system with a sorter is the simplest system. The wastes thrown from the shot cover are collected in a container. It is an ideal system for a single type of waste, but in practice it is seen that it is less efficient than other systems since more than one type of waste is disposed within the system.

Different than the one sorting waste collection and sorting systems, two different types of waste are to be disposed in the two sorting waste collection and sorting systems. However, the three sorting waste separation system is more convenient than the one and two-sorter systems. Hardall International Limited and Wilkinson Chutes, one of the leading companies in the sector, developed three sorting and waste sorting systems on the market. Wastes in this system are paper/cardboard, general garbage and plastic/tin cans (Waste Generation Statistics, 2018).

In this study, a novel waste collection-separation systems is designed to separate waste at the source. Considering the longtime of dissemination especially in nature, the sample of polymer waste collected separately in the source has been discussed. These steps are explained in the flow chart shown in Figure 2 and the developed mechatronic system shown in Figure 3. Additionally, the model-scale prototype design of this mechatronic system was made possible to test the operability of the system.

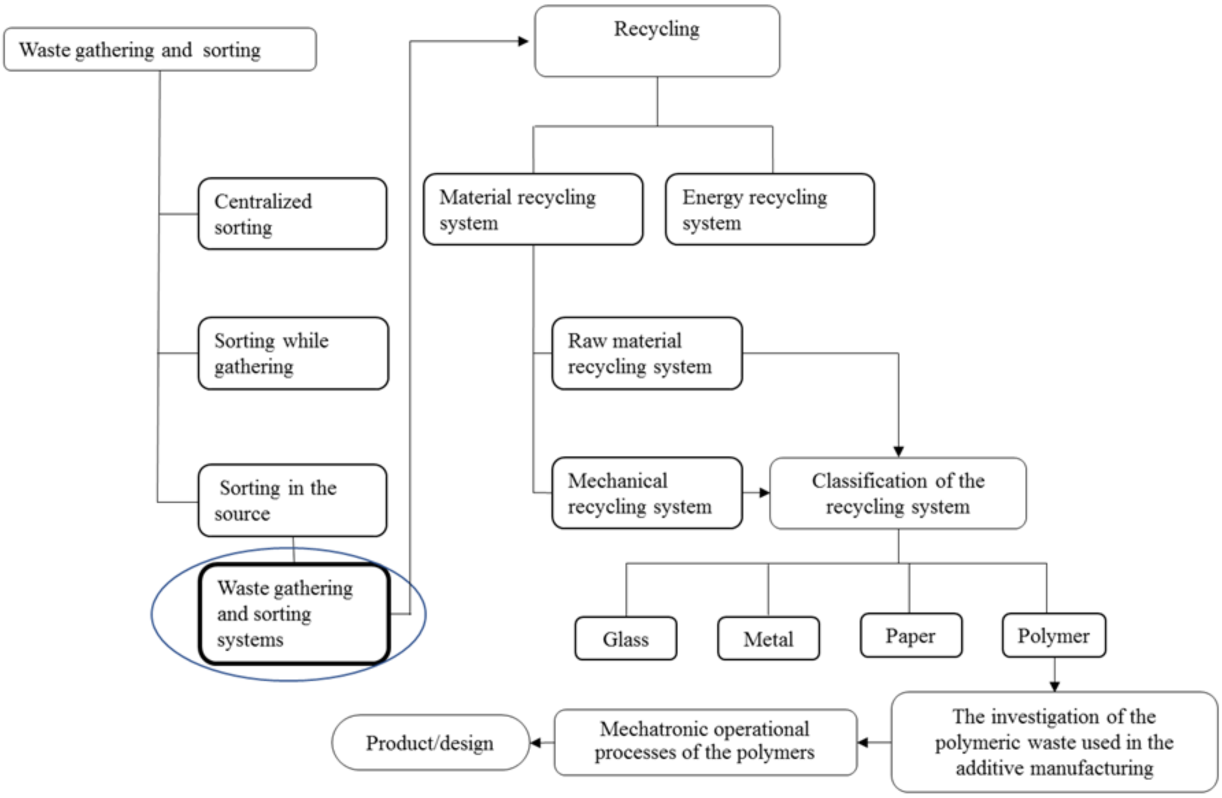


Figure 2. Recycling system flow chart.

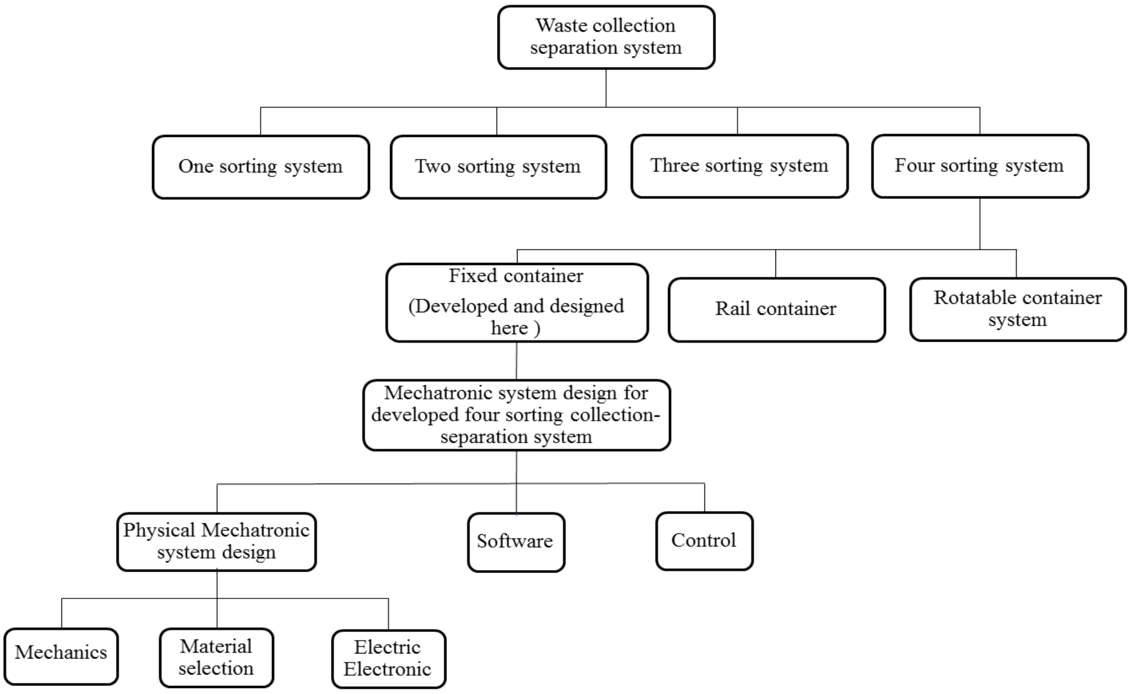


Figure 3. Developed mechatronic system for waste collection and sorting system.

Material and methods

A fixed-container four-sorting waste separation collection system (FCWS) was designed and developed after examining the waste separation systems in use. A model scale prototype design of FCWS was made by unveiling the mechatronic system design (MSD), physical MSD, software and control sub-sections. Sensors, actuators, and PLC control system were implemented for the automation of the model-scale waste collection and sorting system prototype.

The design of the mechatronic system is developed by considering the method of collecting recyclable wastes at the center. The design of mechatronic system is obtained using the standard V Diagram in Figure 4. The physical mechatronics system, software and control sections are configured systematically as shown in Figure 5.

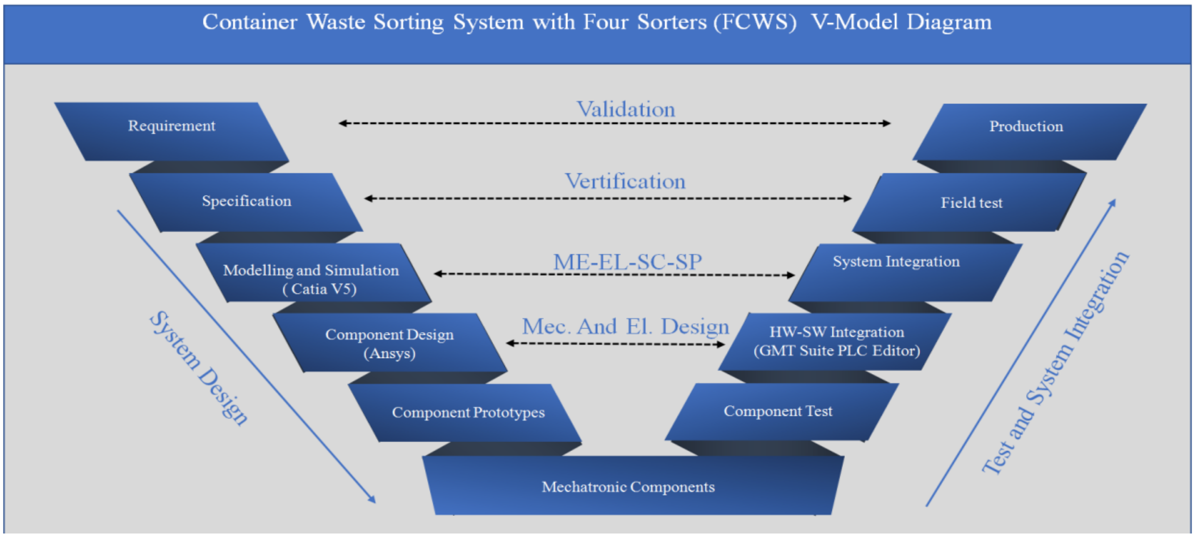


Figure 4. Mechatronic system design using the standard V Diagram (Graessler & Hentze, 2020).

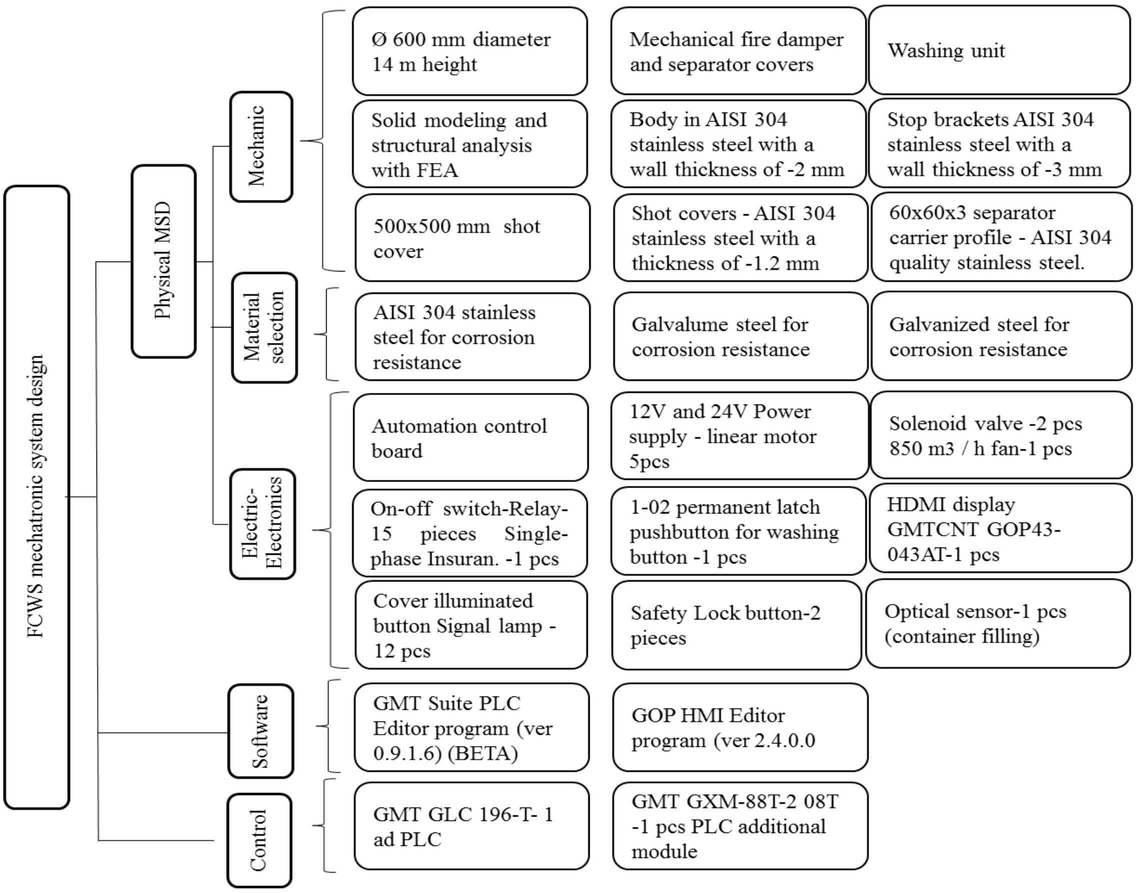


Figure 5. Design of mechatronic system for the collection and separation of waste containers with four sorters (FCWS).

Physical mechatronic system consists of mechanical design, material selection and identification of electrical-electronic equipment. The developed four-sorter system design contains the solid model, sub-components of the system, solid model structural analysis, iterative structural analysis, material-based cost analysis, the model-scale prototype design, identification of the electrical-electronic equipment used in the model scale prototype design, and the test of the system as shown in Figure 6.

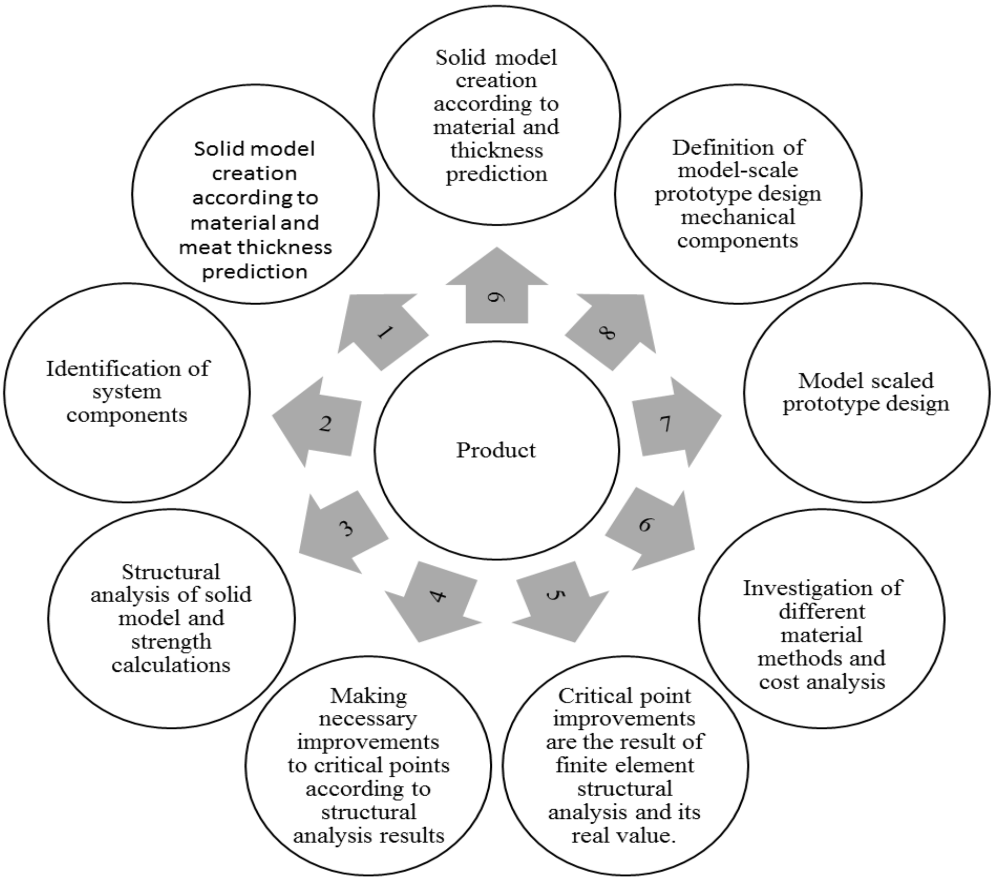


Figure 6. FCWS Physical MSD process flow chart.

Waste sorting system with four sorters are classified into three categories. The rotatable container, rail container and fixed container waste sorting system were designed for comparison purpose as shown Figure 7 and 8.

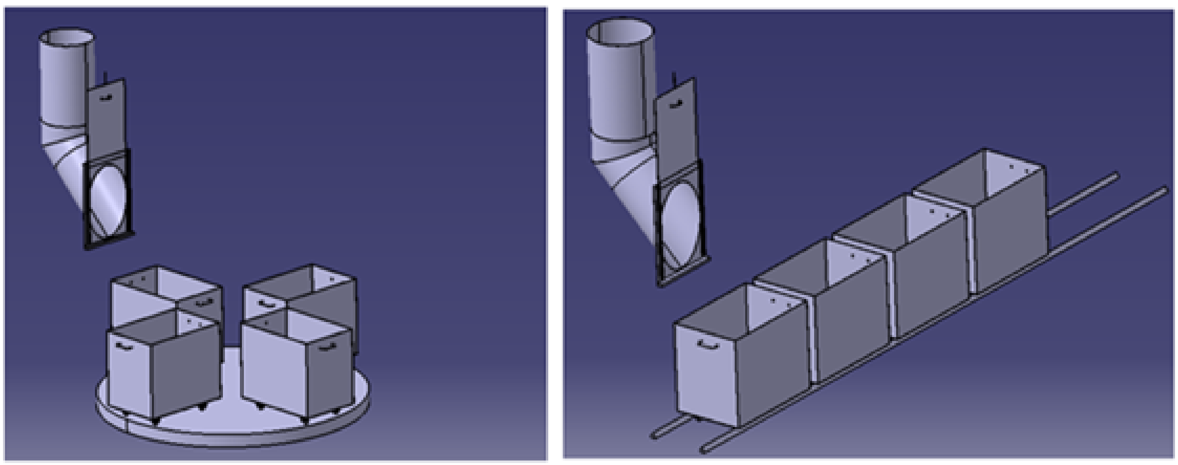


Figure 7. Four sorters a) Rotatable b) Rail containerized waste collection-separation system.

Experimental and numerical results

Design process has taken several steps: firstly, required equipment are determined before examining system and later, real-size design is modeled and analyzed by using ANSYS FEM software, lastly, prototype of scaled model is built to test if the system will work properly or not. In structural analysis of real-size design; materials are selected as the same materials already in use as our focus is on efficiency of new separation methodology. The prototype design of scaled model consists of the addition and programming of electrical and electronic equipment.

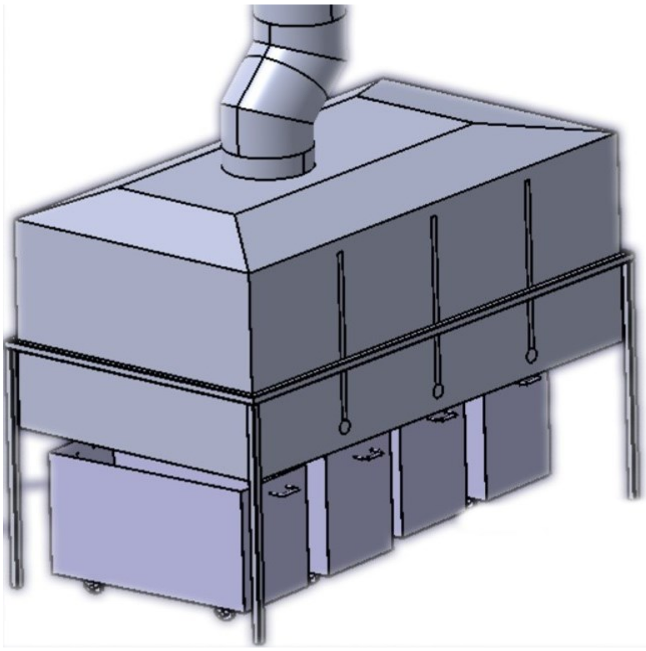


Figure 8. Developed fixed container waste sorting system with four-sorter (FCWS).

Defining system parameters

AISI 304 as the material of carrier system and ϕ600 mm stainless steel pipes are taken into consideration in real size design as existing sorter systems are using them because of, especially, good corrosion resistance characteristics. Before continuing with structural analysis, maximum force value for worst case scenario is calculated (4^{th} floor-50 kg-free fall). In the systems with more than four floors, a speed limiting device is used to reduce the waste speed and a system carrier is installed on every four floors as seen in the solid model design of Figure 9.

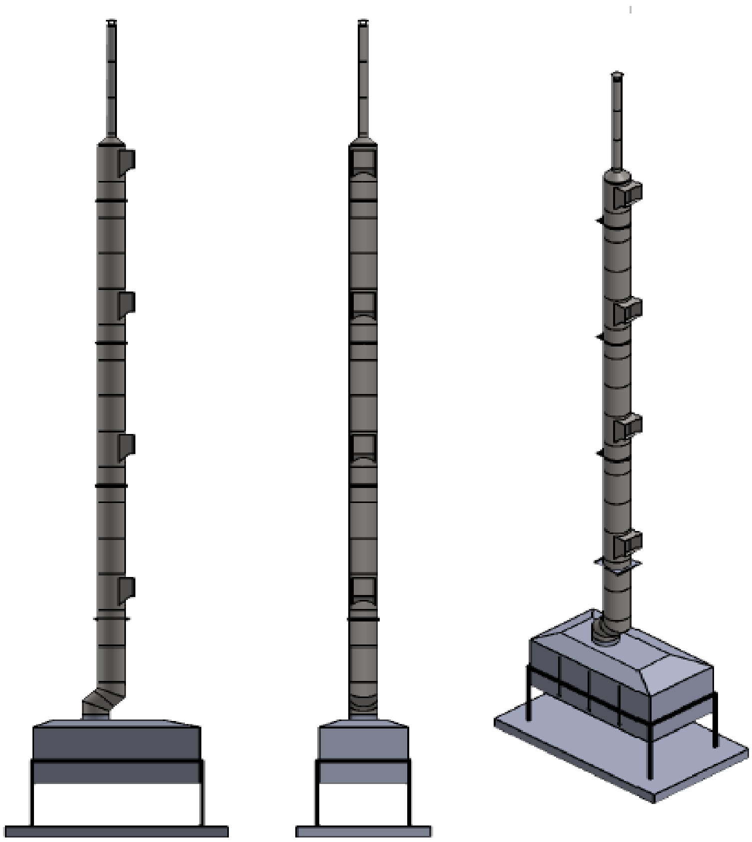
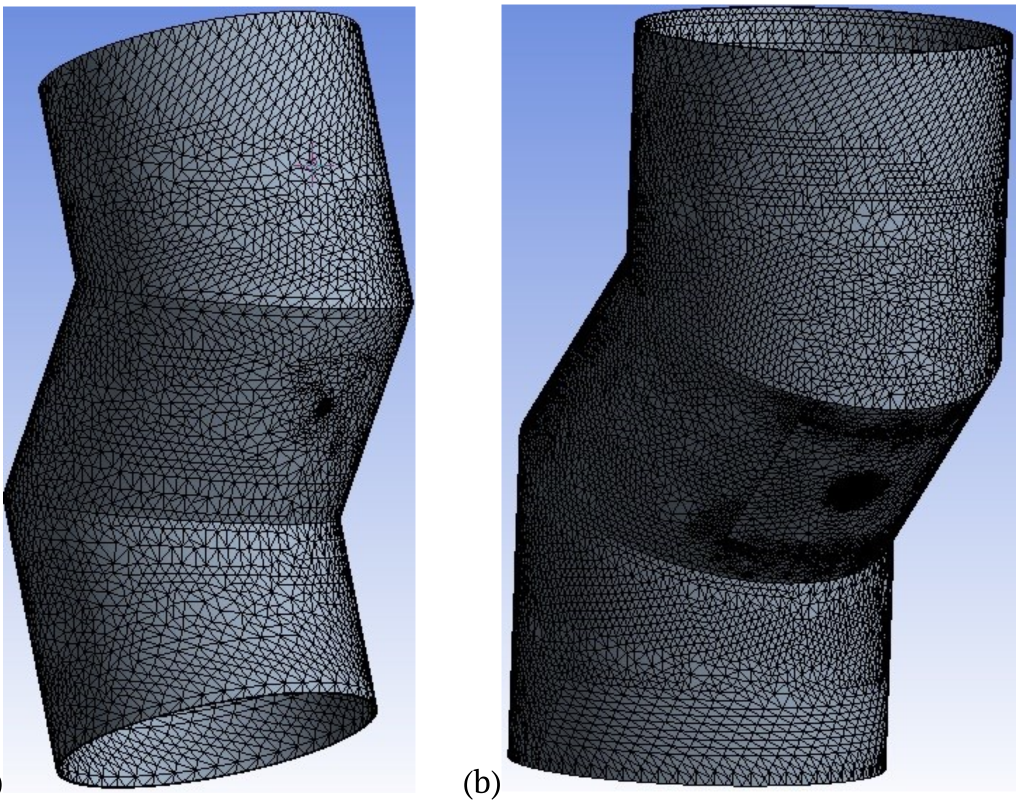


Figure 9. FCWS solid model design.

Real Dimensional Design of FCWS

A new design is proposed and analyzed at that stage. A thin plate (1 mm thickness) is added to the stop elbow to decrease the maximum stress value. The meshed finite element models of the stop elbow designs used in structural analysis are shown in Figure 10. The material properties given in Table 1 are entered into material database. In the analysis, firstly meshed quality is tested for different mesh types (tetrahedrons, hex dominant etc.) and element sizes (20, 5 mm) to obtain mesh independency. At the end, to use sizing at the critical points and surfaces are seen as much more appropriate because increasing element size slows the mesh modelling and solution steps so that computer could get stuck. For example, mesh model of standard stop elbow has 1503919 nodes and 847560 elements for 5 mm element size while mesh produced by default values and body sizing with 20 mm radius sphere and 0.5 mm element size has 500266 nodes and 349912 elements (Figure 10a) and another mesh model with 7 mm element size for hex dominant has 1889581 nodes and 760720 elements. They all resulted approximate stress values.



(a) (b)

Figure 10. Stop elbow models (a) Standard (b) Proposed.

Table 1. Material characteristics.

Material	Modulus of Elasticity	Yield Strength	Poisson Ratio
1.4401-AISI 304	193 MPa	205 MPa	0.29

Moreover, mesh defeaturing option is selected as 0.1 mm in mesh modelling for proposed design as the plate is very thin compared to diameter of pipe and also edge sizing is applied to each edge of the plate (number of division:10). Again body sizing is applied for 50 mm radius sphere and 3 mm element size. Element quality is checked and approved for both model.

Top and bottom sides of stop elbow are modelled as fixed and a 2147 N force is applied downward on a certain area on elbow (to resemble the garbage package).

The resulting Von Mises stress distribution is shown in Figure 11, while the elongation distribution is shown in Figure 12. Here, maximum tensile and elongation amounts were observed around the points where the load is applied (not on the connection edge of stop elbow or edges of added plate).

The maximum Von Mises stress value is obtained as 31.489 MPa and 26.893 MPa for standard and proposed stop elbow respectively. As it is seen, %14.6 reduction in stress value is obtained.

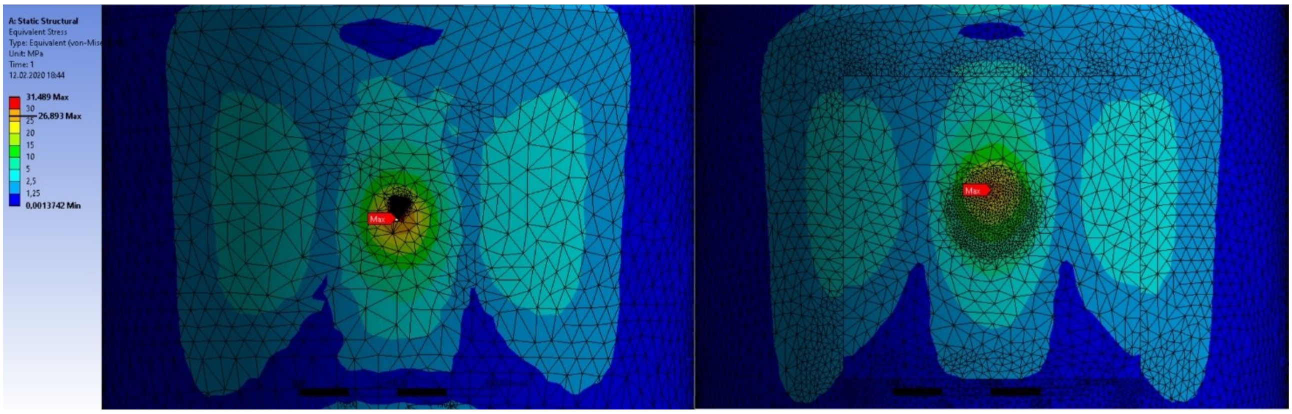


Figure 11. Von Mises stress distribution of stop elbow (a) standard (b) proposed.

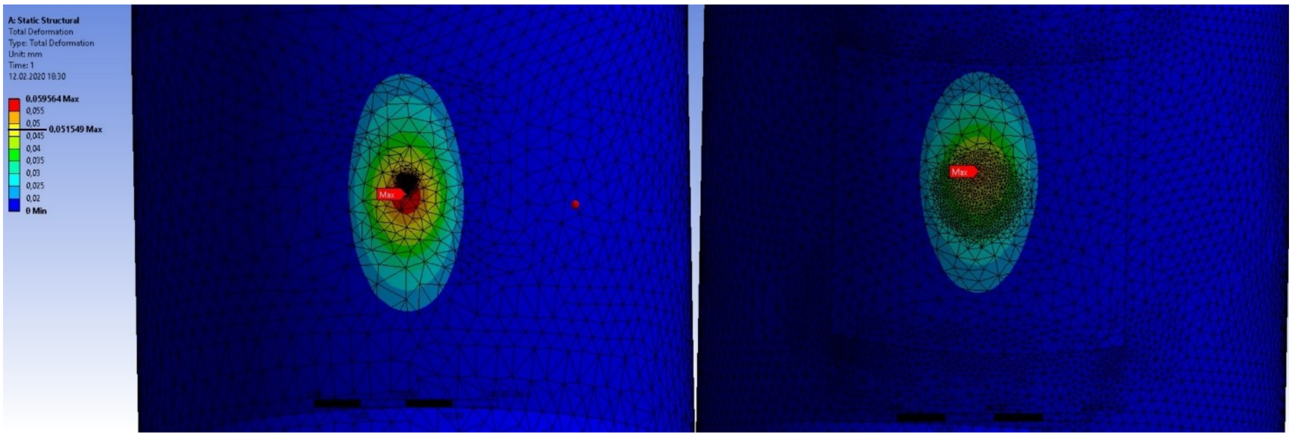


Figure 12. Elongation distribution of stop elbow (a) standard and (b) proposed.

The elongation is obtained as 0.059 mm and 0.051 mm for standard and proposed stop elbow respectively. %13.6 reduction in elongation value is obtained by making different support design. The same system is tested under different material (aluminum is selected in this study) to compare with stainless steel. Figures show that total deformation values are increased approximately 2.5 times but still in an acceptable level (Figure 13).

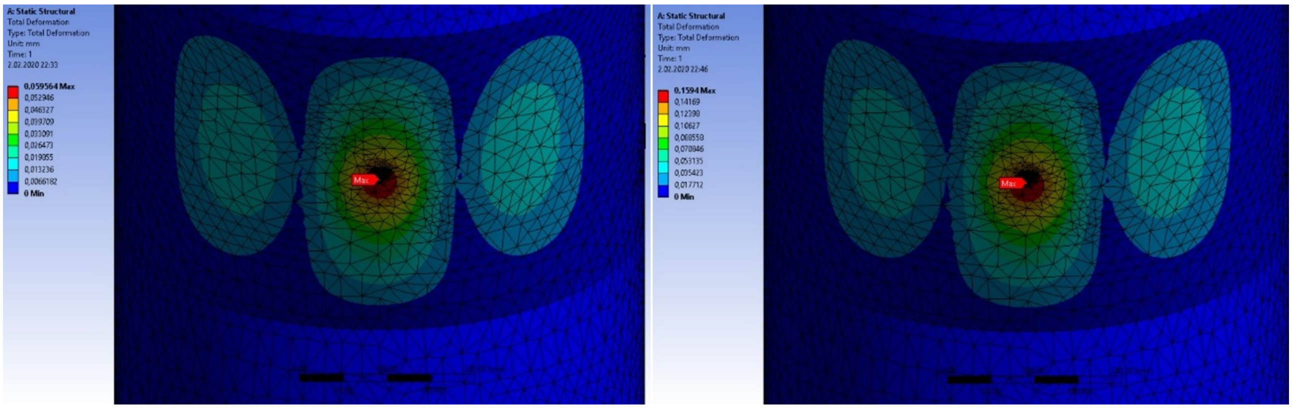


Figure 13. Comparison of deformation on elbow for different materials.

Furthermore, maximum stress values are considered and they are plotted on a graph to see the change in stress. It is seen that even though the stress distribution graphs look same, maximum value is decreased and occurred at a different point in proposed design (Figure 14 and 15).

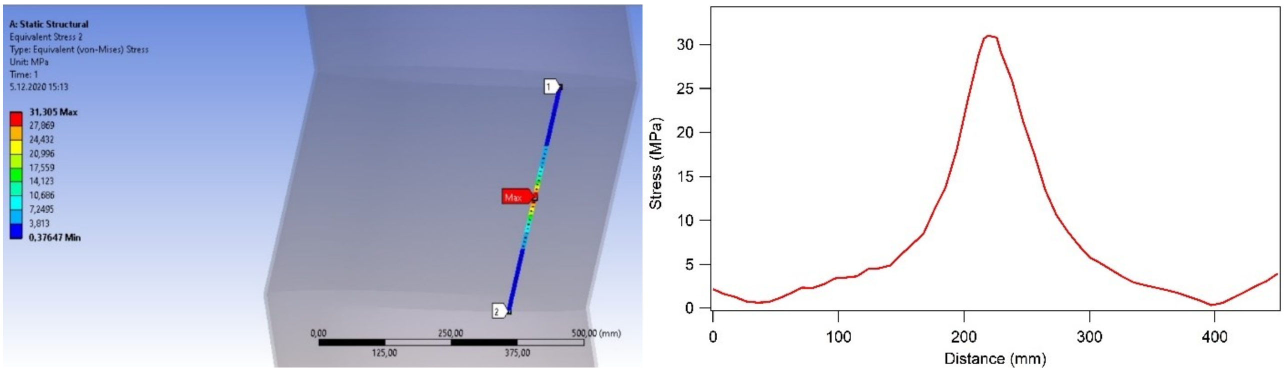


Figure 14. Change in stress along the line where maximum stress occurs (standard elbow).

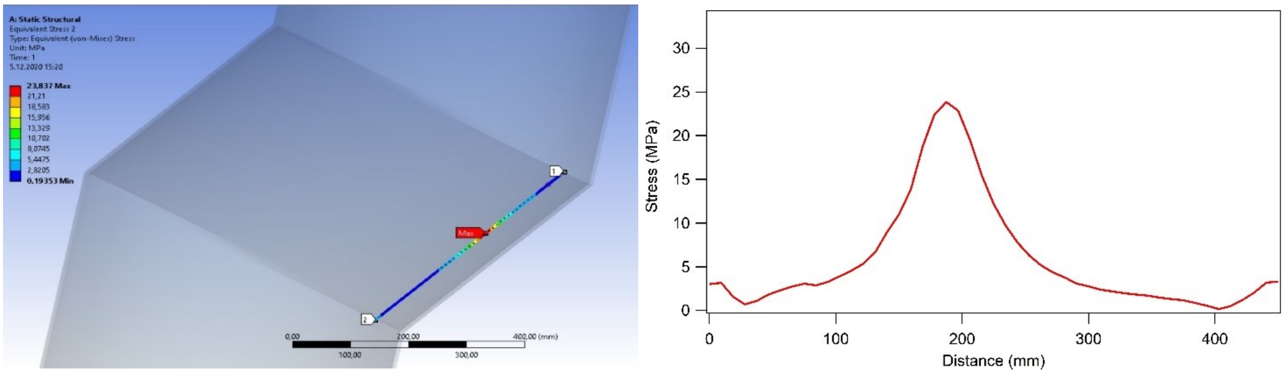


Figure 15. Change in stress along the line where maximum stress occurs (proposed stop-elbow).

Real Dimensional Design of FCWS

The final prototype of the developed FCWS model-scale design is shown in Figure 16.

Figure 16. The model-scale FCWS prototype.

The real-size design was made for a four-floor structure. In order to be suitable for demonstration and testing, a model-scale prototype design was constructed for a two-floor building. The model is equipped with a 4-inch separator fume hood, separator wings, containers, ventilation, cleaning section and a mobile stand for mobile use. Fan and automation panels have been installed in the ventilation section. The body is made of AISI 304 quality stainless steel. The stand is made of box profile and painted with anticorrosion paint.

Figure 16 shows the lids on the sides of the covers indicating to be ready or busy with illuminated warning lamps. For instance, if the green warning lamp is on, it is known that the system is ready for use, and when the button for the paper is pressed, the cover opens with the actuation of the linear motors on the sides. When the waste material is placed, it can be pressed on the button for the paper to close the lid, and the waste material is lowered down. For each type of waste, this process can be carried out. A lock button is designed for the safety of the model-scale prototype.

Discussion

The recycling process is crucial to prevent the exhaustion of resources and pollution of the environment. The collection and separation processes are refined using varied methods for the recovery of the resources. The three-sorter waste separation system is more efficient than the one or two-sorter systems. The waste separation system with three-sorter, made by Hardall International Limited and Wilkinson Chutes, one of the leading companies in the sector, is used in the market. Wastes are collected in these systems by separating them in three parts which are paper/cardboard, general garbage, and plastic/tin cans.

In contrast, in the four-sorter system designed in this study, polymer and metal materials are collected separately from each other at the source. Thus, time saving is achieved without the need to separate these materials in recycling facilities. Additionally, cleaner polymer materials is accessed in this system. Moreover, a cleaner and higher quality recycling system is achieved.

In addition to being resistant to the freefall impacts of the wastes, the design should be made using materials that are resistant to the corrosive effects. The most suitable materials are stainless and galvanized steel. The average cost of the design, using AISI 304 quality material, was found to be $10385, including labor and assembly cost. This system will have added value when its price is made affordable in order to be available to every household. The total cost can be reduced to $6779 when galvanized steel materials are used.

As a result of this research, it was found that the 7000 series aluminum can be used as an alternative to stainless and galvanized steel, considering its resistance to corrosion. However, the rigid structure of these materials causes the undesired bending problems during the manufacturing process. In addition, the fact that welding operation of aluminium is more sensitive than the stainless and galvanized steel. This situation causes an increase in labor costs. To this end, the 7000 series aluminum is not considered as a suitable material for the design.

Finally, the developed system with four-sorter is a unique mechatronic system design for recycling purposes. The actuators, sensors, software, physical MSD, and controller are integrated for recycling using the FCWS mechatronic system design, as seen in Figures 4 and 5. This research revealed that the mechatronic system design has the potential to develop novel recycling systems using the state-of-the-art integration of sensors, actuators, software, and controllers for the specific applications.

Conclusion

In this study, the waste collection at the source was investigated with the necessary waste collection and separation mechanisms. A model-scale fixed-container four-sorting waste collection and separation (FCWS) system was designed, analyzed and developed. Type of material and value of wall thickness were examined using the parameters such as the acting force on the designed system and the required corrosion resistance.

Model-scale prototype design has been constructed to unveil the workability of FCWS in real size design. The model-scale prototype design was created by adding electric-electronics and automation system to the mechanical design. The prototype was placed in a two-floor building including two firing hatches. The model consists of main body, waste throw covers, four-separator fume hood, separator wings, containers, ventilation section, cleaning section, and automation control panel. It was observed that the final model-scale prototype (FCWS) system works efficiently in real-life condition. It is proved that the developed system offers a novel recycling process for the waste collection and separation at the source.

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