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Surgical waste reprocessing: Injection molding using recycled blue wrapping paper from the operating room

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ABSTRACT

Introduction: Hospitals in the Netherlands generate approximately 1.3 million kg of waste from the polypropylene (PP) wrapping paper (WP) used to wrap surgical instruments each year. The aim of this study was to develop a method to recycle WP waste into new medical devices.
Methods: WP was recovered from Maasstad Hospital, Netherlands. The WP was melted into bars, granulated, and mixed with virgin material at different ratios and temperatures. Dog bones were injection-molded from volume (v.%) virgin, mixed (%R), and recycled (100%R) granulate, and a tensile testing machine was used to compare the material properties before and after ten disinfection cycles at the sterilization department. Then, 25 instrument openers were made from the 50%R material and circulated for four weeks.
Results: The data indicated no significant differences in the mechanical properties at different melting temperatures. For dog bones made from the 100%R, 50%R, and virgin granulate, the Young's moduli were 1021 (SD13), 879 (SD13), and 795 (SD14) MPa, and the strains were 8%, 12%, and 14%. Ten disinfection cycles did not significantly change the material properties. After one month, the openers did not show any deterioration or damage other than surface scratches.
Discussion: The results indicated that the initial WP melting temperature did not influence the mechanical properties. Although devices could be produced directly from the recycled WP granulate, increasing the recycled granulate in the mix ratio increased the strength and brittleness.
Conclusions: It is feasible to recycle WP waste into a high-quality raw material for the injection molding of medical devices without using additives. This would allow hospitals to become more compliant with the circular economy enabling economically viable and circular processes that positively contribute to cleaner technical processes, sustainable products, and the reduction of medical waste.

1. Introduction

Urban mining is the process of harvesting materials directly from used products, buildings, or waste, as opposed to geological mining, where virgin materials are extracted from ore that is mined from the earth. The objective of urban mining is to decrease the high environmental impact caused by the extraction and processing of virgin materials in local urban areas (Muller et al., 2019).

Because a hospital is seen as an urban environment, the recovery and recycling of operating room (OR) waste into raw materials is considered to be urban mining (Zhu and Xuan, 2014). From the perspective of urban mining, hospitals could be a good source for raw material extraction because many of the supplies used in hospitals are often made from high-quality materials and are single-use items.

Interest in the reuse or recycling of medical waste is growing globally (Van Straten et al., 2020; Pinjing et al., 2013). There are several motivations for reducing medical waste. First, it may contribute to a decrease in the dependency on natural resources and an increase in the

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availability of medical products in times of scarcity. Several studies have revealed the benefits of reprocessing medical products in times of scarcity (De Man et al., 2020), as well as using alternative materials (Teesing et al., 2020) and reusing filtering facepiece respirators (Harskamp et al., 2020). Second, there are arguments that waste decreasing and recycling activities may not only have environmental benefits but also generate potential financial gains for hospitals (Van Straten et al., 2020; Voudrias, 2018). Third, medical waste has a negative impact on public health, as well as on the environment. It appears that the public does not sufficiently understand medical waste management (Yong et al., 2009), and hospitals seem to manage their medical waste in different ways (Bokhoree et al., 2014) where protective measures should be taken (Zhang et al., 2013). Medical waste is not only a potential threat to employees and patients, but also to surrounding communities (Mesfin et al., 2020). Therefore, medical waste remains problematic (Çetinkaya et al., 2020). Because medical waste can spread diseases (Irianti and Sri, 2013), there is a need to switch to sustainable alternatives (Patricio Silva et al., 2020). It is important to decrease the volume of medical waste to reduce these hazardous effects. Some studies have reported an increase in medical and plastic waste of up to 30% as a result of the Covid-19 pandemic (Patricio Silva et al., 2020; Sutrisno et al., 2020).

As the volume of medical waste has grown (Razali et al., 2010; Manga et al., 2011; Haque et al., 2020), so has the public concern regarding the disposal of this waste (Pullishery et al., 2016; Chudasama et al., 2014). Awareness among hospital staff is highly important and needed (Pinto et al., 2014), especially in the case of sharp medical waste (Ghodrat et al., 2017). In addition to public concerns, because of increasing waste disposal costs, decreasing medical waste could potentially lead to hospital cost savings (Van Straten et al., 2020; Berwick et al., 2012), which could be substantial (Zimmer et al., 2008). Earlier studies reported the possibility of recycling medical materials such as blue (and green) wrapping paper (WP), which is used to pack surgical instrument trays after sterilization to enable transport and storage (Voudrias, 2018; Babu, 2018). The OR is considered to be a large contributor to medical waste (Chang et al., 2020; Stall et al., 2013), which includes wasted energy, water (Wormer et al., 2013), and solid materials (Shinn et al., 2017), and in some cases, it is the largest contributor to the total waste of a hospital (Rigante et al., 2017; Albert et al., 2015). Approximately 30% of all hospital waste is plastic, 30% is cardboard and paper (Lee et al., 2002), and approximately 20% comes from ORs.

The use of WP seems to be a large contributor to waste production because it is used in every type of surgical procedure. WP is used to wrap an instrument tray with surgical instruments. The WP forms a sterile barrier around the tray, allowing the instruments to remain sterile.

WP is made from non-woven polypropylene (PP), which is a thermoplastic polymer, and has a high recycling potential [8]. PP is widely used in many products and is found in many industrial applications (Ajorloo et al., 2020). The automotive sector is a large user of PP-based composites because of their suitable mechanical properties such as their low density and chemical resistance (Wang et al., 2019).

Two aspects should be considered when recycling medical grade PP.

1) Additives: The polymeric materials used in injection molding may be combined with additives, fillers, and/or reinforcements to improve the mechanical properties and color of the polymer or to reduce costs (Suplicz et al., 2020). Reinforcements can be used to enhance the strength or rigidity of plastics by mixing the polymer materials with additives or fillers. These materials such as glass fibers are used to create mechanical bonding between the fibers and the polymer matrix. Other additives and fillers help to create a specific melt flow index; however, the addition of these additives can modify the mechanical behavior of the recycled PP (Jmal et al., 2018).
2) Material degradation: The other aspect is the potential degradation of the recycled material. Several studies have reported changes in the material properties as a result of recycling. The elastic modulus and complex viscosity of recycled PP may decrease with the number of reprocessing cycles. Several studies have shown that recycling at high temperatures can lead to thermo-mechanical degradation (Wang et al., 2019; Spicker et al., 2019). Moreover, it has been reported that during recycling, the material properties of PP change as a result of chain scission and an increase in crystallinity (Aurrekoetxea et al., 2001; Hyie et al., 2020).

Although several studies have focused on the recycling of PP (Aurrekoetxea et al., 2001; Hyie et al., 2020), no studies have been conducted on recycling WP waste from the OR into injection-molded products without using additives.

The main objective of this work was to experimentally determine if a standardized approach is possible for the collection, melting, and granulating of WP waste for use in injection molding to produce new medical products. These products are then used in a hospital, creating a circular loop as shown in Fig. 1.

To investigate the versatility of PP WP waste, it was necessary to determine and compare the mechanical properties of the molded WP waste material when mixed with virgin materials, as this is commonly seen in recycled products. Finally, this study investigated how debris like stickers and tape would influence the injection molding process.

The following research questions were formulated for this study.

Research questions.

1. Does the melting temperature influence the properties of reprocessed WP waste material?
2. Does mixing virgin and recycled PP alter the mechanical properties?
3. Does commonly seen debris such as stickers and tape influence the properties of the reprocessed WP waste?
4. Can the material be used to make new reusable medical products without adding additives to the process?

2. Methods

This study involved eight steps to analyze whether WP waste could be used to fabricate a medical device with sufficient mechanical properties to be used again in a hospital environment. Different steps were used to answer the research questions and included setting up a legally approved logistical process, determining the best melting temperature for WP waste, developing a melting process, setting up an injection molding process, analyzing the material properties after molding, analyzing the influence of debris such as stickers and tape embedded in the WP waste, and designing a process for using the new medical device in the hospital.

This research included the collection of three batches of PP surgical WP from an OR where the WP was used to wrap instrument sets. These batches were recovered over three separate days. A procedure was designed to collect the WP after use, after which a melting process was used to recycle the plastic waste at different melting temperatures. Different methods were evaluated to determine whether discarded medical grade WP could be mined using a standardized process and used for the injection molding of new medical products.

2.1. Logistical process

A dedicated logistical process was set up to collect WP waste at the Maasstad Hospital (Rotterdam, the Netherlands). This type of surgical waste is categorized as medical waste and is subject to legislation for hazardous and medical waste when transported and processed. The OR staff was asked to collect WP at the OR in the preoperative preparation area. This is the area where surgical instrument sets are prepared for surgery. Transparent 160 L PP collection bags were used, in which the WP was collected. The bags were transported from the OR to the waste collection center of the hospital. The bags were collected by a waste

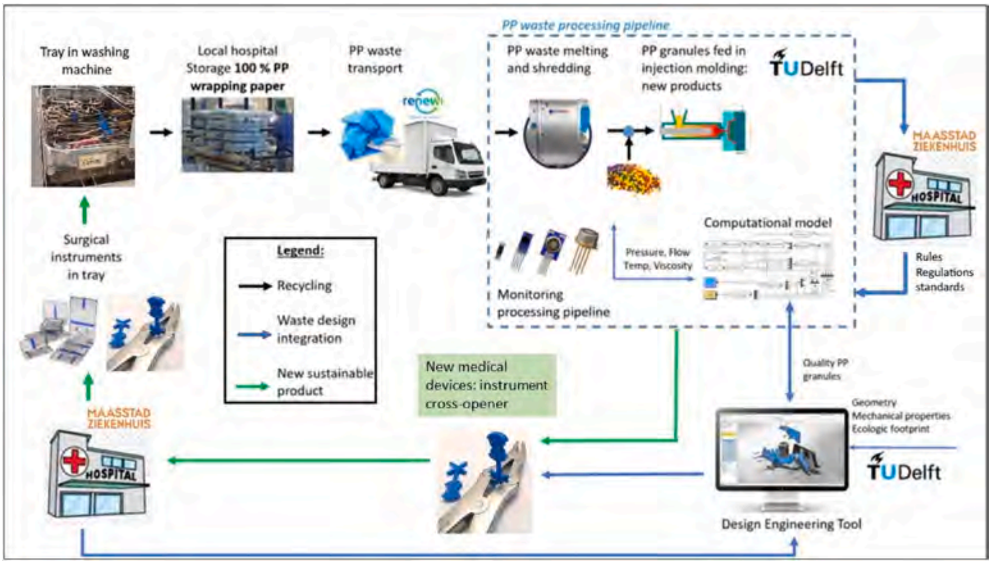

Fig. 1. Potential approach to centralized reprocessing line allowing hospitals to reprocess their waste into new reusable products.

processing company (Renewi Nederland B.V., Eindhoven, the Netherlands). The WP waste was analyzed and weighed after collection. As required by the permit for the transport of medical waste, the WP waste was first transported to a central sterile services department (CSSD) location (CSA Services, Utrecht, the Netherlands), where it was sorted and checked for potential contamination and the presence of other undesired debris. The WP waste was then brought to the Delft University of Technology (Delft, the Netherlands) to be melted.

2.2. *Influence of melting temperature on reprocessed WP waste material*

To determine the influence of the melting temperature of the WP waste, the WP was first melted at 200 °C, 250 °C, and 300 °C. A tubular shape was selected because it was easy to manufacture and fit well inside the cylindrical oven. The PP WP waste was melted into bars after placing it into a tubular-shaped cylinder with a diameter of 100 mm, which was capped at each side and placed in the oven (Fig. 2). The melting temperature that produced the best properties was evaluated and used for melting the next batches.

2.3. *Melting of PP*

The WP was collected and melted in a stainless-steel cylinder in an electrical melting oven (KOS, Electric crucible, series 219029). The WP sheets were manually placed into cylinders and melted at 250 °C. After the material was melted, the molten material was pulled through the filter by gravity. The melted PP bars were granulated using a Moditec grinding mill (Gplus 2) and used for direct injection molding at 200 °C. The virgin granulate was mixed with recycled PP by volume before injection molding (indicated as %R). The dog bones and rectangular bars needed for tensile testing were made from 25%R, 50%R, and 75%R PP. These were compared with each other and with dog bones made from virgin PP and 100%R PP.

2.4. *Injection molding*

Two different molds were made and used for the injection molding (Babyplast, injection molding machine 6/10P). The mold with the dog bone design shown in Fig. 3 was used to make dog bones with different

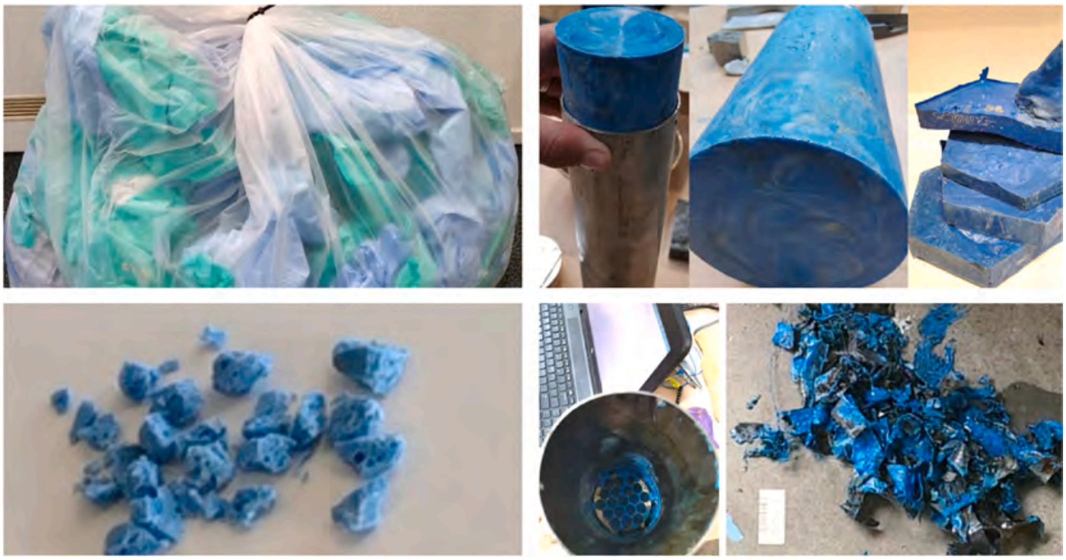

Fig. 2. Overview of different stages of material. From top left to bottom right: collected WP, melted WP formed into bars, granulated WP after melting, filter inside melting tube, and residue removed from filter used to make polluted dog-bones.

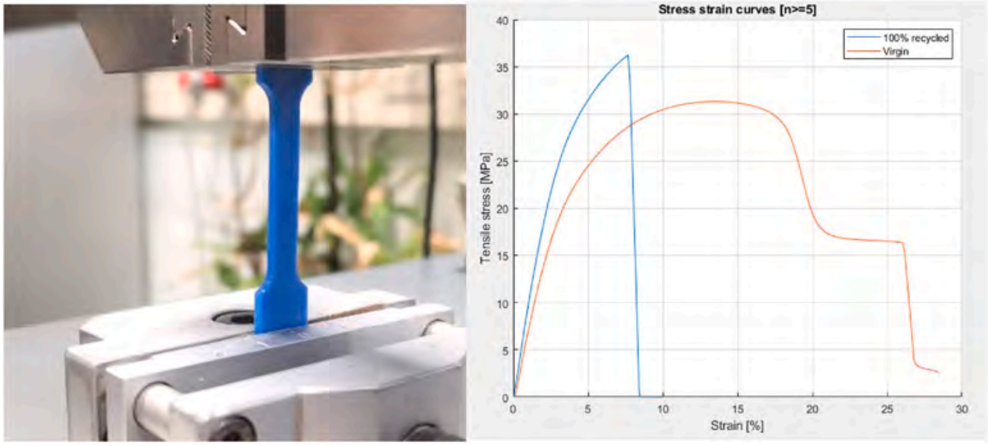

Fig. 3. Tensile testing of dog bones. Left, setup with injection molded dog bone sample installed in hydraulic clamps of test bench. Right, example of stress strain relation of virgin versus 100R material.

qualities for tensile testing (Supplemental file 1). A second mold was used for a medical product, an instrument opener. It had the form of a cross and was designed to keep double-hinged instruments open during washing and disinfection in a decontamination machine at the CSSD to ensure that all the parts of the instruments were cleaned during washing. A circular loop could be created by the urban mining, recycling, and injection molding of WP to fabricate new products and bring the material back into circulation in a hospital.

2.5. *Material properties of 100% reprocessed WP waste and when mixed with virgin material*

For analysis and strength comparison purposes, six different sets of five dog bones each were made from PP that was melted at 250 °C and used for injection molding at different mix ratios at 200 °C.

Six sets of five dog bones with various mixing ratios.

1. 100% virgin PP as the benchmark (virgin)
2. 25% recycled PP WP mixed with 75% virgin PP (25%R)
3. 50% recycled PP WP mixed with 50% virgin PP (50%R)
4. 75% recycled PP WP mixed with 25% virgin PP (75%R)
5. 100% recycled PP WP (100%R)
6. 100% recycled PP WP, polluted with stickers and tape (polluted)

The melting and injection molding parameters used with the collected PP WP are shown in Supplemental File 2.

2.6. *Influence of stickers and tape on properties of reprocessed WP waste*

Paper and other waste such as stickers can enter the WP reprocessing process and pollute the PP end product. This pollution not only influences the material properties but also clogs or damages the melting oven or delicate injection molding machines. A worst-case scenario was included in the experiments by taking the concentrated residue material from the filter after an unsorted batch of WP waste was processed in the melting oven. This residual material, which consisted of approximately of 50 v% pollution, was granulated and used to create five dog bones for tensile and Shore D hardness testing.

2.7. *Analysis*

Tensile strength tests were conducted to analyze the mechanical properties of the dog bones composed of the recycled PP because obtaining acceptable properties is seen as a challenge when PP waste contains different kinds of plastics such as tape and stickers, or when it is mixed with other types of materials (Hyie et al., 2020). The Young's modulus (E) was analyzed by measuring the elastic behavior (relationship between the tension and axial strain: $E = \frac{\sigma}{\varepsilon}$). The ductility of the material was analyzed by measuring the elongation at break as a percentage by comparing the new length after the breakage of the dog bone and the initial length. The ultimate yield strength was measured to show the maximum tensile stress of the material, and the Shore D test was used to measure the hardness of the dog bone. The combined stress–-strain relationships of the dog bones were compared, which were measured using a tensile bench (Delft University of Technology, Faculty of Mechanical Engineering, Zwick Roell, Zwick GmbH & Co.KG, Ulm, Germany), as shown in Fig. 3.

The dog bone bars had shoulders at both ends. These shoulder ends enabled a solid grip when placed in the testing machine. The dog bones were also tested on both shoulder ends with a shore durometer (Sauter, HBD 100–0.HBD 100–0, Durometer, www.sauter.eu), which was used to measure the hardness of the recycled material.

2.8. *New products made from WP*

To determine whether products made from the WP granulate could withstand a cleaning and disinfection process at the CSSD, additional tests were required. To determine whether multiple CSSD cleaning cycles would influence the material properties, dog bones made from virgin, 50%R, and 100%R were tested before and after being cleaned and disinfected ten times in a Getinge G1-WA-04 thermal disinfector (Getinge. Lindholmspiren 7, SE-417 56 Gothenburg, Sweden) at the CSSD. Thereafter, an instrument opener was designed to keep double-hinged instruments open during washing and disinfection. To determine the maximum load on the instrument opener, multiple double-hinge bone cutters were compared and tested by adding masses to a cable that ran through the opening of the hinge (Fig. 4). The 2 mm cable made contact with the metal of the hinge at the same location as the opener. The load was increased in 0.5 kg steps until the hinge remained open under the applied total load, which was defined as Fmax. A virtual finite element method (FEM) analysis was conducted using Solidworks (2020, Dassault Systèmes). The analysis was performed to relate the ultimate tensile strength (UTS) of the measurement outcomes to the dimensions and shape of the instrument opener when loaded with Fmax. This analysis showed the relationship between the design parameters and the material properties of the chosen granulate. Fig. 8 shows how the CAD model was imported and simplified, with half of the cross used in the analysis.

One thousand instrument openers were injection molded using 50% R and 100%R granulate, which should have survived at least ten CSSD disinfection cycles in a thermal disinfector at 90 °C. The Expert Sterile Medical Devices (DSMH) of the hospital was asked to supervise the

Fig. 4. Testing bone cutting hinge force. Left, tested bone cutters ordered from low to high hinge force. Right, bone cutter with highest hinge force opens when loaded with 6 Kg mass.

implementation of 25 instrument openers (50%R) and to inspect each instrument opener before, during, and after the disinfection phase. CSSD user and DSMH feedback was requested four weeks after the introduction of the instrument opener at the CSSD of Maasstad Hospital.

3. Results

The WP was used to package instrument sets after cleaning and sterilization in the CSSD. The WP protected the instruments by creating a sterile barrier after steam sterilization at 134 °C. The collected paper was unwrapped at the OR and did not come into contact with the patients. The Halyard brand WP (12754 Halyard, Kimguard, One Step, H100) was discarded after use in the OR and collected into special PP transparent bags. The OR staff did not report any difficulties while collecting the WP. A total of 8.16 kg, divided over 17 transparent bags, was collected. The majority consisted of H400 114 × 114 WP, with each sheet weighing 160 g and 5–6 sheets in each bag. The bags were transported in a roll container from the OR to the logistical area of the hospital, where they were collected and transported by the waste processor Renewi. After arrival, the WP was manually placed in cylinders and melted into bars, after which it was granulated and used for injection molding.

3.1. *Melting and granulating*

After melting, the PP bars were removed from the cylinders. The bars were granulated into flakes to form a raw material for injection molding. Fig. 6 shows pictures of the dog bones that were injection molded. For clarification, the structure of the polluted dog bone was enlarged 5 times, and the contrast was enhanced to better expose the particles.

3.2. *Influence of melting temperature on reprocessed WP waste material*

During injection molding, when the nozzle temperature was 200 °C, all the input materials flowed well, and no problems were observed during the injection molding with any of the dog bones and instrument openers. The results of the tensile tests are shown in Fig. 5. The dog bones shown from left to right were made out of 100% recycled WP melted at 200, 250, and 300 °C. No significant differences were found between the dog bones produced at different initial temperatures of the melting tube. Because the initial melting temperature of 250 °C seemed to give the best results, the following WP batches of granulate were made from WP melted at 250 °C.

3.3. *Influence of mixing ratio*

Fig. 6 shows the results for the polluted scenario, virgin PP, and different mix ratios. With the exception of the polluted dog bone, the UTS values were all greater than 30 MPa. The UTS increased from 31.5 MPa for the virgin material to 36.5 MPa for 100%R. The dog bones made out of 100%R granulate showed an approximately 6% lower strain than the virgin PP. The strain at break decreased with a decrease in the amount of virgin material in the dog bones. The results showed that mixing recycled PP with virgin PP increased the strain, depending on the mixing ratio, with a maximum of 5%. Fig. 6 (right) shows the material hardness, measured in Shore D values in combination with the Young's modulus. The bars indicate that the tensile stiffness and hardness increased when the material mix contained more recycled PP. The polluted and 100%R dog bones showed similar tensile stiffness and hardness values.

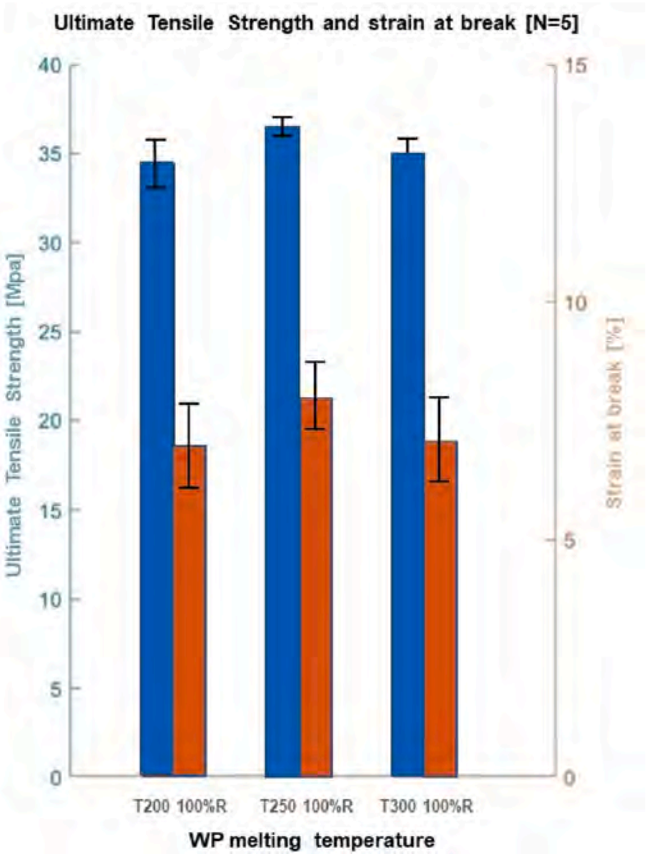

Fig. 5. Ultimate tensile strength and strain of dog bones made from WP melted at different melting temperatures.

For dog bones made from the 100%R and 50%R mixes, the Young's modulus values were 1021 (SD13) and 879 (SD13) MPa, respectively. The average strains for the 100%R and 50%R mixes were 8% (SD2) and 12% (SD4), respectively. Dog bones made from virgin PP showed an average Young's modulus of 795 MPa (SD14) and strain of 14% (SD0.5). The injection-molded instrument opener was subjected to ten washing and disinfection process cycles, and a visual inspection showed no deterioration.

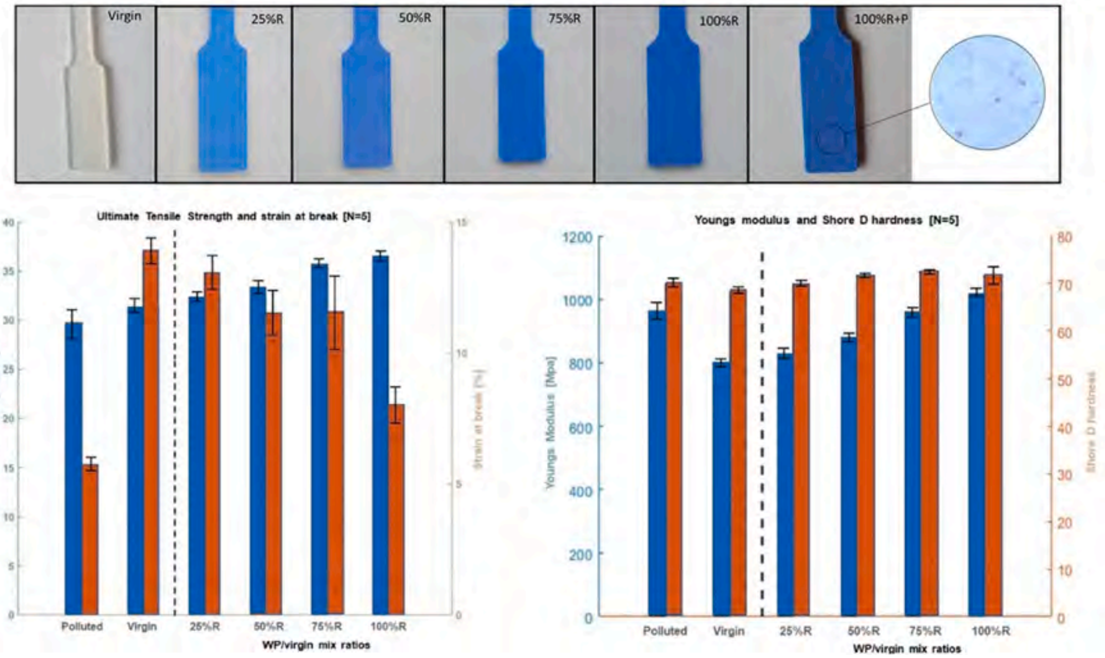

Fig. 6. Dog bones and their material properties. Top: pictures of dog bone. Bottom left, ultimate tensile strength and strain. Bottom right, Young's modulus and hardness measured in Shore D.

3.4. Influence of stickers and tape on properties of reprocessed WP waste

The tensile test conducted on the dog bones that were injection molded with particles from the stickers and tape in the granulate, as a worst-case scenario, showed a strain of 6% (SD1) and UTS of 29.8 (SD1.4) MPa.

3.5. Tensile and shore D tests after ten cycles of washing & disinfection

The results of the tensile and Shore D tests of the dog bones made of virgin, 50%R, and 100%R, which were washed and disinfected for ten cycles in the CSSD (Supplemental File 3) are presented in Fig. 7. Compared to the data in Fig. 7, the virgin PP showed an increase in elongation of 0.7%, an increase in UTS of 1.9%, and a decrease in hardness of 2.86%. The 50%R showed a decrease of 1.8% in elongation, an increase in UTS of 0.9%, and a decrease in hardness of 1.85%. The 100%R showed an increase in elongation of 1.7% after ten disinfection cycles, with a decrease in UTS of 0.69% and no change in hardness.

3.6. Development and validation of new product made from WP

Experiments indicated that a 6 kg load was sufficient to keep the hinge of the heaviest bone cutter open. As shown in Fig. 8, within the model, the highest stresses were found at the center of the cross of the opener, with a maximum compression stress of 59.8 MPa and tensile stress of 20.4 MPa for virgin material, a maximum compression stress of 59.7 MPa and tensile stress of 20.5 MPa for 50%R, and a maximum compression stress of 59.5 MPa and tensile stress of 20.7 MPa for 100% R. To prevent damage due to high contact forces during insertion, the instrument openers were designed with curved edges to ensure that the forces were distributed more equally.

Fig. 8 shows the molded instrument opener design that was used to open hinged spreaders and bone cutting forceps of different sizes. None of the 25 openers suffered damage during the testing period. The following statements show some of the user feedback from the CSSD staff after one month of repeated use: *it is easy to use and straightforward to apply to an instrument; it has an improved design compared to the current openers that are used from a local retail store (these products are not medically validated and appear to leave white debris behind after use in the thermo disinfector); the instrument opener is better to hold in your hands and*

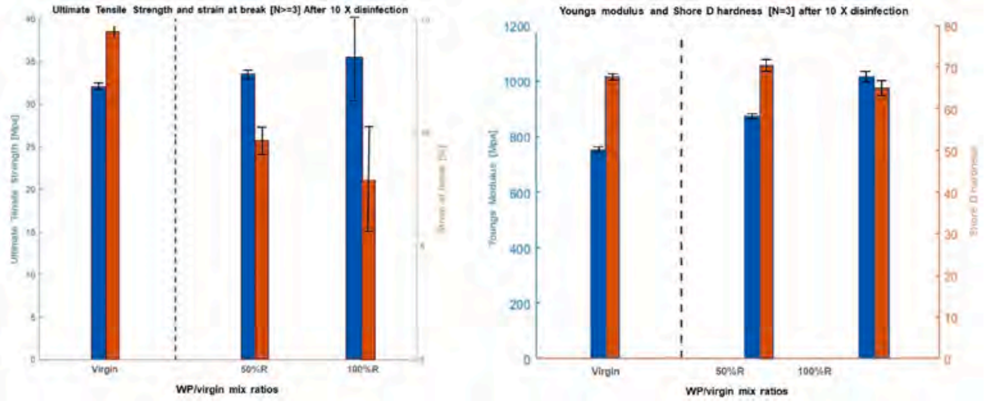

Fig. 7. Ultimate tensile strength, strain, Young's modulus, and hardness after 10 cleaning and disinfection cycles.

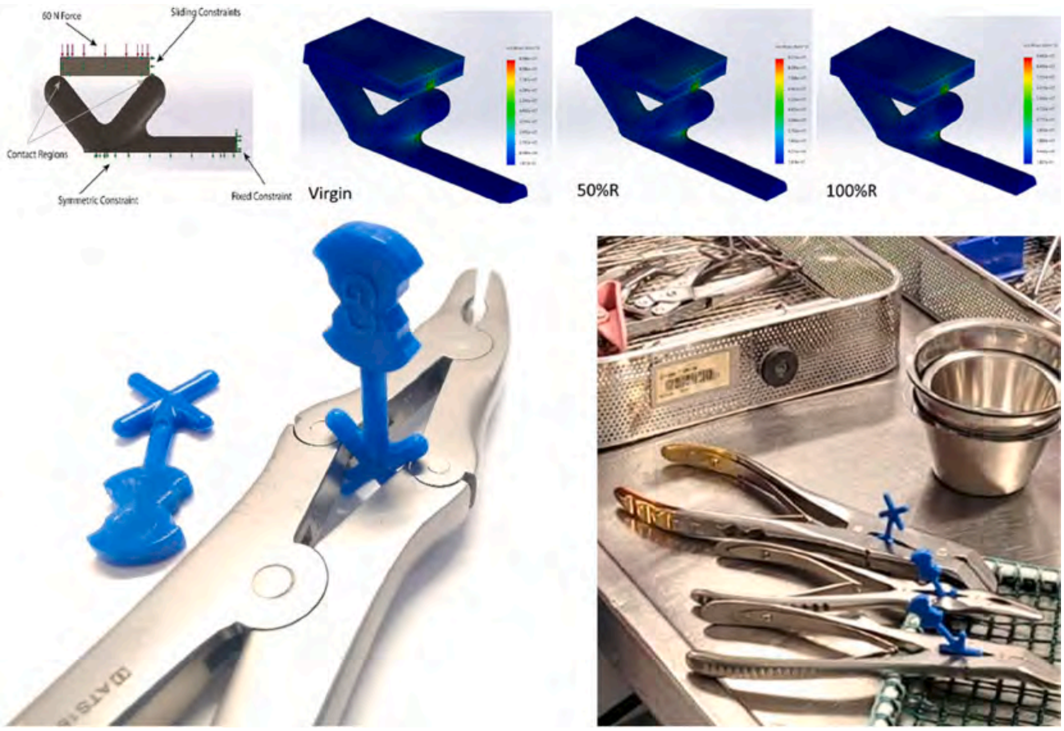

Fig. 8. Design based on WP material properties. Top: screenshots of Finite Element Analysis (FEA) of relevant section of opener/bone cutter hinge interaction indicating area of highest tensile and compression stress around center of cross of model. Bottom: instrument openers made from WP waste and deployed at sterilization department of Maasstad hospital.

to place inside the hinge; the instrument holder is made of recycled material, which is perceived as an advantage; it effectively keeps the instrument open during washing.

4. Discussion

For the first time, medical devices made out of recycled PP hospital waste were used in the harsh environment of the sterilization department of that hospital. The results showed that the study aim was reached, and it was possible to process PP waste into new qualitative products that could be used in the same hospital without the use of additives. The initial melting temperatures of 200–300 °C applied to turn the blue WP waste into bars for granulation did not significantly influence the properties of the injection-molded products. An initial melting temperature of 250 °C combined with an injection molding temperature of 200 °C resulted in satisfactory results. Other studies have reported that the melting temperature of recycled PP has a significant negative effect on the stress at break, with the addition of virgin material compensating for this effect (Czichos and Saito, 2006; Da Costa et al., 2007). However, this study found that for the initial melting step before injection molding, temperature differences between 200 °C and 300 °C did not significantly influence the properties of the final product. From Fig. 6, it can be concluded that the mixing ratio of virgin material to recycled granulate had a strong influence on the material properties. Injection-molded products made from 100% recycled WP were stiffer, harder, and more brittle than those made from 100% virgin PP. The degradation of the material could be reduced by adding virgin material to the recycled PP (Gabriel and Tiana, 2020). However, the increased stiffness and hardness could be an advantage for supportive devices at the CSSD where instruments are heavy and sharp, detergents are used, handling is rough, and washing is done with a high water flow at high pressure.

A comparison of the results for the 25%R and 100%R samples showed that with 25%R granulate the strain at break was 5% higher, while the UTS was 11% lower. These results showed that the mixing ratio had a stronger influence on the strain at break than on the UTS.

In the worst-case scenario simulation, melted WP waste contaminated with stickers and labels was granulated into flakes that were immediately used in injection molding to produce dog bone samples. Although highly polluted, it was found that the strain was only 8% lower than that of virgin PP and 2% lower than that of pure 100%R PP, whereas the UTS was 5% lower than that of virgin PP and 18% lower than that of pure 100%R PP. This showed that pollution with tape and stickers had a limited effect on the mechanical properties. In this case, the color of the molded material changed.

4.1. Potential to make new products without adding additives to process

The FEM simulations indicated that despite the different characteristics of the mixed materials, the difference in the maximal allowable stresses remained low under equal loading conditions. This showed that for simple non-constructive designs that are not deformed during use, manufacturers can safely mix virgin and 100%R granulate depending on the availability and wishes of their clients. In practice, it was found that the instrument openers made from 100% PP and 50%R PP both met the specifications for holding hinged instruments in an open position for multiple disinfection cycles. However, the data indicated that extra attention is needed with respect to device designs containing deformable compliant elements (e.g., snap fingers) because the material becomes more brittle (Hyie et al., 2020; Czichos et al., 2006), with the break properties decreasing (Da Costa et al., 2007) leading to a potential decrease in the mechanical properties (Gabriel and Tiana, 2020; Aurrekoetxea et al., 2001) after multiple cycles of recycling. This indicated that in order to increase the circular use of recycled medical plastics, design choices should be linked to the type of waste and mixing ratio. This could be a basis for developing more medical products manufactured from medical plastic waste such as PP trays, mesh basket accessories, and labels, considering the costs and potential environmental impacts of such products. Every medical product needs to undergo CE approval according to the Medical Device Regulation. Testing is mandatory, and material specifications must be demonstrated in technical files. This includes toxicity testing of the material, which may exclude the toxicity of potential pollutants and unknown substances during recycling, demonstrating that products made out of waste can be safely used in hospitals.

Within the Netherlands, an estimated 1.3 million kg of WP is used each year. Potentially, 8,320,000 cross-shaped openers could be manufactured when collecting WP waste for only one year (Supplemental File 4). Hypothetically, 70,000 instruments with a (double) hinge are circulate in 90 hospitals in the Netherlands. To put this into context, this means that recovering WP waste during a single year would ensure a raw material supply for the manufacturing of instrument openers for the next 119 years in the Netherlands. The urban mining of WP waste could be the answer to the circular manufacturing of a wide range of medical devices. These could include medical products such as cleaning nozzles, tubes, holders, and containers to be used in CSSDs or ORs and manufactured from recycled PP.

4.2. Theoretical and practical implications

This study demonstrated that an OR waste reprocessing method could be conducted locally with potential environmental benefits. The theoretical implications are that the material properties of processed waste could be examined in a standardized manner with dog bones before using the obtained material properties to conduct loading simulations on a new instrument design. The linear relationship between the percentage of recycled material used and the hardness or strength could be used to calculate the mechanical properties of the final product. This characterization of waste material properties would allow designers in practical applications to optimize their products based on the “green” wishes of customers. They would not only need to design future medical products to facilitate easier reprocessing but would also need to consider the fact that recycled materials are used in the design.

4.2.1. Future work

As this study demonstrated the feasibility of reprocessing PP waste from hospitals into new medical products, future studies should investigate the reprocessing options for other types of plastic hospital waste, as well as calculating the environmental and financial impacts from a more holistic point of view.

4.2.2. Study limitations

Although not included in the scope of this study, a Life Cycle Assessment (LCA) study could be conducted to calculate the benefits of the environmental impact, in particular the CO_2 and water impacts, when recycling WP into new products, as compared to its disposal or incineration. In addition, a cost analysis of the urban mining, recycling, manufacturing, and reuse of PP from medical devices, as opposed to disposal after a single use, would be an area of interest for further investigation. However, consideration should be given to the fact that a special logistical routing is needed for this type of waste because it is potentially contaminated, generating extra costs for comparison. In the pilot study, some openers were reused more than 10 times without damage. Because the exact number is unknown, a future study should relate the impact on the material properties of more than ten disinfection cycles, as well as the effect of autoclave sterilization.

5. Conclusions

In this study, Maasstad Hospital became the raw material supplier for its products. The results of this study demonstrated that recycling WP waste into new medical products is feasible. Despite becoming more brittle, the strength and hardness of the recycled PP WP increased, making it even more suitable for use in the specific harsh environment of the CSSD. It was demonstrated that the proposed WP reprocessing method could be conducted locally, reducing waste generation, with potential environmental benefits. This would allow hospitals to become more compliant with the circular economy using circular product lines.

CRediT authorship contribution statement

B. van Straten: Conceptualization, Methodology, Writing – original draft, Project administration. **D.R. van der Heiden:** Data curation. **D. Robertson:** Investigation, Writing – review & editing. **C. Riekwel:** Investigation, Resources. **F.W. Jansen:** Writing – review & editing, Validation. **M. van der Elst:** Writing – review & editing, Validation. **T. Horeman:** Supervision, Writing – review & editing, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.129121.

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