

Analysing the Sustainability of Cascade Recycling in Plastic Manufacturing

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Abstract. This study ventures to further sustainable manufacturing by showing how a cascade recycling approach can be utilised by a plastic cosmetic packaging company. Three reprocessing cycles were assessed from product quality, environmental, financial and social points of view. It is shown how the cascade approach did not negatively affect the quality of the produced parts and when compared to a no-recycling scenario, the proposed three-cascade recycling approach results in 28.1% less costs and 29.3% less carbon footprint. The labour increases up to a maximum of 7 hours per 50,000 products. When compared to a conventional in-house recycling scenario, the proposed approach would reduce the costs by 11.7% and the carbon footprint by 12.9%.

Keywords: cascade recycling, regrind, plastic injection moulding, sustainable manufacturing, cosmetic packaging.

1. Introduction

Sustainable manufacturing in current businesses is no longer solely motivated by economic feasibility, rather it must take into consideration all three pillars of sustainability, that is; environmental protection, economic development and social development [1]. The manufacturing industry, being a large contributor to the use of natural resources and waste generation, results in significant environmental impacts. In fact, in recent years, sustainable manufacturing has stood out to be a comprehensive strategy for reducing environmental impacts whilst advancing the economic performance of manufacturing facilities. Materials used in manufacturing are themselves major sources of environmental impacts, due to the energy and resources required to extract and produce them. Hence, with better material management, minimising material consumption will help in achieving better sustainability performance of a manufacturing process [2].

This study aims to further sustainable manufacturing within the polymer processing industry, specifically the manufacturers of plastic packaging for the cosmetic sector. This analysis focuses on the sustainability of recycling plastic injection moulding waste, a process which consumes energy and requires financial and human resources. The objectives of this study are (i) to analyse the technical, financial, environmental and social sustainability of cascade recycling of plastic injection moulding waste, and (ii) to identify the optimum recycled plastic ratio and recycling approach that yields good quality injection moulded parts which can be produced in a sustainable manner.



2. Plastic Recycling

Today, several recycling approaches exist in relation to the plastic manufacturing industry and these are sustainably assessed and analysed in various studies. Whilst recycling can usually be done at different stages of the product's life cycle, to maximise resource efficiency, inner loop recycling is essential, given its inherent higher energy and value saving potential [3]. Outer loop recycling is also beneficial, as it has considerable advantages over incineration and landfilling [4][5]. In general, the highest environmental benefits are achieved through the substitution of virgin resin with recycled material, the production of which leaves a significantly lower impact on the environment [6].

2.1. Regrind

Regrind, as per definition, is a material that has undergone one or more processing cycles such as injection moulding, exposing it to at least one heating cycle. It is produced by grinding sprues, runners, flash and/or reject parts [7][8][9]. When compared to virgin material, regrind is irregularly shaped, resulting in a lower bulk density. Theoretically, this lowers the machine's specific throughput which in turn decreases the process efficiency. Therefore, an improved feeding process may be required [10]. Due to possible changes in mechanical and rheological properties, manufacturers and consumers still doubt regrind to be a reliable replacement of virgin resin, especially in high quality and surface finished parts. This has also created the perception that recycled resin has a lower economical value. Nonetheless, primary recycling, meaning reprocessing, is considered as the most feasible solution for recycling waste in the plastic industry [11].

2.2. *Regrind and virgin resin mixing*

Many manufacturers assume that a maximum of 25 percent regrind can be used in accordance with third party certification standards, despite the fact that these actually read that regrind can be used up to the 25 percent limit unless further testing is conducted. In fact, there is no limitation on how much regrind may be used in approved components if further testing proves that a material retains its properties and remain within specification limits. Such a misinterpretation can result in excessive and unmanageable regrind stockpile [12]. According to Bryce [9], as a general rule of thumb, regrind can safely be added to virgin material at a rate of between 1 percent and 20 percent with most materials. This statement though assumes that the regrind is of high quality and not degraded or contaminated. Therefore, if regrind has been circulating in a manufacturing facility for a prolonged period, its use would require more attention, as degradation and contamination issues may come into play.

Regrind usually holds a lower quality value compared to its virgin equivalent and can usually be acquired at half its price. Luckily, this relatively low-cost material, if not excessively used and abused, will retain up to 90 percent of its original properties [9], making it possible to use regrind at a 100 percent rate. This being said, it is important to have knowledge on the heating/reprocessing history of the acquired material and on how this was handled and stored due to possible contamination. Nonetheless, actual testing ultimately determines the acceptable level of regrind to be used. In a recent study concerning ABS, PLA and PP30GF in various virgin-to-recycled ratios, regrind content, even at a 100% rate, had no effect on part quality [13].

Tracking the level of regrind in parts may seem possible on paper but not that simple in practice, especially when regrind is used in different amounts and possibly for different components. While it is simple for the first processing cycle, it becomes more complicated with every subsequent cycle. This is because an amount of regrind from each previous cycle, is always present, although in a diminishing manner. Therefore, this calls for proper material handling and storing, which may not be the easiest thing to achieve in a manufacturing facility [7].

2.3. *Cascading regrind approach*

An alternative approach to mixing regrind with virgin resin in a continuous regrind loop is the cascading regrind system. This system is implemented by first using up all virgin resin and then move onto using

subsequent generations of regrind in a 100 percent manner. Until one particular generation of 100 percent regrind is used up, the next generation regrind is stored. This process can continue until almost all the regrind in the system is entirely utilised. In a cascading regrind system no mixing occurs, hence eliminating related problems and issues. Chances of contamination are also reduced and in addition, such a strategy is considered as self-purging. Once regrind is used up, any contamination in the regrind stream is removed. In this way, only a small number of parts are affected [7][8][12]. Since this strategy makes the number of heat histories a known variable, polymer degradation is avoided by not allowing molecules to stay in the system for a long period of time, hence related problems are eliminated [12].

Such an approach raises no questions about the amount of regrind actually being used or if it is being properly mixed. Also, regrind tracking becomes much simpler as parts need only be labelled for the resin lot number and its number of passes through the machine, or better, its heat history. With this approach, further separation of regrind for future use is simplified, and even if not directly utilised, such regrind would hold more value, since it can be classified and tested. Hence, such reground material can be sold at a higher price as buyers can be provided with knowledge regarding how many heat cycles it had been through [12]. From a financial point of view, this results in lower capital costs, since it eliminates the need to invest in mixing equipment [7][8]. Nonetheless, as pointed out by Bozzelli [7] and Solomon [14], one particular issue with the cascading regrind system may be colour matching.


In a laboratory scale cascading regrind study, Janicki et al. [12] illustrate the feasibility of this approach by testing two high impact polystyrenes (HIPS) from different suppliers, ignition resistant polystyrene (PS) and polycarbonate (PC) at each of the first three regrind generations. Results pertaining to the tensile and impact strength tests conducted in this study resulted positive. Furthermore, in view of the fact that average molecular weight is stated to be the most direct indicator of polymer degradation, Janicki et al. [12] noted no significant reduction in this property in any of the materials after three processing cycles, hence, negligible molecular degradation had occurred. Other conducted tests in this study showed the same general trend, hence, property retention was proved to be quite good up to several regrind generations. In another study, Vidakis et al. [15] experienced a 30% increase in mechanical properties when recycling ABS up to five processing cycles but then noticed a rapid degradation after the fifth cycle. When tackling this approach from a financial point of view, although testing of parts produced from 100 percent regrind may be costly, contaminated regrind inventories also come with a price. This is because they are either useless, hence taking up space, or will subsequently result in rejects [8].

3. Materials and methods

3.1. Case study

Being a world leader in the cosmetic packaging industry, Toly Products Ltd was chosen as the industrial partner for this case study. Within Toly's manufacturing facility in Malta, a wide variety of high quality packages for the beauty industry are continuously being manufactured in accordance with the high-quality requirements imposed by such an industry.

3.1.1. Product selection. Due to its frequent demand, colour and material, the Tivoli Large Compact (detailed in Table 1) was selected as a foundation for a sustainability analysis of injection moulding of recycled plastic at Toly Products Ltd. The base and lid components are manufactured entirely from ABS (Novodur® P2H-AT), while the platform component is produced from an ABS-SAN blend in a 1:3 ratio. For this study, all three components were manufactured separately as explained in section 3.2. Any regrind resulting from the manufacture of any part was solely used for the manufacturing of that same part.

Table 1. Tivoli Large Compact specifications.


Component	Material	Colour	Mass (g)	Outside Diameter (mm)
Base	ABS	Black	9.09	72.98
Lid	ABS	Black	9.86	72.98
Platform	1 part ABS 3 parts SAN	Black	2.06	69.00

3.1.2. New targets. Plastic recycling was already common practice at the facility, however it was limited to either customer specifications, material supplier recommendations or problems encountered due to material limitations or current recycling practices. Hence, using a new approach to recycling, new targets were set and this study aims to further plastic recycling at the facility to new levels. This was done by manufacturing parts at different regrind to virgin ratios containing higher levels of regrind than the company's present practices. The three material ratios used in this study were (i) 60% Regrind with 40% Virgin, (ii) 80% Regrind with 20% Virgin, (iii) 100% Regrind with no virgin material.

Although literature suggests that a cascading regrind approach, as explained in section 2.3 (with no mixing), is the way forward to recycling in the injection moulding industry, material properties are very dependent on the grade of the material, which includes different additives depending on its use, hence, generalisation is not suggested. This study, therefore, considered the other two recycled material ratios (60% and 80%), should the 100% regrind products fail to satisfy the necessary quality requirements.

Moreover, the reprocessing capability of the materials used was put to test for each of the three ratios. This was done by adapting the working principles of the cascading regrind approach to each. After manufacturing all the required products, product quality was subsequently analysed as explained in section 3.4. With regard to reprocessing, this study covered up to three reprocessing cycles.

The quality of the products produced using these new material ratios was compared to the quality of virgin equivalent products and also to product samples taken from a typical production run at the factory. Typically, platforms contained 20% regrind, while the base and the lid contained 40% regrind. Furthermore, these samples were manufactured from material of unknown heat history, as no information on reprocessing of material is typically recorded.

3.2. Production

In order to accumulate enough injection moulding waste of known heat history, it was required to first manufacture an adequate number of components from 100% virgin material using three injection moulding machines loaded with the three required moulds of the components making up the Tivoli Large Compact. It is important to note that for consistency reasons, only sprues and runners were ground and used as recycled material throughout this study. This process also yielded virgin products, which later acted as a benchmark during quality testing.

Once virgin production for every component was complete, and the resulting waste ground, the three mixtures embodying the three different ratios were produced for each component making up the Tivoli Large Compact. Furthermore, in order to test their reprocessing capability, these mixtures were successively processed for three times in total by grinding their subsequent production waste, mixing with virgin where necessary (excluding the 100% recycled material ratio) and loading them back into the injection moulding machine. This was done, separately, for all three components making up the compact. The whole process is portrayed in Table 2. R_0 refers to the virgin production, R_1 to a production containing first generation regrind, and similarly R_2 and R_3 refer to productions comprising of the second

and third generations of regrind respectively. Calculations pertaining to the planning of these productions allowed for the least waste possible at the final reprocessing cycle.

Table 2. Production process.

0% Regrind	60% Regrind	80% Regrind	100% Regrind
	R ₁	R ₁	R ₁
R ₀	R ₂	R ₂	R ₂
	R ₃	R ₃	R ₃

3.3. Energy metering system

In order to conduct an energy consumption analysis on the injection moulding process, energy consumption was metered for every process portrayed in Table 2 whilst manufacturing platform components to monitor whether this resulted in any trend or discrepancies in energy consumption. Furthermore, energy consumption was metered during the production of the lid and base components from virgin material, so that any variance noticed with the platform could be mirrored on these too. This study also looked into the energy consumed by the grinding process. Hence, energy was metered accordingly so as to allow for the holistic analysis presented in this study.

3.4. Quality testing

In order to verify whether or not the manufactured products were of good quality, validation tests were conducted on the assembled parts by the quality control lab at Toly Products Ltd. For such tests, around 50 samples from each of the ten production runs previously listed in Table 2 were needed, together with another 50 samples taken from a typical production run at the factory. Samples were taken from each mould impression/cavity for a more holistic representation. Given the fact that the only variation from previous validation tests was coming from the material, more precisely regrind content and reprocesses, and also in view of the lengthy process entailed, tests were limited to quality criteria affected by the material. Furthermore, tests were subdivided into three categories: package integrity, visual aspect and functional aspect.

4. Results and discussion

4.1. Quality results

4.1.1. Package integrity and visual aspect. With regard to package integrity and the visual aspect, all compacts passed the required tests. These included several different drop tests, open/close cyclic tests, stress cracking tests and other tests which measured the mismatch or alignment between the base and lid components and also the gap between the two components when the compact is closed. Additionally, a colour comparison test was carried out, in view of colour matching issues mentioned in section 2.3. This test showed that for the platform, colour was constant throughout, but with regard to the lid and base components, a slightly lighter finish was noticed at high regrind contents. However, for all recycled material ratios, lid and base components from R₃ were noticed to be slightly darker than those from R₁. Nonetheless, differences were very minimal and difficult to detect, hence these were of no particular issue.

4.1.2. Functional aspect. With regard to the functional aspect, three tests were conducted: clip opening, hinge breakage and welding resistance at the hinge area. Both the clip opening tests and the welding resistance tests resulted in positive results for all the different ratios and reprocessing cycles tested. Values related to these tests were all within specified control ranges.

Being the ones most likely to be affected by material changes, hinge breakage tests were required to test for initial bending of the hinges, which plastically deform with increasing force. Most values obtained fall within experimental error. Furthermore, compacts produced using virgin material seem to

have bent prior to compacts containing regrind. Also, from the results obtained, components from the 80% R₁ production seem to have superior strength, while bending at the hinge was impeded for a longer time. The uncertainty related to these results varies between 1% and 2.7%, which is an acceptable range. Similar to the clip opening test, no particular trend was noticed, however, it is clear that regrind content increased the strength of ABS. All values obtained were in excess of 7.0 kg (force equivalent), hence all compacts clearly passed this test in view of the minimum specification of 2.7 kg (force equivalent).

To conclude on quality tests, in view of these results and validation reports generated for all samples, all compacts were validated by the quality control lab at Toly Products Ltd and hence, the Tivoli Large Compact is capable of being manufactured in the three new material ratios. The conducted tests more specifically prove that this particular compact can be manufactured with 100% regrind that has been reprocessed for three times, without any compromise on quality.

4.2. Injection moulding energy consumption

For each production run, injection moulding energy was metered for 10 consecutive cycles, with data readings starting after the 5th cycle from the start of each production run, in order to give chance for the injection moulding machine to reach a stable working state.

It is important to note that for each different production, the injection moulding machine was purged from any remaining material used for the prior batch and reloaded with the required material for the next. Furthermore, energy data was collected over a number of days and therefore some variances could have easily occurred due to possible noise such as changes in ambient temperature and fluctuations in supply voltage. Thus, injection moulding parameters may have varied slightly from one reading to the other. This being said, an effort was still made to keep injection moulding parameters as constant as possible.

In view of the results, most energy consumption values were similar and only vary within experimental error (130 Wh/cycle \pm 3.8%). However, some readings were slightly out of this range, with the most energy consuming production being 80% R₂ (143 Wh/cycle) and the least being 100% R₃ (121 Wh/cycle). The first is attributed to a higher than usual power demand, whilst the second is attributed to a combination of low cycle time and low power demand. All in all, the outcome of this injection moulding energy analysis shows that with different regrind content and reprocessing cycles, variance in injection moulding energy is for the most part slight and erratic, and no trend is evident with increasing regrind content. Moreover, the maximum possible discrepancy noted between 80% R₂ and 100% R₃ is of approximately 19%. Although this cannot be deemed negligible, it is not substantial. In view of the outcomes of this analysis, variances in energy consumption for the injection moulding process were not accounted for in calculations and not included in the following sustainability analysis.

4.3. Sustainability analysis

In view of the promising results obtained and the conclusions deduced from available literature, this analysis focuses on a 100% regrind cascading approach and a breakdown of this is provided so as to analyse and compare the different recycling opportunities the manufacturer can opt for. Recycling opportunities include:

- Manufacturing with virgin material only (waste material is sold for recycling),
- Manufacturing with the recycling approach currently employed,
- Manufacturing with a 100% recycling rate and 1 reprocessing cycle,
- Manufacturing with a 100% recycling rate and 2 reprocessing cycles,
- Manufacturing with a 100% recycling rate and 3 reprocessing cycles.

Different scenarios are also possible for the grinding process, and moreover, different options exist with regard to the sale of post-production injection moulding waste, i.e. the remaining runners at the end of a production run:

- G1. Automated and continuous grinding throughout all injection moulding cycles, where the grinder is left switched on during production.
- G2. Batch grinding at the grinder's maximum throughput, either at the end of every reprocessing cycle, or alternatively, in smaller batches.
- W1. Selling post-production injection moulding waste in runner form to a waste broker at the price of €0.10/kg for any material.
- W2. Grinding post-production injection moulding waste and selling it in regrind form at a price of €1.38/kg for lid and base components and €1.28/kg for the platform component. These prices are 50% of the respective virgin material prices which is an assumption based on the prices of various material suppliers, [16].

The following analysis, summarised in Table 3, compares all possible combinations of the above to a virgin equivalent production utilising waste sale option W1 (values of which can be found in the first row), with this combination being the most basic and simplest recycling opportunity.

Table 3. Comparison of different recycling opportunities for a production run of 50,000 compacts.

Regrind %	Number of Reprocessing Cycles	W	G	Total Cost (€)	Cost Savings	Total CO ₂ Emissions (kg)	CO ₂ Savings	Grinding Labour (h)
0%	0	W1		4,133	-	5,201	-	0.0
		W2	G1	3,634	12.1%	5,377	-3.4%	0.0
			G2	3,581	13.4%	5,208	-0.1%	7.0
Current	Unknown	W1	G	3,365	18.6%	4,221	18.8%	2.8
100%	1	W1	G1	3,302	20.1%	4,140	20.4%	0.0
			G2	3,247	21.4%	4,015	22.8%	5.1
		W2	G1	3,154	23.7%	4,186	19.5%	0.0
			G2	3,102	24.9%	4,017	22.8%	7.0
	2	W1	G1	3,110	24.8%	3,913	24.8%	0.0
			G2	3,057	26.0%	3,760	27.7%	6.3
W2		G1	3,055	26.1%	3,930	24.4%	0.0	
		G2	3,003	27.3%	3,761	27.7%	7.0	
3	W1	G1	3,047	26.3%	3,839	26.2%	0.0	
		G2	2,995	27.5%	3,677	29.3%	6.7	
	W2	G1	3,022	26.9%	3,847	26.0%	0.0	
		G2	2,970	28.1%	3,677	29.3%	7.0	

In Table 3, CO₂ values include emissions from primary material production and emissions from energy required to power the grinding process. Also, grinding scenario G in the fourth row refers to a combination of G1 and G2 according to the current practice at the facility.

4.4. Economic analysis

Results show how grinding scenario G2 is always a cheaper option than G1, whatever the waste sale option. This holds true despite the introduction of labour cost with G2. Such an outcome is attributed to the shorter operating times of grinders, which in turn consume less energy although loaded at their maximum rating. Furthermore, the lower maintenance costs for the grinders in scenario G2 also have a substantial effect on total costs. Waste sale option W2 is always more cost-effective than W1 for similar grinding scenarios. This means that although more energy is consumed to grind the remaining post-production waste, the income related to the higher priced regrind outweighs the higher grinding costs.

Moreover, when comparing possibilities within the 100% regrind approach, manufacturing with more reprocessing cycles results in greater overall cost savings. This is due to less virgin material consumption and more efficient use of injection moulding waste, which in turn results in less post-

production waste. Hence, instead of selling most of this waste at an inferior price, this same waste is replacing more virgin material within the same production. Additionally, savings are seen to increase with increasing regrind percentage, hence a 100% regrind approach is a more cost-effective way to deal with regrind. This analysis concludes that the most economical recycling opportunity is the one using a 100% regrind approach, three reprocessing cycles, waste sale option W2 and grinding scenario G2.

4.5. Environmental analysis

The environmental analysis is based on CO₂ emissions related to grinding energy consumption and primary material production. The CO₂ footprint data was obtained using CES EduPack™ [17]. This analysis shows how grinding scenario G2 results in approximately 2% to 3% reduction in total CO₂ emissions when compared to grinding scenario G1 within the same waste option. This reduction is attributed to the shorter operating times of grinders, which in turn result in lower electricity demands and hence, less CO₂ emissions.

Although, as deduced economically, waste sale option W2 is more cost-effective than W1, this produces more CO₂ emissions for the same grinding scenario due to the increase in energy consumption, as more material is being ground. However, this difference in CO₂ emissions at maximum, results in less than 1% reduction in total CO₂ emissions, and furthermore, this difference is seen to narrow down to a negligible percentage with three reprocessing cycles due to lower quantities of post-production waste. When manufacturing with more reprocessing cycles using a 100% regrind approach, apart from being more cost-effective as previously explained, CO₂ emissions decrease correspondingly. This reduction is attributed to the lower consumption of virgin material, which plays an important part in CO₂ emissions. Furthermore, CO₂ emissions were seen to decrease with increasing regrind percentage.

Recycling opportunities with a virgin production are only limited to external recycling of post-production waste, since, with such an approach, the facility does not make internal use of any of its production waste. Hence, no CO₂ emissions are reduced with regard to primary material production as none of the virgin material is replaced with regrind. To make matters worse, CO₂ emissions related to grinding are further added with waste option W2, hence resulting in more CO₂ emissions than the first and most basic recycling opportunity (0% W1). On top of the current recycling approach, a 100% regrind cascading approach is seen to be furthermore beneficial for the environment.

This environmental analysis concludes that the most environmentally benefitting recycling opportunity is the one using a 100% regrind approach, three reprocessing cycles and grinding scenario two (G2). With regard to the waste sale scenario, technically, W1 is less harmful to the environment than W2, but since the difference in CO₂ emissions is minimal, this is decided upon after an overall analysis.

4.6. Social analysis

Factors discussed in the environmental analysis, also affect society as part of the environment. Less CO₂ emissions, reduce the Global Warming Potential of the operations and indirectly result in a better quality of life. Furthermore, more labour is introduced with grinding scenario G2. With waste option W1, this added labour increases with increasing reprocessing cycles for the 100% regrind approach, whilst with waste option W2 for the same 100% regrind approach, this is constant throughout. When labour hours are compared, any recycling opportunity that makes use of grinding scenario G2 generates more work, specifically green jobs. For 50,000 products, a maximum of 7 hours of labour related to grinding of injection moulding waste is added with waste option W2 and grinding scenario G2. Hence, given the economic and environmental benefits of the 100% regrind approach with three reprocessing cycles, it would be wise to opt for waste sale option W2 and grinding scenario G2.

5. Conclusions

In view of the above analyses, it is clear that in-house post-production recycling affects positively all the three pillars of sustainability. Moreover, a 100% regrind approach with the greatest number of reprocessing cycles is the most benefitting for all the three pillars of sustainability. This study has tested up to three reprocessing cycles, however, more reprocessing cycles would mean less virgin material consumption and less post-production waste, hence more efficient use of regrind. In view of the economic, environmental and social analyses, the sustainable solution proposed concerns a 100% regrind approach with three reprocessing cycles (R_3), where grinding is carried out in batches (G_2) and any post-production waste is sold in regrind form (W_2). When compared to a no-recycling scenario, this will ultimately result in 28.1% less costs, 29.3% less CO₂ footprint, and labour is increased up to a maximum of 7 hours per 50,000 products. When compared to the typical in-house recycling and mixing scenario currently employed by the case study factory, the proposed cascade recycling approach would reduce the costs by 11.7% and the CO₂ emissions by 12.9%. This approach would increase the labour required by 4.2 hours per 50,000 products.

Cost savings are mainly attributed to the low cost of grinding when compared to the virgin material cost. In fact, with regard to ground material, electricity costs amount to less than €0.01/kg, labour costs amount to approximately €0.10/kg and maintenance costs also amount to less than €0.01/kg. When their total of €0.12/kg is compared to the virgin material prices of circa €2.75/kg for ABS and €2.50/kg for SAN, cost cutting opportunities are very evident.

With a simple shift in how regrind is being handled and used, the proposed system would bring remarkable benefits with respect to all three pillars of sustainability. The proposed recycling system produces the least waste possible, hence making the best use of the available material. Therefore, apart from being the most cost-effective system, this reduces the amount of non-biodegradable plastic waste that may in time end up in landfills, affecting positively both the environment and society. Furthermore, the cascading regrind approach on which the proposed system is based makes the material heat history a known factor. This in turn, allows the manufacturer to sell regrind at a higher price than what is normally attributed to post-production waste with an unknown heat history.

This study paves another way for manufacturing companies to further their commitment towards sustainable manufacturing. This is achieved through a reduction in the use of natural resources pertaining to both primary material and energy production, and also through better management and efficient use of inevitable injection moulding waste. As a result of the above, more green-job opportunities are created. Additionally, all this is accomplished with remarkable profits, hence deeming this development economically sound.

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References

- [1] Stark R, Selinger G and Bonvoisin J 2017 *Sustainable manufacturing: Challenges, solutions and implementation perspectives*, Springer Nature
- [2] Yuan C, Zhai Q and Dornfeld D 2012 A three-dimensional system approach for environmentally sustainable manufacturing *CIRP Annals* **61(1)** 39-42
- [3] De Jong A and Mellquist, A 2021 The Potential of Plastic Reuse for Manufacturing: A Case Study into Circular Business Models for an On-Line Marketplace *Sustainability* **13(4)** 2007
- [4] Chen Y, Cui Z, Cui X, Liu W, Wang X, Li X and Li S 2019 Life cycle assessment of end-of-life treatments of waste plastics in China. *Resources, Conservation and Recycling* **146** 348-357
- [5] Hou P, Xu Y, Taiebat M, Lastoskie C, Miller S and Xu M 2018 Life cycle assessment of end-of-life treatments for plastic film waste *Journal of Cleaner Production* **201** 1052-1060

- [6] Gu F, Guo J, Zhang W, Summers P and Hall P 2017 From waste plastics to industrial raw materials: A life cycle assessment of mechanical plastic recycling practice based on a real-world case study *Science of the Total Environment* **601-602** 1192-1207
- [7] Bozzelli J. Regrinding Plastics | Prospector Knowledge Center [Internet]. Prospector Knowledge Center. 2021 [cited 5 March 2021]. Available from: <https://knowledge.ulprospector.com/1468/pe-regrinding-plastics>
- [8] Bozzelli J 2015 Another way to deal with regrind *Plastics Technology* **61(1)** 38-41
- [9] Bryce D M 1996 *Plastic injection molding: manufacturing process fundamentals*. Society of Manufacturing Engineers.
- [10] Thieleke P and Bonten C 2021 Enhanced Processing of Regrind as Recycling Material in Single-Screw Extruders *Polymers* **13(10)** 1540
- [11] Fei N C and a Kamaruddin N M M 2013 A Degradation Study of Virgin and Recycled ABS Blends Subjected to Multiple Processing *International Journal of Research in Mechanical Engineering* **1(1)** 93-102
- [12] Janicki S L, Bain Jr M F and Groleau R J 1992 The material Cascade: An Alternative Form of Regrind Utilization *ANTEC 92--Shaping the Future* **1** 1201-3
- [13] Vassallo C, Rochman A and Refalo P 2020 The impact of polymer selection and recycling on the sustainability of injection moulded parts *Procedia CIRP* **90** 504-9
- [14] Solomon N 2021 Influence of repeated recycling on the quality of molded finished products *International Journal of Environmental Science and Technology*
- [15] Vidakis N, Petousis M, Maniadi A, Koudoumas E, Vairis A and Kechagias J 2020 Sustainable Additive Manufacturing: Mechanical Response of Acrylonitrile-Butadiene-Styrene over Multiple Recycling Processes *Sustainability* **12(9)** 3568
- [16] Plastics News [Internet]. Plasticsnews.com. 2021 [cited 4 August 2021]. Available from: <http://www.plasticsnews.com/resin>
- [17] 2018 *Edupack*, C. E. S. Granta Design Limited