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The impact of polymer selection and recycling on the sustainability of injection moulded parts

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A R T I C L E I N F O

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A B S T R A C T

This study is aimed at providing an overview of how different materials can affect the sustainability of plastic injection moulded parts. A material is typically chosen to satisfy predefined criteria or functions. From a sustainability point of view, one could either choose 'cleaner' virgin materials or consider using recycled supplies. This study looked into three different widely used materials, both in the virgin and regrind state: Acrylonitrile Butadiene Styrene (ABS), Polylactic Acid (PLA) and 30% Glass-Fibre Reinforced Polypropylene (PP30GF). The regrind content of the three materials was analysed at six different virgin-to-recycled ratios. From the analysis, it was clear that no particular material was superior in terms of all the three environmental, economic and social pillars, as this depends on various factors such as the intended function of the product. Each material exhibited several environmental and functional advantages and disadvantages. This makes it rather difficult to rank the materials in order of preference. For the particular case study used in this study, PP30GF with 100% regrind content resulted to be the most apt option.

1. Introduction

The manufacturing industry has a major impact on the three pillars of sustainability, especially the environment. This is because of the large energy consumption and carbon footprint associated with manufacturing practices. In order to address this problem, the concept of sustainable manufacturing is being implemented by many companies (Singh et al., 2016). Injection Moulding is a very popular process in the plastic manufacturing industry due to its multiple advantages over other methods. However, injection moulding is also energy intensive. It is therefore very important to find different solutions on how to achieve a more sustainable process (Thiriez and Gutowski, 2006). In addition to this, material selection plays a very important role in the sustainability of plastics. Some materials are more energy intensive to produce than others. Also, what happens to the material at the end of its use-life is very important to consider. Nowadays, for any particular application, a vast selection of materials is available. Hence, the careful selection of materials is crucial to achieve a process that is environmentally, socially and economically benign.

2. Literature review

2.1. Material selection

The wide range of mechanical properties, durability, performance and cost, enforces the usage of plastic in vast applications. As a consequence, the production of plastics has increased substantially over the recent years and the material selection process has been mainly based on the required functional performance for the given application. This approach is progressively being replaced by life cycle engineering (LCE) in which the environmental and economic impacts throughout the whole product life cycle are concurrently taken into consideration. Material selection is a fundamental part of the product design as it can vastly influence the environmental impacts and product's costs throughout its entire life cycle. In fact, Field et al. (2001) claimed that designers should rely on four main factors when considering materials choice, including: the relationship between the required technical performance of the product and materials specification; the environmental performance of the product; the economic performance; and the practice of industrial design embedded in the product and its functionality.

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2.1.1. Biobased and biodegradable plastics

As the demand for plastics is continuously increasing, more importance has lately been given to the sustainability assessment of the types of plastics available, especially their environmental impact. The problem with the traditional types of plastics is that most of them are not biodegradable. This results in an increasing accumulation of solid waste deposition. Also, traditional plastics are processed from oil and oil products, hence the shortage of petroleum is another concern. Because of this, a lot of research has been going on in search of new alternative materials. Two of the main current alternatives are biodegradable and biobased polymers (Greene, 2014). Compared to the traditional petroleum based plastics, biodegradable plastics generate less waste, carbon emissions and toxic pollution. Through a thermochemical process, biodegradable polymers are converted to biomass, carbon dioxide and water at the end of their use-life. On the other hand, biobased polymers are made from ingredients that are natural or organic, including potato, starch from corn, wheat or rice. The advantage of these polymers is that they possess the same properties as their conventional versions (Greene, 2014).

2.1.2. Reprocessing of plastics

The main issue with the reprocessing of plastics is that when compared to the virgin material, the recycled plastic is considered inferior in terms of mechanical performance due to a loss in its mechanical properties. Rahimi et al. (2014) have concluded that polymer degradation is the main effect on the polymer during reprocessing. They have focused their testing on ABS and found that the impact strength and shrinkage were the two properties mostly effected by reprocessing. Another study on reprocessing of ABS, conducted by Salari and Ranjbar (2008), shows that in five reprocessing cycles, the notched Izod impact strength decreased from 40 kJ/m^2 to 28 kJ/m^2. Cox (1995) has conducted a study on recycling of polyhydroxyalkanoate (PHA), which is a polymer that is both biobased and biodegradable. According to this study, the most applicable composition for PHA is that of 20% recycled polymer with 80% of virgin material. Rahimi et al. (2014) agreed that this statement can also be applied to ABS, after concluding that at 20% recycled polymer, the impact strength was still not greatly affected and it was only a greater percentage that resulted in its sharp decrease. Moreover, Roy and Li (2014) described that as a general rule applicable to most polymers, the percentage of regrind content that could be used without affecting the material properties is between 10% and 30%. However, this statement is too generic and the effect of each material should be studied accordingly.

2.2. Energy and water requirements for injection moulding

2.2.1. Energy utilization

Energy utilization is usually designated as one of the main metrics of injection moulding. This is due to the fact that plastic processing requires energy at every step of the process, hence it is a dominant factor when compared to other sustainability assessment factors. According to Roy and Li (2014), the injection stage is the most energy intensive stage, during which a significant amount of energy is required to force the melt into the mould cavity. Kanungo and Swan (2008) also studied the energy consumption of the main stages of an injection moulding cycle, providing a mathematical representation for each. They agree that the injection stage consumes a significant amount of energy, mainly because of the movement of the screw and the clamping pressure. The study also claimed that the mould opening and closing stages use nearly as much power as the injection stage, however it is over a shorter period of time.

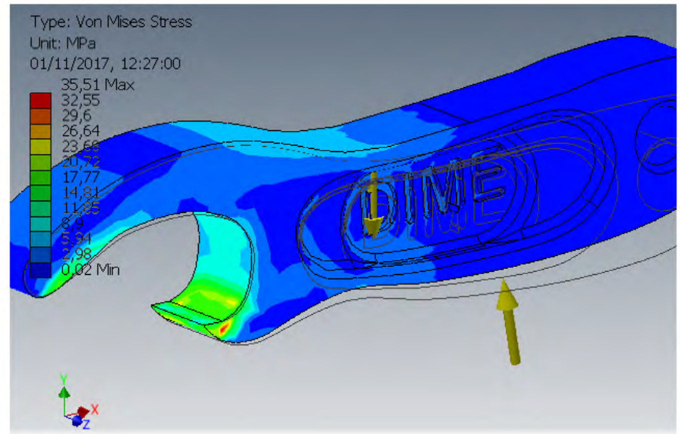

Fig. 1. Stress Analysis of Bottle Opener Part.

2.2.2. Water consumption and pollutants

Although energy utilization has the most pronounced effect on the sustainability of the injection moulding process, other environmental issues such as water consumption and pollutants should also be considered. When considering a cradle-to-gate approach, the highest amount of water consumption is used in the production phase of the virgin material. According to a study by Franklin Associates (Associates, 2011), this amounts to around 80% of the total water usage. Another 18% is used for the production of other materials and incoming process water, while 2% is associated with the steps to extract, process, and deliver the fuels used for the process and transportation phases, including water consumption associated with electricity generation.

When considering pollutants, material selection plays a very critical role. Most plastics are considered non-toxic. However, even inert materials such as polypropylene (PP) and polyethylene (PE) are not completely stable under the influence of mechanical pressure and heat. Under such conditions, plastics can release hazardous substances when decomposed, which may be detrimental to human health (Roy and Li, 2014). This is not only applicable at the production stage but also at the end-of-life. For this reason, if possible, the plastic selection should be such that the plastic products will eventually break down into harmless compounds.

3. Experimental analysis

To study the effects of different materials on sustainability, a part suitable for the injection moulding process was selected. Following the studies by Tranter et al. (2017) and Meekers et al. (2018), a pocket sized bottle opener was selected. The bottle opener idea was first presented by Tranter and then modified by Meekers. The final modified version was also used for this study.

3.1. Material selection process and experimental setup

Different materials suitable for the bottle opener part design had to be selected in order to subsequently compare the sustainability of each material. The bottle opener had to be made of a material that is strong and durable for its use, while being lightweight so that it would be easy to carry. A bottle opener is usually cheap to buy hence the material selection was also restricted by cost. More importantly, the material had to be suitable for processing by injection moulding. A stress analysis was performed using Autodesk Inventor as shown in Fig. 1. The resulting maximum stress value was used to determine the minimum yield strength required from the material. Other material selection criteria included material shrinkage, polymer moulding energy and embodied energy for primary production. A shortlist of materials that meet all of the mentioned criteria was established. After extensive research, three materials were shortlisted, namely Acrylonitrile Butadiene Styrene (ABS), Polylactic Acid (PLA) and Polypropylene with 30% glass-fibre reinforcement (PP30GF).

The grades of ABS, PLA and PP30GF used in this study are Elix ABS P2HAT, Ingeo Biopolymer 4043D and Hostacom G3 U01 L respectively. This study was performed on a hydraulic injection moulding machine (IMM), BOY 22E. Other equipment required for the injection moulding process included a temperature control unit (TCU) and a chiller unit. A plastic grinder was also utilised in order to regrind virgin material scraps. For each material, the energy consumption of the IMM, TCU, chiller and grinder was recorded by means of power loggers, connected separately to each piece of equipment.

3.2. Quality criteria

The quality of the injection moulded parts was measured through five criteria. First, the part mass and part length were measured and recorded, followed by a visual inspection of surface quality. A force was then applied to the part until its failure, and the maximum applied force was recorded. This was done by means of a force gauge. These results were able to determine if the part could endure a force that is greater than the required force to open a beverage bottle cap (27 N (Clerc et al., 2002)), hence confirming that the part is fit for its function. In this step, the displacement was also measured, representing the amount of vertical travel of the force gauge until part failure.

3.3. Choice of experimental design

One independent variable, the material, was analysed at different regrind portions varying between 0% and 100% at 20% increments. Thus, three materials with six factor levels each, resulted in a total of eighteen different trials. For each trial, the energy consumption was measured over ten cycles.

For the injection moulding process, one optimum set of process parameters was chosen for each material. The datasheets for each material were consulted and an extensive research was carried out in order to understand the best processing conditions for ABS, PLA and PP30GF respectively. Following this, a series of tests were carried out on the injection moulding machine with the range of values established for each process parameter. The testing period was a lengthy process that finally yielded the best set of processing parameters that produced parts with the least possible defects. The testing was carried out using virgin material and the best determined set of processing parameters was kept fixed for the rest of the experimental procedure.

4. Results and discussion

4.1. Total energy consumption

The energy consumption to process different materials at different regrind variants was compared. Hence, the data for each trial was gathered and the total energy consumption per cycle of the IMM, TCU, chiller unit and grinder was calculated. The results can be seen in Fig. 2. For all three materials, the chiller consumed the highest value of energy consumption, followed by the IMM, TCU and grinder. The variation of regrind content for each material did not have any considerable influence on the energy consumption values of the IMM and ancillary equipment. Hence, the slight increase in the total energy consumption with an increase in regrind content is due to the energy consumed by the grinder. This is mostly significant for PP30GF which exhibited an increase of 5%

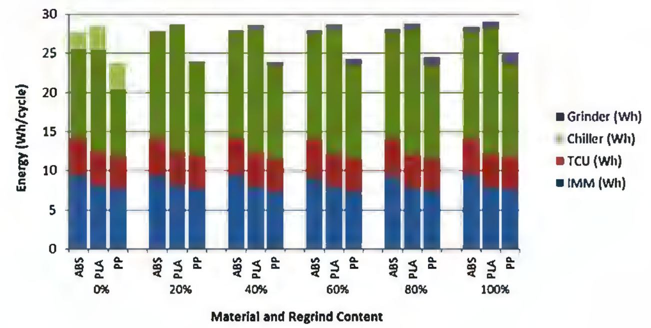

Fig. 2. Energy Consumption of the IMM, TCU, Chiller and Grinder for each Material.

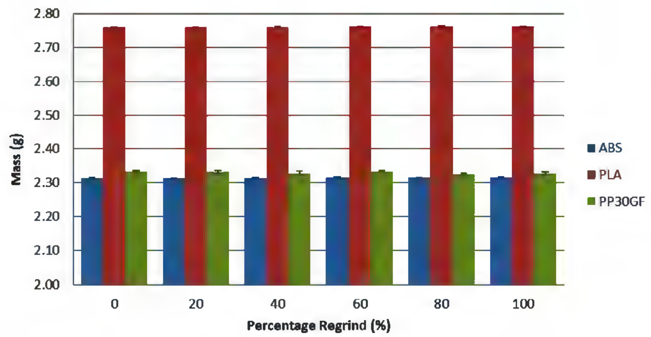

Fig. 3. Graph of Average Part Mass.

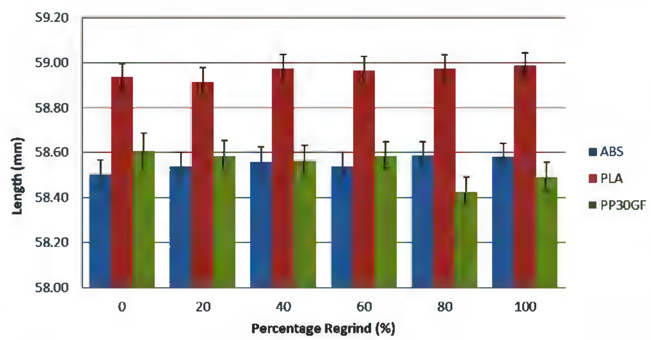

Fig. 4. Graph of Average Part Length.

in energy consumption when comparing virgin material to 100% regrind content.

The material with the least energy consumption was virgin PP30GF with a value of 23.80 Wh/cycle, while the material with the highest energy consumption was PLA with 100% regrind content, with a value of 28.82 Wh/cycle. Hence, the part made of 100% reground PLA required 21% more energy to produce than virgin PP30GF. When solely considering the IMM, ABS consumed more energy than PLA. However, due to its longer cycle time and the large effect of the chiller, PLA ended up consuming the highest total energy per cycle.

4.2. Quality results

To compare the quality results, five random parts were chosen for each material and regrind content variant. All results confirm that the regrind content had no significant effect on the quality of the parts. For each material, the results were very similar for all regrind variants. Figs. 3 and 4 show that the mass and length for ABS and PP30GF parts are very similar to each other while PLA shows a higher result for both mass and length. A higher mass for PLA may be the result of its higher density. On the other hand, the longer lengths of PLA may be the result of the slight flash that was

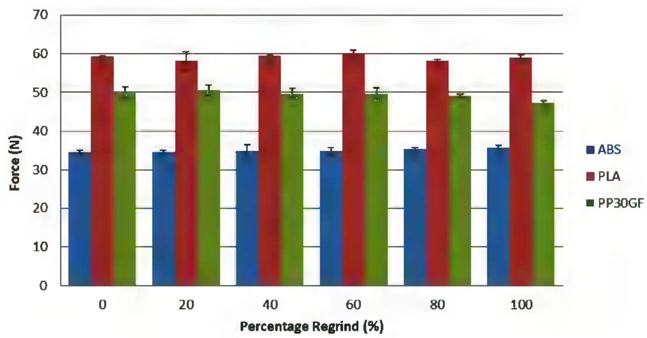

Fig. 5. Graph of Average Maximum Endured Force Until Part Failure.

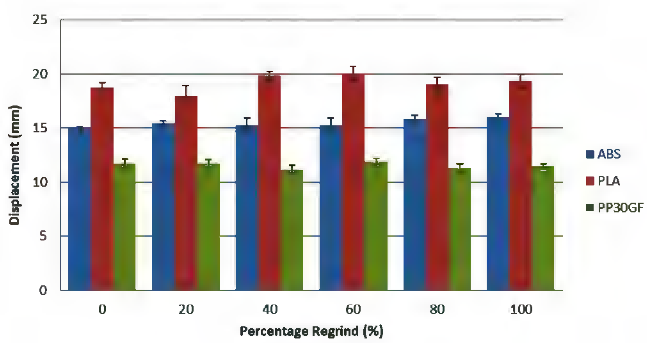

Fig. 6. Graph of Average Displacement until Part Failure.

observed in all the randomly selected samples. Fig. 5 shows that PLA was superior in terms of maximum endured force until failure, with a value of 60 N. The lowest value was that for ABS with 35 N. A force of 27 N is required to open a beverage bottle cap (Clerc et al., 2002). Hence, the quality results confirm that all materials and all regrind variants are valid for the aim of this study as they meet the minimum force requirement. The displacement graph as shown in Fig. 6, is directly related to the maximum force endured. However, it is evident that although PP30GF endured a significant maximum force of 50 N, it showed the least displacement with a maximum value of 11.95 mm when compared to ABS with 16.04 mm and PLA with 20.06 mm. This is likely owing to the higher stiffness of the material, due to the glass fibre reinforcement.

4.3. Costings

For a complete cost analysis, the total cost of material and energy consumption was calculated for each material, assuming a yearly production of 500,000 bottle openers. For the energy consumption costs, the values for the IMM, TCU and chiller unit were included. On the other hand, the cost of the energy consumption of the grinder was considered as a material cost for the production of regrind material. The costs of virgin material were determined from the respective material's datasheet from CES EduPack (Granta Design 2013). For the energy consumption costs, the Maltese non-residential energy tariff rates were used. A comparison of the materials in terms of total cost can be seen in Fig. 7.

The cheapest material was 100% reground PP30GF at €880 per 500,000 parts. On the other hand, the most expensive material was virgin ABS, at €4938 per 500,000 parts. Such a significant difference is mainly because the parts produced from 100% regrind content are utilizing the 'waste' material and no direct cost of material is involved. The cost of material for the regrind content is in fact the cost of the energy consumption of the grinder. For this scenario, it is assumed that the company produces enough 'waste'

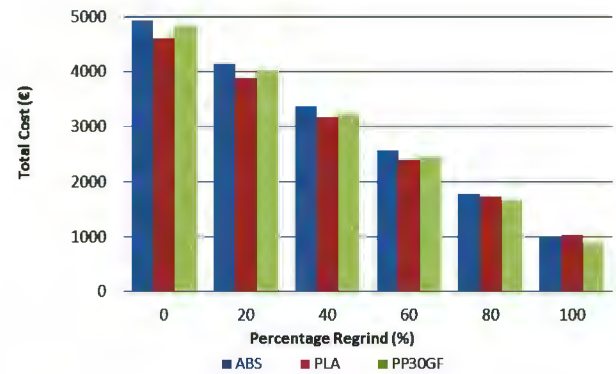

Fig. 7. Total Cost of Material and Energy Consumption per 500,000 Parts.

material that can be ground and used for the production of the part.

4.4. Analysis

4.4.1. Environmental analysis

The environmental pillar is the most adversely affected sustainability pillar in the manufacturing industry due to the high energy consumption and carbon dioxide emissions. From the energy consumption results, it was determined that virgin PP30GF requires the least amount of energy to process. Hence, this material also has the lowest carbon footprint to produce by injection moulding.

In Malta, electricity generated from local power stations, the Malta-Italy interconnector and renewable energy sources results in around 444 gCO_2/kWh (National Statistics Office Malta, 2017; ISPRA, 2018). Per 500,000 bottle openers, the carbon footprint of the production of virgin PP30GF parts, is therefore 2641 kg. On the other hand, the material that consumed the most energy was found to be PLA with 100% regrind content. This has a carbon footprint of 3129 kg per 500,000 parts, which is an 18% cent increase over PP30GF.

Unlike ABS and PP, PLA is both biobased and biodegradable. For this reason, PLA is considered to be more environmentally friendly. However, other factors should also be considered such as the embodied energy, water usage, CO_2 and environmental footprint, related to primary production. Although PLA is a biobased material, it still generates a higher carbon footprint during its primary production than PP30GF, and the environmental footprint, represented by the Eco-indicator 99 is also much higher, according to the material's datasheets from CES EduPack (Granta Design, 2013). On the other hand, the embodied energy and water usage for primary production of PLA are lower than those of PP30GF. All values for ABS are higher than for the other two materials as shown in Table 1.

The substitution of fossil-based plastics by biobased plastics can have other environmental effects, such as a lower non-renewable energy use and reduced greenhouse gas (GHG) emissions. However, the reduction in GHG emissions may be negatively influenced by land-use change, either directly or indirectly. In addition to this, biobased plastics usually have a higher impact than fossil-based plastics on categories that are related to agriculture, including acidification and eutrophication (Greene, 2014).

From the quality results, it was determined that ABS fails at an average force of 35 N, PLA at 60 N and PP30GF at 50 N. Since the force required to open a beverage bottle is approximately 27 N, ABS is more likely to fail after less uses than PLA and PP30GF. PLA will therefore theoretically have the longest use-life which is undoubtedly another environmental benefit.

Table 1
Environmental Analysis Data for ABS, PLA and PP30GF (Granta Design 2013).

Material	Primary Material Production Embodied Energy (MJ/kg)	CO_2 Footprint (kg/kg)	Water Usage (l/kg)	Eco-Indicator 99 (millipoints/kg)
ABS	90.3–99.9	3.64–4.03	167.0–185.0	352
PLA	49.0–54.2	3.43–3.79	65.6–72.5	278
PP30GF	62.3–68.9	2.04–2.25	111.0–122.0	191

4.4.2. Economic analysis

As determined in Section 4.4, when considering both the material cost and energy consumption, the cheapest material per 500,000 parts was 100% PP30GF at €880, and the most expensive was 0% ABS, at €4938. It is evident that although the regrind content did not have any effect on the energy consumption or part quality, it did have a significant effect on the material cost. The cost of recycled material is significantly cheaper than virgin material. Hence using regrind is not only beneficial for the environment but it is also much more economical from a financial point of view.

4.4.3. Social analysis

The social pillar is also widely affected by the manufacturing industry. PLA is a favoured choice in this pillar as it does not contribute to resource depletion. Also, although PLA is meant to be composted, it does not produce toxic fumes if incinerated, unlike traditional plastics. However, one can also argue that PLA production depends on large fields of crops. Therefore, although the sources used to create PLA are renewable, the fields used to grow these crops could be used to produce foodstuff for the world's growing population. Sudesh and Iwata (Sudesh and Iwata, 2008) have studied the sustainability of biobased and biodegradable plastics. They agreed that the use of these materials is generally accepted as being sustainable and eco-friendly since it leads to the reduction of fossil resources use. However, they argued that there are concerns that the production of these materials may not essentially be environmentally friendly. This is because they heavily rely on plant biomass which is also the primary source of our food supplies.

On another note, the plastic manufacturing industry is socially inclusive and offers a wide range of jobs. Plastic has also become beneficial in many industries such as in construction, transportation and healthcare. In modern day healthcare, plastic products are essential for use in drug delivery systems, surgery, pharmaceuticals, healthcare products and medical packaging.

5. Conclusion

In this study, the effect of material selection on the sustainability of plastic injection moulded parts was evaluated. In order to achieve the objectives and aim of this study, several steps were involved in the process. First, an extensive research was conducted in order to understand the background of the problem and to analyse the work that has already been done on the subject. The next step included a material selection process which has led to the final shortlist of three materials, namely ABS, PLA and PP30GF. Each material was studied at six different regrind variants and for each variant, the energy consumption of the IMM, TCU, chiller and grinder was recorded. Quality testing and inspection was then performed on the injection moulded parts for each regrind variant.

Sustainability includes several aspects that are mainly represented by three pillars: the environmental, economic and social pillars. From the analysis, it was clear to note that no particular material was superior in terms of all the three pillars. Each material exhibited several advantages and disadvantages and this makes it difficult to rank the materials in order of preference. However, for the case study used in this study, PP30GF with 100% regrind content resulted to be the most apt option after thoroughly evaluating all results. This result may have varied if a different case study part was used. However, the behaviour of ABS, PLA and PP30GF when used in injection moulding, was well distinguished especially by the cycle and cooling time along with other processing parameters.

Another interesting result is that the regrind content did not have any effect on either the energy consumption or the quality results that were tested for this study. From the literature review, it was expected that the quality results of the parts with 30% or more regrind content would be inferior to the parts made of virgin material. However, this was not the case for the bottle opener part. This is a good result for manufacturers that produce parts of similar size, material and function. Making use of regrind material is not only much cheaper than virgin material but doing so is also a sustainable option both environmentally and socially.

CRediT authorship contribution statement

Chantel Vassallo: Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing - original draft, Writing - review & editing. **Arif Rochman:** Formal analysis, Methodology, Resources, Supervision, Writing - review & editing. **Paul Refalo:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing - review & editing.

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