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Exploring the Benefits of Remanufacture during Product Prototyping: A Cost and Time Based Analysis

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Abstract

Whilst remanufacture is identified as a key enabler for sustainable manufacture in future industry, its role within the context of new product development remains unclear. Where prototypes often go through multiple iterations with varying degrees of change, could remanufacture be adopted to reduce the time and cost components of design iteration? This paper presents a computational study to explore the potential savings afforded by remanufacture across stages of a rapid prototyping process. Results suggest significant reductions to development time and cost can be achieved.

Keywords: *rapid prototyping, remanufacturing, change management, cost management, hybrid prototyping*

1. Introduction

New Product Development (NPD) is a key strategic activity in the management of product innovation, aligning the objectives of an organisation with wider societal demands for more efficient, cost effective and competitive products. The role of prototyping in NPD is regarded an essential part of the development process, where designers employ a range of methods and methodology to probe a particular design challenge or opportunity. Thus, it is widely accepted that increased prototyping in the development stage leads to improved products (Camburn *et al.*, 2017). However, prototyping often predetermines a large portion of resource deployment (Camburn *et al.*, 2017), where in some cases prototypes go through thousands of iterations before satisfying design and stakeholder requirements (Dyson, 2001) it is evident that reducing iteration time, cost and the environmental impact of prototyping is of significant value to enterprises engaged in NPD. In recent years methods to save energy and raw materials in the production process have seen increased uptake from manufacturers across sectors. One such method is remanufacture, where functioning/non-functioning complex assemblies are brought to a 'like-new' functional state by replacing, and rebuilding their component parts; recovering a substantial fraction of the materials and value added in its first manufacture at low additional cost (Ijomah *et al.*, 1999). Further, (Xing *et al.*, 2007) identify the potential for remanufacture to not only restore, but upgrade products by accommodating incremental changes/improvements to the products functionality. Examples of which are given by an industry study (Jensen *et al.*, 2019) where Siemens Wind Power (SWP) is shown to improve the efficiency of in-use turbine blades by 1.5%, using remanufacture to implement upgrades at '*negligible cost*'. Philips Healthcare further highlight a reduction of up to 80% in material use by adopting remanufacture in their business practice. Whilst the benefits of remanufacture are apparent, in the context of prototyping remanufacture lacks as clear a definition, posing the question as to its potential for application in NPD, and more specifically to prototyping. Where in prototyping, a part may go through multiple versions, the capability to synchronise/reduce transmission time across physical/digital domains, coupled with the potential time, cost, and energy savings afforded by remanufacture, present a strong value proposition for the investigation of such methods in prototyping. This could include remanufacture as a repair, upgrade/refresh of current (prior) generation of product, reusing iterations of prototypes, or remanufacture using donor parts which represent the 'nearest-to' net-shape. There is a clear case to expect prototype remanufacture to support reduced numbers of individual physical prototype versions, reduced material use, reduced cost, and increased process speed. However, there is no clear investigation of remanufacture applied to prototypes specifically, of the scale of benefits that may be achieved, or the break-even points at which remanufacture becomes more or less costly than simply refabricating a prototype part in its entirety. We therefore outline a simulation study to explore three real-world cases to which remanufacturing (RM) methods are applied, comparing the theoretical time and cost to remanufacture from a version 1 part to a version 2 part, against the time and cost for refabrication (RF). Selected cases represent the common types of change between versions of a prototype in product development, including to add functionality, or part optimisation such as light-weighting. We consider both additive and subtractive steps in the remanufacturing method and focus on accessible Rapid Prototyping (RP) tools widely used in industry, including a desktop 3-axis Material Extrusion (MEX) 3D printer, and desktop 3-axis CNC milling machine. Results were analysed to detect difference between methods across all cases, and at varying model scales. Finally, the paper reflects on the potential benefits of remanufacture in the prototyping context and identifies opportunities for future work.

2. Methodology

To investigate the potential for remanufacture in the prototyping process a 4-step computational study was outlined to simulate real-world cases to which remanufacturing methods could be applied. Results were measured in terms of time and cost with evaluation made against the calculated values for refabricating. In this section we present the rationale for selecting case studies, study methods, and metrics for evaluation. An overview of steps featured in this section are given in Figure 1.

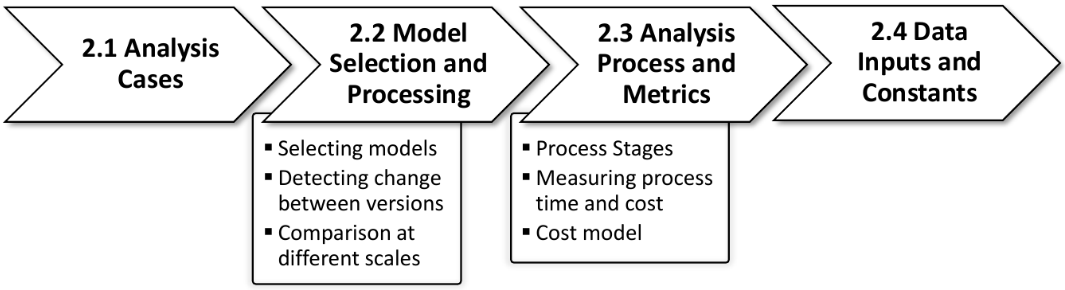

Figure 1. Study methodology flowchart

2.1. Selection of Analysis Cases

By observing the types of change to most frequently propagate through versions of a prototype in product development (Smith and Tjandra, 1998), we conceive three separate cases for this study of remanufacture. Each differentiated by the operations required, and order thereof to theoretically remanufacture a given part from version 1 to version 2. Definition of the cases are as follows:

a) **Boolean remanufacture:** a single additive or subtractive operation to an existing part without need for prior modification.
b) **Sequential remanufacture**: requiring a sequence of local additive and subtractive operations.
c) **Multi-orientated remanufacture**: where both cases *a* and *b* may apply at different locations of the prototype, requiring more than one part orientation and operation for completion.

Models were selected to best illustrate each of the cases, with the operations required to implement change between model versions corresponding to the above definitions for remanufacture.

2.2. Model Selection and Processing

For each case, a dataset of models representing different versions of a part was curated from the CAD model sharing website thingiverse.com[1]. Thingiverse allows users to share digital design files, providing free open-source hardware designs under the Creative Commons license. The thingiverse database was queried using the terms '*v1*' and '*v2*' for projects featuring multiple versions of a design in their project files. Model versions were subsequently aligned and compared using mesh and point cloud analysis tools such that change between versions could be detected and quantified.

2.2.1. Selecting Models

Search results were filtered to curate a dataset of STL models with discernible change between part versions. A total of 60 suitable model pairs were downloaded and reviewed, from which three pairs of models were selected for the study based on their congruity to the definition of cases (A, B, C) outlined in section 2.1.

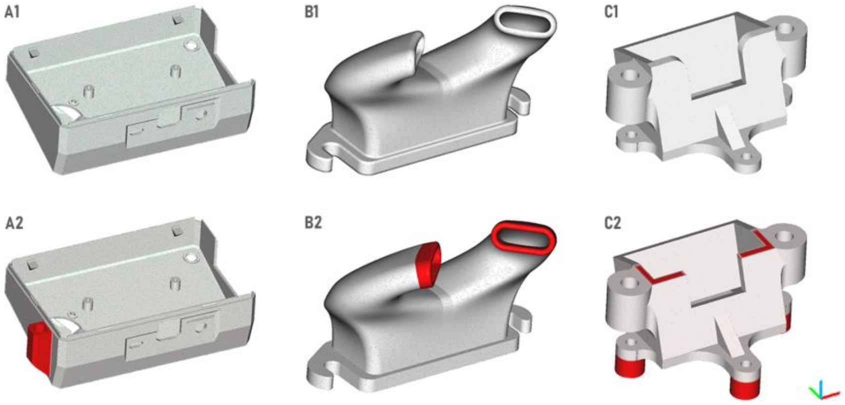

Figure 2. Versions 1 and 2 of models A, B, C with highlighted changes.

Models selected for each case are shown in Figure 2, with locations of change between versions highlighted in renders **A**2, **B**2, **C**2. To give further insight as to the characteristics of change, a description for each model is given in the points below:

- **A**: Raspberry Pi casing - altered to *add functionality* by including a pen holder. Boolean change adding a volume to the existing design.
- **B**: 3D printer cooling duct - refined to *improve performance* by altering nozzle profile. Sequential change requires subtraction of old material (plane cut) before adding new material.
- **C**: Camera mount - *functional improvements* made to the design through refinement. Multi-oriented change; requiring Boolean additive and subtractive steps with reorientation between.

2.2.2. Detecting Change Between Versions

To detect and measure change between model versions, native STL mesh files were sampled to create dense point clouds using CloudCompare 2.12 alpha 2021. Overlapping sections between model versions were aligned using a Root Mean Squared (RMS) fitting method to achieve a 100% theoretical overlap between version point clouds. Cloud to cloud distances were computed for each of the cases to highlight areas of change and determine the scale of deviation between model surfaces.

2.2.3. Calculating and Comparing at Different Scales

Relationships between model scale and remanufacturing feasibility were additionally investigated. Each model was increased in size whilst retaining its original properties to fit surface areas of 1000 mm², 10,000 mm², and 30,000 mm², representative of small, medium, and large-scale parts (relative to

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[1] URL: www.thingiverse.com

the build volume of a desktop 3D printer). Results of variation in scale were evaluated and compared against results for refabricating at equivalent scale.

2.3. Analysis Process and Metrics

In order to analyse the time and cost components of remanufacture using additive and subtractive steps, the process was separated into stages. These are adopted from (Xu et al., 2001) who identify RP processes to be broadly comprised of 3 stages: *data preparation, fabrication, and post-processing*. We adopt these stages in our analytical method to compare the theoretical time and cost of remanufacturing throughout a typical RP process. This work further elaborates on the definitions presented by (Xu et al., 2001) to include additive and subtractive methods under '*fabrication*', thus the following stage definitions are proposed:

1. **Pre-processing**: where data transfer, conversion, part orientation and slicing, parameter setting, and path generation are performed under the constraints of a RP platform.
2. **Execution**: concerning the addition and removal of material volumes and any necessary setup/fixturing/localisation.
3. **Post-processing**: includes finishing operations such as removal of support structures and cleaning.

Each stage was further delineated to better understand the factors contributing to overall process time. Identified factors are presented in steps 1-8 of Figure 3. Additionally, a time value was allocated to each step for use in the calculation of total processing time across cases.

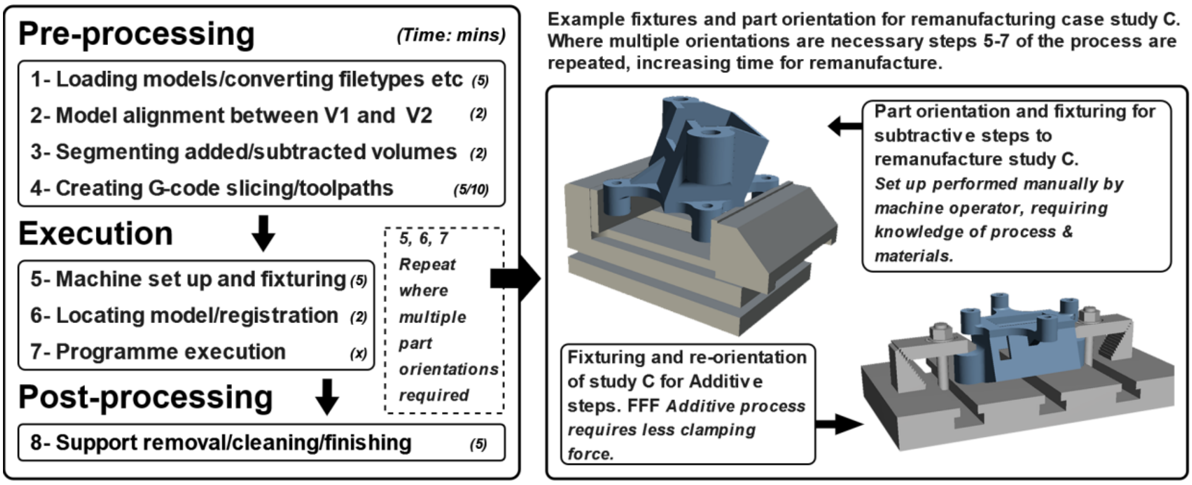

Figure 3. Breakdown of Stages in the process of Remanufacture

Time estimates were based on empirical results, averaging the time of a proficient user to perform each step, these are denoted by the bracketed values in Figure 3. Time values at step 4 account for the difference between slicing for AM and toolpath generation, with toolpaths for subtractive machining requiring twice the time *for the given cases*. For programme execution, time is dependent on machine running time. Therefore, overall time can be estimated as the sum of process steps, including repeated steps for multiple orientations.

2.3.1. *Measuring Time and Cost of Additive/Subtractive Operations*

To determine time and cost of additive and subtractive RP processes (step 7) each case (***A, B, C***) was simulated to estimate values for both refabricating, where version 2 is made as a new part, and remanufacture, where only the changes between versions are implemented (Figure 4). Remanufacture times were calculated by simulating processes to add or remove segmented, and any obstructive volumes. Machine parameters for calculating process times were based on an Ultimaker© S3 printing PLA with a layer height of 200 μm, 60 mm/s print speed (150 W). For subtractive, parameter values were based on a Pocket NCv2-10 with a 1 mm depth of cut and speed of 6.6 mm/s (150 W). Toolpaths were generated using profiles set up with additive and subtractive machine parameters in the CURA 4.5 slicing application, outputting estimate values for *machine time* and *material usage* per operation.

2.3.2. Cost Model

A model for calculating costs based on the works of (Baumers *et al.*, 2015; Henrique Pereira Mello *et al.*, n.d.; Xu *et al.*, 2001) was developed to analyse the time and cost of each case for comparative evaluation. Cost of labour and machine depreciation were not included in the model, although can be calculated by using the time for processing stages requiring user input multiplied by an hourly local cost of labour. The model reflects the stages presented in 2.3.1 to show calculations for time and cost per stage.

Pre-Processing

The cost of pre-processing C_{Pre} is given by equation 1, where Pc_e is the workstations power consumption in Watts, P_{kh} is the local energy price per kWh, and T_P is the sum of time to pre-process in hours.

$$C_{Pre} = (Pc_e \cdot P_{kh})T_P \tag{1}$$

Execution

Equation 2 shows the time calculation to execute idealised remanufacture T_{exe}, where Ta is the additive time for version 1, and Ta_i for version 2. Correspondingly Ts is the subtractive time for version 1 and Ts_i, version 2. Tsp relates to set-up time and is derived using relative values from steps 1-8 (Figure 3.). T_{exe} is therefore the sum from i = 1 to i = n where n is the number of required orientations.

$$T_{exe} = \sum_{\mathrm{i}=1}^{\mathrm{i}=n}(Ta_{\mathrm{i}} - Ta) + (Ts_{\mathrm{i}} - Ts) + Tsp \tag{2}$$

Calculation for the cost of execution C_{exe} is given in equation 3, where Pa_e is the additive machine power and Ta the total time for additive steps. PS_e is subtractive machine power and Ts subtractive step time. Cm is the cost of material derived from simulated outputs, and based on volume utilised in mm³.

$$C_{exe} = (Pa_e \cdot P_{kh})Ta + (PS_e \cdot P_{kh})Ts + Cm \tag{3}$$

Post-Processing

Given the non-complex attributes of the models selected for this study we assume a constant post-processing time of 5 minutes per model. The cost of post-processing is therefore not included in the calculated values for each case as cost would be dependent on labour cost.

Refabrication Time and Cost

To calculate time for refabrication**,** model versions were sliced for 3D printing using the parameters outlined in 2.3.1. Total refabrication time includes steps 1, 4, 7, and 8. Calculating total cost for refabrication, energy values for pre-processing and execution are summed and added to the cost of material.

2.3.3. Data Inputs and Constants

Inputs for the calculation of cost and energy are given in Table 1. As the volumetric difference between versions is in some cases nominal, material costs were calculated per mm³, and 2.85mm PLA (~£18/kg) set as the base cost value. Values for machine power consumption were determined by considering the manufacturer specifications and RP forum discussions on energy usage with similar machining parameters/materials to those of this study.

Table 1. Values used to calculate cost and time for both Remanufacture and Refabrication

Variable	Value (units)	Description
Pc_e	200 (W)	Power consumption of computer at mid load
Pa_e	150 (W)	Ultimaker S3 power consumption printing at PLA temperatures
Ps_e	150 (W)	Pocket NC mid load rating power consumption
P_{kh}	0.173 (£)	Average price per kWh in the UK
PLA	2.25e-5 (£)	Cost of material per mm³ used to calculate Cm

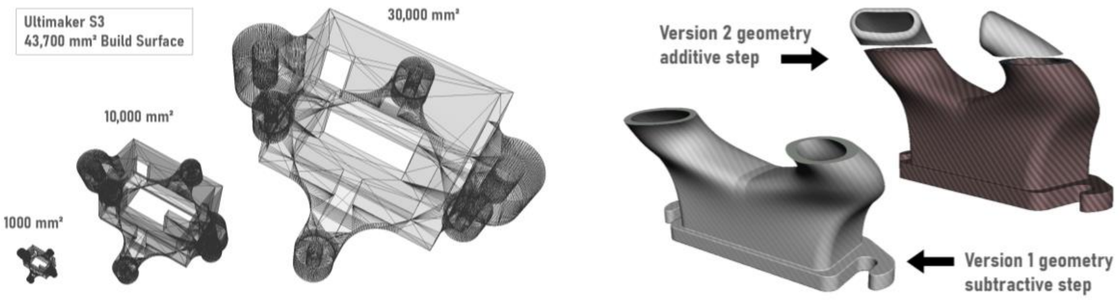

Figure 4. Model resizing relative to build surface (left) Example of planar cut and reprint (right)

3. Results

Figure 5 shows results in terms of time and cost for each of the cases, both refabricated and remanufactured. Additionally, a breakdown of total time to remanufacture is given, where execution, pre-processing, and post-processing times are further detailed. Thus, identifying the contribution of different stages to overall time.

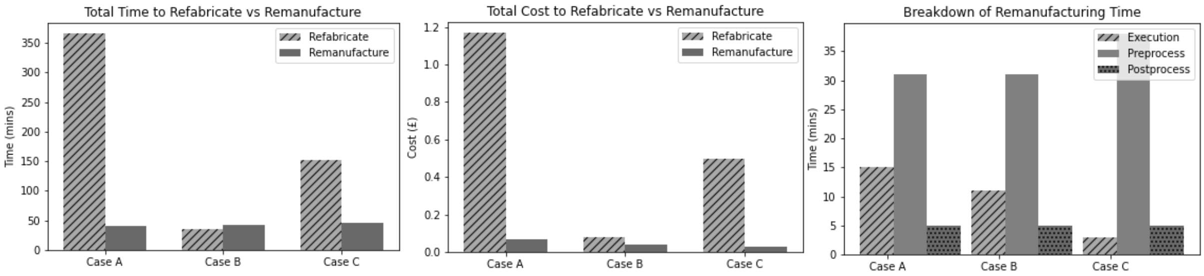

Figure 5. Comparison of Time and Cost for Remanufacture against Refabrication and a Breakdown of Remanufacturing time

Looking at ***results for cost*** it is evident that both time and cost savings are achieved by remanufacture in each of the cases, demonstrating a significant cost reduction in cases A (94%), and C (95%). In case B, where the part, and the scale of change between part versions is low a reduction in cost of 53% is observed. ***Results for time*** further demonstrate savings in cases A, and C with respective reductions in time of 87% and 73%. For case B, results show refabrication to outperform remanufacture by 17%, this again may be a consequence of scale as the model takes only 36 minutes to print, however the nature of sequential remanufacture, where material must be first removed before implementing new version changes also factors in performance against refabricating. Analysing the ***time per stage of remanufacture*** (Figure 5. Right) it is clear that pre-processing accounts for the largest proportion of time to realise a theoretically remanufactured part across all cases. This result suggests pre-processing time to pose an obstacle to the utilisation of remanufacture in prototyping; where in certain cases, such as that of Case B, it may take longer to set-up for remanufacture than to make a new part. Although, in such instances the cost savings afforded by remanufacturing, particularly with material of high value or scarcity may justify the increased time. Execution times for each case are shown to be consistently lower than that of pre-processing, for Case C this difference is significant (-88%), thus supporting the above findings.

Table 2. Comparison of Time and cost of Remanufacture (RM) against Refabrication (RF) with percentage improvement (Diff)

	Case A			*Case B*			*Case C*		
	RM	**RF**	**Diff**	**RM**	**RF**	**Diff**	**RM**	**RF**	**Diff**
Time (mins)	46	366	87.43%	42	36	-16.67%	41	152	73.03%
Cost Total (£)	0.06	1.17	94.39%	0.03	0.08	52.49%	0.03	0.50	94.74%
Material Cost (£)	0.04	1.02	95.35%	0.01	0.06	81.82%	0.03	0.44	99.35%
Energy Cost (£)	0.02	0.15	96%	0.02	0.01	91%	0.00	0.06	99%

When further evaluating specific costs (table 2.) energy costs are shown to average 22% of total cost for remanufacture, and 12% of cost for refabrication; perhaps reflecting the increased computational requirements of pre-processing for remanufacture. Whilst energy values are relatively low (the highest energy cost being £0.15), higher power processes such as Electron Beam Melting, where power requirements can be in excess of 3 kW, could add weighting to energy as a factor of total cost.

Initial results indicate remanufacture to have significant potential to reduce iteration time and cost in prototyping. However, it is evident that this is not true of all cases, particularly where refabrication time is low. As such, the influence of part scale on generated results is investigated for cases A, B, and C in the following section.

3.1. Rescaling Study

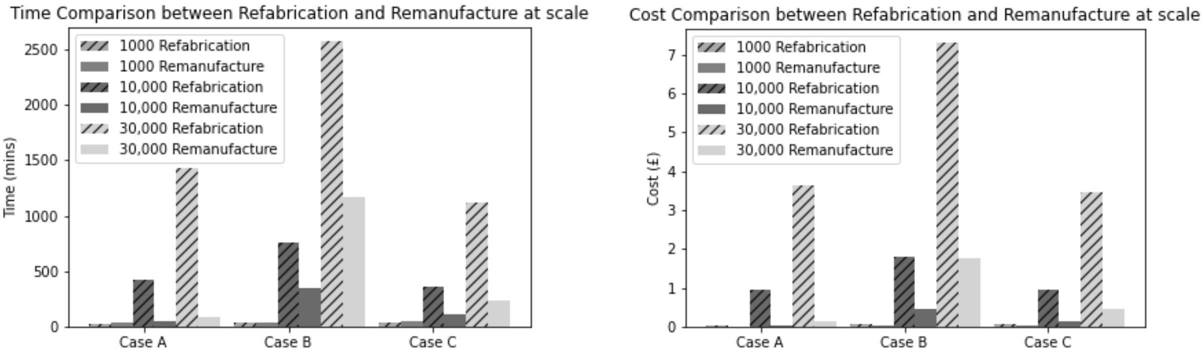

Figure 6. Results from rescaling study with time and cost for each model evaluated at surfaces areas of 1000 mm², 10000 mm², and 30000 mm²

Costs are observed to scale proportionally in Case A, however Cases B, and C, exhibit non uniform scaling when comparing refabrication and remanufacturing costs. This is due to pre-processing times remaining constant as scales increase, and therefore accounting for less of the total cost to remanufacture. Consequentially, the cost efficiencies of remanufacture improve as model sizes increase beyond a given point. ***Time*** comparisons highlight further improvement against refabricating when increasing scale. Case B shows remanufacturing times to be closer to that of refabricating across all scales and considered a result of the time to execute subtractive steps prior to adding new material in sequential remanufacture. Thus, where significant material must be removed prior to an additive change, the potential time savings of remanufacture are diminished. Whilst this is also true of Case C, the extent of the subtractive steps involved does not have significant impact on the overall time to remanufacture. Finally, the scaling behaviour shown in the chart of Case B suggests a transitioning point between 1000 mm² and 10,000 mm² model surface sizes, where the time to remanufacture at some point becomes lower than the time to refabricate. The point at which this happens, and influencing factors are yet to be defined.

4. Discussion and Future Work

Fundamentally, remanufacturing proposes a strong value proposition with significant potential savings to time and cost, and further environmental benefits to be realised when prototyping. In addition to this, successfully implementing a methodology for remanufacture in the product development domain portends opportunity for diversified industry applications; ranging from high value engineering sectors such as aerospace, where cost savings are a driver for innovation (Najmon *et al.*, 2019), to low-cost rapid product prototyping where development time is a critical factor in the success of a products launch (Cooper and Kleinschmidt, 1995). Although, the 'cost' of pre-processing currently poses an obstacle to the adoption of remanufacture, where cost implies not only currency, but also time, and user capability to navigate the multitude of complex physical and computational processes involved. We identify pre-processing as a cornerstone issue to the democratisation of remanufacturing processes in rapid prototyping. Reducing the time to pre-process and developing tools to streamline workflow promise scope for further research and improvement. Furthermore, this exploratory study highlights a number of specific points for discussion and considerations for future work.

- It is evident that the scale of the model, or that of the change relative to the model are key factors to the feasibility of remanufacture with a breakeven point observed in all cases. This point shows that it is not always effective to remanufacture and is dependent on the sum of time to pre-process and execute additive/subtractive steps, compared to refabricating.
- Generally, it is observed that larger scale models elicit better results from remanufacturing. This is perhaps due to pre-processing time and cost accounting for less of the total to implement changes from a part version 1 to version 2. Other factors such as number of part orientations and the spread of changes across the part merit further investigation.
- Analysis cases defined in section 2.1 are fairly generalised to the types of change common in iterative prototyping cycles. Although, we do not know if this is all of the strategies for remanufacture and thus require a more exhaustive exploration of strategies.
- The study was conducted using a 3-axis MEX 3D Printing process but could be translated to other processes such as metal AM where material and energy costs are significantly higher, and the potential benefits of remanufacture thus more pronounced. Additionally, 5-axis processes could mitigate the need for many part reorientations further benefitting results.
- From a process perspective, the user experience should be considered as to remanufacture currently requires knowledge of various processes and a high proficiency with CAD tools to align, segment and slice volumes. For the low-end market, streamlining the process of remanufacture according to good practice guidance is necessary. Further, it is not clear how a remanufacturing process might influence design outputs. Future works should investigate this issue to identify obstacles in the remanufacturing process and contributions of using such methods on design output.
- Opportunities for novel process methods such as remanufacturing with mixed materials are apparent, allowing any removed volumes to be added back with different properties. While additive processes are limited in their material capabilities, subtractive processes are more flexible, giving the opportunity for subtractive remanufacture across prototype media.

Future Work

As the findings presented in this study are derived from the simulation of various processes, expanding this work to include observations from the physical implementation of version changes on a prototype part promise significant further insight as to the process's feasibility in real-world applications. Works could include a review of localisation and metrology methods, fixturing requirements, and performance evaluation of remanufactured parts. The models used in this study are representative of common changes between prototype versions but are limited in scope. Expanding the analysis dataset to include versions with many different types of change e.g., functional, or aesthetic changes, would be relevant in mapping the range of savings that remanufacturing could create. In particular, spread of changes over a large portion of the surface of a prototype may require multiple part re-orientations and greater pre-processing times. As such, characterising benefits against the localisation or distribution of changes would be valuable. Additionally, characterising change between part versions in a large model repository could detect trends in the rationale to a design change. It is reasoned that a design change must be governed by an underlying principle, for example the Function-

Behaviour-Structure (FBS) framework (Gero and Kannengiesser, 2004) evidences such relationships in its situational representation of design. Thus, through a better characterisation of common changes between versions at such scale, insights could be generated to better support design methods, for instance integrating with machine learning/AI tools to pre-empt future version design changes.

Future work could also investigate the potential to couple remanufacture with modular design concepts, where an existing part could be adapted/remanufactured to incorporate modular elements by using the coupled process to create reconfigurable modules and their connection points, such that geometry could be altered between versions rapidly. Remanufacturing as considered here requires geometry to be altered either subtractively or additively, with all changes then created via these processes. For larger changes, and specifically with re-use in mind, there may be value in creating modular prototypes that can be reconfigured. A question posited by the discussion in this paper highlights an additional dimension to the scope of this research; where in this study time and cost have been the primary metrics for evaluation, there is little notion as to how the adoption of remanufacturing methods in the prototyping stage may influence design output, could it encourage designers to consider aspects of circularity in the early phases of NPD? (Shahbazi and Jönbrink, 2020). With Circular Economy (CE) methods for design being a prominent topic in design research, it may be of value to investigate remanufacture in this capacity i.e., could it support designers to better consider aspects of CE, and lead to products better designed for re-use or repair in a circular economy. The need to further expand the study with more cases, different processes, and sensitivity analysis of values is additionally acknowledged.

5. Conclusions

Whilst the findings presented here are grounded in a theoretical study with idealised conditions, the results indicate significant potential for remanufacture to save not only time and cost, but further improve the socio-environmental impact of prototyping in NPD for a range of different cases. As organisations frequently deploy product design management methods to optimise resource use in the development of innovation, reduce costs, and improve sustainability (de Guimarães *et al.*, 2021) the implications of this work give direction to explore new methods and methodologies for prototype remanufacture in NPD with potential diverse industry applications.

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