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Galimberti, G.; Doubrovski, Zjenja; Guagliano, M.; Previtali, B.; Verlinden, Jouke

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INVESTIGATING THE LINKS BETWEEN THE PROCESS PARAMETERS AND THEIR INFLUENCE ON THE AESTHETIC EVALUATION OF SELECTIVE LASER MELTED PARTS

G. Galimberti[a], E.L. Doubrovski[b], M. Guagliano[a], B. Previtali[a], J.C.Verlinden[b]
[a]Politecnico di Milano, Italy
[b]Delft University of Technology, The Netherlands

Abstract

This study is a precursor to gaining a deeper understanding of how each parameter of the Additive Manufacturing (AM) process influences the aesthetic properties of 3D printed products. Little research has been conducted on this specific aspect of AM. Using insights from the work presented in this paper, we intend to develop design support tools to give the designer more control over the printed products in terms of aesthetics.

In this initial work, we fabricated samples using Selective Laser Melting (SLM) technology, and investigated the parameters geometry, building strategy, and post-processing. We asked participants to evaluate the visual and physical interaction with the manufactured samples. Results show that, in addition to geometry and post-processing, the aesthetic evaluation can also be strongly influenced by the SLM process' building strategy. This understanding will enable us to develop tools to give designers more control over the part's aesthetic appearance. In addition, we present a systematic procedure and setup to evaluate the aesthetic appearance of products manufactured using AM.

Introduction

Additive Manufacturing (AM), or three-dimensional Printing (3D Printing), is increasingly being applied as a means of production in consumer product manufacturing (Wohlers & Caffrey, 2014). The digitally controlled and layer wise manufacturing process of AM introduces new principles to the product manufacturing domain (Gao et al., 2015). Compared to traditional manufacturing, such as injection molding, the production costs of AM depend less on the complexity of the geometry and batch size. The new principles provide opportunities to make customized products, and create complex structures with unique mechanical properties (Doubrovski, Verlinden, & Geraedts, 2011). However, this also requires new approaches to Design for Additive Manufacturing (DfAM).

The need for new DfAM approaches is widely recognized (Gibson, Rosen, & Stucker, 2010; Hague, Campbell, Dickens, & Reeves, 2001) and in the literature there are a number of DfAM approaches which support the different phases of the design process (Kumke, Watschke, & Vietor, 2016). These include supporting designers in the creative phases of the design process (Maidin, Campbell, & Pei, 2012), design rules for AM (Thomas, 2009), methods for structure generation (Wang, Chen, & Rosen, 2005), and design evaluation for AM. The majority of these approaches are focused on obtaining the desired mechanical properties and functional behavior of printed parts. However, when designing and manufacturing consumer products, appearance plays an important role (Fallis, 2013). A number of DfAM-related studies focus on appearance, such as surface quality of AM parts (Strano, Hao, Everson, & Evans, 2013) and the readability of raised and recessed text on the surface of AM parts (Seepersad, Govett, Kim, Lundin, & Pinero, 2012), however there is very little knowledge on the subjective precipitance of parts made using AM.

Based on our analysis, we identified the need for design tools that provide information on how the choices during the design and AM process influence the perceived appearance of the surface of the fabricated object. To develop such a tool, it is necessary to understand which parameters of the AM process influence the perceived appearance of printed results, and how they do so. The tool should support designers in the concept, modeling, slicing, and post-processing phases (Figure 1). The literature shows that, apart from geometry, AM process parameters influence the product's structure, which in turn influences its properties (Rosen, 2007). Yet, we do not know how the process parameters influence the perceived appearance of the surface. Therefore, the goal of the work presented in this paper is to develop a method to link AM process parameters to the aesthetic evaluation of the printed result.

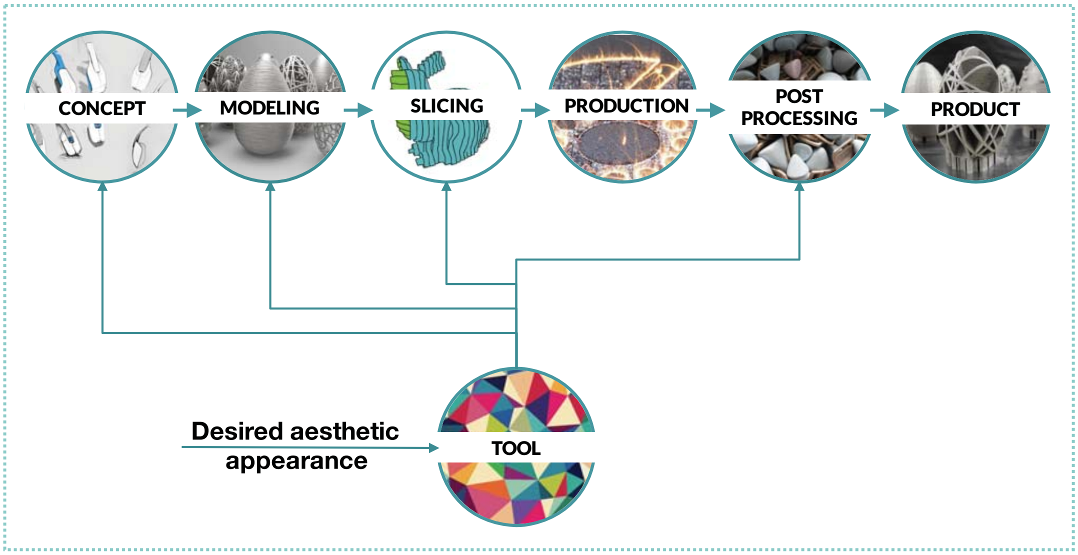


Figure 1: Design phases of a tool to support the designers' decision-making

As a first step to achieving this goal, we present an approach in which we match AM process parameters to the perceived aesthetic evaluation of the 3D printed result. In our preliminary experiments, we manufactured samples using the Selective Laser Melting (SLM) AM process. Their visual appearance was evaluated by participants. Figure 2 illustrates the procedure for collecting the data that we intend to use for developing the envisioned design tool. SLM is currently applied in many industries, including aerospace, automotive, and medical. However, SLM fabrication is also increasingly being used for manufacturing consumer products ("i.materialise," n.d.), which makes it important to consider aesthetic properties for this technology as well (Galimberti, Guagliano, Previtali, & Rampino, 2015).

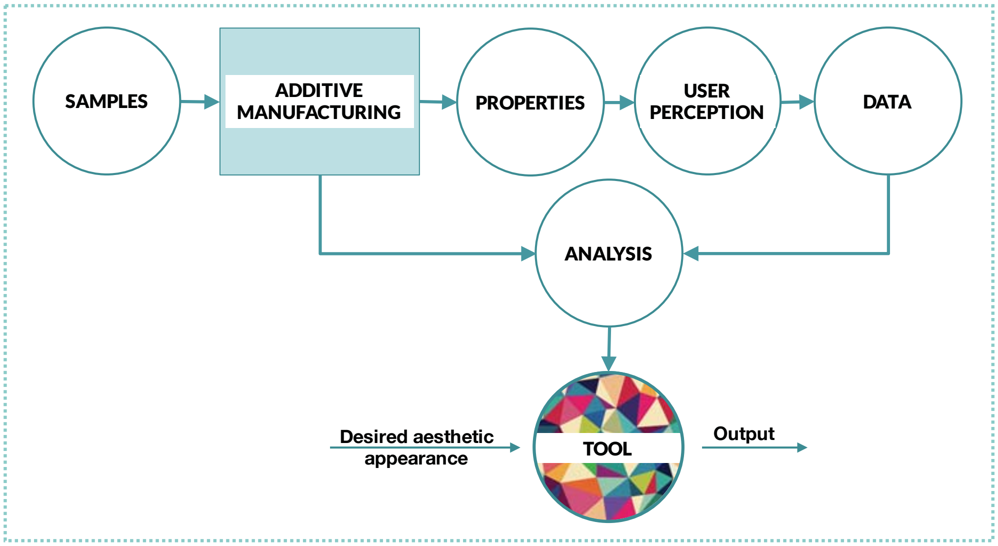


Figure 2: Procedure for the development of the design tool

SLM is an AM process belonging to the category powder bed fusion (Wohlers & Caffrey, 2014). In this process, a wiper deposits a layer of metal powder on a build platform. A laser melts areas of the layer representing a slice of the 3D model that is being built. After completing a layer, the build platform is lowered and the next layer of powder is deposited. This process is repeated until the part is completed. The concentrated heat of the laser can cause distortions and thermal stresses within the part. To prevent distortions, support structures are built alongside the model using the same material and different strategies, making them more fragile, which allows them to be mechanically removed. The SLM process takes place in a controlled environment with argon or nitrogen gas, to avoid oxidation of the metal. The main materials used for SLM are steel, titanium, aluminum alloys, Co-Cr and others. After the AM fabrication phase, the printed part usually undergoes post-processing to change its mechanical properties or perceived aesthetic appearance.

Outside the AM domain, we found several studies that objectively evaluate product appearance using a systematic approach (Pham, 1999). These studies on aesthetic appearance share some aspects of the methodologies used. The aesthetic appearance is often evaluated by presenting samples to participants who, in turn, score these using a rating system. These samples can be physical (Karana, Hekkert, & Kandachar, 2009, 2010), digital (Tractinsky, Cokhavi, Kirschenbaum, & Sharfi, 2006), or photographs of products (van Rompay, 2005). We intend to apply a similar experimental setup using physical samples and human perception to investigate the links between the parameters and aesthetic appearance of SLM products.

Method

Outline of experiment

The aesthetic evaluation took place by asking participants to interact with different 3D printed samples created on an SLM system. Participants could touch and interact with the samples and closely observe the surfaces, before answering questions regarding the samples surface. We gave the participants a pair of samples and they were asked to choose which of the two samples best matches the description in the question. This setup and experimental procedure combines the methodologies and the testing environments observed in other studies (Karana et al., 2010; Riva, 2013).

Samples

AM system and material

We fabricated 40 samples using a Renishaw AM50, an SLM system equipped with a 200W pulsed laser and a printing volume of 250x250x300mm. The material used for the samples is an AISI Grade 18Ni (300) Maraging steel (European classification 1.2709). The powder is a gas-atomized powder with particle size between 15µm and 45µm. This steel has high stability, good weldability, and high mechanical strength, and is generally used for the fabrication of molds for injection molding and die-casting, and parts requiring particularly high strength and hardness. The three parameters that were varied were:

- Geometry
- SLM building strategy
- Post-processing

Variations in geometry

The basis of the geometry for all samples resembles the outline of an egg with a height of 60mm and maximum diameter of 40mm. We chose this as it has a variable curvature and does not represent (a part of) a product. We created 12 variations to the base geometry, comprising both sparse and massive geometries. Figure 3 illustrates a finished printing tray with the 12 variations of the geometry. The samples were modeled using the Grasshopper plug-in for Rhinoceros 3D software. The different geometries were made with the intention of including a variety of common design features in the samples. These include continuous and discontinuous surfaces, round and sharp edges, and sparse and massive structures.

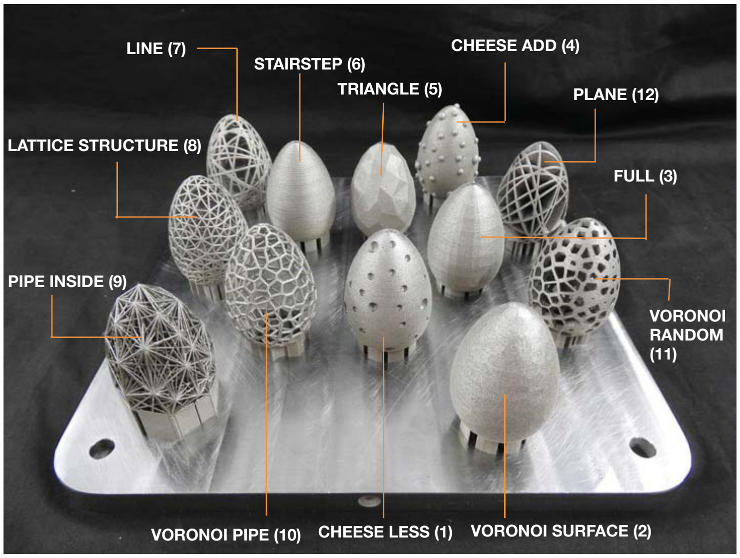


Figure 3: Finished printing tray with the 12 variations of the geometry.

Variations in SLM building strategy

The Renishaw SLM system's slicing software (Magics developed by Materialise) allows us to vary the number of building strategy settings. The samples were created by varying the laser power, exposure time, point distance, and border distance, as these were expected to influence the resulting surface appearance. As illustrated in Figure 4, the *point distance* is the distance between the centers of two successive melt pools, and the *border distance* is the perpendicular distance between the laser contours at the border of the object.

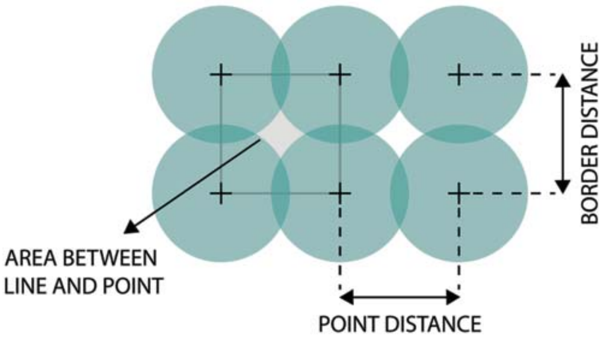


Figure 4: Point distance and line distance of the laser

By varying the settings, four custom presets were made defined by power (P) of the laser and the overlap (OP) of the melt pool:

High P – Low OP (high power and low overlap)
Low P – High OP (low power and high overlap)
Low P – Low OP (low power and low overlap)
High P – High OP (high power and high overlap)

The settings for the four presets were chosen while keeping the energy input between 100 J/cm^2 and 1000J/cm^2. One of the custom presets had an energy input below this range, namely 40 J/cm^2. The energy input is expressed as *fluence* and is used to estimate whether the powder will melt sufficiently to ensure a solid product. The fluence is calculated using Equation 1, which was derived from (Cherry et al., 2014).

$$Fluence[J/cm^2] = \frac{Power \cdot ExposureTime}{PointDistance \cdot LineDistance}$$

Equation 1: Calculation of fluence

In the four custom presets, the number of borders was set to 3, while in the default settings the number of borders is 1. In addition to the four custom presets, one preset was set at the recommended Renishaw settings. The samples were fabricated by applying the 5 presets of the building strategy settings (Table 1). All 12 geometries were printed with the recommended settings. The four custom presets were applied to fabricate two selected geometries. One of the two geometries represented a sparse geometry (Figure 3, geometry n.10), while the other represented a massive geometry (Figure 3, geometry n.5).

No.	Strategy code	Power [W]	Exposure time [µs]	Point distance [µm]	Border distance [µm]	A [µm^2]
1	Renishaw	100	50	20	200	4000
Custom strategies						
2	High P - Low OP	150	75	30	300	9000
3	Low P - High OP	85	43	17	170	2890
4	Low P - Low OP	85	43	30	300	9000
5	High P - High OP	150	75	17	170	2890

Table 1: Strategy settings for custom presets

Varying the post-processing

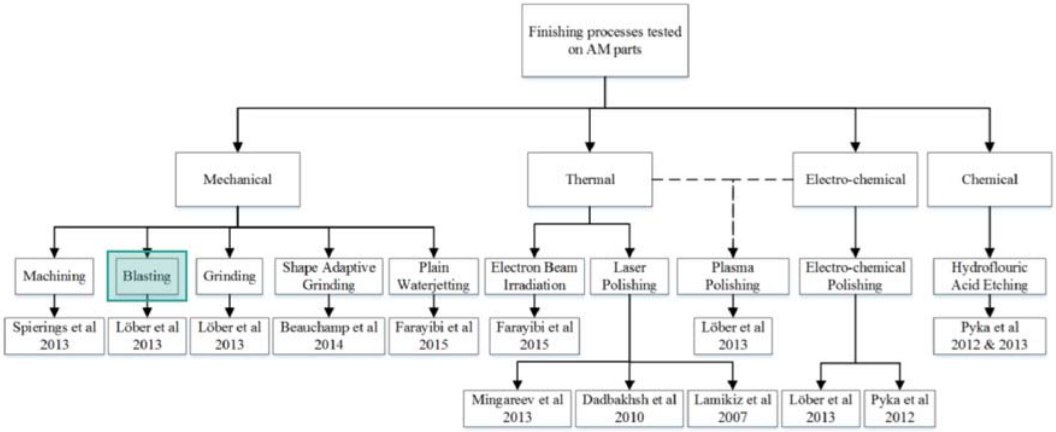


Figure 5: Post-processing tree organization (Gordon & Dhokia, 2015)

Several post-processing procedures common to conventional technologies can be used for 3D printed objects (Gordon, E. R., Shokrani, A., Flynn, J. M., Goguelin, S., Barclay, J., & Dhokia, 2016). Figure 5 gives an overview of conventional post-processes that are available for AM products (Gordon & Dhokia, 2015). Generally, these post-processes are applied to improve the mechanical properties (Alrbaey, Wimpenny, Tosi, Manning, & Moroz, 2014; Löber, Flache, Petters, Kühn, & Eckert, 2013). However, some post-processes are also applied to change the aesthetic appearance of jewelry (Parraman, 2012). In this study, we were mainly interested in the effect of post-processes on the aesthetic evaluation. We used sandblasting as the post-processing parameter of choice for this initial research. Samples which were not post-processed after the SLM process are referred to as ‘untreated’. The manual machine used for the sandblasting was a Guyson Formula 1400 with internal blast chamber, with dimensions 815x560x591mm. The sand type we used was dried silica sand 510 Bacchi S.p.A. The grains are round and the size is between 0.4mm and 1mm. Of the geometries printed using the Renishaw strategy, 12 geometries were sandblasted, while 12 others were left untreated. 2 geometries (Figure 3, geometries 5 & 10) printed using the 4 custom strategies were both sandblasted and left untreated.

Experimental setup

We found several systems used to describe appearance in the literature (Fleming, Wiebel, & Gegenfurtner, 2013; Karana et al., 2010; Riva, 2013). In these approaches, a list of adjectives was developed that we used to evaluate and describe appearance. In our approach, we selected 10 of these adjectives for our questioning: glossy, rough, faceted, sharp, light (color), reflective, detailed, homogeneous, pleasant, attractive.

The participants were briefly informed about the goal of the experiments and the procedure. They were asked to evaluate the surface appearance by comparing the printed samples by following instructions and questions shown on a screen. They were seated in front of the setup, and a batch with the samples for evaluation (Figure 6) was placed on their left. All the samples were given a unique identification number and a QR code. The instructions on the screen informed the participants which two samples to examine. The participants were asked to indicate which sample was chosen for each question by scanning a QR code at the bottom of the sample.

The questions that appeared on the screen were structured as follows "Which surface is more [adjective]? Scan the chosen egg". A random set of 5 pairs of samples was generated for each participant and prepared on a tray (Figure 6). Each pair was used twice for two consecutive questions. The combination of samples in each pair was randomly generated. For each pair, one parameter was varied, while the other two parameters were fixed. The possible combinations are pairs with:

- identical geometry, identical strategy, different post-processing
- identical geometry, different strategy, identical post-processing
- different geometry, identical strategy, identical post-processing

Figure 6: Example of prepared batch of samples

The generated sets were given to the participants on a tray on which the samples were placed in an order connecting them to the related questions. The first line (0.1,0.2,0.3) is different from the rest; this included three eggs where the geometries were identical: either geometry number 5 or 10 (Figure 3). These three eggs were used to investigate which adjective participants used to describe and define the surface. The second part of the matrix comprised five different pairs used to evaluate the ten adjectives. The batch structure was:

- Pair 1.1 and 1.2: glossy | rough
- Pair 2.1 and 2.2: faceted | sharp
- Pair 3.1 and 3.2: light (color) | reflective
- Pair 4.1 and 4.2: detailed | homogeneous
- Pair 5.1 and 5.2: pleasant | attractive

In order to ensure that the samples were evaluated under constant and controlled lighting conditions, the experiments took place a light box, which was illuminated using several LED spots. The LED spots created a diffuse and homogeneous lighting, avoiding hard shadows. During the experiments, the external ambient light in the room was kept dark, making the LED spots the main illumination of the samples.

The questions were displayed on a screen mounted on the rear wall of the light box. The camera used for scanning the QR codes was positioned on the right of the screen (Figure 7). The participants were visitors to the International Festival of Technology (July 2016, Delft) and students from the faculty of Industrial Design Engineering of the Delft University of Technology. In total, data from 35 participants was collected. The interviewed participants were gender equal: 50% male and 50% female, and aged <20 (n=4), 20-40 (n=26) >40 years (n=5).

Figure 7: Impression of experimental procedure

Results

The resulting data was analyzed based on the comparison of how many times a sample has been selected for a question, as a percentage of how many times that sample occurred in that question. In the first part of the results section, we present the influence of the single parameters on the participants' perception of sample appearance. In the second part, we analyzed the interaction of the parameters: *post-processing* and *geometry, post-processing* and *building strategy, and geometry* and *building strategy*. The graphs illustrate a selection of the results; the complete graphs of the collected data can be found in Appendix A.

Introductory question

The remarks noted by the participants were analyzed on the occurrence of words that were used to describe why the participants found one sample to be different. The most frequently used words were: *rough*, *smooth*, *texture* or *pattern*, *structure*, *finishing*, *bright*, *rounded* and also *homogeneous*. Some participants also noted a difference in color.

Individual parameter analysis

Post-processing

The main differences in evaluation between sandblasted samples and untreated samples were found for the questions related to *glossy*, *rough*, *reflective*, and *pleasant*.

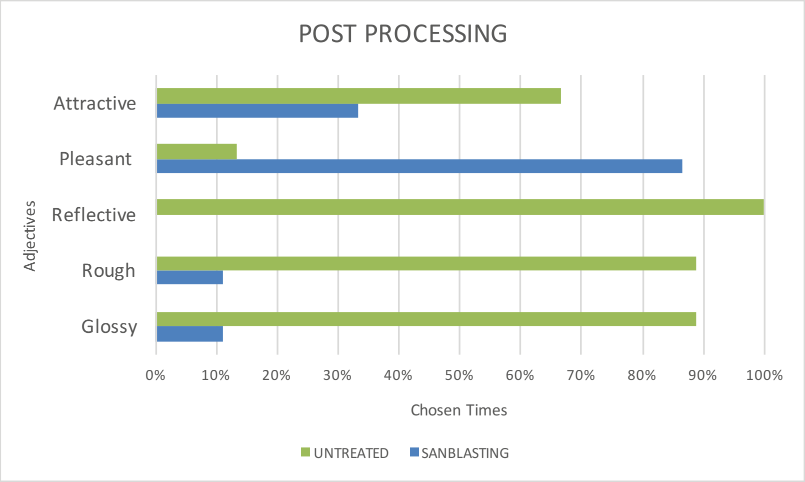
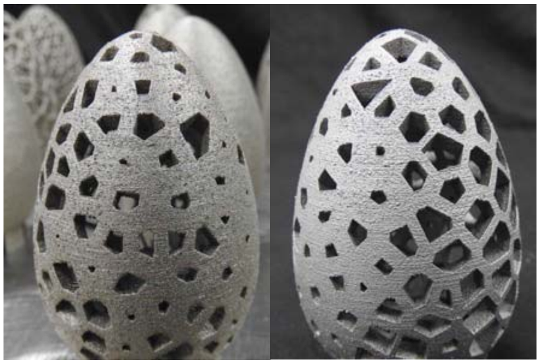


Figure 8: Scores for post-processing evaluation

As illustrated in Figure 8, it is noticeable that sandblasted samples were scored more often as being *light (color)*, *homogeneous*, and *pleasant*. As Figure 9 shows, sandblasting produces lighter, and more homogeneous surfaces, compared to the untreated samples. Sandblasting visibly smoothens irregularities on the surface and results in a distinct mat appearance. Remarkably, the sandblasted samples were more often categorized as *pleasant*, while the majority of untreated samples were noted as being *attractive*. This may be due to associating the adjective *pleasant* with both touch and sight, while *attractive* is more related to visual appearance. In other words, a sample can be evaluated as being visually attractive while not being pleasant to touch.



a b

Figure 9: Untreated and sandblasted samples (a: untreated, b: sandblasted) illustrating the different lightness and homogeneity

The untreated samples were more often chosen for being *glossy*, *reflective* and *rough*, compared to sandblasted samples. Even though untreated samples have surface-irregularities resulting in a rough surface (both visually and to the touch), they still have a glossier surface compared to sandblasted samples (Figure 10).

Figure 10: Example of an untreated surface illustrating a rough but glossy surface

Building strategy

The analysis of the *building strategy* was carried out by grouping the building strategy presets into two groups: recommended *Renishaw* strategy and *custom* strategies, where custom strategies include all four custom process presets. The most distinct differences were found for the results from the questions regarding *homogeneous*, *pleasant*, and *attractive* (Figure 11).

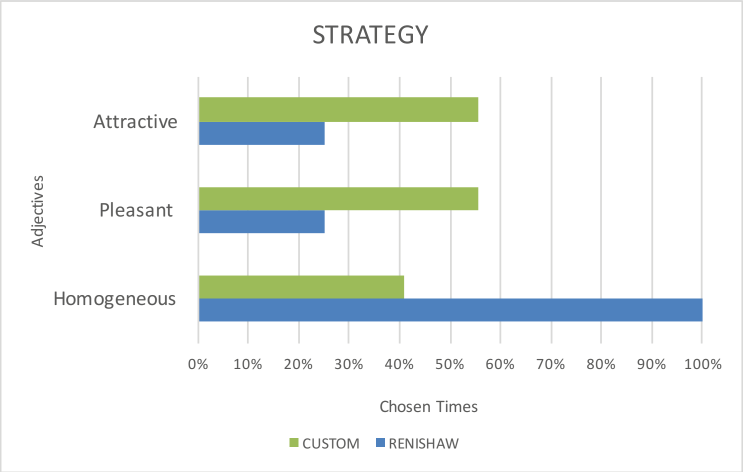


Figure 11: Scores for strategy evaluation

Samples fabricated using the *Renishaw* strategy were more often chosen by the participants for the questions regarding *rough*, *sharp*, *light (color)*, *reflective*, and *homogenous*, especially for the latter term. The samples fabricated with *Renishaw* strategy appear more uniform and have less texture on the surface, as shown in Figure 12.

We found that the *custom strategies* with higher laser power resulted in a glossier and more reflective surface. However, this was not found in the data, probably because this category also included strategies with lower laser power. Samples fabricated using custom strategies were more often categorized as *glossy*, *pleasant*, and *attractive*.

Figure 12: A sample made using Renishaw strategy illustrating a uniform surface

When observing the surface of the samples made with high laser power, we found distinct patterns on the surface, as illustrated in Figure 13. The origin of these periodic patterns on the surface has yet to be determined; they may play a role in making why some samples were selected as being more attractive. Furthermore, samples created with higher laser power resulted in a darker surface color.

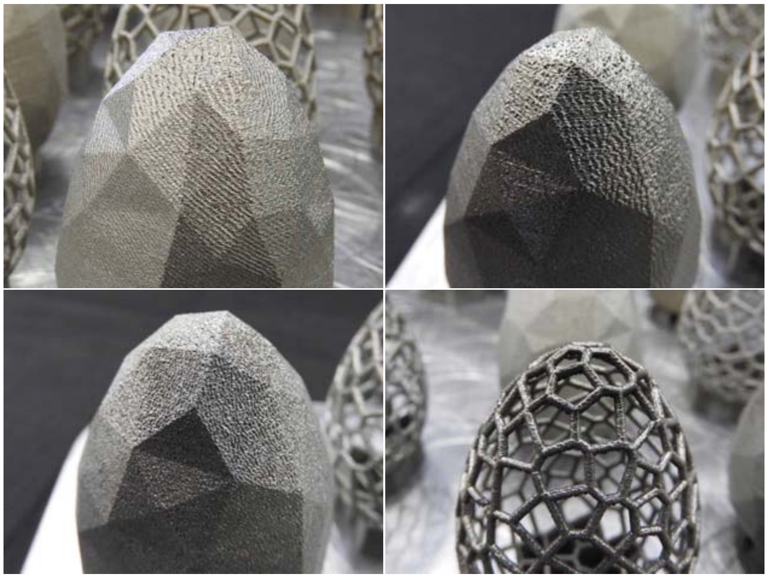


Figure 13: Samples made using custom strategy that show a distinct texture on the surfaces From top left to bottom right: High P, Low OP; High P, High OP; Low P, High OP; High P, High OP

Geometry

The designed geometries were grouped into two categories: *massive* (Figure 3 1-6) and *sparse* (Figure 3 7-12). We note that the geometry category did not influence the perception of descriptors *glossy* and *rough;* it becomes relevant when the participants evaluate the samples as *pleasant* and *attractive* (Figure 14). The *massive* geometries were more often found to be *faceted*, *light (color)*, *reflective*, and *homogeneous*.

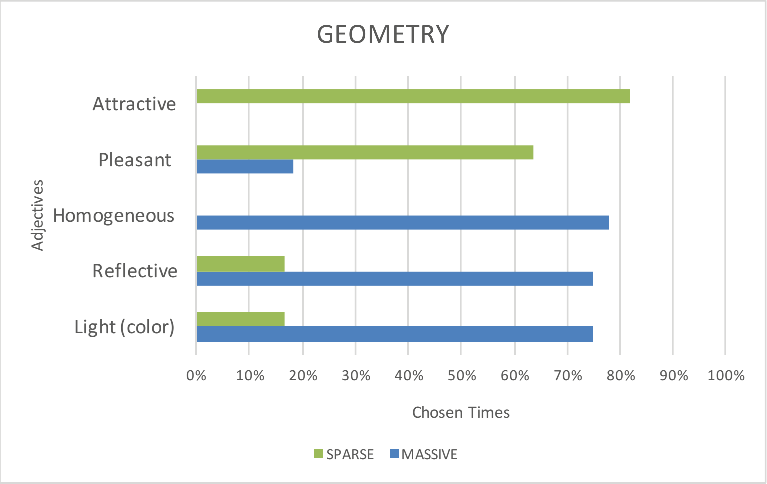


Figure 14: Scores for geometry evaluation

Sparse geometries were more often scored as *sharp*, *detailed*, *pleasant,* and *attractive*. The *sparse* geometries in our set were those that are typically difficult or impossible to manufacture using traditional production methods, and are therefore less commonly found in products. This may be a factor that results in the *sparse* geometries being considered as more intriguing and evaluated as being more attractive. We also observed that during the experiments, participants inspected the sparse geometries more closely compared to the massive geometries.

The interaction of the parameters

Post-processing and Geometry

The data shows that compared to *geometry*, the *post-processing* parameter has a stronger influence on how the surface is evaluated (Figure 15). However, for the evaluation of the *lightness (color)* and *homogeneity* of the surface, the samples' *geometry* also appears to have an influence: when *sandblasted*, a *massive* geometry was evaluated as being *lighter (color)* and more *homogenous* compared to a *sandblasted sparse* geometry. Regarding attractiveness, sparse structures were chosen most often, disregarding the post-processing. However, for *massive* samples, *post-processing* did have an influence, with *sandblasted massive* structures being considered the least *attractive*.

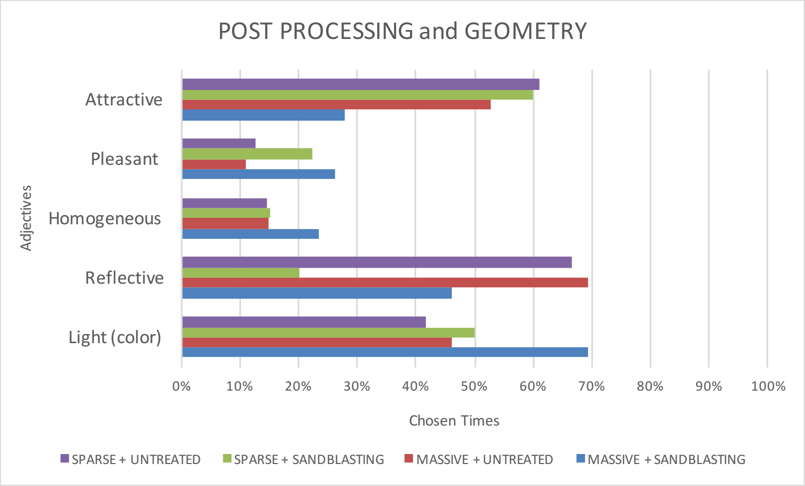


Figure 15: Scores for post-processing and geometry evaluation

Post-processing and Strategy

Our results show that for samples fabricated using *custom* strategies, the *post-processing* does not significantly influence the evaluation of the samples in the majority of the questions (Figure 16). However, if *Renishaw* strategy is used, post-processing does influence the evaluation of the samples in the questions on *pleasant*, *reflective*, *light (color)*, *faceted*, *rough*, and *glossy*. For the evaluation of attractiveness, the highest scoring samples had the combination of either *custom* strategies and *sandblasting* or *Renishaw* strategy and *untreated*.

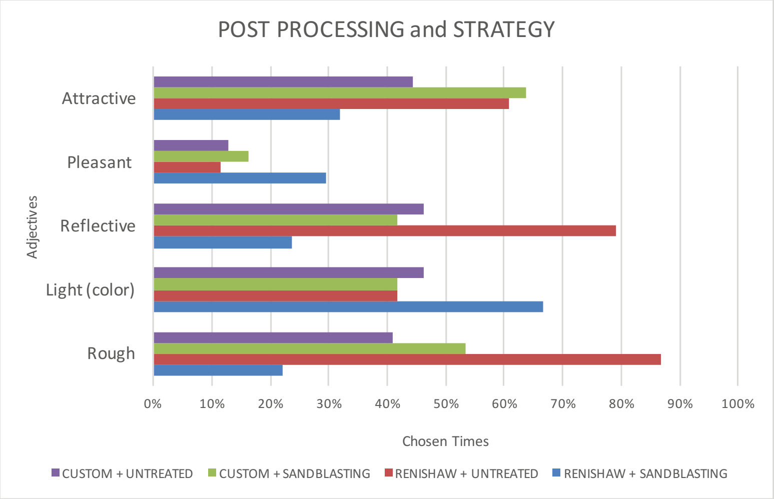


Figure 16: Scores for post processing and strategy evaluation

Geometry and Build strategy

For the *sparse* geometries, there was no influence of the *build strategy* on the evaluated surface (Figure 17). However, for *massive* geometries, we observed the influence of strategy in the questions related to *homogeneous*, *reflective*, *light (color)*, and *faceted*. For attractiveness, geometry appears to be more important than the *build strategy*, with the *sparse* geometry being considered more often as *attractive*, disregarding the strategy. Samples with the combination of a *massive* geometry and *Renishaw* parameters were least often scored as being attractive.

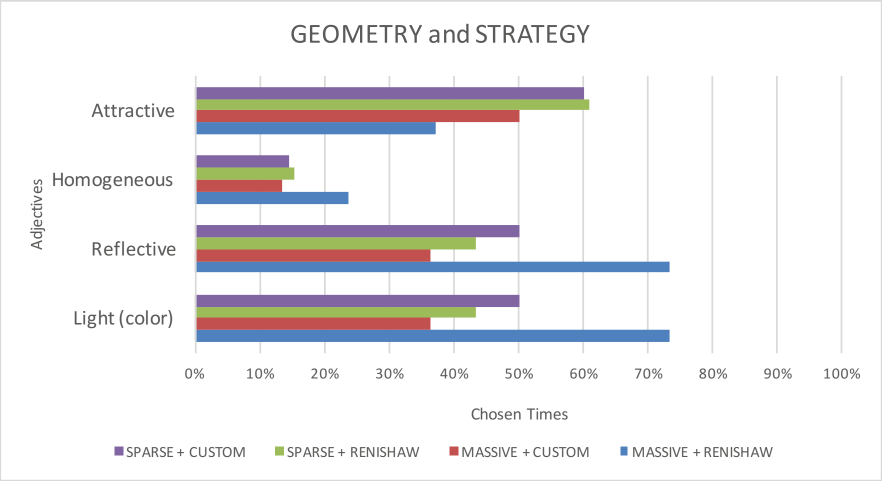
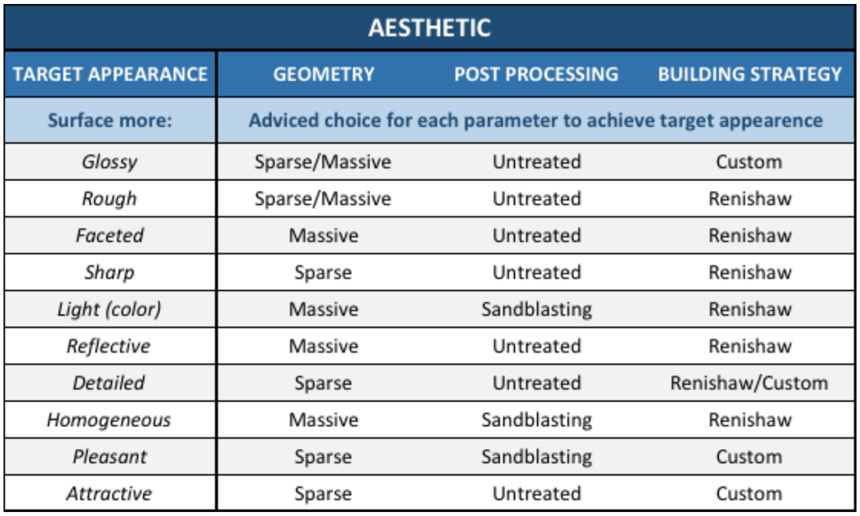


Figure 17: Scores for geometry and strategy evaluation

Figure 18 presents a summary of the results, showing the choice advised for each parameter to achieve the desired surface appearance. This advice is based on the preliminary results from the participants' perception experiments and is applicable to parts made on an SLM Renishaw AM250 system.



AESTHETIC			
TARGET APPEARANCE	**GEOMETRY**	**POST PROCESSING**	**BUILDING STRATEGY**
Surface more:	**Adviced choice for each parameter to achieve target appearence**		
Glossy	Sparse/Massive	Untreated	Custom
Rough	Sparse/Massive	Untreated	Renishaw
Faceted	Massive	Untreated	Renishaw
Sharp	Sparse	Untreated	Renishaw
Light (color)	Massive	Sandblasting	Renishaw
Reflective	Massive	Untreated	Renishaw
Detailed	Sparse	Untreated	Renishaw/Custom
Homogeneous	Massive	Sandblasting	Renishaw
Pleasant	Sparse	Sandblasting	Custom
Attractive	Sparse	Untreated	Custom

Figure 18: Summarizing results (preliminary study) of aesthetic guidelines for design for SLM

Discussion

In this preliminary experiment, we selected 35 participants, who made a total of 350 pair-wise comparisons. The data provided first insights into which parameters are involved in appearance and how they are evaluated.

We found that the geometry of a sample influences the evaluation of the surface appearance. Therefore, the results cannot be directly applied to all possible geometries. However, we expect that the results will be valuable for new geometries that have sufficient similarities with features of a tested sample. A limitation is that the results are only valid for the SLM system, material, and the specific building strategy used in this experimental setup.

We initiated this project to develop a methodology that includes a procedure and experimental setup to gain a deeper understanding of the influence of the different parameters in the 3D printing process on the aesthetic evaluation of 3D printed parts. The setup used has proved to be a valuable tool for obtaining data on the links between different parameters. This setup could be extended in follow-up research with increased numbers of variables.

Conclusion and future work

This study is a precursor to gaining a comprehensive understanding of how each parameter of the AM process influences the aesthetic properties of the 3D printed result. With this understanding, we intend to develop design support to give the designer more control over the printed products in terms of aesthetics. We used SLM technology for the initial research project, and investigated the parameters geometry, building strategy, and post-processing.

Our results have given us early insights into the links between these parameters and the product's aesthetic appearance. Importantly, this work presents a viable systematic procedure and setup to evaluate the fabrication process with regards to aesthetics, based on physical models being assessed by people.

We used SLM to produce a collection of 40 samples with varying parameters: geometry, building strategy, and post-processing. The samples were evaluated by 35 participants who answered questions on their visual and physical interaction with the printed samples. Our results show a clear relationship between the three parameters (geometry, building strategy, and post-processing) and the human perception of 3D printed parts for some aspects of surface. This method thus is valid and applicable to evaluating other AM technologies and parameters.

As discussed earlier, there are a large number of post-processing options, of which only one was investigated in our experiment. In future work, we intend to include samples that have been post-processed using additional surface finishing techniques, such as electro-polishing and tumbling. Also, we will include samples with new geometry features and building strategies. In addition, new parameters should be included, such as different materials and AM processes. In the next step, we also intend to expand the data by using a similar experimental setup to evaluate surface appearance of SLM, but asking the participants to score the samples in a different way. In the evaluation method presented in this paper, participants were asked to compare two samples for each question. In the future, we intend to ask participants to score one sample at a time using a Likert scale. This approach will allow us to keep expanding the dataset with evaluations of new samples. Apart from continuing the aesthetic evaluation, the next challenging point is to investigate how such results can be presented meaningfully to the designers.

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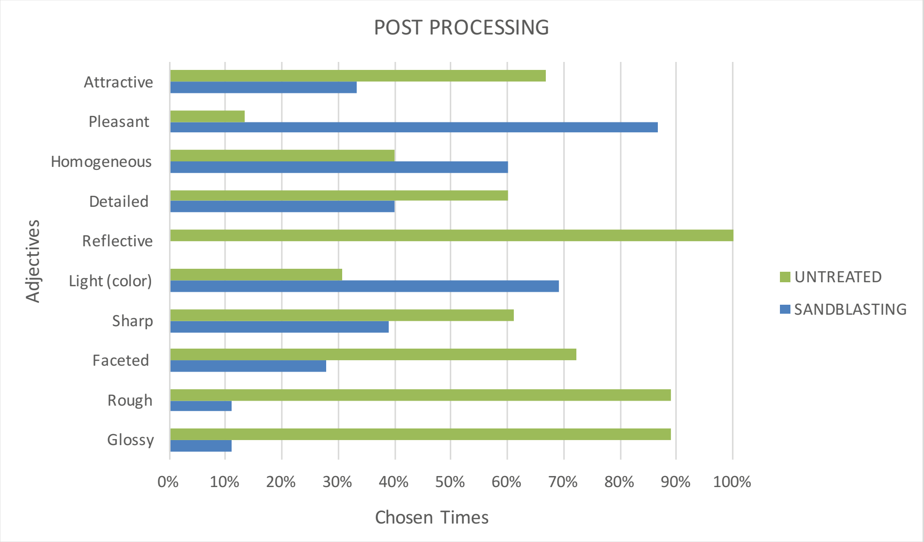
Appendix

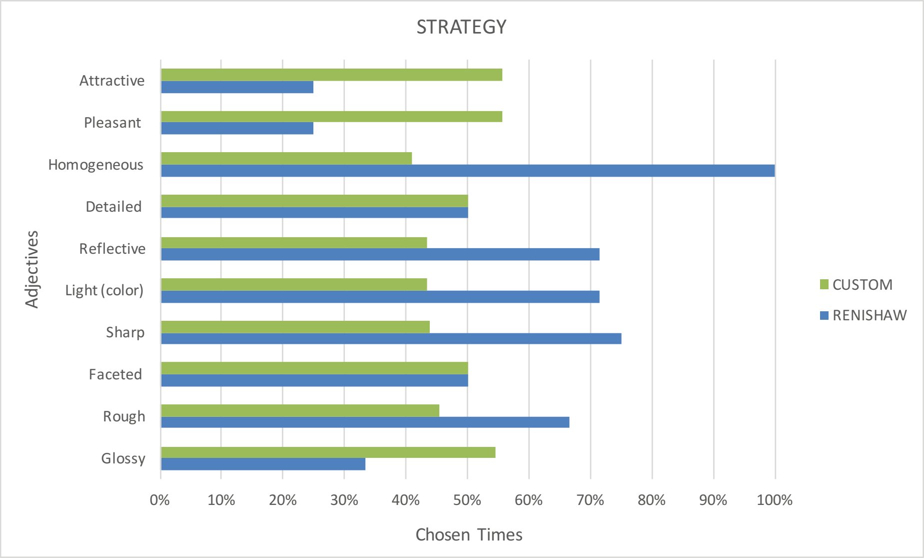
APPENDIX A

INDIVIDUAL PARAMETER ANALYSIS

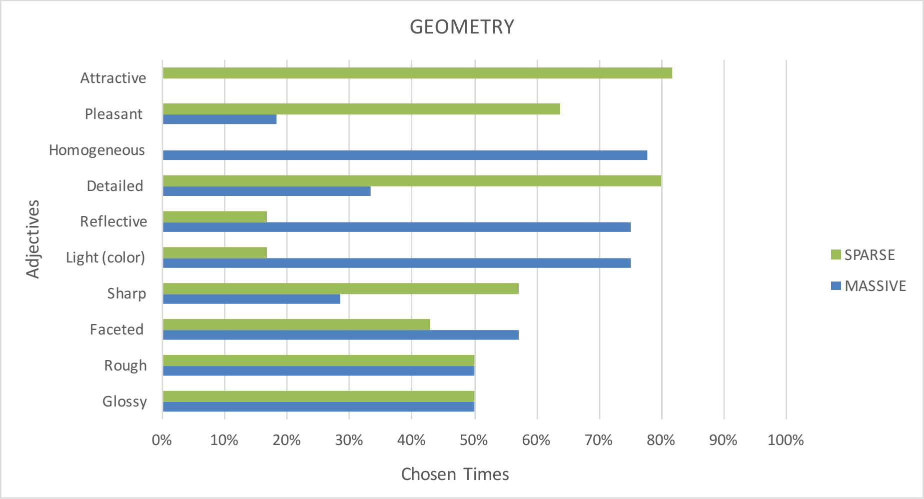
Post-processing



Building strategy

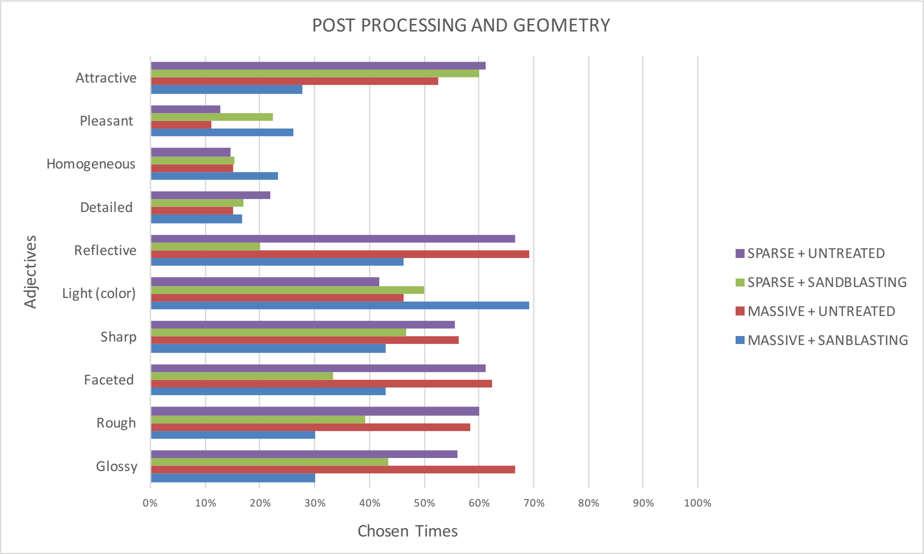


Geometry

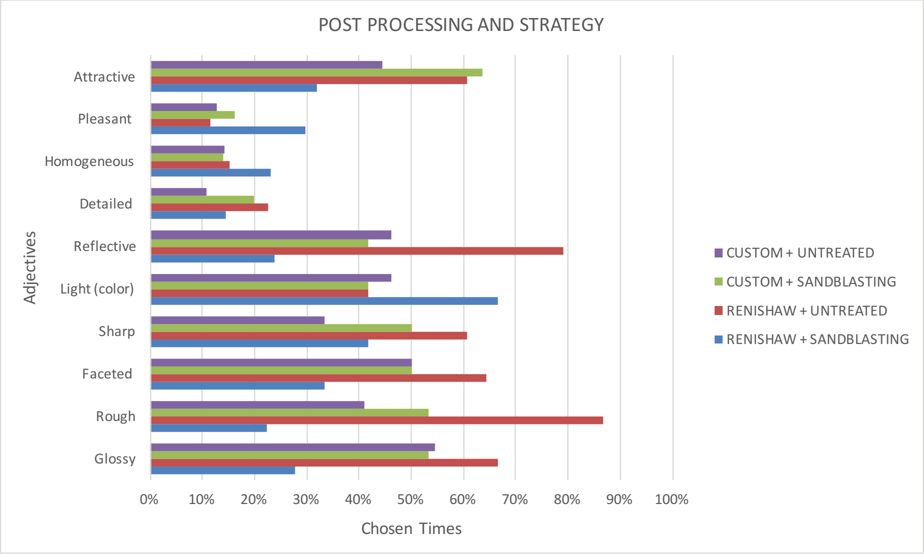


THE INTERACTION OF THE PARAMETERS

Post-processing and Geometry



Post-processing and Strategy



Geometry and Strategy