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A Data Visualization Dashboard for Exploring the Additive Manufacturing Solution Space

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Abstract

This paper will examine the use of data visualisation tools as a method for exploring the additive manufacturing (AM) solution space. One of the challenges of AM is understanding the trade-offs that occur within the design space. It is often challenging to understand the overall performance of a design if there are many performance indicators. This paper presents an AM data visualisation dashboard which is characterised by a three stage filtering process. The first stage utilises a parallel coordinate plot to search through groups of solutions by category and reduce the size of the solution space. Secondly, the filtered solutions are displayed on a scatter plot, providing the designer with the ability to check for correlations between AM specific design variables. Finally, the designer is able to select designs from the scatter plot to evaluate an individual part performance further using both a bar and radar chart. A visual representation of the part is also shown. A case study is presented in which the solution space for an additively manufactured part is explored. A parametric model was used to generate a series of design alternatives to be explored using the interactive visualization dashboard. Three design iterations were performed with the results from each iteration used to inform the development of the next parametric model. The results from this study show that interactive data visualization tools are key to exploring AM solution spaces, assisting designers to gain a deeper understanding of the problem statement and allowing for the generation of improved design solutions.

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1. Introduction

The engineering design process typically begins with ill-defined, imprecise design goals. As the design process continues further design goals and constraints are developed until a final design that fulfils the design requirements is met [1]. This process can be done manually, however, it typically involves the use of some form of computational aid.

Computer aided design (CAD) software gives the designer the opportunity to test different design iterations, however, the majority of CAD software is not suitable for design exploration with part design software generally focusing on a single design instance. There is therefore a requirement for CAD tools that allow for a greater exploration of the design space.

The design space describes the mathematical definition of the design. It includes the design variables and the constraints of the system [2]. The solution space refers to the set of all designs that are produced as a result of sampling the design space.

Additive manufacturing (AM) has increased the set of possible manufacturable part geometries. This is due to the geometric part complexity that is possible to produce when using layered manufacturing techniques. As such, finding optimal design solutions given the range of geometric possibilities is extremely challenging.

Design for Additive Manufacturing (DfAM) is a field of design in which design techniques are applied to maximize the performance of additively manufactured parts [3]. With current

CAD tools it is often challenging for designers to generate a vast range of AM specific designs, explore an AM specific solution space and hone in on the most appropriate design.

To overcome some of these issues, this paper presents an interactive data visualization environment to be used as a method for navigating through large computationally generated solution spaces. The role of the designer is to select the most appropriate solutions based on a set of AM specific evaluation criteria. This process can be repeated until a solution that adequately fulfils the design specification is found.

A case study is presented as an example of how such a data visualization dashboard can be used to discover feasible design solutions.

2. Previous work

Much of the precedent associated with visualizing large design spaces comes from the architectural domain. Ashour and Kolarevic [4] proposed a visualization tool developed within Rhino Grasshopper3D, a parametric modelling CAD environment, to be used in conjunction with a multi-objective genetic algorithm. The authors highlighted that exploration of sub-optimal solutions can yield better design exploration than searching for a single optimum. Results showed that the use of real time visualization tools can increase the level of design space exploration and improve the quality of design solutions.

Chaszar *et al* [5] used an interactive parallel coordinate plot in combination with an interactive x-y scatter plot to explore designs created using the ParaGen model [6]. The results showed that interactive plots are key to aiding comprehension and modification of the design space. A secondary result showed that the use of data visualizations can also aid in the validation of design models.

The Living design studio [7], used an evolutionary approach to design a number of novel chair designs. The designs were displayed on a parallel coordinate plot to allow for further design exploration. The results showed that the designer was able to reduce the mass of the chair from 10.3kg to 2.9kg by specifically designing a chair for the AM platform.

Smith *et al* [8] studied eighteen designers in tasks where computational design tools were used to generate conceptual design ideas. From the study, the authors derived a number of points that must be considered when managing alternative ideas in early design. These included 1) making it easy to switch between ideas, 2) providing an efficient way of viewing multiple ideas at once, 3) providing multiple ways of classifying ideas and 4) to be able to identify ideas both pictorially and textually.

3. Data visualization dashboard for AM

From the literature it is clear that interactive data visualizations provide users with a greater understanding of design spaces. However, work is required to extend the levels of interaction within these visualizations and apply an interactive exploration tool to the AM domain.

To achieve a flexible method for visualizing and exploring the solution space for a specified design problem, a web-based

interactive visualization dashboard was developed using the D3.js library.

The interactive visualization dashboard is comprised of three stages, guiding the designer from an entire solution space exploration to a single design solution. Multiple visualization techniques are applied, which are best suited to the amount of data being presented at each stage. The following section will describe the implementation of an interactive AM visualization dashboard. For clarity, figures 3-4 have cursors and mouse paths, indicated by dashed lines, included within the visualization to highlight where the user interactive zones occur.

3.1. Stage 1 - Solution space visualization

A parallel coordinate plot is used for the first stage of the data visualization. Parallel coordinate plots have been shown to be an effective way of visualization vast quantities of high-dimensional data [9]. This gives the user the opportunity to view the entire solutions space. Studies have shown that parallel coordinate plots require a level of interactivity to be useful as a plot when large datasets are to be shown [10]. Brushing is therefore applied to the axes to permit the user to generate a subset of the solution space by reducing the domain of a selected axis. The filtered results from the parallel coordinate plot serve as an input to stage two of the visualization.

3.2. Stage 2 – Filtered solution space visualization

The goal for this visualization stage is to understand the relationships within the dataset. A scatterplot was selected for this stage of the visualization as this plot type allows the designer to easily see patterns within the data set determining correlations between design variables.

An α -transparency value of 0.7 is applied to all filtered designs to allow the designer to distinguish the filtered designs from the rest of the solution space. Further interactivity is available to the designer within this stage, firstly, by allowing the designer to select the axis type. By selecting different axes, the designer is able to view correlations between any two variables. A zoom function is also implemented within the scatterplot to allow the user to zoom into areas that show multiple design instances with similar values. This is particularly important when large datasets require exploration.

The designer is able to highlight particular design instances by clicking on the circle. Upon doing this, the circle is highlighted and individual part information appears in a table below the scatter plot. This part information is also fed into stage three of the visualization tool.

3.3. Stage 3 – Individual solution visualization

The final stage of the data visualization involves feeding individual part data back to the user for selection of the most appropriate design solution whilst also giving the user the opportunity to provide feedback on the qualitative aspects of the design.

The objective of this visualization stage is to allow the user to evaluate and select superior designs from the solution set. The part data within this stage is presented as normalized data from the entire solution set. A further requirement at this visualization stage is to provide feedback on qualitative aspects of the part design, such as aesthetics.

A number of charts are provided to aid the designer in evaluating individual design instances. Two primary charts are selected for this visualization, namely a radar chart and a bar chart. The radar chart is provided to visualize a normalized comparison of the part for five user selected criteria against the solution set. Radar charts provide a method of visualizing high dimensional quantitative data.

A bar chart is also presented which contains part specific information including elements to judge how easy the part will be to manufacture. Three manufacturability criteria are provided: build height, support structure quantity and aspect ratio. The manufacturability data provided is scaled against the data set and scaled to a value between 0-10. This is so that the designer can easily get numerical feedback on a part's quality relative to the entire solution set. A pictorial representation of the design is also shown to allow the designer to judge the part on qualitative specification criteria such as part aesthetics.

Qualitative feedback provided by the designer is captured using an interactive slider bar. The designer is given the opportunity to rate the design from 0 to 10. When the user clicks the 'Rate and Compare' button the current design image and slider bar value are stored above the radar chart; these designs can then be accessed at any point by clicking on the image. Two designs can be stored at any time. The evaluation score for each part name is stored within an array and can be accessed or exported from the visualization environment at any time.

4. Case study

To test the efficacy of the visualization dashboard the following example was conceived. A test part to demonstrate their design capabilities. A chair design is required that fulfils the following part design specification criteria.

- Should have max dimensions of 1000 x 500 x 500 mm
- Should have a high surface to volume ratio
- Should be manufactured using a polymer
- Should be aesthetically pleasing
- Cost should be considered throughout the design process

In order to produce designs which are capable of fulfilling these design requirements a CAD model was developed within Grasshopper3D that could be used to parametrically design a number of chairs. The chair was initially divided into seven dimensional parameters, labelled A-G and shown in figure 1 with the corresponding values in table 1.

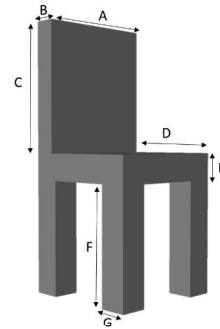


Fig. 1. Labelled dimensions chair parameters.

Table 1. Parameter description for initial chair designs.

Parameter letter	Parameter name
A	Backrest width
B	Backrest thickness
C	Backrest height
D	Seat width
E	Seat height
F	Leg height
G	Leg thickness

Each of the parameters were designated an exploration range and a Python script was written in Rhino to automate the creation of each design. Each time a parameter value is changed, a new design instance is created and data associated with that design is recorded.

The quality of each design instance is measured by how well each design fulfils the given performance requirements derived from the part design specification. A number of evaluation criteria were derived to be able to assess the quality of each design. The evaluation criteria were recorded in a data tree for each design instance and input into the visualization dashboard.

The criteria derived from the part design specification require knowledge of the parts geometry. The overall part height which was recorded as the sum of parameters C, E and F. The seat height recorded as the sum of parameters E and F.

$$\text{Part height} = C + E + F \quad (1)$$

$$\text{Seat height} = E + F \quad (2)$$

The volume and surface area of each chair are also recorded. These values will be useful in determining the surface area to volume ratio, which is a further specification point. The mass of the chair was determined from the product of the part volume and density of the selected material.

As one of the main specification points dictates that the part should be additively manufactured, two materials were selected for design exploration. Due to the size of the part, the fused deposition modelling (FDM) process was deemed to be the

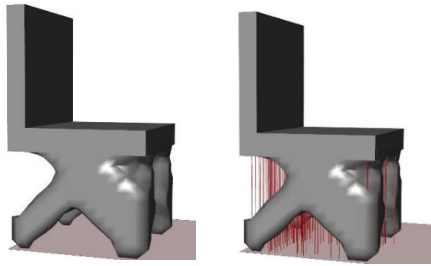


Fig. 2. Chair design (a) before and (b) after support structure algorithm is applied.

most suitable process and therefore two common plastics for the FDM process, PLA and ABS were selected for evaluation.

The amount of support structure was determined using a custom algorithm developed using a script written in Grasshopper3D. The support structure density was kept constant for each design instance and support structure was generated on all structural elements which have an angle of greater than 45° between the design and the build plate. An example of a design instance shown with and without the support structure algorithm is shown in Figure 2. The support generation algorithm requires the user to orient the part to the desired position before the support structures are generated. Whilst it may be beneficial to employ an optimised part orientation algorithm to minimise structure [11], this was deemed to be beyond the scope of this paper.

The total length of the support structure was then calculated. The amount of support structure was then feature scaled between 0 and 10 to allow for ease of comparison between design instances.

The part manufacturability was defined as the sum of two criteria, the aspect ratio of the part, and the amount of support structure required in the part build. Parts with a large aspect ratio are more difficult to build and support structure amounts to wasted time and material.

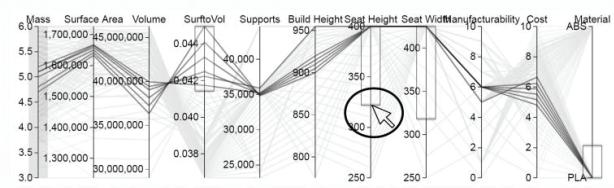
The manufacturability of each part was feature scaled between 1 and 10 to provide a relative manufacturability score for each part. The smaller the value, the easier the part will be to manufacture.

The relative cost of the part in AM is estimated to be a function of its direct build costs, for example, build time and material costs and indirect costs such as post-processing labor and setup costs [12]. It is assumed that design instances will have fixed indirect costs, therefore a cost model is devised which is only a function of the direct costs associated with build time, and the material usage. As build time is highly correlated with the part height [13], determined from equation 1, this value is used as a measure of the build time. The material usage is estimated to be the sum of the part volume (V_{part}) and total support structure volume ($V_{support}$). An estimate for part cost is derived using equation 3.

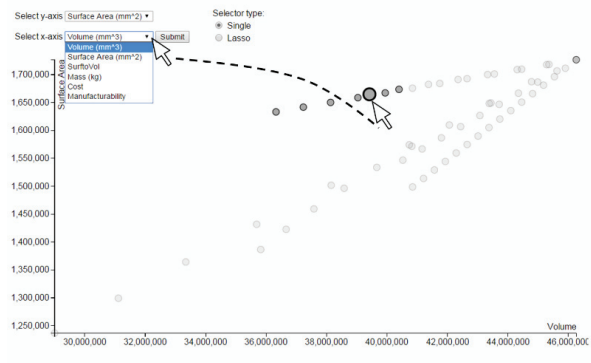
$$Relative\ Cost = (C + E + F) \times (V_{part} + V_{support}) \quad (3)$$

The cost value is used to provide a relative comparison between all generated design instances therefore the cost value is feature scaled between 1 and 10.

Stage 1 - Solution Space



Stage 2 - Filter Outputs



Stage 3 - Output Comparison

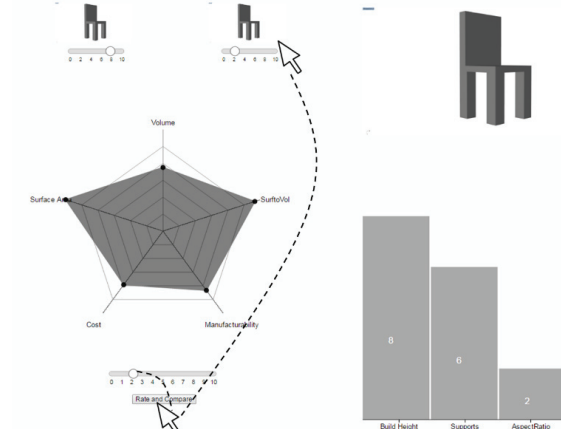


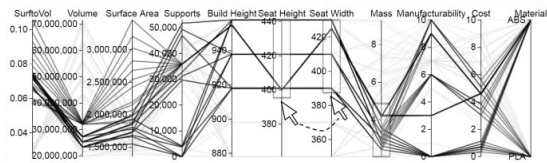
Fig. 3. Interactive visualization dashboard for parametric chair design

Initially, 128 design alternatives were generated by varying the parameters specified in Table 1 and also by varying material type. This data was saved into a .CSV file and used to populate the AM solution space dashboard shown in Figure 3.

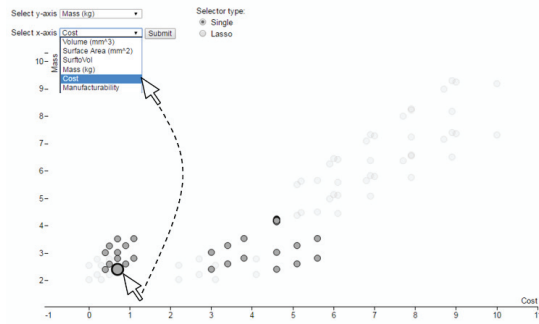
A designer is able to rapidly search through the solution space in the first stage by applying brushes to the coordinate plot. In this case, all chair designs with a seat width below 325mm, all chairs with large amounts of support structure and parts made with ABS are filtered.

The filtered designs appear in the stage two comparison. Once a satisfactory number alternatives have been explored by clicking on the circles; stage three is updated with individual part information and a table under the scatter plot is updated with information associated with that particular design

Stage 1 - Solution Space



Stage 2 - Filter Outputs



Stage 3 - Output Comparison

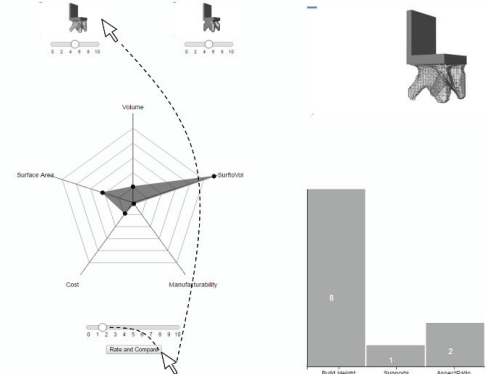


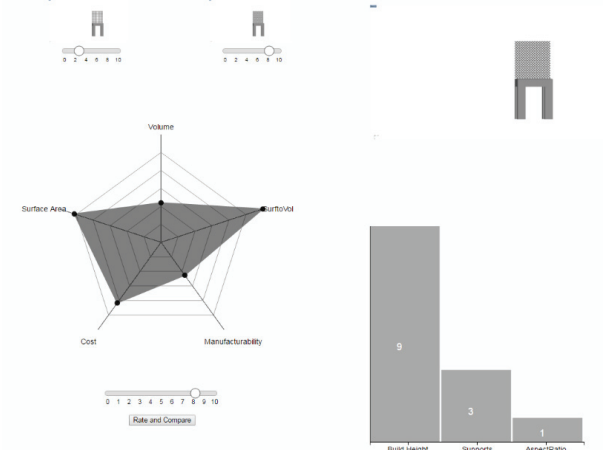
Fig. 4. Visualization dashboard output for second design iteration.

instance. The objective of this design iteration is to fulfil as many of the part specification criteria as possible.

Taking into account the values from the radar chart and the relative manufacturability from the bar chart, a number of designs were evaluated and compared using the slider bar. A part was then selected which best fulfilled the dimensional requirements from the design specification. Results from stage three show that whilst the overall part dimensions have been satisfied, one of the specification requirements, the surface to volume ratio, of the parts generated in this set were very poor. It was determined that the part cost can be reduced by cutting down the amount of required support structure.

Using the most satisfactory design instance from the first iteration as a guide for the overall chair dimensions, an improved part specification can be drawn up with increased knowledge gained from the initial solution space exploration. The design specification was changed and designs were required to fulfill the following performance requirements.

Stage 3 - Output Comparison



Stage 3 - Output Comparison

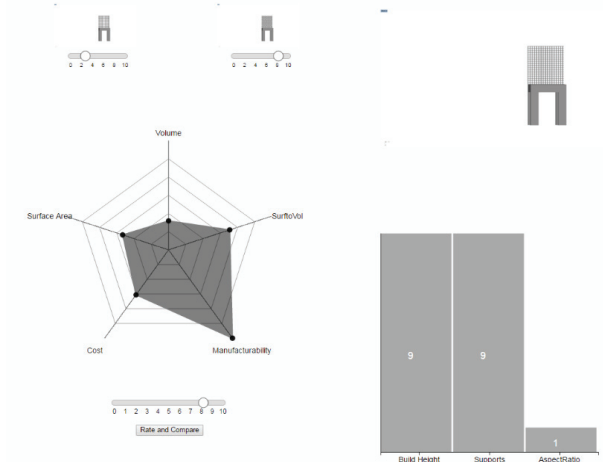


Fig. 5. Stage three visualization dashboard comparison of two lattice unit cell types.

- Should have an organic looking structure
- Should have a low mass
- Should have a maximum build height greater than 930mm
- Seat height should be greater than 400mm from the ground

A second parametric model was developed in Grasshopper3D utilizing the Millipede plug-in as an exploratory tool for generating organic structures. A further 128 designs were generated before translation into the interactive AM visualization dashboard for exploration. The results from the second interaction are shown in Figure 4.

Akin to the first iteration, the parallel coordinate plot in the primary stage is used to filter out the solutions that do meet the



Fig. 6. (a) Grid unit cell (b) cross unit cell

initial specification requirements of a chair with a greater height than 930mm and a seat height greater than 400mm.

As the main objective was to minimize the mass of the chair the scatter plot axes were changed to highlight the relationship between the mass and the relative cost of the part. A design was chosen which was low mass, a low relative cost factor, as well as a good manufacturability rating.

The mass of the design could be further reduced by applying a lattice structure into the backrest region of the chair. A further iteration was carried out and the final stage filter for two different lattice unit cells, a grid unit cell and a cross unit cell, shown in Figure 6. Results show that whilst part performance is similar for both parts, the amount of support structure required for the grid lattice is far greater than the cross lattice. This is due to the lattice struts 45° overhang angle within the structure. The stage three visualization results from the third design iteration are shown in Figure 5.

From the information gained from these design iterations, it was decided that a combination of the two best solutions, the organic lattice structure in the leg region, combined with the diamond cell unit structure in the back rest of the chair fulfils all of the main specification criteria defined within the design specification. The final chair design is illustrated in Figure 7.

5. Conclusions and future work

This paper provides one of the first attempts at developing and using interactive data visualizations throughout the early stages of the AM design process. The visualization tool comprises a web-based three stage interactive dashboard that allows the designer to explore and compare numerous design concepts.

A case study was developed whereby a parametric modelling tool to develop an initial solution space of chair designs that the designer could explore. A number of evaluation criteria including AM elements such as part manufacturability and cost were developed to further inform the designer about the quality of generated solutions. Three iterations of the design were performed before a design fulfilling all of the specification criteria was achieved.

The major outputs of this paper are:

- 1) The realization of an AM visualization dashboard which is shown to assist the designer in narrowing vast solution spaces of computationally generated design solutions.
- 2) Interactive data visualization tools are a key component to design exploration in early stage DfAM and by using interactive visualization tools, designers are able to gain further knowledge of the design problem and therefore generate more suitable part design solutions.
- 3) This work provides the underpinning knowledge required for a future generation of CAD tools to support design synthesis and exploration.

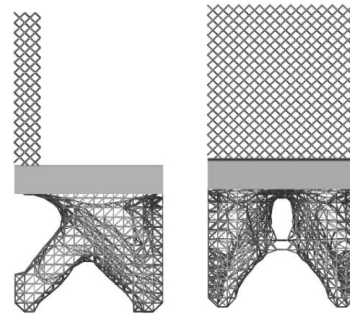


Fig. 7. Final chair design (a) side view and (b) front view after three iterations using AM visualization dashboard

Further work will be undertaken to extend the accuracy and the number of evaluation criteria, with the aim to improve the quality of output designs and reduce the time taken to find satisfactory design solutions.

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