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GE Jet Engine Bracket Challenge: A Case Study in Sustainable Design

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Abstract

Open crowdsourcing competitions can provide a large repository of data which can be used to achieve more sustainable product designs. This study looks at the recent General Electric challenge, a competition to minimize the mass of a titanium jet engine lifting bracket, to illustrate the benefits that can be accrued. In the light of current literature the benefits and challenges of crowdsourcing have been considered. Samples of the entrants to the challenge have been compared to identify critical characteristics for interpreting sustainable designs for additive manufacture. Focusing initially on topological optimisation and orientation of the additive manufacture build, critical features have been highlighted. The availability of many CAD designs has been most useful and has potential for future developments. Crowdsourcing as an innovation approach can also be beneficial for both companies and individuals particularly if the entries are open source.

1. Introduction

General Electric (GE) recently launched a design challenge for additive manufacture (AM) on the GrabCAD website [1] which generated over 700 entries. This open source competition enabled free access to both geometry and image files, providing a rich source of data to inform future sustainable design.

The focus of this paper is two-fold, firstly to consider the benefits of an open crowdsourcing challenge to both the company and the individual and then to investigate the competition entries to improve future designs for AM production. Topologically optimised design and build support properties were considered in detail.

2. Design Study

The challenge was to redesign an existing titanium lifting bracket for a jet aircraft engine in order to minimise the weight. The bracket was to be produced by Direct Metal Laser Sintering (DMLS). A precise design envelope was specified (see Figure 1) and the bracket was required to satisfy the four load conditions shown in Figure 2.

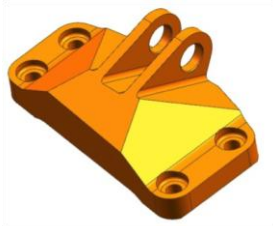


Figure 1: Original Design Envelope for Engine Bracket [1]

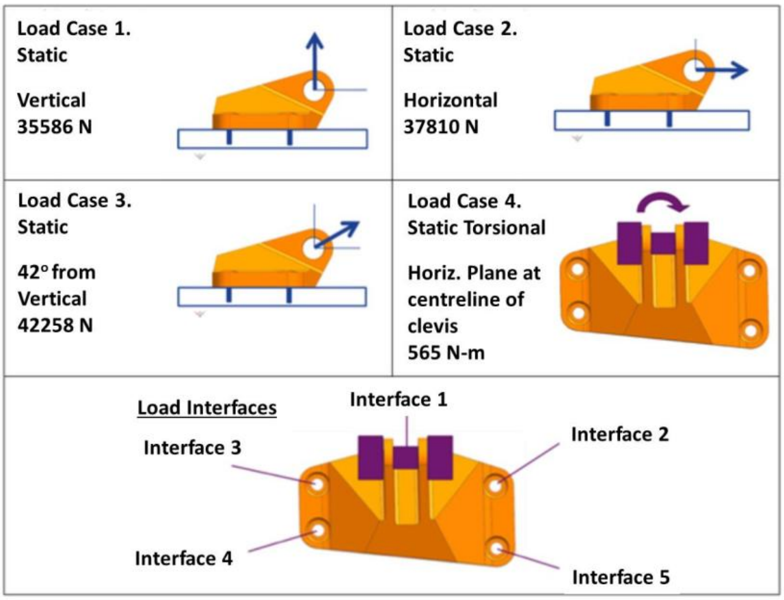


Figure 2: Four Load Conditions Specified by GE [1]

3. Environmental Sustainability

The challenge was clearly focussed on producing an environmentally sustainable product. Reducing the weight of any aircraft component has an impact on fuel usage and emission levels. Fewer raw materials are used in a smaller part reducing the energy usage and emissions in mining and manufacture. This is particularly pertinent as titanium production consumes high levels of energy [2]. A recent cradle-to-grave life cycle analysis (LCA) by Norgate *et al* [3] showed titanium to have a gross energy requirement of 361 MJ/kg, more than 15 times that of steel. Persistent rogue elements can make alloys of titanium difficult to recycle [4], however due to its excellent corrosion resistance and high strength, titanium products have much greater longevity than other lightweight metals.

It has been estimated that AM produces 80% less waste material than standard subtractive machining methods [5], though the longer build time tends to lead to higher energy consumption. An LCA carried out by Serres *et al* [5] on a titanium aerospace part showed that the total environmental impact for an AM part was about 70% of the impact of a machined part. Greater freedom in geometric complexity with AM can enable lower mass when compared to more traditional methods [6].

Sustainability extends however beyond product design. A more holistic view of the subject will be discussed in the following sections.

4. Open Crowdsourcing

Crowdsourcing has been defined as "… the act of a company or institution taking a function once performed by employees and outsourcing it to an undefined (and generally large) network of people in the form of an open call" [7].

Organisations may crowdsource using competitions with financial rewards but some large projects attract volunteers with common interests [8]. Crowds may need to have specific skills, but often the value to the client lies in the volume of information acquired rather than in the contribution of a single individual e.g. supermarket loyalty cards data.

In conjunction with the internet, crowdsourcing can give access to individuals over a large geographical area with diverse interests and skills. This will be considered in two key areas in the following sections: company sustainability and individual sustainability.

5. Sustainability of Companies

The design of sustainable products is only an academic exercise unless components are manufactured and used. Sustainability therefore becomes more than just "green" issues but is about the ability of the products to endure and have prolonged or repeated usage. Businesses themselves therefore need to be sustainable with increased efficiency in time, labour and knowledge transfer to ensure their own stability and resilience.

Small and medium-sized enterprises (SMEs) generally have great agility and flexibility in responding to new innovation and technology being unencumbered by large organizational structures. They may however, be limited by the number of employees or available funding. A recent paper by Xu *et al* [9] highlighted how crowdsourcing has been used in China with SMEs to access resources outside of the company to improve product innovation and R & D. This approach can enable SMEs to accomplish much more that can be achieved by their limited work-force.

One perpetual crowdsourcing initiative is the on-line T-shirt retailer Threadless [10]. Design and evaluation are undertaken by crowdsourcing. This creates a very sustainable model for the business as potential customers have already been identified before any of the designs are printed.

There are risks however in taking this approach. The uptake on the call may be limited or the quality of the submissions poor. The response may be large and significant additional resources may be needed in the evaluation process. Careful planning is required to clearly define the problem while removing all company-specific details and integration of crowdsourcing with other research initiatives must be managed carefully to avoid alienation of existing staff.

6. Individual Sustainability

Recent studies indicate that individuals engaged in R & D in the future are much more likely to be freelance contractors than have long-term careers with one company [11]. Crowdsourcing enables individuals to showcase their work to potential clients whether for consultancy or possible recruitment. It has been found that the high degree of autonomy and lack of hierarchy in crowdsourcing can provide a greater degree of satisfaction compared to more traditional organizational structures [12]. When an open approach is used for crowdsourcing, opportunities are created for peer feedback and discussion.

Conversely, many participants have become disillusioned with crowdsourcing since relatively few benefit from the prizes and some resent the apparent exploitation by large companies. Competitions alone do not provide a reliable form of employment.

The following sections will look closely at how these factors are reflected in the experience of the GE challenge.

7. The GE challenge - Results & Discussion

The design challenge received approximately 700 entries from 320 designers. The mass reduction, ranged from 7-96% of the original bracket weight. Approximately 70% of the entries had a mass of 40% or less.

The majority of the designs could be classified into four main categories as shown in Figure 3:-

a) An "Open Mouth". The concave surfaces from the underside form steep angles to the horizontal indicating that low levels of support material would be needed in the AM build. There were many designs of this type with the lowest at 10% of the original weight.
b) A pocketed design. The boundary of the original domain was clearly visible and material had been excavated normal to the external surfaces. This design spanned the whole weight range, but 12% was the minimum.
c) Flat designs. The clevis pin support was perpendicular to the upper surface. Some of these had large flat bases which would require low level support material across the whole base area depending on build orientation. Minimum weight 10%.
d) A "Butterfly". Smooth concave surfaces between the clevis pin holes and the bolt holes achieved a pleasing aesthetic design. The low angles at the base however, would require support during manufacture. The minimum weight achieved was 19%. Lighter designs down to 10%, were submitted but these did not fit within the original design envelope.

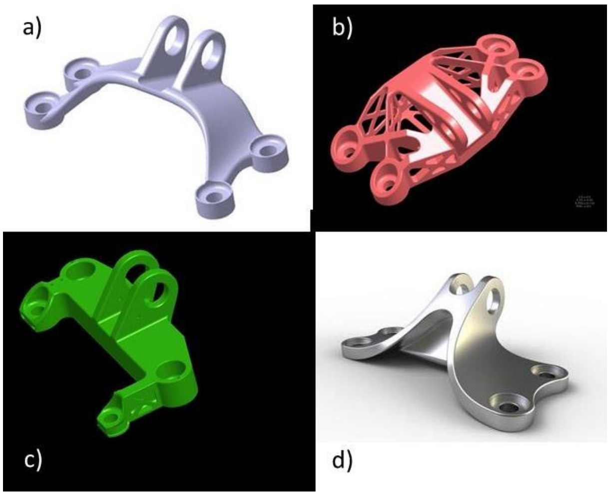


Figure 3: The four main categories of design submitted

The designs, once submitted were open to public scrutiny. Some designers deliberately posted entries early to solicit feedback and in some cases assistance with FEA analysis.

7.1 Benefits to the Company

Cost

Where recorded the time spent on the design ranged from 40-160 hours. Taking the lower of these values as typical the entries represent a total of 700 working weeks or 14 man years. If it is assumed that the cost for setting up the challenge is similar to the prize money then the client has paid just over $2 an hour for the designs, less than a third of the US statutory minimum wage. This figure does not include the cost of the equipment or software licences used which have been contributed by the participants. The Company also benefited from ownership of all the Intellectual Property rights according to the GrabCAD agreement [1].

Sustainability

The designers came from 56 different countries, approximately a quarter of them were from the USA with the next highest group (11%) from India. GE was able to access expertise from a large geographical area with no additional costs or impact on the environment.

Quality

27% of those for whom there was data available identified themselves as University/College students. The majority of the remainder were engineers or designers predominantly mechanical or industrial designer. Some of these operate their own companies or consultancies. Where levels of expertise were indicated a number of people were shown to have 10 years or more experience. It would appear that the crowd accessed through GrabCAD were sufficiently skilled to provide quality entries.

7.2 Benefits to the individual

It is difficult to assess the overall benefits to the individuals from the GE challenge aside from the financial remuneration to the winners ($30,000 shared amongst 10 finalists). Certainly there were individuals who were able to showcase their skills and in some cases their areas of research interest [13].

Difficulties have arisen with this challenge. The original deadline was extended as the GrabCAD community pushed for precise details of the analysis approach to be used by the judges. Some discontent has been expressed over the choice of the winning entries announced in phase 1.

On a more specific individual level the remainder of this paper will present research carried out at Swansea University in two areas using the crowdsourced data to inform the topological optimisation of a sustainable part and the critical parameters for support material in the AM build.

7.3 Topological Optimisation

Using Altair Optistruct 11.0 [14] the material within the design envelope was optimised using the Solid Isotropic Material with Penalization (SIMP) [15] method incorporating all four load cases. Non-design material was retained in the region of the bolt holes and clevis pin. Figure 4 a) shows the result of the topological optimisation for element densities 0.3 and above. It appears to be of the "Open Mouth" type a). The mass of this part is approximately 8% of the original though it does not have sufficient integrity to provide a practical solution at this stage. An FEA analysis showed stress levels well above the elastic limit of 903 MPa at the filleted edge near the clevis pin hole and the rear bolt holes (see Figure 4 b))

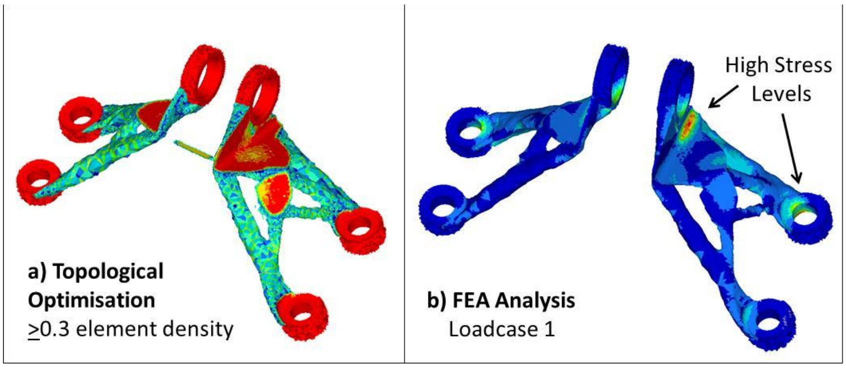


Figure 4: Results of Topological Optimisation of Bracket together with Stress Analysis

A large number of the entries to the GE Challenge were based on an initial topological optimisation. Ten designers specified either the software or algorithm used to achieve these results. Table 1 shows a comparison of these designs with the weight achieved, the bracket type and a measure of the complexity of the design indicated by the number of surfaces in the CAD. The designers published maximum stress levels within the elastic limit for those designs marked with an asterisk.

It can be seen that the majority of the designs were of type a), though three of these also had a partial flat base. Type d) was not predicted by any of the algorithms. The resulting entries spanned a large weight range (13-61%).

Some CAD/Optimisation software e.g. Altair Optistruct, are now capable of creating geometry directly from the optimisation results but this can lead to a component with a non-smooth appearance caused by a large number of surfaces e.g. designs (vii) & (ix). This may be acceptable for parts hidden after assembly but is unlikely to be so for a "state of the art" jet engine. Some interpretation of the design was therefore required and the availability of the challenge entries enabled different designs to be investigated without the time, effort or expertise required to produce new geometry.

Table 1: Details of 10 designs where Topological Optimisation method was specified

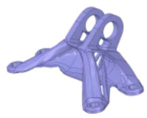
	Software	**Algorithm**	**% weight of original**	**Type**	**Complexity** (Number of surfaces)	**Design**
i	ANSYS	Evolutionary Structural Optimisation (ESO) [16]	13%	a (with partial flat base)	334	
ii		Level set method [17]	15%	a	205	
iii	Altair Solid-Thinking Inspire*		18%	a	509	
iv	Abaqus		20%	a	274	
v	ParеTO	Topological Sensitivity[13]	20%	b	441	
vi	*	Covariance Matrix Adaption Evolution Strategy (CMA-ES) [18]	23%	c	212	
vii	Catia V5		23%	a	3421	
viii	CREO		29%	As (i) above	203	
ix	MSC .Nastran		40%	As (i) above	1007	
x	ANSYS 14.5 (beta)		61%	c	133	

Figure 5 shows the topology results of Figure 4 overlaid on design (viii) of Table 1. The diagrams show an excellent fit. The design satisfied all the loading conditions but the weight has been reduced to only 29%. The partial flat base has ensured low stress values at the bolt holes but may be problematic in building the part.

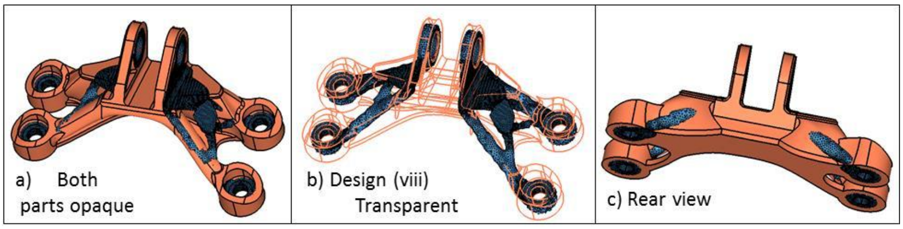


Figure 5: Overlay of Result of Topological Optimisation on Design (viii)

Two lessons have been learnt from comparing the topology result with the Challenge designs of lower weights

i) All the other designs of a similar shape have a lower upper surface than the topological design. This has reduced the high stress level as the pelvis pin interface. A good example of this is shown in Figure 6.

ii) This design also highlights how the stress concentration at the bolt hole was minimised by constructing a fairly robust leg that extended horizontally from the bolt-hole surface at the base.

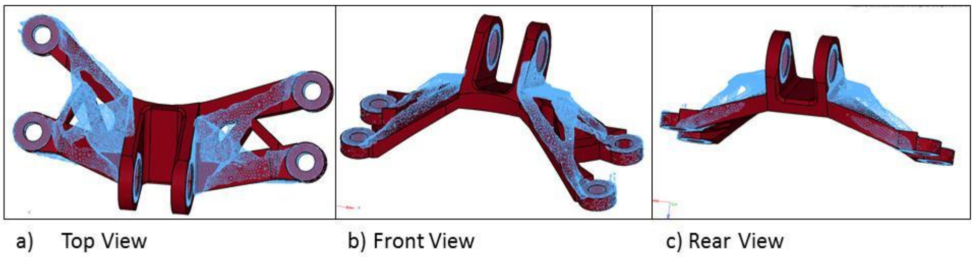


Figure 6: Overlay of Topological Optimisation on Compact Design

The design of Figure 6 has a weight of 18% and a relatively simple geometry. It was not one of the designs detailed in Table 1, but one of the finalists from the first phase of judging.

7.4 Orientation of parts for efficient Additive Manufacturing

Using the data from the ten finalists of phase I of the Challenge and using Marcam Engineering AutoFab software for a Renishaw AM250 Selective Laser Melting machine an investigation was carried out to determine the variation in support material needed to build these components. Two orientations were considered:-

i) Least height
ii) Least foot print or horizontal projection

Support material was applied to all surfaces at an angle less than 45° to the base plate to provide stability to the surfaces during the build. The product and support material were cut into 50 µm slices. The total volume was calculated together with the actual build time and the material costs for the part and support.

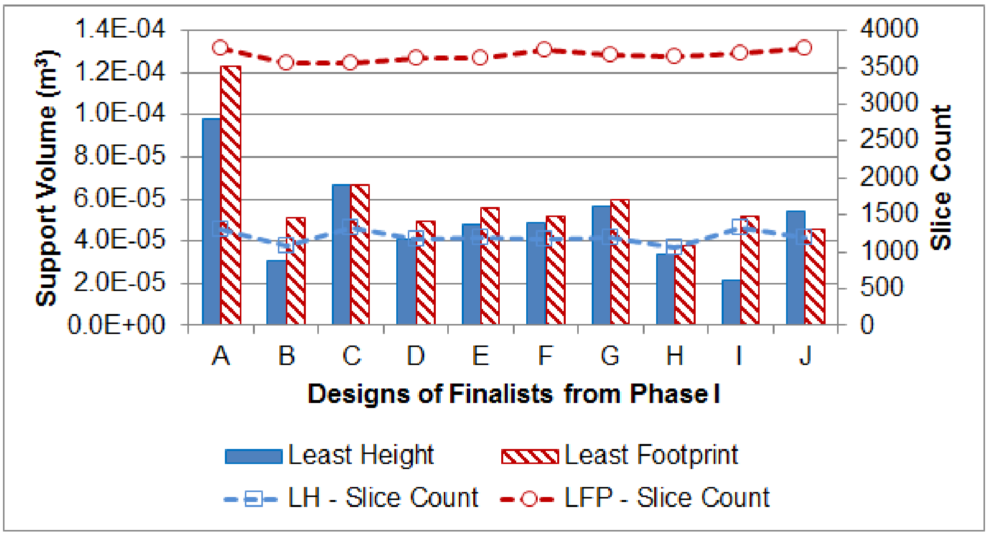


Figure 7: Support Volume and Slice Count for the 10 final designs at two orientations

Figure 7 shows the volume of support material required for each of the ten designs with the two different orientations. In all but design J more support was needed for the least footprint orientation, though in a number of cases e.g. design C, the difference was very small. This small variation was surprising as the height, as reflected by slice count curves in Figure 7 was significantly different in the two orientations.

Design I required the least support material at 'least height' orientation. The design is shown in Figure 8 a). Each of the four legs is hollow and openings have been created at the bolt holes to ensure any loose powder can be removed after manufacture. It can be seen that the vertical angle of the front leg with the base is ~20° which required support material along its whole length. Figure 8 b) indicates the areas highlighted in blue on the underside of the bracket that require support. Support would also be required to build the round holes for the clevis pin.

On closer inspection it can be seen that the upper surface of the front leg, highlighted in black in Figure 8a) is a little over 30° from the horizontal. This would require support material inside the leg, but this has not been taken into account in the results of Figure 7 as the interior surfaces were not visible for selection.

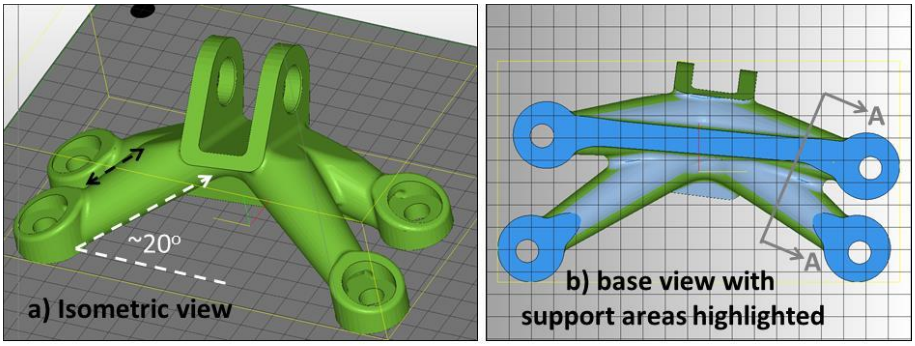


Figure 8: Design I of the 10 finalists

Figure 9 shows the section A-A from Figure 8b) and the red arrow indicates where internal support material might be required along the leg length as the oval cross section flattens. This support could not be removed after manufacture and so would add to the weight, but would also impact on the stress patterns within the bracket. More work is required to determine whether by changing the build angle these internal supports could be eliminated.

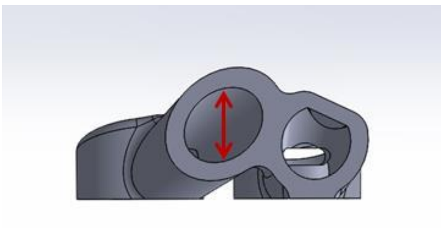


Figure 9: Section through A-A of Design I

8. Conclusions

Open Crowdsourcing has been shown to be one of a number of modern methods of innovation that can provide sustainable solutions to large and small organisations when carefully managed. Internet challenges enable designers and engineers to showcase their work not only for monetary reward but for potential consultancy and employment opportunities.

The data provided by the entries for the GE Challenge has been used to compare different optimisation tools, inform the interpretation of topological optimisation results and highlight some of the critical features in building components using AM. There is still considerable scope however, for further use of the data for educational and research purposes.

9. Acknowledgement

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10. References

1. GrabCAD. *GE Jet Engine Bracket Challenge*. 2013 [cited 2013 20th June]; Available from: https://grabcad.com/challenges/ge-jet-engine-bracket-challenge.
2. Seong, S., O. Younossi, and B.W. Goldsmith, *Titanium - Industrial Base, Price Trends and Technology Initiatives*. 2009: RAND Corporation.
3. Norgate, T.E., S. Jahanshahi, and W.J. Rankin, *Assessing the environmental impact of metal production processes.* Journal of Cleaner Production, 2007. **15**(8–9): p. 838-848.
4. Lu, X., et al., *Thermodynamic analysis of separation of alloying elements in recycling of end-of-life titanium products.* Separation and Purification Technology, 2012. **89**(0): p. 135-141.
5. Serres, N., et al., *Environmental comparison of MESO-CLAD® process and conventional machining implementing life cycle assessment.* Journal of Cleaner Production, 2011. **19**(9–10): p. 1117-1124.
6. Wong, K.V. and A. Hernandez, *A Review of Additive Manufacturing.* ISRN Mechanical Engineering, 2012. **2012**: p. 10.
7. Howe, J. *Crowdsourcing: Why the power of the crowd is driving the future of business*. 2006 [cited 2013 27th Sept]; Available from: http://crowdsourcing.typepad.com/cs/2006/06/crowdsourcing_a.html.
8. *Indexing Makes Records Free and Searchable*. 2013 [cited 2013 11th October]; Available from: https://familysearch.org/indexing/.
9. Xu, C., S. Qin, and Z. Xiao. *Crowdsourcing Based Product Innovation Design Service Model for Small and Medium-Sized Enterprises*. in *18th International Confeence on Automation & Computing*. 2012. Loughborough University, Leicestershire, UK.
10. *Threadless*. 2000 [cited 2013 11th October]; Available from: http://www.threadless.com/.
11. Farrington, T., C. Crews, and J. Blenkle, *IRI 2038: Envisioning the Future of R&D.* Research Technology management, 2013. **56**(1): p. 58-59.
12. Schenk, E. and C. Guittard, *Towards a Characterization of Crowdsourcing.* Journal of Innovation Economics & Management, 2011. **1**(7): p. 93-107.
13. Suresh, K., *Efficient generation of large-scale pareto-optimal topologies.* Structural and Multidisciplinary Optimization, 2013. **47**(1): p. 49-61.
14. Altair Hyperworks. *OptiStruct 11.0 User Guide*. 2011 1 Sep 2011]; Available from: http://www.altairhyperworks.co.uk/.

15. Rozvany, G.I.N., M. Zhou, and T. Birker, *Generalized shape optimization without homogenization.* Structural and Multidisciplinary Optimization, 1992. **4**(3): p. 250-252.
16. Xie, Y.M. and G.P. Steven, *A simple evolutionary procedure for structural optimization.* Computers & Structures, 1993. **49**(5): p. 885-896.
17. Wang, M.Y., X. Wang, and D. Guo, *A level set method for structural topology optimization.* Computer methods in Applied Mechanics and Engineering, 2003. **192**: p. 227-246.
18. Hansen, N. and A. Ostermeier. *Adapting arbitrary normal mutation distributions in evolution strategies*. in *Evolutionary Computation, 1996., Proceedings of IEEE International Conference on*. 1996.