Design and Performance Assessment of Innovative Eco-Efficient Support Structures for Additive Manufacturing by Photopolymerization

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Summary

The continued expansion of additive manufacturing (AM) techniques, evolving from its initial role as a rapid prototyping method, toward effective resources for generating final products, is reshaping the production sector and its needs. The development of systematic methodologies for the generation of mechanically optimized support structures for AM processes is an important issue which impacts the eco-efficiency and quality of final parts. The shift from regular lattice support structures and complex support meshes, toward bioinspired support structures, using, for instance, tree-like and fractal geometries, may provide feasible solutions with optimal ratios between mechanical performance and quantity of material used. In a similar way as biomimetics has provided revolutionary solutions to fields including architecture, mechanical engineering, and civil engineering, it may well impact the field of solid freeform fabrication. The possibilities relate not just to aspects related to part geometries and final applications (as is already happening), but also in manufacturing challenges such as the problem of obtaining eco-efficient and reliable supports. In this article, we summarize a recently developed methodology in the framework of the European Union (EU) “ToMax” Project, for the generation of bioinspired fractal or tree-like support structures and provide six application examples, starting with very simple geometries and generalizing the process for more complex parts. Eco-efficiency is assessed by a final comparative study using support structures generated with conventional software.

Introduction

Additive manufacturing (AM) technologies, promoting freedom of design and the generation of complex structures for products with enhanced functionality, are helping to reinvent product development and related industries (Gebhardt et al. 2010). Complex geometries can be defined with the help of computer-aided design resources, three-dimensionally printed and used as rapidly obtained prototypes for validations or as final parts. Constructing models in an additive way has several advantages, including: (1) the opportunity to manufacture highly complex geometries with inner details impossible to...
obtain by traditional processes, hence promoting “freedom of
design” and product customization; (2) the possibility of rapidly
obtaining preproduction series, prototypes, and even final parts,
without resorting to expensive mass production tools; and (3) the
reduction of positioning tools typical of subtractive proce-
dures. AM technologies, commonly “three-dimensional (3D)
printers” (Diegel et al. 2010), have greatly evolved in the last
two decades and remarkable improvements in precision, speed,
available materials have been achieved. Currently, an impres-
sive portfolio of polymers, ceramics, metals, composites,
and biomaterials can be additively processed using laser poly-
merization, laser melting or sintering, digital light processing,
fused deposition modeling, electron beam melting, and elec-
trospinning, among others (Stampfl and Hatzenbichler 2014).
Depending on the technology, raw materials are processed in
different aggregation states, including liquids, emulsions, gels,
slurries, powders, foils, and solid rods. At present, the highest
precision and the best part size/precision ratio are obtained using
photopolymerization (Felzmann et al. 2012; Jacobs 1992; Hague
and Reeves 2000), which typically works with liquid monomers
or polymeric slurries with ceramic or metallic powders.

In spite of the aforementioned advantages and versatility
of these technologies, there are still some drawbacks to over-
come in order to improve the utility of AM technologies and
to make them substitutes that can challenge established mass-
production procedures (Faludi et al. 2015). Main challenges are
linked to further improving final part quality, surface aspect,
mechanical properties, mechanical isotropy, manufacturing speed,
precision of larger parts, and cost of the most demanding technologies (Bourhis et al. 2013). All these aspects are
being thoroughly studied and important advances have been
made in the last years. Another critical aspect, which has not
yet been systematically addressed, is related to the overall eco-
efficiency (Saling 2005) of most AM processes. Regarding final
part quality and material consumption, it is important to draw
the attention to the problem of supporting structures, which
are mechanical elements produced as part of the object being
constructed to provide structural integrity during manufacture,
but which are not intended to be part of the final product
and must be removed, usually manually (Järvinen et al. 2014;
Strano et al. 2013). In fact, most AM processes, especially those
operating with liquid raw materials, require support structures
for the manufacture of cantilevers and overhanging features.
These supports must be manually removed, leave marks upon
the surfaces, and constitute a source of useless material, hence
limiting automation potential, surface quality, and process eco-
efficiency. Support structures are automatically incorporated
into the computer-aided designs by AM software (or “slicers”)
that convert 3D mesh models, usually in .stl format, to print-
able slices and related paths for driving the manufacturing pro-
cess. Normally, support generation processes are just aimed at
promoting mechanical stability of the whole construct, and,
in general, the quantity of generated supports importantly ex-
ceds what is strictly needed from a mechanical perspective,
thus wasting expensive and frequently environmentally harm-
ful materials (Stava et al. 2012). Software resources such as
3D Lightyear™ (3D Systems) generate regular meshes with re-
peated unit cells, while others such as Preform (Formlabs) tend
to incorporate more random structures as supports.

In some cases, designers can modify the generated supports
by changing parameters such as density of the support struc-
tures, size of the support extremes interacting with part surface,
and the presence of inner supports (Vanek et al. 2014), but
predictions about mechanical stability of the designed supports
are difficult and usually based on designers’ experience. Re-
cently developed software like Preform, supporting low-cost 3D
printers (Form1+ by Formlabs in this case), incorporate advice
presented in visual form about the stability of refined supports.
More often than not, however, the predictions fail and the
parts are obtained with important defects. In some cases, just
the support structure is generated and the whole part is lost. In
consequence, the development of systematic methodologies for
the generation of mechanically optimized support structures for
AM processes is a relevant issue, which will impact final part
quality and eco-efficiency in a significant way (Luo et al. 1999).
The shift from regular lattice support structures and complex
support meshes toward bioinspired support structures, using, for
instance, tree-like and fractal geometries, may provide suitable
solutions with optimal ratios between mechanical performance
and quantity of material used. In a similar way as biomimetic
has provided revolutionary solutions to fields, including archi-
decture, mechanical engineering, and civil engineering, it may
well impact the field of solid freeform fabrication. This is not
just important for all aspects related to part geometries and fi-
nal applications (as is already happening), but also for solving
manufacturing challenges, such as the problem of obtaining eco-
efficient and reliable supports. Some software programs, such as
Preform, are starting to incorporate “smart” support modules
combining lattice support structures and columns with variable
width, but more systematic procedures are needed for improving
final results, for promoting surface quality and for minimizing
material consumption and related environmental impacts. 1

In this article, we summarize a recently developed methodology
for the generation of bioinspired fractal or tree-like support
structures and provide six application examples, starting with
very simple geometries and generalizing the process for more
complex parts. Eco-efficiency is assessed by a final comparative
study with supports obtained with conventional software. The
following sections detail the materials and methods used, main
results obtained, and current challenges and future directions.

Materials and Methods

Design Process for Eco-Efficient Support Structures

In the search for an optimized support generation strategy
for additive manufacturing, it is useful to start with some simple
geometries. Such geometries do not benefit from the obvious
advantages of using additive manufacturing technologies, that
is, the generation of complex forms one of the most remarkable.
However, simple geometries are useful for the initial develop-
ment stages of a new procedure. Our first optimization attempts

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are linked to a couple of examples, for which different types of supports are constructed, trying to spare material and to use biomimetic strategies. The first application example is a lintel structure, shown in figure 1, and the second one is a semisphere, shown in figure 2. The support structure design process begins with two main design parameters dependent on the material and technology being used: (1) the largest obtainable cantilever or the largest distance between two supporting points, so that the surface being constructed may not collapse, and (2) the allowable overhang angle or deviation from the vertical for an unsupported line.

Design guides for AM technologies typically name them “maximum horizontal support span” and “maximum overhang angle,” respectively. In principle, larger values of both parameters would allow for the generation of lighter support structures and related material savings. In our case, working with laser stereolithography and based on the experience at Universidad Politécnica de Madrid Product Development Lab, we work with a maximum horizontal support span of 8 to 9 millimeters (mm) and with a maximum overhang angle of 30°. Having these values in mind, we design different “fractal” and “tree-like” supports for both structures. Figure 1 shows several fractal or tree-like support structures for the lintel structure. Figure 2 shows bioinspired support structures for the additive manufacture of a semisphere, including a parametric tree-like structure with potential as mechanically optimized support geometry, a semisphere supported by a tree-like structure, and an alternative support structure combining two concentric rings of columns and a central “tree-like” geometry.

These initial design trials and the prototypes obtained allowed us to select the more adequate features and develop a more versatile process adapted to more complex geometries. For instance, the fractal tree-like structure used as support for the semisphere is valid only for simple and spherical structures and is difficult to adapt to more complex geometries. In the case of the lintel structure, parallel fractal-like geometries are adequate, but the distance between them can be again optimized taking account of the maximum horizontal support span. It is interesting to evaluate if the fractal-like support can be adapted to more complex geometries, such as the ones included in figure 3.

In order to make the process more versatile and functional for more complex geometries, we can start from a reference plane, the more parallel to the regression plane, the better. In the reference plane, we construct a grid, with points separated a distance shorter than the maximum horizontal support span.
Figure 2  Bioinspired support structures for the additive manufacture of a semisphere. (a) Parametric tree-like structure with potential as mechanically optimized support geometry. (b) Semisphere supported by the mentioned tree-like structure of the upper figure. (c) Alternative support structure for semispheric parts obtained by combining the two concentric rings of columns and a central bush-like geometry as ad-hoc support structures.

(in our case approximately 7 mm). Following a direction perpendicular to the reference plane (vertical direction), we project the point of the grid onto the surface intended for manufacture. The projected points are the contact points between the support structure being designed and the surface to support. Taking the points in groups of four, starting from one extreme of the surface, we start to construct the support lines. The reference plane, with height $z = 0$, acts as the horizontal construction platform of the AM machine. Each group of four points upon the surface has four reference points, the vertexes of a square, upon the horizontal reference plane. From the lowest height point of each group of four points upon the surface, we generate a line intersecting and forming 30° with a vertical reference line constructed on the center of the reference square upon the plane. We join the intersection point with the three remaining points of the group upon the surface, hence obtaining the first four support lines. Repeating the process for the different groups of four points upon the surface, we obtain a first support layer starting from the surface and ending in the intersection points, which constitute a new theoretical surface. Repeating the process, we obtain the complete support structure. The whole support generation process is schematized in figure 3 and applied in the following sections to alternative designs.
RESEARCH AND ANALYSIS

Figure 3 Systematic generation of supports for the additive manufacture of a complex surface. The supporting lines are generated so as to avoid deviations from the vertical larger than 30° and following bioinspired processes leading to tree-like structures.

Although the proposed process artificially increases the building height and related building time, in the case of applying it to single surfaces, it may be perfectly suited for cage-like structures, complete housings, 3D machine parts, or objects with overhanging features with roof and walls, to cite a more common example. We provide and discuss additional examples dealing with more complex geometries in the Results section. The eco-efficiency of the approach is also analyzed, comparing the proposed process with more conventional supports generated by state-of-the-art AM software.

In the examples provided below, the process is additionally optimized by eliminating one of the two support lines meeting at the surface points. It is also possible to work with other groups of projected points so that, from each point upon the surface, just a single support line is generated. The process has some common features with the more recent versions of commercial support generation software, but, in general terms, is novel and more systematic. For instance, the 2015 release of the Formlabs support generator includes some tree-like supports, but with randomly generated branches, thus leading to more random manufacturing qualities. In any case, the examples from the following section and the comparative data included in the Supporting Information available on the Journal’s website may help to further understand the benefits of the proposed approach. Prototyping with different materials and machines will also help to validate and improve the process and to compare it with available resources in terms of environmental and economic impacts.

Computer-Aided Designs of Eco-Efficient Support Structures

The optimized support generation process, described earlier and shown schematically in figure 3, is further applied to more complex geometries, including: a wavy structure and a geometry resembling a sombrero (a Mexican-style hat), like typical exotic and eye-catching roofs and covered surfaces from modern buildings, and a sensor housing aimed at applications linked to industrial engineering. Figure 4 shows the systematic generation of supports for the additive manufacture of the mentioned wavy structure and the final optimization of support structures by elimination of coincident supports, which constitutes an additional improvement to the previously described process and leads to geometries with supports ready for their fabrication using AM approaches. Additional illustrative examples are included in figure S-1 in the supporting information on the Web to further show the process applied to the sombrero-shaped object and to the sensor housing.

Prototypes Obtained Using Eco-Efficient and Traditional Support Structures

Figure 5a provides some examples of different additively manufactured prototypes showing traditional lattice structures and mesh-like supports, together with the optimized bioinspired support structures. They have been manufactured with the commercial laser stereolithography system “SLA-3500” by 3D Systems (3D Systems, 333 Three D Systems Circle, Rock Hill, SC 29730, USA). Epoxy resin “Accura® 60” (also developed by 3D Systems) is used.

Clear differences can be appreciated between the conventional support structures generated with the help of 3D
Lightyear™ file preparation software and the optimized support structures (see figure 5 and tables of the supporting information on the Web). 3D Lightyear™ software receives STL or SLC files as inputs and prepares them for part building on any of 3D Systems’ stereolithography (SLA) systems. The described stereolithography machine, material, and software constitute industrial references in the field of additive manufacture by photopolymerization and can be used as “gold” standards for present project. The branched supports from figure 5b are obtained using commercial software (by Formlabs) and are more massive and difficult to remove than those designed and manufactured as explained in the present work. The impact of support mass is analyzed and detailed in the summary tables of the supporting information on the Web. Regarding support removal—also a relevant procedure for both part quality and the environmental impact of AM by photopolymerization—it is important to include some considerations.

First, the supports obtained by our proposed process do not require the use of any solvents and are easily extracted by manual processes. In addition, as we have tried to minimize support thickness down to the limits of the stereolithography procedure by using cross-sections of around 250 microns for the supports; their impact on surface quality and the marks they leave are almost negligible. However, the supports obtained by other commercial procedures are sometimes so massive that their removal leads to surface and part breakage, which is unacceptable from the perspective of quality.

The used cross-sections provide the most adequate thickness considering the precision of our laser stereolithography system. Other additive photopolymerization processes, such as digital light processing or direct laser writing, may provide even thinner supports, although usually with more limited part dimensions, when compared with SLA-3500 by 3D Systems. The cross-sections of the supports are circular, as we believe it to be an optimal geometry, considering that the laser beam is also...
circular (150 microns leading to a minimal polymerized cross-section of around 225 to 250 microns).

Regarding additional improvements to the supporting structures, it is important to mention the potential use of tapered support links as a means of simplifying the manual process for extracting the supports from the final part and to optimize part surface quality. However, the impact of reducing the contacts between the support structures and the geometries being constructed should be additionally addressed, as overly light contacts may promote, in some cases, part collapse. It is also important to highlight that, even if the process of bioinspired or tree-like support generation artificially increases the construction height of single surfaces, when applied to conventional objects with side walls or cage-like structures, the construction height may remain almost the same. Consequently, when comparing different support generation processes and the eco-efficiency of AM in the following sections, the construction height of the test surfaces has been set to the same building position.

Currently, we are in the process of further improving the proposed procedure by combination of finite-element modeling strategies and innovative design procedures. The use of topology optimization resources may be an interesting option for further exploration of the generation of alternative eco-efficient support structures for AM. However, these procedures are typically oriented to optimizing the mechanical performance of
very massive solids and usually lead to “organic” forms with variable cross-sections, instead of the linear geometries of optimal supports. In any case, extending the already common use of topological optimization procedures for redesigning parts—aimed at benefiting from the complex geometries attainable by AM technologies—for improving also the generation of supports may open new horizons in this topic of study.

Finally, a preliminary comparative study, including eco-efficiency measurements, has been conducted and is presented by using volume and manufacturing time measurement tools (Faludi et al. 2015; Yoon et al. 2014), available within the CAD resources used for designing the different geometries and for preparing the manufacturing processes. The assessment is presented in the following section and includes some measurements carried out upon already manufactured geometries by weighing on a precision scale, as well as some evaluations done with the help of CAD resources. The study is intended to complement previous groundbreaking studies in the field of AM, regarding the assessment of sustainability and eco-efficiency for AM (Kellens et al. 2013). We expect it may help to extend previously proposed methodologies for laser-based sintering and melting processes (Kellens et al. 2011) to the photopolymerization-based procedures. Four different geometries printed (wavy membrane, lintel, sombrero-shaped object, and sensor case) are shown in figure 6, which are representatives of the complexity achievable using SLA AM technology in terms of shapes, overhanged areas, flat and curve faces, etc.

**Eco-Efficiency Analysis**

In this section, we present an evaluation of the eco-efficiency of the design strategy, based on an environmental and economic score at a micro level. For that purpose, we compare it with other potential alternatives to generate support structures for the previously shown figures, but within the same optimal domain to obtain such products via SLA technique and removing previously the irrelevant options. The three different alternatives studied to generate supports are: (1) using the proposed optimized procedure, (2) by 3D-Lightyear software from 3D Systems, and (3) Preform software from Formlabs. The environmental aspects of SLA processes include resource consumption and emissions (Huppes and Ishikawa 2005) in each phase of the life cycle: material extraction/production, energy consumption, residue, material toxicity, landfill, waste processing, and recycling. The analysis presented here, however, encompasses only the following stages in one phase of the life cycle of the part: (1) loading material into the printer, which can vary depending on the SLA manufacturing process from milliliters up to dozens of liters; (2) proper building the part layer by layer; (3) cleaning; and (4) postprocessing. Since the aim of the strategy lies in reducing material consumption and printing time, the output data used for the evaluation are: part weight, manufacture time, and number of layers (calculated by using Formlabs software: Preform 1.8.2).

**Evaluation of the Environmental Performance**

Evaluation of the environmental performance of the alternatives presented in this paper ideally should encompass the entire life cycle, but in this analysis, we focus only on the material and energy consumption (EC) and on the carbon dioxide (CO$_2$) emissions arising from manufacturing of a part. The EC impact of the manufacturing step is estimated, in a simple approach, by taking account of the power rate (PR) (kilowatt-hours per
Evaluation of Costs

The analysis of the economic performance relies on the cost of operating hours, related to the machine’s energy consumption and to the machine’s amortization. Further study should be carried out to assess a full cycle of the product and to determine standardized values. Nevertheless, the data shown can be considered as an initial approximation since the main difference among the alternatives reside in the manufacturing phase and it can be assumed that rest of the impacts are negligible or identical. Thus, the assessed parameter for the cost of energy consumption (CEC) depends on several factors obtained from the price list (table 2) of 2015 from the main power supplier in Spain, such as: the Pw (power prices), the power factor Pf, which is related to the electric power contracted, and the At (access toll), which refers to the price for the transport of the energy (Ghenai 2012).

Considering an estimated work time of 1,000 hours and a hypothetical case of 365 days per year, the mean daily work time is 2.74 hours. The final equation to estimate the CEC is shown by equation (3):

\[
CEC = EC \cdot (Pw + Pf + At) \text{[€]}
\]  

The cost of the machine is around 300,000 €, amortized over 10 years. With the previously mentioned 1,000 hours per year, the coefficient of reference for this factor per hour worked is 30 €/h (A). The price of the Accura® 60 is 300 €/kg (kilogram) (Mp). Therefore, the final equation to represent an estimation of the total cost (TC) involved in the manufacturing of one part is shown by equation (4):

\[
TC = CEC + A \cdot t + m \cdot Mp \text{ [€]}
\]  

Experimental measurement of the part weight was carried out after performing all the manufacturing steps and the post-processing. The weight measurements were taken using a precision scale (Kern PCB 100–3, Kern & Sohn GmbH) with a readability of 0.001 g and measuring range of 100 g. The parts, including the support structures, were measured and afterward a second measurement was made for only the bulk part and another for the supports already removed. The processing time was controlled manually by a chronometer, and the printer timing was previously evaluated with a time estimation provided by Preform software.

Results

The main results from current research are summarized in tables 3 to 4 and are shown graphically in figure 6 using the previously described equations and measurements and applying them to the different part and support geometries. We compare

### Table 1: CO₂ emissions per quantity of epoxy resin used and standard power consumed

| Index             | CO₂ emissions |
|-------------------|---------------|
| Cfe [kg CO₂/kWh]  | 0.4           |
| Cfm [kg CO₂/kg]   | 5.7           |

Note: Cfe = CO₂ emissions related only to the energy consumed during processing. Cfm = production of the epoxy resin used for the complete part, including not only the mass of the bulk parts, but also of the support structures. CO₂ = carbon dioxide; kg = kilograms; kWh = kilowatt-hours.

### Table 2: Factors used for the estimation of the cost of energy consumption

| Factor         | Cost of energy consumption |
|----------------|----------------------------|
| Pw [€/kWh]     | 44.027E-03                 |
| Pf [€/kWh]     | 38.044E-03                 |
| At [€/kWh]     | 4E-03                      |

Note: Pw = power prices; Pf = power factor; At = access toll; kWh = kilowatt-hours.
the different support generation processes in terms of material used, CO₂ emissions, and cost. The ratios of material saved, CO₂ emissions reduction, and cost savings are calculated by applying the proposed support generation process for the different parts under study and are shown in table 3. The table presents the ratios of actual values using our bioinspired supports structures, when compared to those obtained by using commercial software (Formlabs and Lightyear). In order to give the readers an overall view of the eco-efficiency linked to the use of the new strategy for support generation, table 4 gives the ratios for material, energy, and emissions regarding their eco-efficiency. These ratios compare the three different methods considered in this research per monetary cost of each representative part. These results provide evidence that, in general terms, a considerable reduction of material waste and, consequently, of CO₂ emissions and of final part costs are achieved when a bioinspired design strategy of support structures is applied. The printed examples are adequately supported during the manufacturing process, being successfully printed following a bottom-up approach. Therefore, the convenience of the structures is confirmed, although further research should be conducted to validate more complex models. The data gathered suggest that the eco-efficient performance of our supports has direct relation with the part geometry, complexity, and covered area. As perceived from table 4, the customized bioinspired supports for 3D printing have a relevant impact on the reduction of material consumption. Almost in all cases it also affects carbon emissions and energy consumption in a desired way, leading to minimized eco-impacts.

Figure 6 presents a comparative study of savings when using the proposed bioinspired support structures. The uncertainty bars account for an error of 5%, which corresponds to the distortions occurred during the weighting process due to several circumstances, such as: the tolerance of the balance, the state after cleaning of the measured part or those inherent to the operator, and, subsequently, its influence on the emissions and costs calculations. In the case of the sombrero-shaped object, showing a percentage of carbon savings with a negative value, our calculations. In the case of the sombrero-shaped object, showing a percentage of carbon savings with a negative value, our calculations. In the case of the sombrero-shaped object, showing a percentage of carbon savings with a negative value, our calculations. In the case of the sombrero-shaped object, showing a percentage of carbon savings with a negative value, our calculations.
methodology for the generation of bioinspired fractal or tree-like support structures and provided six application examples, starting with very simple geometries and generalizing the process for more complex parts. Eco-efficiency has been assessed by a final comparative study with supports generated with commercial software. The stability of the presented support structures is remarkable, especially when considering their reduced mass in comparison with conventional support structures. Depending on part geometry, support material savings reach values typically ranging from 40% to almost 80%, accounting for an overall material savings from around 10% to around 50% considering the complete parts. Related cost reductions typically reach values from around 10% to around 40%. We expect that the incorporation of the proposed procedure to AM software for promoting the automated generation of bioinspired supports may improve final part quality and eco-efficiency of several AM procedures. Future studies will be devoted to assessing the viability of similar supports for other AM technologies based on photopolymerization working with an additional degree of precision and a wider range of materials.

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Note

1. In a driver-pressure-state-impact-response (DPSIR) framework, resource consumption and emissions would be labeled as a pressure.

References

Ang, B. W. and B. Su. 2016. Carbon emission intensity in electricity production: A global analysis. Energy Policy 94: 56–63.

Bourhis, F. L., O. Kerbrat, J.-Y. Hascoet, and P. I. Magnol. 2013. Sustainable manufacturing: Evaluation and modeling of environmental impacts in additive manufacturing. The International Journal of Advanced Manufacturing Technology 69(9–12): 1927–1939.

Diegel, O., S. Singamneni, S. Reay, and A. Withell. 2010. Tools for sustainable product design: Additive manufacturing. Journal of Sustainable Development 3(3): 68–75.

Faludi, J., C. Bayley, S. Bhogal, and M. Iriarte. 2015. Comparing environmental impacts of additive manufacturing vs traditional machining via life-cycle assessment. Rapid Prototyping Journal 21(1): 14–33.

Felzmann, R., S. Gruber, G. Mitteramskogler, P. Tesavibul, A. R. Boccaccini, R. Liska, and J. Stampfl. 2012. Lithography-based additive manufacturing of cellular ceramic structures. Advanced Engineering Materials 14(12): 1052–1058.

Gebhardt, A., F.-M. Schmidt, J.-S. Hötter, W. Sokalla, and P. Sokalla. 2010. Additive manufacturing by selective laser melting the realizer desktop machine and its application for the dental industry. Physics Procedia 5(pt B): 543–549.

Chenai, C., ed. 2012. Sustainable development—Energy, engineering and technologies—Manufacturing and environment. Rijeka, Croatia: InTech.

Hague, R. J. M., and P.E. Reeves. 2000. Rapid prototyping, tooling and manufacturing. Shropshire, UK: Rapra Technology Ltd.

Hammond, G. P. and C. I. Jones. 2008. Embodied energy and carbon in construction materials. Proceedings of the Institution of Civil Engineers-Energy 161(2): 87–98.

Huppes, G. and M. Ishikawa. 2005. A framework for quantified eco-efficiency analysis. Journal of Industrial Ecology 9(4): 25–41.

Jacobs, P. F. 1992. Rapid prototyping & manufacturing: Fundamentals of stereolithography. Dearborn, MI: Society of Manufacturing Engineers.

Jarvinen, J.-P., V. Marilainen, X. Li, H. Piili, A. Salminen, I. Makela, and O. Nyrhila. 2014. Characterization of effect of support structures in laser additive manufacturing of stainless steel. Physics Procedia 56: 72–81.

Kellens, K., W. Dewulf, J.-P. Kruth, and J. R. Duflou. 2013. Environmental impact reduction in discrete manufacturing: Examples for non-conventional processes. Procedia CIRP 6: 27–34.

Kellens, K., E. Yasa, R. Renaldi, W. Dewulf, J.-P. Kruth, and J. Duflou. 2011. Energy and Resource Efficiency of SLS/SLM Processes (Keynote Paper). https://lirias.kuleuven.be/handle/123456789/314470. Accessed May 2017.

Luo, Y., Z. Ji, Ming, C. Leu, and R. Caudill. 1999. Environmental performance analysis of solid freedom fabrication processes. In Electronics and the environment, 1999, ISEE-1999. Proceedings of the 1999 IEEE international symposium on, 1–6. IEEE. http://ieeexplore.ieee.org/abstract/document/765837/. Accessed May 2017.

Morrow, W. R., H. Qi, I. Kim, J. Mazumder, and S. J. Skerlos. 2007. Environmental aspects of laser-based and conventional tool and die manufacturing. Journal of Cleaner Production 15(10): 932–943.

Saling, P. 2005. Eco-efficiency analysis of biotechnological processes. Applied Microbiology and Biotechnology 68(1): 1–8.

Stampfl, J., and M. Hatzenbichler. 2014. Additive manufacturing technologies. In CIRP Encyclopedia of Production Engineering, edited by The International Academy for Produ et al. Berlin, Germany: Springer-Verlag.

Stava, O., J. Vanek, B. Benes, N. Carr, and R. Meech. 2012. Stress relief: Improving structural strength of 3D printable objects. ACM Transactions on Graphics 31(4): 1–11.

Strano, G., L. Hao, R. M. Everson, and K. E. Evans. 2013. A new approach to the design and optimisation of support structures...
in additive manufacturing. *The International Journal of Advanced Manufacturing Technology* 66(9–12): 1247–1254.

Vanek, J., J. A. G. Galicia, and B. Benes. 2014. Clever support: Efficient support structure generation for digital fabrication. *Computer Graphics Forum* 33(5): 117–125.

Yoon, H.-S., J.-Y. Lee, H.-S. Kim, M.-S. Kim, E.-S. Kim, Y.-J. Shin, W.-S. Chu, and S.-H. Ahn. 2014. A comparison of energy consumption in bulk forming, subtractive, and additive processes: Review and case study. *International Journal of Precision Engineering and Manufacturing – Green Technology* 1(3): 261–279.

**Supporting Information**

Supporting information is linked to this article on the JIE website:

**Supporting Information S1**: This supplementary information provides detailed information regarding the geometries under study and the different supports used as well as their masses, information regarding the number of manufacturing layers and manufacturing times, and summaries of manufacturing costs and equivalent CO₂ emissions used for the analyses described in the body of the article.