Sustainable Impact Evaluation of Support Structures in the Production of Extrusion-Based Parts

Henrique A. Almeida and Mário S. Correia

Abstract Sustainability creates and maintains the conditions under which humans and nature can exist in a productive harmony, fulfilling the social, economic and other requirements of present and future generations. Environmental and social concerns about human society's impact on the natural environment have been pushing sustainable development issues. Sustainable industrial practices can contribute to the development of more sustainable materials, products, and processes. It is critical to apply eco-design principles and develop greener products and production processes, reducing impacts associated with production and consumption. Bearing this in mind, additive manufacturing has the capability of producing components with the lowest amount of raw material. Alongside with the raw material, in some additive manufacturing systems, support material is needed in order to undergo the production. This present work aims to evaluate the environmental impact of the support production methodologies in order to deliver awareness to the users of extrusion-based systems for a lower environmental impact assessment. The extra production time involved in the production of the support structures and the support structure removal is evaluated. The evaluation consisted of correlating the volume of support material and the time needed for its dissolution. Two different models were then compared with different support material production schemes, regarding the total energy consumption and its environmental impact. The results demonstrate that different support production schemes have significant environmental impact regarding both production and its dissolution.

Keywords Additive manufacturing · Environmental impact · Fused deposition modelling · Support structures · Sustainable manufacturing

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1 Introduction

Since the start of the industrial revolution, manufacturing processes have shown a rapid and escalating development. Processes and practices have improved, new technologies have been developed and the size and scale of industrial production has expanded enormously, increasing the consumption of both raw materials and energy, in spite of the growing developments in the material field and new sources of energy. According to Gebler et al. (2014), the Industrial Metabolism (the transformation of matter, energy and labour into goods, services, waste and ambient emissions) has generated high levels of economic wealth, simultaneously increasing human interference with the biosphere (Ayres and Simones 1994; Solomon et al. 2007; UNEP 2012). Therefore, cleaner production and environmental sustainability have become a key concern for worldwide government policies, businesses and public in general (Finnvedena et al. 2009). Sustainability is a consideration of resource utilisation without depletion or adverse environmental and ecological impact, minimising the impacts of human actions. In manufacturing, sustainability issues include raw material, energy consumption, waste generation, water consumption, use of environmentally damaging process enablers (e.g., cutting fluids, lubricants, etc.) and the environmental impact of the manufactured part in service (Sreenivasan et al. 2010; Mihelcic et al. 2003). Resource-efficient means of production can contribute to the development of more sustainable products and manufacturing processes (Berry 2004; Howarth and Hadfield 2006), preventing climate change impacts, exhaustion of natural resources and disruptions of ecological systems (Ayres and Simones 1994; Parry et al. 2007).

Among the existing manufacturing technologies, additive manufacturing is an innovative way of producing components and it possesses good environmental characteristics (Gebler et al. 2014; Luo et al. 1999; Beaman et al. 1997). Additive manufacturing has the potential of reducing resource and energy demands as well as process-related CO_2 emissions (Gebler et al. 2014; Kreiger and Pearce 2013; Baumers 2012; Baumers et al. 2011; Campbell et al. 2011; Petrovic et al. 2011). According to Serres et al. (2011), the energy consumed by additive manufacturing to produce parts is also limited when compared to conventional machining processes (Bourhis et al. 2013, 2014). By utilising only the amount of material needed for the building of the final part, additive manufacturing technologies reduces the material mass and energy consumption when compared to conventional subtractive techniques by eliminating scrap, on top of eliminating the need for tooling and the use of environmentally damaging process enablers (Gebler et al. 2014; Sreenivasan et al. 2010; Hague 2005).

A variety of industrial sectors have also embraced additive manufacturing for remanufacturing existing products, an effective approach to reduce simultaneously both costs and environmental impacts, instead of beginning an original production. Additive manufacturing also has the ability to eliminate completely supply chain operations associated with the production of new tooling, enabling the repair and remanufacture of obsolete or failed tools and dies (Sreenivasan et al. 2010; Reeves 2009; Morrow et al. 2007).

Additive manufacturing machines are usually small and therefore can be easily located near to any existing market, thereby reducing the logistics of moving products around the world (Gibson et al. 2015). On the other hand, raw materials for additive manufacturing systems are quite common, which also leads to a large reduction in both transportation costs related to accessibility (Gibson 2011) and the carbon footprint decrease with the consequent reduction of fuel consumption.

Several authors, namely Sreenivasan et al. (2010), Reeves (2009), and Bourell et al. (2009), have defined the carbon footprint reduction of additive manufacturing technologies. According to them, there are five main environmental and sustainable benefits in adopting these technologies:

- More efficient and reduced usage of raw materials required in the supply chain. Hence, reduced need to mine and process primary material ores from our natural resources.
- Displacing of energy-inefficient and wasteful manufacturing processes, such as casting or processes such as CNC machining which requires cutting fluids.
- Ability to design more efficient products with improved operational performances that are more efficient than conventionally manufactured components by incorporating conformal cooling and heating channels and gas flow paths, etc.
- Ability to eliminate fixed asset tooling, allowing for manufacture to occur at any geographic location, such as near to the customer, reducing transportation costs within the supply chain and contributing to diminishing the carbon footprint.
- Lighter weight parts, which when used in transport products such as aircraft increase fuel efficiency and reduce carbon emissions.

Additive manufacturing also presents some sustainability disadvantages. Some processes require support structures that are discarded after each part is built, which in some cases can be equivalent to the amount of part material, if the initial preparation phase isn't properly analysed or even more depending on the complexity of the part being produced (Gibson 2011; Hopkinson et al. 2006). Additive manufacturing machines need a controlled environment without excessive heat and humidity for both machine and raw material, and the energy used to keep the machines working effectively is a negative. In addition, the energy usage for additive manufacturing systems is generally unfavourable (Atkins 2007), as some machines need to use pre-heated and air controlled building chambers, as well the energy required for the processing of raw materials, such as lasers (Gibson et al. 2015; Chua and Leong 2014).

This present work aims to evaluate the ecological impact of the support production methodologies to deliver awareness to the users of extrusion-based systems for a lower environmental impact assessment. The evaluation consists of correlating the volume of support material and the time needed for its dissolution. Two different models are then compared with different support material production schemes, regarding the time involved in the production of the support structures, support dissolution, energy consumption and its environmental impact.

2 Additive Manufacturing

According to Wohlers Associates, additive manufacturing is defined as the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies (Caffrey and Wohlers 2015). The main feature of additive manufacturing, its ability to produce parts of virtually any shape complexity, is huge, as the process is capable of creating mind boggling geometries in spite of their functionality, requirements and materials (Gibson et al. 2015; Hascoet et al. 2014; Hopkinson et al. 2006).

All existing additive manufacturing processes require input data from a 3D digital model, either a solid or surface Computer Aided Design (CAD) model or an existing STereoLithography (STL) file model, which is the current industrial standard for facetted models. In the case of a CAD model, it is tessellated and exported as an STL file so that it may be imported to the manufacturing system's proprietary software. In some additive manufacturing systems, support structures are necessary to embrace overhangs; in this case, the system's proprietary software performs the design of these support structures. The model is then sliced and the sliced data are sent to the additive hardware machine for the production of the final physical part (Gibson et al. 2015; Bártolo et al. 2009).

In addition to the standard importing file, the STL file format, all additive manufacturing systems share another common concern, the part's orientation during production. Part orientation refers to the building direction regarding the part in which the slices are built in the additive manufacturing system (Gibson et al. 2015; Rosen 2014; Allen and Dutta 1995). Determination of the optimal part orientation is a critical issue during the production process in additive manufacturing (Gibson et al. 2015; Rosen 2014; Zhang and Bernard 2013; Alexander et al. 1998), because the building direction has a significant effect on the part's characteristics: such as:

- Dimensional accuracy (Volpato et al. 2014; Saqib and Urbanic 2012; Equbal et al. 2011; Sood et al. 2009, 2010)
- Surface roughness (Vijay et al. 2012, 2014; Armillotta 2006; Onuh and Hon 1998)
- Mechanical properties (Kotliniski 2014; Sood et al. 2012; Majewski and Hopkinson 2011; Quintana et al. 2010; Lee et al. 2007; Ajoku et al. 2006; Ang et al. 2006; Chockalingam et al. 2005; Gibson and Shi 1997)
- Building time and support structures(Gibson et al. 2015; Rosen 2014; Pham and Demov 2001; Chua and Fai 2000; Alexander et al. 1998)
- Cost (Durgun and Ertan 2014; Kumar and Regalla 2011)

Determining the optimal part orientation is both a difficult and a time-consuming task as one has to trade off various contradicting objectives such as part surface finish and building time (Gibson et al. 2015; Rosen 2014; Pham and Demov 2001; Chua and Fai 2000; Alexander et al. 1998). An inadequate choice may result in physical models with a significant "staircase effect" resulting in parts of poor surface quality (Thrimurthulu et al. 2004). Another aspect to be considered is the production of the support structures during production. An inappropriate orientation may result in an excessive production of support structures around the physical part or creation of supports within specific areas of the physical part, which are difficult or almost impossible to remove, increasing significantly the effort and energy for the removal of the support structures (Gibson et al. 2015; Chua and Leong 2014).

According to the ASTM Committee F42 on Additive Manufacturing Technologies, the existing additive manufacturing technologies are classified as follows (ASTM F2792 2015; Gao et al. 2015; Gibson et al. 2015):

1. Material extrusion—process that creates layers by mechanically extruding molten thermoplastic material onto a substrate.
2. Powder bed fusion—these techniques use an energy beam, either a laser or electron beam, to melt selectively a powder bed.
3. Vat photopolymerization—an ultraviolet laser is used to polymerize selectively a UV curable photosensitive resin to create a layer of solidified material. Layers are subsequently cured until the part is complete.
4. Material jetting—processes that directly deposit wax or photopolymer droplets onto a substrate via drop-on-demand inkjetting.
5. Binder jetting—process that deposits a stream of particles of a binder material over the surface of a powder bed, joining particles together where the object is to be formed.
6. Sheet lamination—layers of adhesive-coated paper, plastic or metal laminates are successively glued together and then cut to shape with a knife or laser cutter.
7. Directed energy deposition—metallic powder or wire is fed directly into the focal point of an energy beam to create a molten pool.

According to the previous classification, each additive manufacturing process has its particular process of producing the necessary support structures for embracing the physical parts, along with a method for removing them. Brief descriptions of some of the most relevant processes and how the support structures are produced and then removed are presented in the following sections.

2.1 Material Extrusion

The material extrusion technique, commercially known as Fused Deposition Modelling (FDM), was developed by Crump (1989). Thin crystalline or amorphous thermoplastic filaments are melted by heating and guided by a robotic device controlled by a computer, producing 3D objects (Fig. 1). The model material leaves the extruder in a liquid form and begins to harden (Gibson et al. 2015; Hopkinson et al. 2006). The previously formed layer is the substrate for the next layer and, to assure good interlayer adhesion, the extruded polymer must be maintained at a temperature just below its solidification point. This is possible through

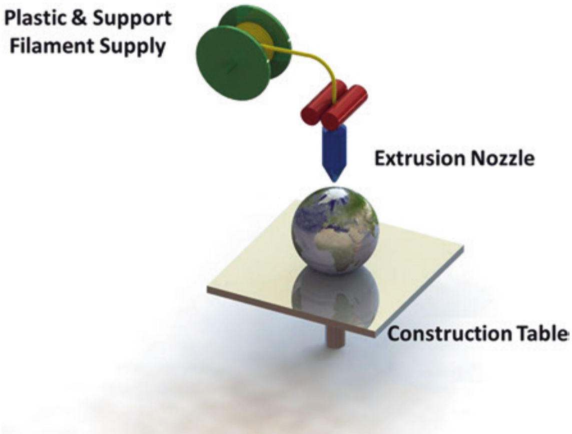

Fig. 1 Illustration of the material extrusion process

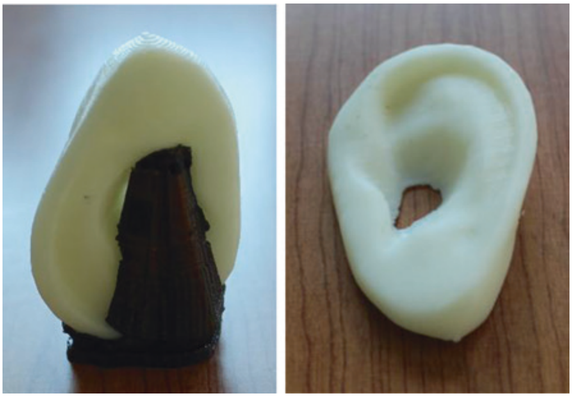

Fig. 2 Physical part with its support material before and after the removal process

previously heating the building chamber and maintaining its temperature during production (Gibson et al. 2015; Chua et al. 2003).

During the production of the extruded parts, two modeller materials are dispensed through a dual tip mechanism in the extrusion head (Gibson et al. 2015; Hopkinson et al. 2006). As mentioned before, a primary modeller material is used to produce the physical part and a secondary material is used to produce the support structures bonding the primary material of the physical model (Chua et al. 2003). For FDM systems, there are two types of release materials, namely, release materials that can be easily broken off (Break Away Support System) or simply washed away (WaterWorks™ Soluble Support System). Figure 2 illustrates a produced part with its support material before the removal process.

The support structures can be generated either automatically or in more expensive systems, and the user is able to design the best strategy to build the supports structures. To remove these support structures from the parts, even in the case of washable supports, strategy or planning should be taken in account. For instance, features with hollowed out parts, undercuts, constraining features and other interlocking features may be a challenge to achieve complete success in the task of removing the support structures. Currently, as stated earlier, there are two types of support materials, namely, support materials that can be easily broken off or simply washed away.

2.2 Powder Bed Fusion

This process uses an energy beam, either an infrared laser or an electron beam, to heat selectively powder material just beyond its melting point. The laser traces the shape of each cross-section of the model to be built, sintering powder in a thin layer. It also supplies energy that not only fuses neighbouring powder particles, but also bonds each new layer to those previously sintered. Once a layer is scanned, the piston over the model retracts to a new position and the next layer of powder is spread via a rolling mechanism. The powder that remains unaffected by the laser acts as a natural support for the model and remains in place until the model is complete (Fig. 3). Polymer powder bed fusion, namely the Selective Laser Sintering (SLS), which was initially developed by Deckard and Beaman in the mid-1980s, only processed polyamides and polymer composites. Other systems such as Direct Metal Laser Sintering (DMLS), Selective Laser Melting (SLM) and Electron Beam Melting (EBM) were developed later in 1995 and made commercially available in 2005 by EOS GmbH (Germany) and Arcam AB (Sweden), respectively. The actual building process is carried out in a vacuum or inert environment to avoid metal oxidation.

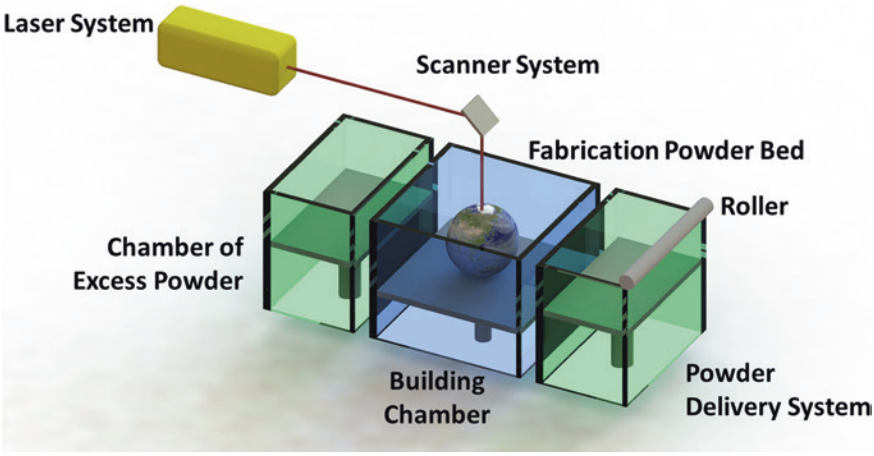

Fig. 3 Illustration of the powder bed fusion process

Regarding the use of support structures during production, there are two differences between the SLS process and the DMLS, SLM and EBM processes. During production, the powder bed serves as a support structure for the model being built, whereas with the other three processes, in spite of the powder bed, the system still produces support structures to sustain the model being built.

2.3 Vat Photopolymerization

In 1984, Charles Hull of 3D System Corp. developed the first stereolithographic apparatus. Stereolithographic processes involve selective polymerization or solidification of liquid photosensitive polymers, namely UV curable resins, through the use of an irradiation UV light source, which supplies the energy needed to induce a chemical reaction, bonding large numbers of small molecules and forming a highly cross-linked polymer. These processes usually employ two distinct methods of irradiation. The first is the mask-based method in which an image is transferred to a liquid polymer by irradiating through a patterned mask. The irradiated part of the liquid polymer is then solidified (Fig. 4). In the second method, a direct writing process using a focused UV beam or laser produces the solid polymer structures.

In the vat photopolymerization process, the support structures are built in the same material as the model part, but in thinner thicknesses of material so that they may be removed manually after concluding the production.

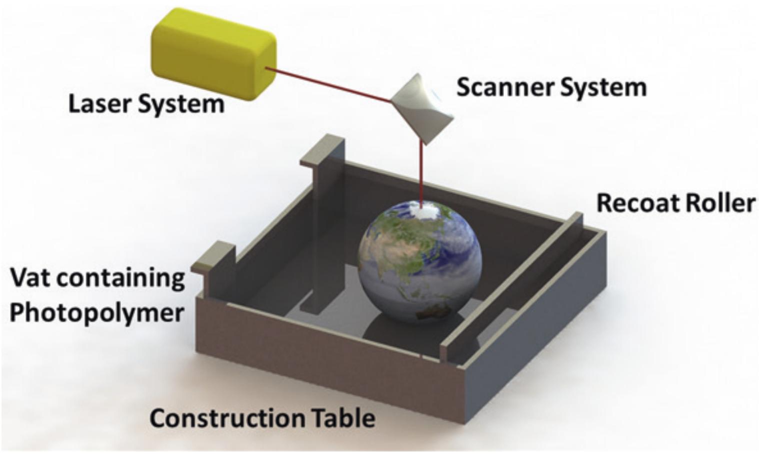

Fig. 4 Illustration of the vat photopolymerization process

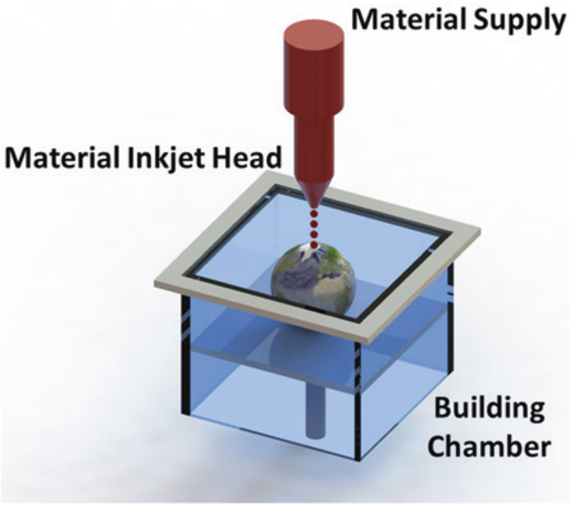

Fig. 5 Illustration of the material jetting process

2.4 Material Jetting

Similar to the normal ink-jet printing technology which transfers ink droplets onto a sheet of paper, material jetting processes directly deposit wax and/or photopolymer droplets onto a substrate via drop-on-demand inkjetting (Fig. 5). The solidification of the jetted droplets occurs via heating or photocuring.

2.5 Binder Jetting

The binder jetting process deposits a stream of particles of a binder material over the surface of a powder bed, joining particles together where the object is to be formed. Recoating occurs via powder spreading as a piston lowers the powder bed so that a new layer of powder can be spread over the surface of the previous layer and then selectively joined to it (Fig. 6). After completing the fabrication process, the unbounded powder material is removed and then part is submitted to an infiltration during post-processing in order to acquire sufficient strength. This method was first studied in MIT and later on commercialized by Z Corporation and ExOne. Similar to the SLS process, the powder bed serves as a support structure during the construction of the part.

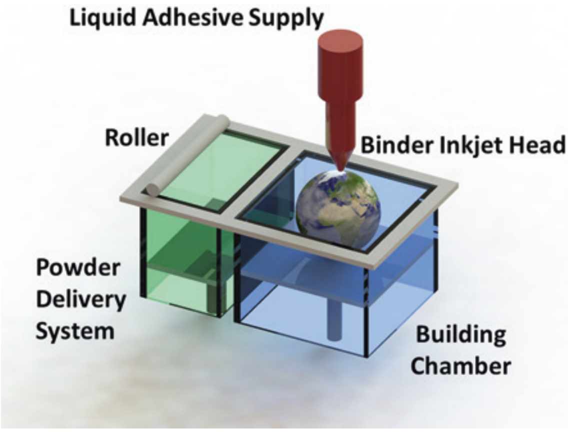

Fig. 6 Illustration of the binder jetting process

2.6 Sheet Lamination

Helisys Inc., now known as Cubic Technologies, commercialize systems using the Laminated Object Manufacturing (LOM) process, which was developed in 1986 and patented in 1987. For the production of the physical parts, this process employs the successive cutting, stacking and gluing of profiled material sheets, either polymer or metallic laminates. The advantages include low internal tension and fragility of the parts, high surface finish details, and lower material, machine and process costs. Disadvantages of this process include the possibility of delamination of the produced part, effort and time involved in decubing the excess material and production of high amounts of waste material.

2.7 Directed Energy Deposition

In these processes, metallic powder or wire is fed directly into the focal point of an energy beam to create a molten pool with the aid of a robotic multi-axis system. In summary, the processes are essentially three-dimensional welding machines. Lasers and electron beams are commonly used as a directed energy source during the process. This process not only allows the production of new metal components but is also used to repair parts, when the damaged portion is reconstructed selectively. Another advantage is the capability of improving tribological performance of any engineered products and the ability to add coatings to existing surfaces. Laser Engineered Net Shaping (LENS) was developed in 1995 at Sandia National Laboratories and is being commercialized by Optomec.

3 Case Study

Our study focussed on one of the existing material extrusion processes in order to evaluate the environmental impact of the energy involved during production and the removal of the support structures. One of the existing FDM systems is the Fortus 450mc 3D Production System from Stratasys (Fig. 7) which enables both parts and models to be built quickly and directly from a CAD STL model. This printer builds three-dimensional parts by extruding a bead of thermoplastic material through a computer-controlled extrusion head, producing high quality parts ready to use immediately after completion. This printer builds models in a wide range of materials: ABS-M30 in six colours for great tensile, impact and flexural strength; ABS-M30i for biocompatibility; ABS-ESD7 for static dissipation; ASA for UV stability and the best aesthetics; PC-ISO for biocompatibility and superior strength; PC for superior mechanical properties and heat resistance; FDM Nylon

Fig. 7 Fortus 450mc 3D production system from Stratasys (Stratasys Ltd. 2015)

12 for maximum toughness; and ULTEM 9085 for high strength-to-weight ratio and favourable FST rating. The Fortus 450mc system builds parts with a maximum size of 406 × 355 × 406 mm.

Regarding the support material, the Fortus 450mc system uses washable and breakaway support materials. In the case of washable release material, this system has four possible support building schemes to support the desired part during production. These four schemes are: Smart, Sparse, Basic and Surround. In each type of support production scheme, not only does the amount of support material vary, so does the global production time of both part and support material. Higher production times mean higher consumption of energy. Afterwards, in the washable support removal tank, greater amounts of support materials increase the time taken for support removal from the final part. Therefore the focus of our study is to evaluate the environmental impact of the support material. The environmental impact value of the release material was not considered because there is no eco-indicator value for the given material. The system supplier only mentions that the support material has an Ecoworks pH level of 12.6, and that it meets most worldwide wastewater requirements (Stratasys Ltd. 2010). Nevertheless, during production, the energy consumption includes the energy for the extrusion of the model and the release material and the energy needed for the support removal tank. Because energy consumption has an eco-indicator impact value, it is considered in this study.

Our research work concerned two steps:

1. The first step was to evaluate and define a relationship between the time necessary to dissolve the support material and the volume of support material
2. The second step considered a case study of two models that were to be produced considering all four schemes of production of support material embracing the desired parts.

3.1 Relationship Between Dissolution Time and Material Volume

As mentioned before, the first step of our research was to evaluate and define a relationship between the time necessary to dissolve the support material and the volume of support material. In order to obtain a relationship between the dissolution time and material volume, three square blocks of different sizes of support material was produced, which would later be dissolved and timed. For each block size, three samples were considered. The blocks had the dimensions, volumes and production times as given in Table 1.

To evaluate the dissolution of the blocks, an experimental set-up was defined as illustrated in Fig. 8. A heated stirring plate was used in order to heat the solution until a temperature of 70 °C. A magnet was used with the stirring plate to provide movement to the solution. During the dissolution process of the support material

Table 1 Block dimensions, volume of support material and production time for each of the blocks

Block dimensions (mm)	Volume of support material ($cm^{3)}$	Production time (h:min)
10 × 10	0.811	00:05
30 × 30	9.670	00:20
50 × 50	39.400	00:42

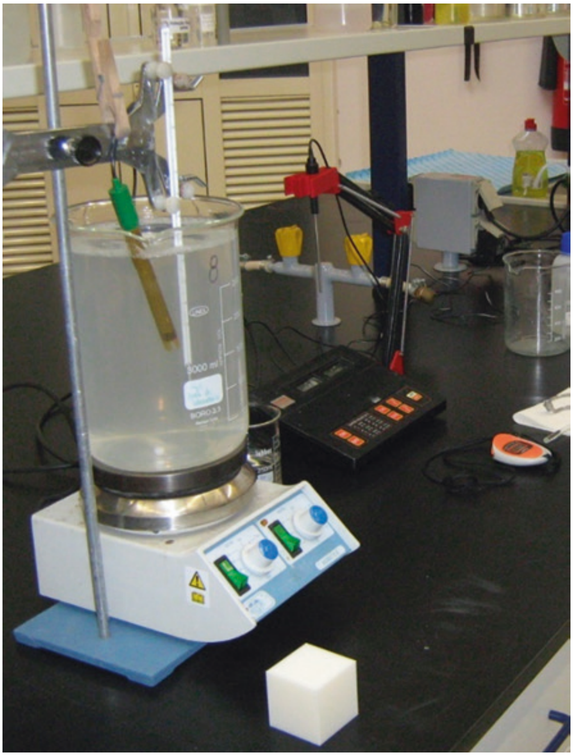

Fig. 8 Experimental setup for the dissolution of the support material blocks

blocks, besides timing the experiment, both the temperature and pH level were constantly being monitored. Regarding the pH level, during all nine experiments, the pH level was maintained within its recommended levels of optimal performance. A 30-L glass flask was used for the dissolution the support material blocks. According to the recommendations provided by the WaterWorks solution, 48.45 g of powder was diluted in 2142 mL of water. Each time a block was dissolved, a new waterworks solution was prepared.

Fig. 9 Illustration of the dissolution process of one of the support material blocks

Table 2 Dissolution and average dissolution times for each sample

Block dimensions (mm)	Volume of support material (cm^3)	Sample number #	Dissolution time (min:s)	Average dissolution time (min:s)
10 × 10	0.811	1	21:32	23:38
		2	22:42	
		3	26:40	
30 × 30	9.670	1	30:37	32:45
		2	33:56	
		3	33:43	
50 × 50	39.400	1	42:41	47:56
		2	53:48	
		3	47:21	

Fig. 10 Linear correlation between the support material volume and dissolution times

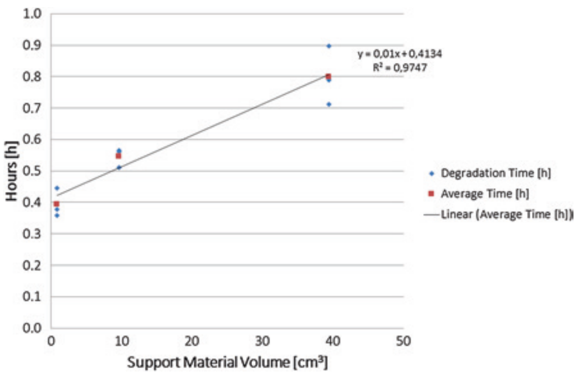

Figure 8 also shows the 50-mm square block, and Fig. 9 illustrates the dissolution of the same block during the experiment. It is possible to observe the interior filling of the block and how the support material was extruded in the block's interior.

Table 2 presents the dissolution times of each sample according to the amount of material of each block and an average dissolution time for each block size. Based on this data, it was possible to define the chart shown in Fig. 10 from which a correlation could be created between the amount of support material and dissolution time.

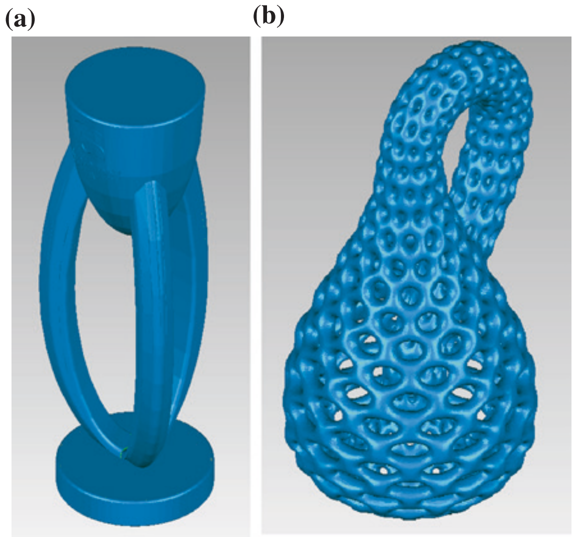

Fig. 11 CAD STL models of **a** Super Rugby Trophy 2015 and **b** Klein Bottle

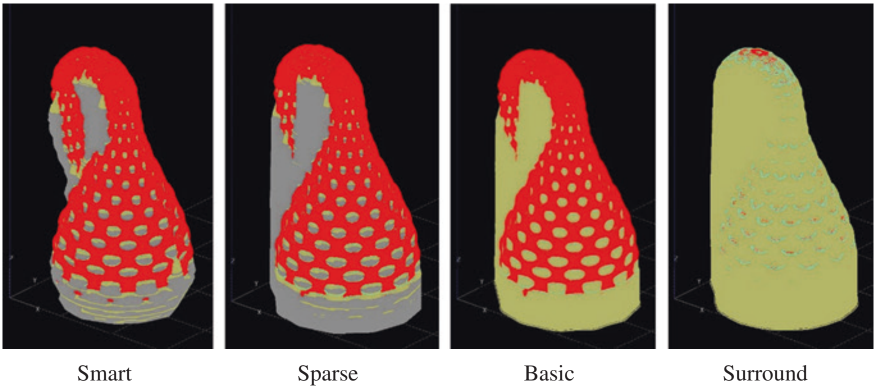

Fig. 12 Types of support material production schemes

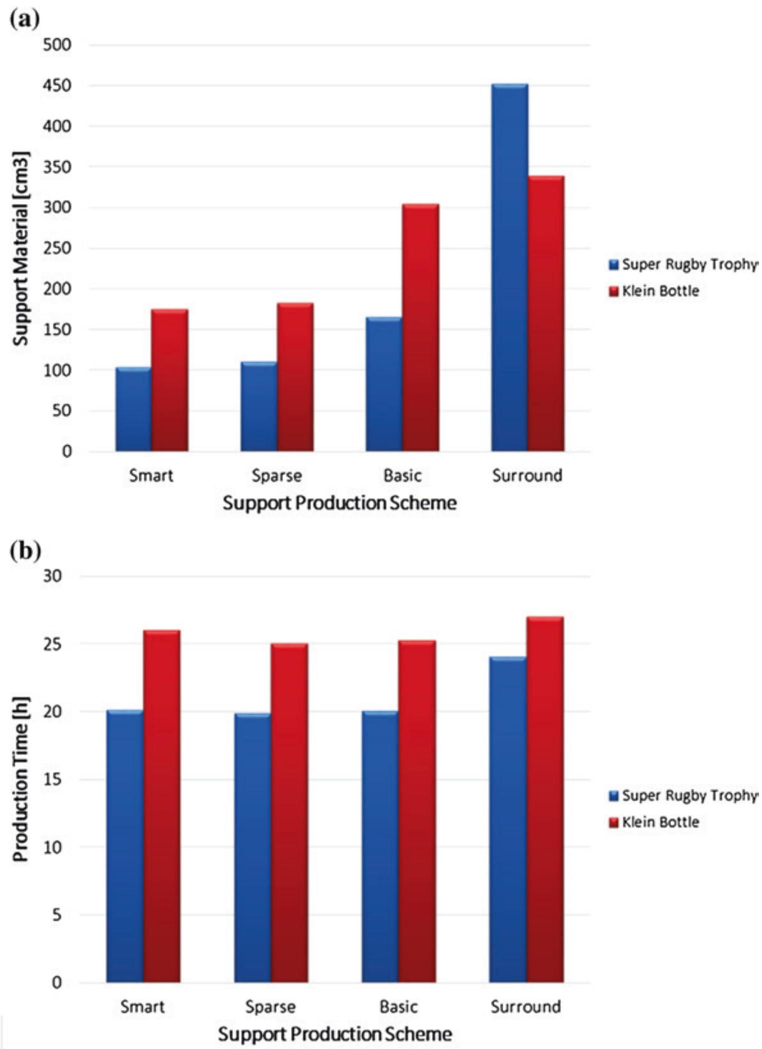

Fig. 13 Amount of **a** support material and **b** production times for each support material production scheme

3.2 *Super Rugby Trophy 2015 and Klein Bottle*

After defining the correlation between the amount of support material and dissolution time, the next step of our research focused on two case studies where the models were to be produced according to all four types of support material production schemes. Figure 11 illustrates both models. In each production scheme, the parts were placed and oriented in the same position. At this stage, we only

Table 3 Amount of model material, support material and production times for each of the support material production schemes

Support production scheme	Model material (cm^3)	Support material (cm^3)	Production time (h:min)
Super Rugby Trophy 2015			
Smart	625.120	103.200	20:05
Sparse	625.100	109.560	19:50
Basic	626.130	165.130	20:00
Surround	628.200	451.770	24:02
Klein Bottle			
Smart	277.810	174.720	26:01
Sparse	278.070	182.550	25:01
Basic	280.010	303.520	25:13
Surround	280.770	338.950	26:59

accessed the Insight 10.4 software and simulated the production of both parts. Figure 12 illustrates the four types of support production schemes considered, namely: Smart, Sparse, Basic and Surround.

It possible to observe from Fig. 12 that the amount of support material around the model is different in each case, whereas the Surround scheme presents the highest amount of support material. Figure 13 illustrates the difference in amount of support material along with the production time for each type of support production scheme. In terms of the amount of support material, both the Basic and Surround present the highest amount of material needed in the process. Regarding the production time, all four support production schemes present similar production times, except for the Surround which presents the highest time (Table 3).

From the technical specifications of the Fortus 450mc system, it was possible to calculate the energy consumption and respective environmental energy consumption impact. Because the energy consumption and the environmental energy consumption impact are time dependent, the variations observed in the chart of the production times are also observed in these two charts. In other words, for the Smart, Sparse and Basic, in spite of slight variations, the variation might not be considered relevant enough, but for the Surround scheme the difference is relevant enough for discussion (Fig. 14).

Based on the support material dissolution experiment, it is possible to determine the dissolution times for each of the support material production schemes for each model (Fig. 15a). Once the dissolution times were determined, the energy consumption and energy consumption impact for the support material removal was determined (Fig. 15b, c).

Considering that the entire production cycle is composed of both the extrusion and support removal process, Table 4 presents the total values of the production times, energy consumption and energy consumption impacts. The Energy Consumption Impact value is calculated by multiplying the Electricity indicator value of 47 (Electricity Low Voltage Portugal) by the amount of consumed energy

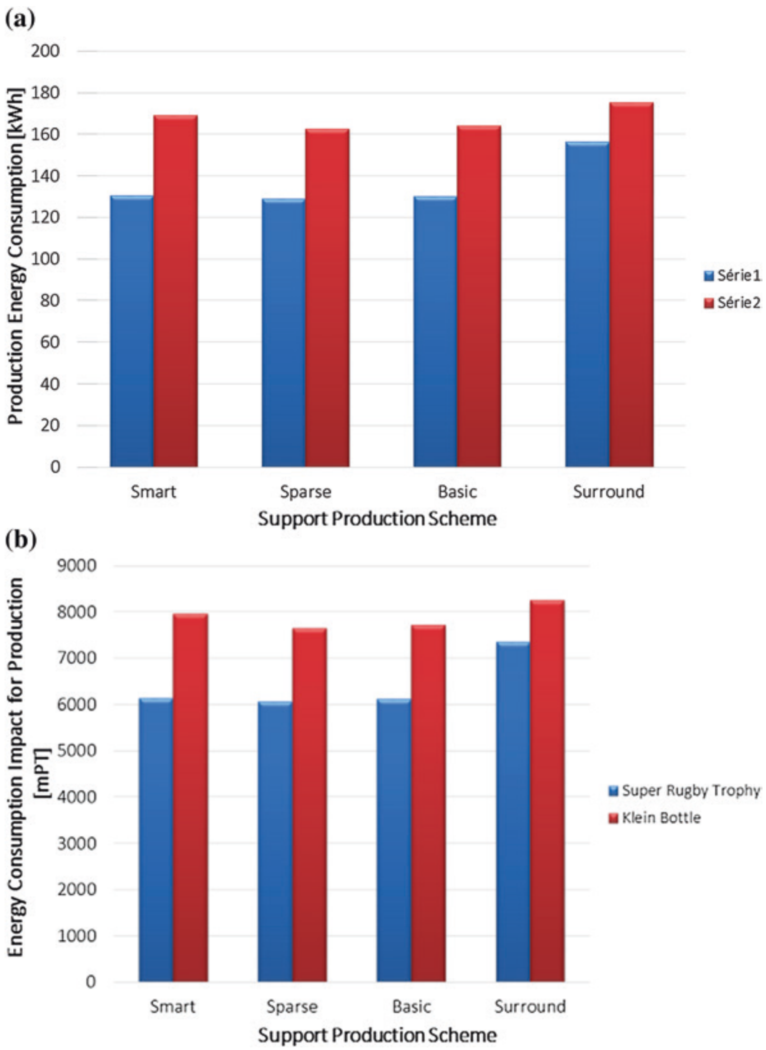

Fig. 14 Amount of **a** production energy consumption and **b** production energy consumption impact for each support material production scheme

during the production process and support structure removal (Lofthouse 2006; Goedkoop and Spriensama 2001; Ministry of Housing, Spatial Planning and the Environment 2000).

From the data presented, it is possible to observe that there is a difference of 7.622 h (production time), 34.144 kWh (energy consumption) and 1604.778 mPt (energy consumption impact) between the Surround and Sparse support material production scheme for the Super Rugby Trophy model. Regarding the Klein model, the difference is 3.530 h, 15.911 kWh and 747.833 mPt between the

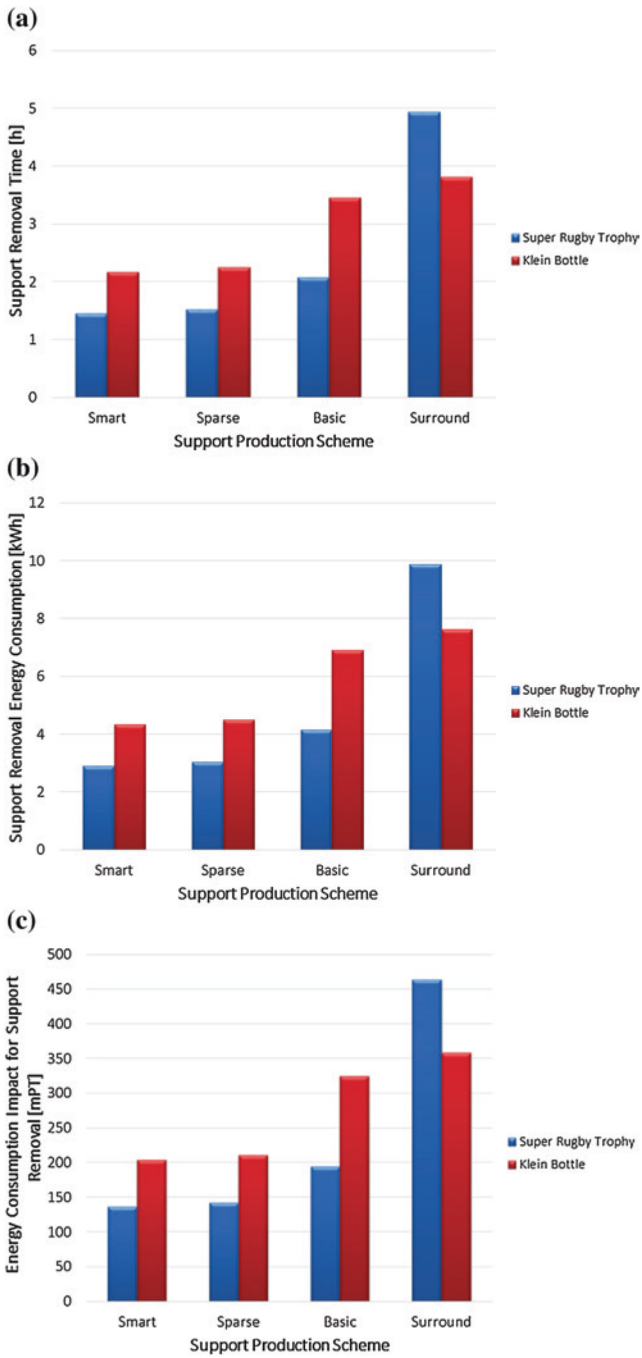

Fig. 15 Support material removal: **a** times, **b** energy consumption and **c** energy consumption impact for each support material production scheme

Table 4 Totals of production times, energy consumption and energy consumption impact values for each support material production scheme

Support production scheme	Total production time (h)	Total energy consumption (kWh)	Total energy consumption impact (mPt)[a]
Super Rugby Trophy 2015			
Smart	21.529	133.432	6271.326
Sparse	21.342	131.935	6200.929
Basic	22.065	134.129	6304.082
Surround	28.964	166.079	7805.707
Klein Bottle			
Smart	28.177	173.430	8151.188
Sparse	27.256	167.086	7853.048
Basic	28.665	170.806	8027.860
Surround	30.786	182.997	8600.881

[a]Milli-points per kWh—standard unit for Eco-indicator points (1 Pt is representative for 1000 of yearly environmental load of one average European inhabitant) (Ministry of Housing, Spatial Planning and the Environment 2000)

Surround and Sparse support material production scheme. From the results, it can be seen that if a part can be produced in a specific orientation irrespective of the type of support production scheme used, an inappropriate selection may increase the production time dramatically, thereby increasing the energy consumption and environmental impact. After analysing both case studies, in spite of additive manufacturing being considered a sustainable technology, one must still be aware that each of the production variables and/or parameters may influence both production times and energy consumptions that have a direct effect on the environment.

4 Conclusions

Sustainability creates and maintains the conditions under which humans and nature can exist in productive harmony, enabling fulfilment of the social, economic and other requirements of present and future generations. Environmental and social concerns about human society's impact on the natural environment have been pushing sustainable development issues. Sustainable industrial practices can contribute to the development of more sustainable materials, products and processes. It is critical to apply eco-design principles and develop greener products and production processes, reducing impacts associated with production and consumption. Bearing this in mind, additive manufacturing has the capability of producing components with the lowest amount of raw material needed. Along with the raw material, in some additive manufacturing systems, support material is needed to enable production.

This present work aims to evaluate the ecological impact of support production methodologies to make users of aware extrusion-based systems for a lower environmental impact assessment. The extra time involved in the production of both models between the Surround and Sparse support material production scheme totals 11.152 h, 50.055 kWh and 2352.611 mPt with respect to the production time, energy consumption and energy consumption impact, respectively. After analysing both case studies, in spite of additive manufacturing being considered a sustainable technology, one must still be aware that each of the production variables and/or parameters may influence both production times and energy consumptions that have a direct effect on the environment.

References

Ajoku U, Saleh N, Hopkinson N, Hague R, Poonjolai E (2006) Investigating mechanical anisotropy and end-of vector effect in laser-sintered nylon parts. Proceedings of the Institution of Mechanical Engineers Part B Journal of Engineering Manufacture 220(7):1077–1086

Alexander P, Allen S, Dutta D (1998) Part orientation and build cost determination in layered manufacturing. Comput Aided Des 30(5):343–356

Allen S, Dutta D (1995) On the computation of part orientation using support structures in layered manufacturing. Journal of Design and Manufacturing 5:153–162

Ang KC, Leong KF, Chua CK, Chandrasekaran M (2006) Investigation of the mechanical properties and porosity relationships in fused deposition modelling-fabricated porous structures. Rapid Prototyping Journal 12(2):100–105

Armillotta A (2006) Assessment of surface quality on textured FDM prototypes. Rapid Prototyping Journal 12(1):35–41

ASTM Standard F2792 (2015) “Standard Terminology for Additive Manufacturing Technologies” URL: http://www.astm.org/Standards/F2792.htm

Atkins (2007) ATKINS Manufacturing a Low Carbon Footprint, ATKINS project report (http://www.atkins-project.com/pdf/ATKINSfeasibilitystudy.pdf)

Ayres RU, Simones UE (1994) Industrial Metabolism— Restructuring for Sustainable Development. The United Nations University, Tokyo/Japan

Bártolo PJ, Almeida HA, Laoui T (2009) Rapid Prototyping & Manufacturing for Tissue Engineering Scaffolds. Computer Applications in Technology 36(1):1–9

Beaman JJ, Barlow JW, Bourell DL, Crawford RH, Marcus HL, McAlea KP (1997) Solid freeform fabrication: a new direction in manufacturing. Kluwer Academic Press, Boston

Baumers M (2012) Economic Aspects of Additive Manufacturing: benefits, Costs and Energy Consumption (Doctoral Thesis) Loughborough University, Leicestershire, United Kingdom

Baumers M, Tuck C, Wildman R, Ashcroft I, Hague R (2011) Energy inputs to additive manufacturing: does capacity utilization matter? In: Conference Paper: Solid Freeform Fabrication Symposium 2011, Austin (TX)/USA

Berry M (2004) The Importance of sustainable development. Canada, Columbia Spectator

Bourell DL, Leu MC, Rosen DW (2009) Roadmap for additive manufacturing: identifying the future of freeform processing. The University of Texas at Austin

Bourhis FL, Kerbrat O, Dembinski L, Hascoet JY, Mognol P (2013) Sustainable manufacturing: evaluation and modelling of environmental impacts in additive manufacturing. Int J Adv Manuf Technol 69:1927–1939

Bourhis FL, Kerbrat O, Dembinski L, Hascoet JY, Mognol P (2014) Predictive model for environmental assessment in additive manufacturing process. Procedia CIRP 15:26–31

Caffrey T, Wohlers T (2015) Wohlers Report 2015—Additive Manufacturing and 3D Printing State of the Industry—Annual Worldwide Progress Report, Wohlers Associates, Inc. ISBN: 978-0-9913332-1-9
Campbell T, Williams C, Ivanova O, Garrett B (2011) Could 3D printing change the world? Technologies, and implications of additive manufacturing. Atlantic Council, Washington DC/USA
Chockalingam K, Jawahar N, Ramanathan KN, Banerjee PS (2005) Optimization of stereolithography process parameters for part strength using design of experiments. Int J Adv Manuf Technol 29(1–2):79–88
Chua CK, Fai LK (2000) Rapid prototyping: principles and applications in manufacturing. World Scientific
Chua CK, Leong KF (2014) 3D printing and additive manufacturing—principles and applications, 4th edn. World Scientific Publishing
Chua CK, Leong KF, Lim CS (2003) Rapid prototyping: principles and applications in manufacturing, 2 edn. World Scientific
Crump SS (1989) Apparatus and method for creating three-dimensional objects, US Pat. 5121329
Durgun I, Ertan R (2014) Experimental investigation of FDM process for improvement of mechanical properties and production cost. Rapid Prototyping J 20:228–235
Equbal A, Ohdar RK, Mahapatra SS (2011) Prediction of dimensional accuracy in fused deposition modelling: A fuzzy logic approach. Int J Productivity Qual Manage 7(1):22–43
Finnvedena G, Hauschildb M, Ekvallc T, Guinée J, Heijungs R, Hellweg S, Koehler A, Pennington D, Suh S (2009) Recent developments in Life Cycle. J Environ Manage 92(1):1–21
Gao W, Zhang Y, Ramanujan D, Ramani K, Chen Y, Williams CB, Wang CCL, Shin YC, Zhang S, Zavattieri PD (2015) The status, challenges, and future of additive manufacturing in engineering. Comput Aided Des 69:65–89
Gebler M, Uiterkamp AJMS, Visser C (2014) A global sustainability perspective on 3D printing technologies. Energy Policy 74:158–167
Gibson I (2011) Is additive manufacturing a sustainable technology? In: Bártolo H et al (eds) Proceedings of SIM2011 Sustainable Intelligent Manufacturing. IST Press, pp 583–589
Gibson I, Shi D (1997) Material properties and fabrication parameters in selective laser sintering process. Rapid Prototyping J 3:129–136
Gibson I, Rosen D, Stucker B (2015) Additive manufacturing technologies—3D printing, rapid prototyping and direct digital manufacturing, 2nd edn. Springer, New York
Goedkoop M, Spriensama R (2001) The eco-indicator 99: a damage oriented method for Life Cycle Impact Assessment. Methodology Report, Netherlands
Hague R (2005) Unlocking the design potential of rapid manufacturing. In: Hopkinson N et al (eds) Rapid manufacturing: an industrial revolution for the digital age. Wiley
Hascoet JY, Marya S, Marya M, Singh V (2014) Materials science challenges in the additive manufacturing of industrial parts. In: Kai CC et al (eds) Proceedings of the 1st International Conference on Progress in Additive Manufacturing (Pro-AM2014). Research Publishing Services, pp 133–138
Hopkinson N, Hague RJM, Dickens PM (2006) Rapid Manufacturing—an industrial revolution for the digital age. Wiley, England
Howarth G, Hadfield M (2006) A sustainable product design model. Mater Des 27(10):1128–1133
Kotliniski J (2014) Mechanical properties of commercial rapid prototyping materials. Rapid Prototyping J 20(6):499–510
Kreiger M, Pearce JM (2013) Environmental life cycle analysis of distributed three-dimensional printing and conventional manufacturing of polymer products. ACS Sustain Chem Eng 1(12):1511–1519
Kumar GP, Regalla SP (2011) Optimization of support material and build time in Fused Deposition Modeling (FDM). Appl Mech Mater 110–116:2245–2251
Lee CS, Kim SG, Kim HJ, Ahn SH (2007) Measurement of anisotropic compressive strength of rapid prototyping parts. J Mater Process Technol 187–188:627–630

Lofthouse V (2006) Ecodesign tools for designers: defining the requirements. J Clean Prod 14(15–16):1386–1395

Luo Y, Ji Z, Leu MC, Caudill R (1999) Environmental performance analysis of solid free-form fabrication processes. In: Proceedings of the 1999 IEEE International Symposium on Electronics and the Environment (ISEE-1999), IEEE

Majewski C, Hopkinson N (2011) Effect of section thickness and build orientation on tensile properties and material characteristics of laser sintered nylon-12 parts. Rapid Prototyping J 17(3):176–180

Mihelcic JR, Crittenden JC, Small MJ, Shonnard DR, Hokanson DR, Zhang Q, Chen H, Sorby SA, James VU, Sutherland JW, Schnoor JL (2003) Sustainability science and engineering: the emergence of a new Metadiscipline. Environ Sci Technol 37(23):5314–5324

Ministry of Housing, Spatial Planning and the Environment (2000) Eco-indicator 99 Manual for Designers—a damage oriented method for life cycle impact assessment. Ministry of Housing, Spatial Planning and the Environment, The Netherlands

Morrow WR, Qi H, Kim I, Mazumder J, Skerlos SJ (2007) Environmental aspects of laser-based and conventional tool and die manufacturing. J Clean Prod 15:932–943

Onuh SO, Hon KKB (1998) Optimising build parameters for improved surface finish in stereolithography. Int J Mach Tools Manuf 38(4):329–342

Parry ML, Canziani OF, Palutikof JP, Linden PJ, Hanson JE (2007) Technical summary. Climate change 2007: impacts, adaptations and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp 23–78

Petrovic V, Gonzales JVH, Ferrado OJ, Gordillo JD, Puchades JRB, Ginan LP (2011) Additive layered manufacturing: sectors of industrial application shown through case studies. Int J Prod Res 49(4):1071–1079

Pham DT, Demov SS (2001) Rapid manufacturing: the technologies and applications of rapid prototyping and rapid tooling. Springer, London Limited

Quintana R, Choi JW, Puebla K, Wicker R (2010) Effects of build orientation on tensile strength for stereolithography-manufactured ASTM D-638 type I specimens. Int J Adv Manuf Technol 46:201–215

Reeves P (2009) Additive Manufacturing—A supply chain wide response to economic uncertainty and environmental sustainability. International Conference on Industrial Tools and Material Processing Technologies, Ljubljana, Slovenia

Rosen D (2014) What are the principles for design for additive manufacturing? In: Kai CC et al (eds) Proceedings of the 1st International Conference on Progress in Additive Manufacturing (Pro-AM2014), Research Publishing Services, pp 85–90

Saqib S, Urbanic J (2012) An Experimental Study to Determine Geometric and Dimensional Accuracy Impact Factors for Fused Deposition Modelled Parts. In: ElMaraghy HA (ed) Enabling Manufacturing Competitiveness and Economic Sustainability. Springer, Berlin, Heidelberg, pp 293–298

Serres N, Tidu D, Sankare S, Hlawka F (2011) Environmental comparison of MESO-CLAD® process and conventional machining implementing life cycle assessment. J Clean Prod 19(9–10):1117–1124

Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (2007) Technical summary: climate change 2007: the Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY

Sood AK, Ohdar RK, Mahapatra SS (2009) Improving dimensional accuracy of Fused Deposition Modelling processed part using grey Taguchi method. Mater Des 30(10):4243–4252

Sood AK, Ohdar RK, Mahapatra SS (2010) Parametric appraisal of mechanical property of fused deposition modelling processed parts. Mater Des 31(1):287–295

Sood AK, Ohdar RK, Mahapatra SS (2012) Experimental investigation and empirical modelling of FDM process for compressive strength improvement. J Adv Res 3(1):81–90

Sreenivasan R, Goel A, Bourell DL (2010) “Sustainability issues in laser-based additive manufacturing”, LANE 2010. Phy Procedia 5:81–90

Stratasys Ltd. (2010) uPrint® and uPrint® Plus Personal 3D Printers User Guide. Stratasys Ltd

Stratasys Ltd. (2015) Fortus 380MC and 450MC Spec Sheet. Stratasys Ltd

Thrimurthulu K, Pandey PM, Reddy NV (2004) Optimum part deposition orientation in fused deposition modeling. Int J Mach Tools Manuf 44:585–594

UNEP (2012) Annual Report 2012. United Nations Environment Programme, Nairobi, Kenya

Vijay P, Danaiah P, Rajesh KVD (2012) Critical parameters effecting the rapid prototyping surface finish. J Mech Eng Autom 1(1):17–20

Vijay I, Chockalingam K, Kailasanathan C, Sivabharathy M (2014) Optimization of Surface roughness in selective laser sintered stainless steel parts. Int J ChemTech Res 6(5):2993–2999

Volpato N, Foggiatto JA, Schwarz DC (2014) The influence of support base on FDM accuracy in Z. Rapid Prototyping J 20:2

Zhang Y, Bernard A (2013) Using AM feature and multi-attribute decision making to orientate part in additive manufacturing. In: Bártolo PJ et al (eds) High value manufacturing. CRC Press, pp 411–416

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