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Cataloging the 3D web: the availability of educational 3D models on the internet

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Abstract

Purpose – The number of 3D models available on the internet to both students and educators is rapidly expanding. Not only are the 3D model collections of popular websites like Thingiverse.com growing, organizations such as the Smithsonian Institution and NASA have also recently begun to build collections of 3D models and make these openly accessible online. Yet, even with increased interest in 3D printing and 3D scanning technologies, little is known about the overall structure of the 3D models available on the internet. The paper aims to discuss this issue.

Design/methodology/approach – To initiate this project, a list was built of 33 of the most widely used 3D model websites on the internet. Freely downloadable models, as well as models available for purchase or as 3D printed objects were included in the list. Once the list of 33 websites was created, the data for each individual 3D model in the collections was manually assembled and recorded. The titles of the 3D models, keywords, subject headings, license information, and number of views and downloads were recorded, as this information was available. The data were gathered between January and May 2015, and compiled into a CSV database. To determine how online 3D model content relates to a variety of educational disciplines, relevant subject terms for a variety of educational disciples were extracted from the EBSCO database system. With this list of subject terms in hand, the keywords in the CSV database of model information were searched for each of the subject terms, with an automated process using a Perl script.

Findings – There have been many teachers, professors, librarians and students who have purchased 3D printers with little or no 3D modelling skills. Without these skills the owners of these 3D printers are entirely reliant on the content created and freely shared by others to make use of their 3D printers. As the data collected for this research paper shows, the vast majority of open 3D model content available online pertains to the professions already well versed in 3D modelling and Computer Aided Design design, such as engineering and architecture.

Originality/value – Despite that fact that librarians, teachers and other educators are increasingly using technologies that rely on open 3D model content as educational tools, no research has yet been done to assess the number of 3D models available online and what educational disciplines this content relates to. This paper attempts to fill this gap, providing an overview of the size of this content, the educational disciplines this content relates to and who has so far been responsible for developing this content. This information will be valuable to librarians and teachers currently working with technology such as 3D printers and virtual reality, as well as those considering investing in this technology.

Keywords Digital libraries, Technology, Online cataloguing, Education, Digital preservation, Technology infrastructure

Paper type Research paper

1. Introduction

While the increased interest in 3D printing technology in recent years has led to a much wider exposure of web-based collections of 3D models (Robertson, 2015), it is important to note that, since the late-1980s, 3D models have been collected and openly

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shared on the internet. These collections have long held an important place in education, too, especially in relation to the subjects of computer science and engineering (Funkhouser *et al.*, 2003).

With the growing popularity of 3D printing, and to a lesser extent, 3D scanning technology, interest in 3D models is now greater than it has ever been. This interest is especially notable in higher education, where biologists, chemists, historians, librarians, and many others have taken an interest in both the digitization of physical objects via 3D scanning technology as well as the reproduction of 3D models using 3D printing and similar on-demand manufacturing technologies (Krassenstein, 2015).

For those unfamiliar with 3D printing, 3D printing is essentially a manufacturing process that takes a 3D model and turns it into a physical object by recreating the 3D model layer by layer, with each additional layer built upon the previous one (after the first layer has been set). 3D printing is similar to other on-demand manufacturing technologies such as Computer Numeric Control (CNC) machines and laser cutters, in that these technologies all create physical replicas of digital designs. The notable difference with 3D printing, though, is that it creates objects through a process of addition, adding material to already existing material, whereas other on-demand manufacturing methods work through methods of subtraction, carving out a smaller design from a larger object such as a block of wood. 3D printing is also notable for its accessible price point, with lower-end 3D printers retailing for around US$500 (Groenendyk and Gallant, 2013).

As part of the overall makerspace movement, 3D printers have become regular fixtures in universities all over the world, and faculty members are increasingly relying on 3D models as instruction aids for their course lectures and assignments (Kurti *et al.*, 2014). As 3D models begin to take a more important role within higher education, however, there is still little known about who controls the 3D models being shared online, who is creating them, how many of the models are actually suitable for educational purposes, and how many of the models can legally be used as teaching tools.

This paper addressed each of these questions. First, by providing a detailed list of all major providers of 3D content online. Next, by assessing each of the collections, and then, finally, by describing what portion of the collections could be of potential use to higher education.

1.1 A brief account of the early history of 3D models on the internet (1980s-2005)

3D models have a long history on the internet. The earliest examples of websites providing sizeable collections of 3D models date back to the late-1980s. At that time the collections often included models in based on the Virtual Reality Marketing Language (VRML) format. This language debuted in 1994 as a way for web designers to share 3D content online through websites (Luttermann and Grauer, 1999). As part of the early enthusiasm about VRML technology and the promise of a 3D web, a number of websites emerged with the sole purpose of providing designers with free VRML models, in the hope that free models would help encourage the adoption VRML technology.

Early examples of larger 3D model collections include the website 3dcafe.com, which first appeared in 1989 and offered about 100 freely downloadable models. The target audience for this collection was animators and webmasters (3DCafe, 1997). Amazing3D.com, which debuted in 1997, also offered around 100 downloadable models for free and about another 2000 models for sale. The Avalon Public 3D Archive, which was launched in the same year, offered approximately 1,000 3D models at no cost. While the Avalon Public 3D Archive seems to have gone offline around 2004/2005, its archive of 3D models, as of June 2015, is still available through its mirror site (ftp://ftp.uniovi.es/pub/mirrors/avalon.viewpoint.com/).

In the early days of the internet, universities were also one of the major contributors to the 3D models made available online. In August 2000, for example, Stanford University created the Stanford 3D Scanning Repository. Still accessible, this repository contains a number of freely downloadable models based on 3D scanning data. Most notably, this collection includes Stanford University's famous 3D scan of Michelangelo's statue of David (https://graphics.stanford.edu/projects/mich/).

Also in 2000, the Georgia Institute of Technology launched the Large Geometric Models Archive (2015), stating that its primary goal was to: "provide large models to researchers in computer graphics and related fields". The larger 3D models provided computer science researchers with more opportunities to deal with complex problems, which the very small 3D models commonly found on the internet did not. In this example, the 3D models were shared freely, like other collections and were intended to be used primarily by students, educators and researchers.

Around 2004 a shift towards providing larger, more graphic-intensive 3D models began to occur. The AIM Shape Repository was one of the most notable examples of an early, graphic-intensive 3D model collection. This repository focused on collecting 3D models at the higher end of what the technology was capable of delivering at that time. At its launch, the repository contained 521 highly detailed 3D models related to the fields of architecture and geometry. AIM (2015) stated that its overall objective was to "build a shared conceptualisation of a multi-layered architecture for shape models, where the simple geometry is organized in different levels of increasing abstraction: geometric, structural and semantic layers".

In the early years, 3D models were often quite difficult to find online, especially by individuals unfamiliar with 3D technologies and 3D-related software programmes. Many different sources of models existed and most sources were relatively small in size, with less than a thousand models in each collection. The quality of the collections varied widely, too, and it could be especially difficult to locate professional quality models. Unique at the time, though, was that the majority of websites hosting 3D models provided the content for free, often to aid research being conducted with 3D graphics, or to help those interested in 3D graphics learn more about the subject.

1.2 The 3D marketplace era (2005-2010)

Beginning in 2005, a number of online 3D model marketplaces began to appear, with the primary purpose of allowing designers to sell their 3D designs over the internet. While these websites still offered 3D models as free downloads, the free models tended to be a very small percentage of the overall collections, and the models of the lowest quality. The largest of these 3D marketplaces, such as TurboSquid and CGTrader, are still in existence, and continue to make up a sizeable portion of the number of models currently available online.

The 3D model marketplaces can be divided into two distinct types. One is represented by companies selling 3D models related to 3D animation and design and the other by companies collecting Computer Aided Design (CAD) models from smaller suppliers, which are then made searchable by engineers and manufacturers with the expectation of increasing sales of the manufactured versions of the CAD parts. The main difference between CAD models and animation-related 3D model file formats is that CAD models – used primarily by engineers and architects – are typically designed with the intention that the model will be physically created. As such there is often a different thought process behind the design of CAD models, where how the model will appear and function in the real world is a significant consideration. Engineers, for example, commonly use CAD software to design machine parts that, as CAD models, can later be created through an automated manufacturing process such as CNC milling, injection moulding or 3D printing (Solidworks, 2015).

For CAD models and models related to 3D animation, there is a large number of both open source and proprietary formats available. CAD programmes such as Solidworks or Solidform all have their own proprietary formats, but there are also open-source CAD formats such as the Initial Graphics Exchange Specification format. The same is true of 3D animation file formats, where in addition to the proprietary formats exclusive to animation programmes such as 3D Studio Max or Maya, there are also open-source formats such as the Wavefront Object (OBJ) format. For 3D model marketplaces, 3D models are typically provided in an open-source format, as this allows the models to be used by the largest amount of users.

Notable examples of 3D model marketplaces selling 3D models related to 3D animation and design include CGTrader and TurboSquid. The content on these websites is typically divided into animation-related themed subject areas such as vehicles, furniture and animals. Originally these marketplaces only provided 3D models in file formats related to 3D animation; but, due to the recent interest in 3D printing, many have begun offering models in the 3D printable stereolithography (STL) format as well.

Notable examples of 3D model marketplaces that work with various parts suppliers to collect and index CAD models include CADENAS, TraceParts, ThomasNet and 3DContentCentral. The 3D models collected by these marketplaces are almost universally classified under the International Classification for Standards (2015) System, using set classification subject headings such as "Equipment for the Chemical Industry" or "Petroleum and related technologies". Users are able to download these models in a variety of CAD-related formats, including the 3D printable STL format.

While the CAD models indexed on the supplier parts marketplaces are usually free to download, strict limits are placed on how many models can be downloaded. The usual requirement for downloading CAD models is that an account be created first, which includes user contact information such as an e-mail address and full name. Once a model is downloaded, the user's contact information is passed on to the supplier that created the CAD model who would then contact the user about potentially purchasing the manufactured part.

In terms of the size, these collections tend to be very large, often containing millions of downloadable models. A caveat exists, however; the models can be customized on demand for many different sizes and dimensions. Thus, while a very large number of 3D models are available on these websites, the vast majority are only slight modifications of specific base models, which makes the overall number of unique models listed on these websites difficult to track.

Outside of the two main types of 3D model marketplaces, others also exist. These marketplaces typically appeal to much smaller niche audiences, though, and their 3D model collections pale in comparison to the larger collections of animation and engineering related models. An example of one of these outlier 3D model marketplaces is Plastic Boy (2015), which began selling anatomy based models in 2005 and still continues to do so. This collection only contains about 100 3D models though, which is substantially smaller than the hundreds of thousands, and sometimes millions, of models offered by the larger marketplaces.

1.3 The 3D printing era (since 2010)

The next important development for online 3D model collections was prompted by the increased popularity of 3D printing technology, which received substantial public exposure beginning in 2010 (Vance, 2010). Like the earlier 3D model marketplaces, two very distinct types of 3D printable 3D model collections developed, but rather than being divided between animation and engineering, this division exists between 3D models intended for download and 3D printing by users, and models that are 3D printed elsewhere and then shipped to users.

The first large collection of 3D models specifically intended to be 3D printed by users was originally created by the community involved with the open-source 3D printing movement, most notably Dr Adrian Bowyer's RepRap (2015) project. Before this project, 3D printing technology was very expensive and access was mostly limited to engineers or architects working in specialized areas of their professions. However, after the RepRap project released the blueprints for its Darwin 3D printer in 2008, 3D printing technology become available to anybody for about a thousand dollars and the time and capability to devote to assembling the components required to build a 3D printer of their own.

Eventually the original RepRap Darwin design led to fully assembled 3D printers now sold by companies such as MakerBot and Ultimaker that have become popular in many schools and libraries (Thompson, 2014). At the earlier stages of the RepRap project, though, when hobbyists were still experimenting with customized 3D printer designs, they needed 3D models to print that they could use to compare and test the performance of the 3D printers. Due to this new demand for 3D printable 3D models, the website Thingiverse emerged, which provided a platform for those with 3D modelling experience to share their models with others who needed 3D printable content.

Similar to Thingiverse, another website called GrabCAD also emerged around the same time. Whereas Thingiverse was specifically focused on 3D printing, though, GrabCAD gave more attention to engineering in a broad sense. GrabCAD behaved in much the same way as Thingiverse, however, by bringing together 3D designers and working with them to build an open community for their design output. Although the majority of the designs indexed on GrabCAD are available in the 3D printable STL file format, they often exist in other various CAD-supported file formats as well, which are easily converted to STL, unlike other 3D model file formats.

In contrast to the community-centred 3D model collections of websites such as Thingiverse and GrabCAD, 3D model marketplaces also developed in another distinct direction. Companies like Shapeways and I.Materialize began to leverage 3D printing technology as a means to allow designers to sell physical replicas of their 3D designs, rather than the designs themselves. These companies have built very large collections of 3D models but the models themselves are not made available, only the physical, 3D printed reproductions. Due to the strong interest in 3D printable 3D model files, many sites, like Shapeways, have begun to give designers the option to make their 3D models available to users. At this point, though, as this paper illustrates below, freely downloadable, 3D models made up a very small portion of the collections available through these websites.

1.4 The current era (ca. 2015)

Thingiverse's 3D model collection, much like the earliest examples of 3D content online, was originally created as a source for free 3D models to help encourage the interest in, and adoption of, an emerging technology, in this case 3D printing. This desire for openness quickly changed, however. On Monday, 24 September 2012, in a blog post on MakerBot.com, MakerBot CEO Bre Pettis announced that MakerBot would stop openly releasing the designs of its 3D printers to its user community – as was commonly the case within the RepRap community that MakerBot emerged from – and would become closed source (Pettis, 2012).

In moving to closed source, MakerBot was accused of claiming ownership of many community developed designs that had been freely shared through Thingiverse and were used to improve the MakerBot 3D printers. Essentially, critics claimed MakerBot stole the open-source work created by its community (Biggs, 2014). Shortly after Bre Pettis's announcement, MakerBot and the MakerBot-owned Thingiverse were purchased by Stratasys, a major 3D printing company, which, along with 3D systems, have dominated the 3D printing market for the last twenty years and, by holding the vast majority of 3D printing related patents, continues to do so. A few weeks after acquiring MakerBot and Thingiverse, Stratasys also acquired GrabCAD, placing the two largest collections of free, community created, 3D printable content under its control (Stratasys, 2014).

As a result of what many in the hobbyist 3D printing communities saw as MakerBot selling out, a number of new websites emerged, which attempted to build 3D model collections to rival Thingiverse, at the same time promising they would always remain true to the community's open-source, open-hardware ideals. At this same time, driven by the sharp increase in popularity of 3D printing technology, and the success of companies like Shapeways and I.Materialize, a number of similar companies also began to emerge online, attempting to collect 3D models from designers to resell either in a 3D printed form or simply as 3D printable files protected by pay walls. In a sense, these developments returned to the practices of the earlier era of the 3D model marketplaces characterized by CGTrader and TurboSquid.

Due to this sudden increase in the number of websites collecting and indexed 3D models, considerable confusion currently exists regarding the online availability of 3D models, especially in relation to the location of the content and how it can be used.

2. Cataloguing the 3D web

To initiate this project, a list was built of 33 of the most widely used 3D model websites on the internet. Freely downloadable models, as well as models available for purchase or as 3D printed objects were included in the list. A variety of sources were consulted to create the list. Notably, Reddit threads on the subject of 3D models collections, as well as posts on various forums related to 3D printing and 3D animation forms were checked. In addition, two 3D model search engines, Yeggi and Yobid3D, which index 3D model content found online were consulted and the websites included in the indexes were included in the list. Sites that only indexed content from other websites without providing any of original content were not included in the list. The 33 websites included in this list vary widely in the type of 3D models they collect, but are all known within various online communities reliant on 3D models and to varying extent have developed significant, loyal user bases.

3D model collections outside of those included in this list probably exist. However, the collections are likely very small in comparison to the larger sources noted in the list. In addition, these small collections are quite difficult to find, and likely have small, niche audiences, with limited relevance to educational institutions.

Once the list of 33 websites was created, the data for each individual 3D model in the collections was manually assembled and recorded. The titles of the 3D models, keywords, subject headings, license information, and number of views and downloads were recorded, as this information was available. The data were gathered between January and May 2015, and compiled into a CSV database.

To determine how online 3D model content relates to a variety of educational disciplines, relevant subject terms for a variety of educational disciples were extracted from the EBSCO database system. With this list of subject terms in hand, the keywords in the CSV database of model information were searched for each of the subject terms, with an automated process using a Perl script. Evert time a model record matched a subject term, the record was the subject, such as physics or chemistry. In cases where a model two subjects, such as biology and chemistry, the model was assigned to the subject category to which the majority of the keywords.

The educational subjects used in this study included architecture, engineering, math, chemistry, biology, physics, medicine, geography and history. For the latter subject 3D scans of historic artefacts and art were considered relevant.

3. Results

3.1 The availability of 3D models online

Table I gives the names of each website identified in this research, ranked in order of the total size of collection and the percentage of freely downloadable content on each.

Due to the vast number of CAD models available through the CAD marketplaces, such as CADENAS, and the difficulty in determining the exact number of models, since these models can be customized by users, these websites are given in a separate table (see Table II).

As can be seen in Table I, the volume of content on the websites varies widely, and a clear distinction exists between the larger collections, such as Thingiverse and GrabCAD, and the smaller, specialized collections, such as OpenGameArt or Dalhousie University's collection of biology-related 3D scans. A clear separation also exists between the four websites collecting CAD models (Table II) from the others (Table I). Not only are the collections in the websites in Table II the largest by far, they are also the only websites to offer customization of the 3D models in their collections, which is the main reason for their significant size difference.

The separation between companies that sell 3D models and companies that only provide openly downloadable 3D content is noticeable in Table I. Companies that focus on providing free 3D models, offer all models for free. Though companies that sell 3D content have begun to offer free 3D content, the volume of free content varies considerably. For example, PinShape offers almost 62 per cent of its content for free, whereas for Shapeways less than 1 per cent of the content is freely downloadable.

Despite the recent increase in the practice of selling 3D models and 3D printed replicas, the majority of 3D content available online still appears to be freely downloadable. About 75 per cent of the content of the websites in this investigation is available for free, which is reminiscent of the trend established in the late-1980s. The overall pattern of free vs paid 3D model content is seen in Figure 1 (which does not include the CAD model collections noted in Table II).

3.2 The license restrictions placed on 3D models

Freely downloadable 3D model content typically falls under some form of Creative Commons license. The most popular is the "Attribution – Share Alike" license, which allows re-use or re-work of a model, even for commercial purposes, as long as the

Provider name	Size of collection	Free to download	% free
3D Warehouse	2,582,758	2,582,758	100.00
Turbosquid	538,983	20,259	3.76
Thingiverse	322,045	322,045	100.00
123D App	265,274	265,274	100.00
GrabCAD	194,858	194,858	100.00
Shapeways	185,650	1,443	0.78
Clara.io	88,197	88,197	100.00
CGTrader	82,470	12,478	15.13
Archive3D.net	38,112	38,112	100.00
CGStud.io	26,816	0	0.00
Blend Swap	14,013	14,013	100.00
YouMagine	5,709	5,709	100.00
TF3DM	5,700	5,700	100.00
MyMiniFactory	2,975	152	5.11
Cubify	5,659	2,687	47.48
Pinshape	2,865	1,771	61.82
3DModel Free	2,260	2,260	100.00
Instructables	2,124	2,124	100.00
OpenGameArt	1,714	1,714	100.00
Cults3D	1,599	575	35.96
I.Materialise	1,497	0	0.00
3DLT	1,088	1	0.09
NIH 3D Print Exchange	911	911	100.00
Blender-Models	509	509	100.00
3D File Market	509	492	96.66
Treasure Island	399	399	100.00
Repables	373	373	100.00
Columbia 3D Models Archive	170	170	100.00
3DScience.com	64	64	100.00
Smithsonian X3D Collection	26	26	100.00
Rhombik	25	25	100.00
Dalhousie 3D Model Archive	10	10	100.00
Standford 3D scanning repository	8	8	100.00
Total	4,375,370	3,565,117	74.75

Table I.
Size of 3D model collections/open vs for-pay content

Provider name	Size of collection	Free to download	% free
CADENAS	10,000,000+	10,000,000+	100[a]
TraceParts	10,000,000+	10,000,000+	100[a]
3DContentCentral	10,000,000+	10,000,000+	100[a]
ThomansNet	10,000,000+	10,000,000+	100[a]
Total (not including CADENAS, Traceparts of 3DContentCentral)	40,000,000+	40,000,000+	100[a]

Note: [a]Models are free to download but there is a download limit and the contact information of the user is passed on to the model owner(s)

Table II.
Size of CAD marketplace 3D model collections/open vs for-pay content

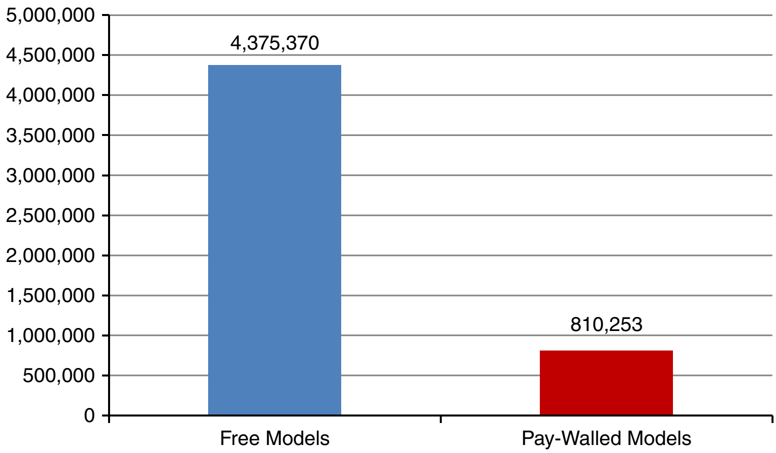

Figure 1.
Free vs pay-walled 3D models online

original creator is given credit, and that new 3D models produced from a model are shared under the same license. The second most popular option is the "Attribution" license, which is very similar to the "Attribution – Share Alike" license but even more open, removing the clause that a derivate work must be shared under the same license, permitting the new 3D model to be used in commercial projects. In addition to these popular licenses are two others, namely, the "Attribution-Non-Commercial-Share Alike" and "Attribution – Non-Commercial" licences, which prohibit all commercial use of the 3D models. Beyond these four main licenses, other Creative Commons licenses receive very little use.

Although Creative Commons licenses are adopted by 3D model creators, very few sites that provide free 3D models also include licensing information for the models in their collections. Even for those that do, it is not always certain that the designers understand the restrictions of the licenses they select, or that changes will not be made to the licenses if a 3D model suddenly becomes popular. Of the 3D model collections that accurately list licensing information, Thingiverse is the most notable example, where almost every model in its collection has been associated with some type of license. Since Thingiverse also has one of the largest collections of 3D models, it was used as a benchmark for determining what licenses are most popular with designers who freely share their work. The distribution of licences in the Thingiverse collection for models that include license information is given in Figure 2.

As Figure 2 shows, where license information is available, the majority of free models are shared under the Creative Commons licenses related to "Attribution" or "Attribution – Share Alike", meaning that the majority of freely available 3D models would be suitable for use in education, or for educational purposes, as long as the original creator of the models are given appropriate credit.

3.3 The educational subject-area breakdown of 3D models

The majority of websites collecting 3D models provide models related to education in some form. These models can either be purchased or are freely downloadable, but their intent is to be used as tools to help educators teach various subjects, or for students to learn more about a particular subjects. In many cases, however, whether a 3D model was made with educational intent is not clear. As the majority of websites – especially

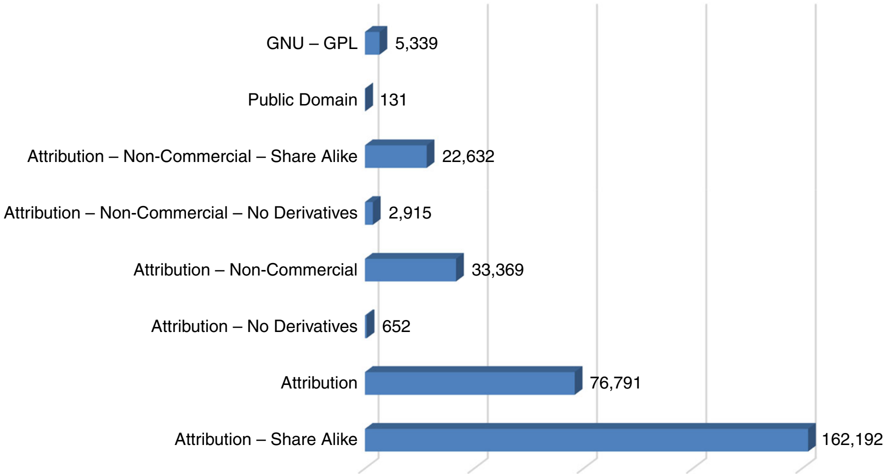

Figure 2.
License distribution for free 3D models on Thingiverse

those collecting free 3D models – allow open submissions from users, the descriptions of the models vary widely. The designers' intentions for the models are not always obvious, even when a model is described as educational.

A large number of 3D models related to engineering are available, largely due to the fact that engineers have had a major role in the development of 3D models as well as 3D scanning and 3D printing technology, in comparison to other disciplines. If 3D models provided by CAD sites like CADENAS are included, the number of models related to engineering is in the millions. As a consequence, the total number of 3D models designed for the education of engineers, or have the potential to be used for an educational purpose, is very high and overshadows the content available for other disciplines. Whether all these engineering 3D models are actually suitable for higher education purposes, though, is debatable.

Models related to the subject architecture show a similar pattern, with a very large number in existence as examples of historic buildings and other educationally notable structures. A total of 621,854 models related to architecture were found in the various 3D model collections that matched the EBSCO subject term for architecture.

While few 3D models were found based on GIS or mapping data, a large volume of GIS data are available online. Much of this data are free to download as well. While the GIS data does not exist on its own in a 3D format, this data can be turned into 3D visualizations fairly easily by experienced ArcGIS users, using ArcScene or ArcGlobe software usually included with the ArcGIS package (ArcGIS, 2015).

For subjects other than engineering and architecture, many fewer models are available. The distribution of these models is shown in Figure 3.

The majority of 3D models noted in Figure 3 were tagged with keywords linking them to one of the EBSCO subject disciplines. The number of models specifically created for use in education, however, is much smaller. If the subjects of architecture and engineering are included, only 21,617 3D models were cataloged as being specifically relevant for educational purposes. At less than 0.001 per cent, this number represents only a small fraction of the overall number of 3D models available online. The number of these educationally tagged 3D models that would actually be of use to faculty, researchers or students within higher education

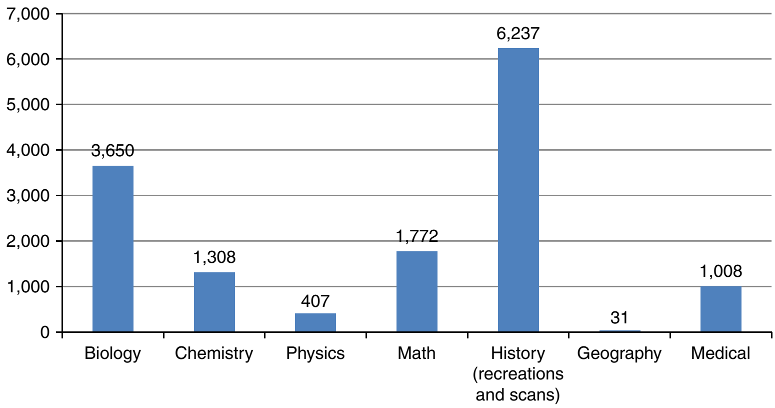

Figure 3.
Distribution of free online 3D models by subject

is likely to be considerably lower as well. Nonetheless, the number of 3D models that could be used for educational purposes is substantially higher than those explicitly tagged for education.

3.4 Key suppliers of educational 3D models

The data gathered for this study shows that the supplier of the largest number of educationally related 3D models is the website is Thingiverse (see Table I). Due to the size of this collection, and the interest that various educators have taken in it, Thingiverse stands out and encompasses the largest number of educational disciplines as well. For example, numerous 3D scans of historic objects, including artwork owned by the Metropolitan Museum of Art (2014) in New York City, such as a scan of a Sphinx of Hatshepsut are available in the Thingiverse database. A small collection of 46 3D models related to the human body (www.thingiverse.com/glitchpudding/collections/your-body) are also found in Thingiverse. In addition, Thingiverse offers 3D printable GIS data, 3D models related to the visualizations of molecules, 3D models that involve simple engineering projects and many other educationally related 3D models as well.

Through Thingiverse, MakerBot has begun creating set lesson plans for teachers, for example a 3D printable, simulated frog dissection kit (MakerBot, 2014), though these lesson plans are designed largely for school children rather than a university-level audience. Thingiverse has also introduced a subject category called "learning", which attempts to catalog new models broadly intended to support learning about various subjects. Still, whether a 3D model is classified for educational learning is entirely up to creator who submits the model, and the accuracy of the model is not guaranteed.

Instructables is another major provider of educationally relevant 3D model content. While Instructables provides a substantially smaller collection compared to Thingiverse, the content is completely focused on instructional lessons. For each educational model in the collection, detailed instructions about how the model can be used to teach a particular idea or technical skill are included. Currently, Instructables' educational content is almost entirely focused on the subjects of computer science and engineering; however, the collection is expanding.

A third major collection providing educationally related 3D models is the National Institute of Health's (NIH) 3D print exchange. This exchange contains a collection of 916 models related to health and medicine. While the collection is still quite small in comparison to the overall number of 3D models available, this effort to make science-specific 3D models more widely available, shows the importance that some educators are beginning to place on the potential that 3D models and 3D printing technology have for instructional purposes.

The Smithsonian Institution's initiatives to digitize objects in the immense collections of its museums and galleries and post online as 3D printing 3D models is now becoming notable. However, the digitization projects currently being undertaken are managed by a very small team of two people, and so far only 26 objects have been digitized and made available online. While the Smithsonian Institution plans to increase its collection of 3D models (Chanthadavong, 2015), the current number is tiny in comparison to other sources. The Smithsonian's digitization initiatives seem to receive greater media attention than other sources, though.

In May 2014, the 3D model marketplace Threeding announced that it was teaming up with a number of museums, to 3D scan items from their collections and then sell the resulting 3D models online through its website, giving the museums an undisclosed share of the profit (Krassenstein, 2014). Threeding is pioneering in its attempt to sell this educational content. Nonetheless, of the small volume of content available online suitable for education, the majority is available for free. Outside of these sources, small pockets of educational 3D models are available in other collections, but as a whole these collections represent a very small percentage of the overall educational 3D content available.

Interestingly, many 3D printing companies, such as MakerBot, that heavily promote their 3D printers as educational tools, often refer to the online availability of 3D models for learning instruction (MakerBot, 2015). However, the data gathered in this study have shown that this is not the case, and that among numerous disciplines very little educational 3D content is available to the owners of 3D printers. The actual download statistics for 3D models from these websites also show that educationally related 3D models are rarely downloaded by users of the larger 3D model collections. For example, the Thingiverse website, which has the largest volume of educationally purposed content, the most frequently downloaded 3D models by far relate to engineering, 3D printers themselves and various Thingiverse-promoted 3D printable "trinkets", that are often the first item printed when 3D printers are acquired. To illustrate this observation, the titles and the number of downloads of the most downloaded models in Thingiverse are given in Table III.

The most frequently downloaded model relates to an open-source robotic hand created by the InMoov project, which is designing a 3D printable robot that could be seen as having educational applications (InMoov, 2015). The same can be said of the Open Source Action Figure, the 20th most frequently downloaded model. These models differ from the majority of the Thingiverse's collection, though, as they have been extensively marketed through press releases (Bushwick, 2015), and it is difficult to determine whether the downloaded models have actually been put to real use.

Many of the other models, such as the "Cute Octopus Says Hello" and the "Eiffel Tower" exist mainly as 3D printable trinkets, and are very popular test models or example models commonly used by owners of 3D printers to demonstrate, present or test the technology. Other models listed in Table III, such as "The Essential Calibration Set", relate to the configuration or modification of 3D printers, and fulfil a very specific and needed purpose.

Over half of the models in Thingiverse have been downloaded less than 100 times. For educationally relatable models, especially those focusing on the natural or physical sciences or mathematics, it is rare for the models to have been downloaded over ten times. Overall, the top 10 per cent most frequently downloaded models on Thingiverse

Title	Number of downloads
InMoov Right Hand Solidworks Model	58,946
Low Poly Mask	56,128
The Essential Calibration Set	47,430
Cute Octopus Says Hello	35,959
Treefrog	34,052
Winged Victory of Samothrace	30,677
5mm Calibration Cube Steps	30,349
Stretchy Bracelet	29,507
Twisted 6-sided Vase Basic	28,767
Fully assembled 3D printable wrench	27,706
Gear Bearing	27,329
British WW1 Mach Tank	27,194
Lyman Filament Extruder II	25,032
Eiffel Tower	24,857
Cellular Lamp	23,849
Elephant	23,740
3DK Launcher – 3DKitbash.com – Print & Play	22,891
Praxis Slamfire lockplate	20,692
Open Source Action Figure	20,497

Table III. Thingiverse number of downloads from May 2008 to May 2015

represent more than 50 per cent of all model retrieved from the website, and educational models fall within the bottom 10 per cent in terms of model popularity.

For other websites, such as GrabCAD or CGTrader, the overall downloads show a similar trend. A handful of models have become very popular, often because a model is very well designed or it solves a common problem. However, the vast majority of models in the collections are rarely downloaded at all. So, while the collections continue to grow rapidly, with many companies announcing that hundreds of thousands or millions of 3D models are available in their collections, the proportion that are actually used is considerably smaller. The open submission system of these websites, where anyone can submit a 3D model regardless of its quality, likely contributes to this situation. Models created by professional model designers, or models created for specific purposes, are far fewer in number.

3.5 The quality of educational 3D models

The vast majority of educational 3D model content existing online is controlled by user-submission sites such as Thingiverse and Instructables. To submit models to these websites, a user simply needs to register an account and then upload a model file. This ease of submission provides no guarantee of the authenticity or quality of 3D models. Representations of molecules available in Thingiverse, for example, could be entirely incorrectly designed. Similarly, human anatomy models could present incorrect features. 3D scans of historic items could be mislabelled with incorrect information attached to them. Neither Thingiverse nor Instructables provides any verification of the credentials of model uploaders, or confirmation that the submitted information correctly describes uploaded models.

The 3D model "DNA Sculpture (Parameterised)" (Cathalgarvey, 2010), for example, was heavily featured on the Thingiverse website, and with 3,139 downloads, it is one of the most popular models in the Thingiverse collection. It was created by a user named cathalgarvey, who describes himself as a "biohacker and nerd" who "studied Genetics in UCC years back". This description does not discredit the accuracy of the model, but it is unlikely the majority of Thingiverse's users would be able to verify the accuracy of the model or the background and experience of the creator. Thus, a potential problem exists regarding the accuracy of information of the models, very similar to the challenges faced by Wikipedia in verifying the information contained in its vast collection of articles (Brown, 2011). The straightforward process by which model creators can falsely claim an academic background and/or deliberately upload incorrect information creates the potential for models to be used by a large number of students who do not realize that the models are not accurate representations, an example of this being a 3D model representing a human heart but with an incorrect number of valves.

While there are 322,045 3D models available in Thingiverse's collection, only 76,239 users have submitted models. Of these submitters, 44 per cent have submitted a single model, while the top 10 per cent of active users has submitted just under 50 per cent of all available 3D models (see Table IV). Thingiverse's most active user, "edscifest", has submitted a staggering 2,047 models but has provided absolutely no biographical information about who they are (see Table V). Many of the 20 top 3D model submitters typically provide no information about themselves. MakerBot itself ranks as the

Table IV. Most active 3D model submitters vs percentage of contribution to the overall collection

Model submitters	Number of users	% of contribution to total models
All submitters	76,239	100
Top 10% of submitters	7,624	49
Top 25% of submitters	19,060	70
Top 50% of submitters	38,120	86

Table V. Top 20 model contributors on Thingiverse

User name	Number of models uploaded	% of overall collection
edscifest	2,047	0.64
lokilaufeysen	781	0.24
cerberus	506	0.16
davidmus	454	0.14
leonk	384	0.12
rickdegreef	379	0.12
makerbot	365	0.11
barrstudent	341	0.11
maxtary	338	0.10
dutchmogul	276	0.09
meson	273	0.08
tbuser	273	0.08
awesomea	251	0.08
kblnn	249	0.08
mizliz	248	0.08
pmoews	247	0.08
bazaff	244	0.08
microsoftstore	239	0.07
fredini	235	0.07
charleschan	232	0.07

seventh largest contributor to Thingiverse collection, with 365 model submissions, and it is also the largest contributor to Thingiverse's educational content.

Besides Thingiverse and Instructables, the 3D model collections created and curated by organizations that can currently be trusted to provide accurate, reliable educational content – such as the Smithsonian Institution and the NIH – are very small. Since these collections exist outside the substantially larger community bases associated with websites like Thingiverse and GrabCAD, the 3D models in their collections are not nearly as visible either.

Both Columbia University in New York, and Dalhousie University in Halifax, Nova Scotia, have begun to collect curated 3D models but, currently, their collections are tiny compared to other sources. No other universities are known to have attempted to build or curate their own collections of 3D models.

A significant challenge in making high-quality educational 3D models more readily available is that few educators are familiar with CAD or 3D modelling software. An examination of both the subjects of educational 3D models, and the entire content of online collections, clearly demonstrates that quality 3D models are overwhelming created by engineers, animators and architects. This finding is expected as these professionals are trained in 3D design and also actively produce 3D models in their day to day work.

In other subject areas, such as history, fine arts, biology and chemistry, there is growing interest in 3D models, 3D visualization and 3D printing technology. However, very few who work in these areas are knowledgeable about 3D printing technology and are also capable of utilizing 3D modelling, 3D scanning or other similar methods to create models needed to make this technology useful. At this point in time, without more active contributions of 3D model content related to history, science and other fields lacking 3D modelling expertise, the visibility of such content tends to be hidden within the larger, rapidly growing online collections of 3D models, making quality educational 3D models difficult to find.

The number of 3D models available online is growing rapidly as more and more people begin to take an interest in 3D printing technology. Figure 4 shows that two of

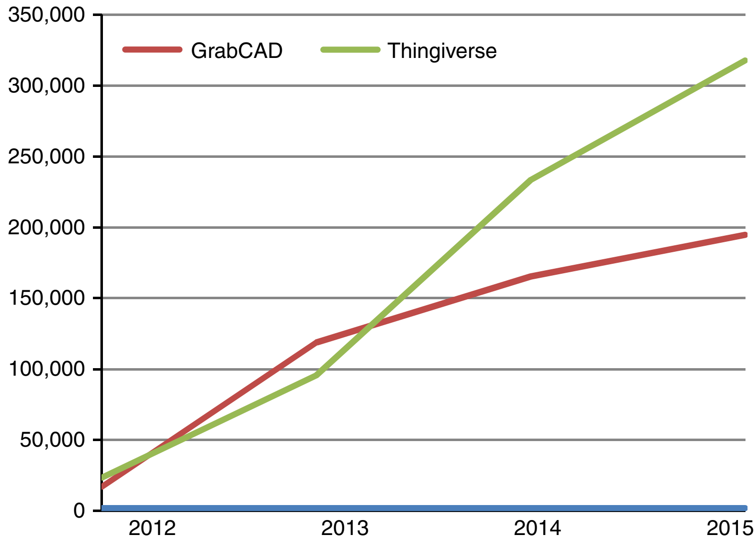

Figure 4. Thingiverse and GrabCAD growth rates by overall number of models

the largest collections of free 3D models, Thingiverse and GrabCAD, have grown exponentially since 2011.

While GrabCAD's growth rate seems to have slowed somewhat over the last two years, Thingiverse has experienced a rapid increase in the size of its collection since 2013. Through 2013 and 2014 Thingiverse grew, on average, by 377 new 3D model submissions per day. So far, in 2015, Thingiverse has received a daily average of 562 new model submissions. In comparison, when Thingiverse was launched in 2011, about 21.4 submissions were received per day. Only a very small fraction of new content submitted to GrabCAD and Thingiverse is related to particular educational subjects. Even though Thingiverse is the largest provider of educational models, this content only represents 0.44 per cent of its collection, and if this submission trend continues, educational content will be increasingly hidden.

Although many schools, universities, libraries and other educational institutions have begun to embrace 3D printing technology, very little work to develop the content related to this technology, or to contribute to the overall availability of educational 3D model content online is currently evident. Outside of a few teachers and educational institutions, who is creating the majority of the small volume of educational content is not easily determined, and the quality or accuracy of the content is not obvious either.

4. Conclusion

The 3D printers have already been purchased. The company MakerBot, especially, has been very successful in getting their 3D printers placed in college and university campuses all over the world, with their 3D printers now spread out across engineering labs, libraries and faculty offices.

For desktop 3D printers, after the past two or so years of hype, there is now, however, somewhat of a cooling off period taking place (Dignan, 2015). At first it was interesting to have a desktop 3D printer capable of creating physical replicas of 3D designs on demand, but the problem has emerged that without 3D design skills, which many owners of 3D printers' lack, the uses for 3D printing become limited very quickly. This previous statement is not in any way meant to diminish 3D printing technology, or the potential that this technology has to change the future of manufacturing, but the problem is that many newcomers to 3D printing technology see the future of this technology as its present state. While 3D printing is very useful for prototyping or for small run manufacturing, it has been used for these same tasks for the past 30 years and little has changed.

There have been many teachers, professors, librarians and students who have purchased 3D printers with little or no 3D modelling skills. Without these skills the owners of these 3D printers are entirely reliant on the content created and freely shared by others online to make use of their 3D printers. As the data collected for this research paper has shown, the vast majority of open 3D model content available online pertains to professions already well versed in 3D modelling and CAD design, such as engineering and architecture. For any biology professors or amateur historians who bought 3D printers hoping to begin projects visualizing new molecules or recreating ancient cities in plastic, there is, unfortunately, little content currently available for them to work with. This situation also applies to students. Many have heard about 3D printing technology, many are excited about its future possibilities, but few are actually experienced in the tools necessary to create 3D models, and little educational content is available for them to experiment with or learn from.

This is not to say that there is not enormous potential for utilizing 3D models in education. The BeAnotherLab, for example, has released both the source code and the

3D printable CAD models that will allow students or other researchers to use an Oculus Rift virtual reality headset in conjunction with mobile web cameras to redirect one person's vision from another's body (BeAnotherLab, 2015). This project illustrates the potential that open-access 3D models and 3D printing can have in furthering research, allowing researchers to more easily – and affordably – recreate an existing project, and begin building on top of the foundations other researchers have created.

The Egyptian Museum of Berlin has engaged in a number of significant projects to digitize and then 3D print extremely rare and fragile objects from their collections, which would normally have been closed off to the general public (Mendoza, 2014). If the Egyptian Museum of Berlin chose to make the scanned 3D models openly available, not only would patrons in Berlin be allowed to see these objects, but researchers from around the world would be able to recreate and study these objects at a significantly reduced expense to themselves and their institutions.

Much like the open-source software movement and the increased interest move away from expensive, proprietary software programmes, the open-hardware movement is now causing a similar shift. Many university researchers are exploring ways to reduce their reliance on expensive, proprietary hardware and turning to 3D printers to allow them to re-produce and utilize open-hardware designs. This is the argument put forward by J.M. Pearce (2014) in a recent article in *Nature*, where he argues that outside of developing open-access data and software, researchers also need to begin developing open-source hardware as well, as by sharing these CAD models with the larger research community the cost of doing experiments can be radically reduced. This open-hardware trend is now making its way into university classes themselves as well, with the University of Michigan now offering a course in open-hardware 3D design (Pearce, 2015).

The developments in 3D printing, 3D scanning, open hardware and virtual reality are all helping to drive the demand for wider, more accessible, more available 3D content. Yet, though these technologies offer great promise for academia, the 3D models these technologies rely on currently exist in an extremely disorganized state. This is especially true in terms of educational 3D model content. High-quality, educationally related 3D models do exist, but there are very little of them and they are buried underneath a mass of CAD parts, movie and video game figurines, and amateur 3D printing experiments. Even when quality educational 3D models are found, it can be even more difficult to identify who created the model or to verify the model's accuracy.

If schools, libraries and universities continue to adopt 3D printing technology at the rate they are, something needs to be done about the current state of 3D models. There needs to be a system in place where high-quality, educational 3D models can be preserved and curated, and the validity and accuracy of these 3D models can be verified.

The current trend for 3D model collections like Thingiverse is to encourage everyone with even the slightest knowledge of 3D models to create and share their models online. While this is great in terms of growing 3D model collections, and making the companies that control these collections look more significant, this amateur content is displacing the quality 3D models that do exist. The idea of curated, quality 3D model collections, such as those created in the late nineties and early-2000s by Stanford University, the AIM Shape Repository, the Georgia Institute of Technology's Large Geometric Models Archive, has become much less popular now, with the focus instead being placed on collection size rather than quality.

There is also a further challenge in ensuring that the 3D models that exist today as free downloads remain open and freely accessible. While the majority of 3D models are shared freely for now, for the most part this content is controlled and managed by a handful of large companies, and access to the models could easily become more restricted, such as has been the case with many other types of academic information.

There are always challenges faced when adopting new technologies for education. At this time, in the realm of 3D printing, it seems that although educators have become very interested in the technology itself, the content needed to support this technology is being neglected. Going forward this needs to change. As more 3D models are created by professors, students, museums and the many others new generating this content, systems need to be created to preserve and index these 3D models, as well as to evaluate which 3D models are worthy of long-term preservation. Without these systems in place, the current disorganization of 3D models online can only get worse, posing serious risks to the preservation of high-quality and culturally significant 3D models, and the role these 3D models might take within education in the future.

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