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The role of higher education in 3D printing research and innovation

Habtamu Diriba[1], Grischa Fraumann[1] and Jon Maes[1]

[1] *Masters in Research and Innovation in Higher Education (MaRIHE), University of Tampere, Finland.*

Contact: diriba.habtamu.x@student.uta.fi; fraumann.grischa.x@student.uta.fi; maes.jon.x@student.uta.fi

Bio: Habtamu Diriba is currently a graduate student in the Erasmus Mundus Masters in Research and Innovation in Higher Education (MaRIHE). Before joining the MaRIHE programme, he completed a two year graduate study in Master of Business Administration (MBA) at Jimma University. His research interests mainly consist of topics relating to university entrepreneurship and innovation, higher education governance, and policy, and internationalization.

Grischa Fraumann is currently a graduate student in the Erasmus Mundus Masters in Research and Innovation in Higher Education (MaRIHE). He studied his bachelor’s degree in Hispanic Studies, Sociology, and History at the University of Mannheim, Germany, and University of Deusto in Bilbao, Spain. His research interests are research impact assessment, third mission, and internationalisation of higher education.

Jon Maes is currently a graduate student in the Erasmus Mundus Masters in Research and Innovation in Higher Education (MaRIHE). Before joining the MaRIHE programme, he completed a year of studies at Drexel University for a Master of Science in Higher Education with a focus on Global and International Education. His research interests mainly consist of topics relating to higher education governance, higher education policy, campus operations, and internationalization processes.

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The role of higher education in 3D printing research and innovation

Habtamu Diriba, Grischa Fraumann and Jon Maes

Over the past three decades, the development of 3D printing has accelerated rapidly. In considering theories about the economic impact of disruptive technologies, this paper addresses how 3D printing has attracted unprecedented attention from various public and private stakeholders with signs that it will be a major driver of the next economic wave. Outlining the major changes that 3D printing has undergone since its inception, an argument is made that 3D printing has the potential to be widely applicable across higher education settings. Reflecting also on the Triple Helix Model of university-industry-government relationships, this paper contends that higher education institutions (HEIs) should take the lead as key players for 3D printing collaborations across these three sectors. In this regard, several examples of 3D printing's uses in the higher education sector are described and analysed. However, HEIs must also be mindful of the social, ethical, and legal challenges that 3D printing involves. The paper concludes with possible future advancements of 3D printing along with practical implications for colleges and universities.

Key words: Higher education; 3D printing; innovation; disruptive technology; foresight research.

Introduction

The underpinnings of economic development have always been an area of concentration for researchers and practitioners alike. For a long time, however, economists equated economic development with the commonly known factors of production, namely: land, labour and capital *(Catch the wave* 1999; Rosenberg 2004; *Divining reality* 2014). However, according to US economist Abramovitz these factors of production only explain 15 per cent of economic development, which leaves 85 per cent unattended. This is where innovation comes in. According to contemporary economic theories, technological innovation is responsible for at least some proportion of the unexplained percentage of economic development (Rosenberg 2004; Cohen 2011; *Divining reality* 2014).

Nearly a century ago, Russian scholar Kondratieff recognized the influence that innovation has on economic upswings in his landmark book "*The Major Economic Cycles"*. Decades later, his theory was extensively explored and expanded on by Austrian economist Joseph Schumpeter (*Divining reality* 2014). Briefly stated, Kondratieff identified a repetitious pattern in the world economy that recurs in approximately 50-year periods. He argues that during each cycle, four distinct phases exist: prosperity, recession, depression and improvement (Šmihula 2009).

There is evidence that a disruptive innovation enters the market before the start of each cycle (*Catch the wave* 1999). First was the steam engine and cotton that lifted the global economy in the 1800s followed by railway steel in the 1850s before remarkable innovations in electrical engineering and chemistry reinvigorated the economy in the 1900s. Then, petrochemicals and the automobile helped pave the way for the economic upswing of the 1950s before information technology transformed the world in the 1990s (1999). In line with this theory, various stakeholders—ranging from large entities to individual investors—are curious to know that the next breakthrough innovation will be that will be capable of lifting the global economy.

One innovation that has caught the attention of many in the most recent past is Additive manufacturing (3D printing). 3D printing has witnessed a tremendous improvement over the past few years with signs that it is the next disruptive innovation. However, a quick look at several technological innovations that created a lot of optimism only to find themselves out of the market without any profound impact makes one retreat from making any premature conclusions (Leitner 2012). Therefore, whether 3D printing technology has the potential to deliver on the bold economic promise requires careful investigation. Secondly, with the development of the technology, the possibility of its misuse and other adverse consequences are coming to the surface, necessitating the need for further exploration. A preliminary review of the relevant literature indicated a lack of consolidated research investigating the aforementioned issues.

Therefore, the purpose of this research paper is to fill this gap, by answering the following research questions: Does 3D printing technology have the potential to bring about global economic disruption? If so, how can higher education institutions (HEIs) and 3D printing technology mutually reinforce each other's development? Lastly, what legal and ethical challenges do HEIs and 3D printing face in order to avoid any adverse consequences that the technology may cause?

In pursuit of answers to these questions, this paper is structured into six parts. Section 1 outlines the method of inquiry and analytical frameworks employed along with a brief overview of 3D printing's technological progress in Section 2. The three sections that follow after that address each of the three research questions raised above. Section 6 then makes general predictions about the future of 3D printing. Lastly, the final section includes concluding remarks with recommendations for how HE should proceed with 3D printing enterprises.

Methodology and theoretical framework

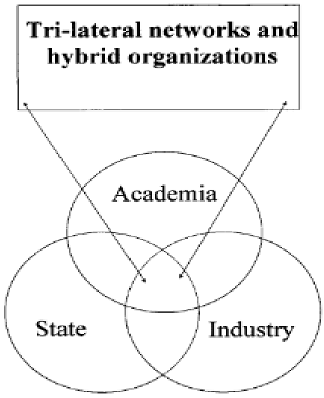
Three complementary theoretical frameworks will be used as a guide to answer the abovementioned questions: the Hype Cycle, Triple Helix, and Open Innovation.

Firstly, the Hype Cycle (Gartner 2015) is a conceptual tool that evaluates the potential of emerging technologies over time. To be more precise, the chart depicts the relative position of emerging technologies in a five-stage cycle: Innovation Trigger, Peak of Inflated Expectations, Trough of Disillusionment, Slope of Enlightenment and Plateau of Productivity. It is applicable in the discussion of 3D printing's development.

Figure 1. Gartner Hype Cycle chart (Gartner 2015)

Secondly, Etzkowitz & Leydesdorff's (2000) Triple Helix model sheds light on the interactions that exist amongst state, academia and industry in spurring innovation. It echoes the transition from the conventional two actor innovation model, which involves only the state and industry, to a triadic relationship that incorporates universities as a main actor.

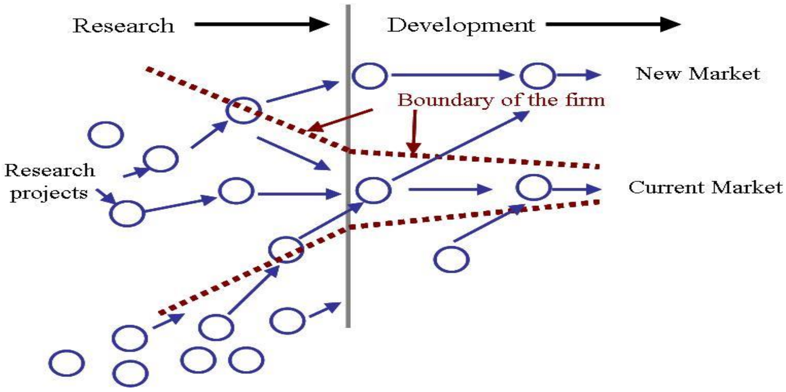
Figure 2. The Triple Helix model of university-industry-government relations (Etzkowitz and Leydesdorff, 2000)



The main thesis is that "in today's knowledge-based global economy the innovation and economic progress lies in a more prominent role for the university and in the hybridization of elements from university, industry and government to generate new institutional and social formats for the production, transfer and application of knowledge" (Ranga, Hoareau, Durazzi and Etzkowitz 2013). By doing so, a case will be made as to why and how HEIs should take the lead in advancing 3D printing technology.

Thirdly, within the broader framework of the Triple Helix model is the Open Innovation model. Open Innovation is a concept developed on the assumption that not all great innovations originate inside a company and that the key to success depends on the ability of an organization to create synergies between internal innovation units and external partners (OpenInnovation.eu 2015). It therefore promotes a porous organizational boundary where there are continuous interactions and collaborations between research and development units residing inside and outside the organization, which ultimately lead to greater value creation (2015). This analytical framework is included to further illuminate the mutually beneficial relationship between HEIs and 3D printing in both the advancement of this technology, while at the same time utilizing the technology to also bring improvements to higher education settings.

Figure 3. Open Innovation model (OpenInnovation.eu 2015)

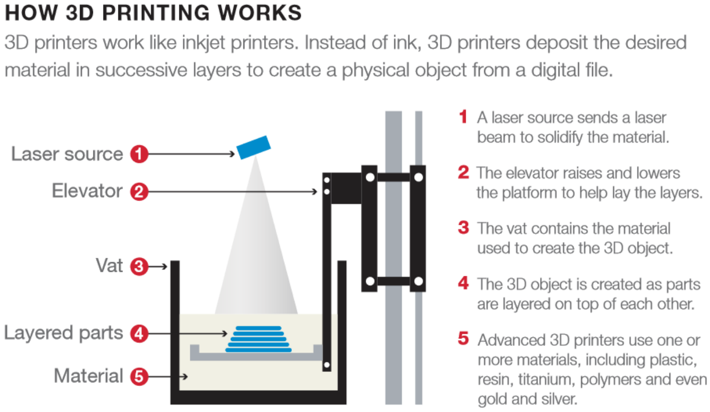


Finally, with respect to methodology, this research rests on an extensive review of the relevant literature of 3D printing technology as a whole and its application in higher education settings. This includes various books, academic articles, periodicals, company reports, and technology websites.

3D printing: a brief overview

This section is devoted to discussing the major changes that additive manufacturing has undergone since its inception in the 1980's. The story begins in 1983 when Charles Hill—an engineering physics graduate from University of Colorado, USA—created Stereolihtography (SLA). It was the first technology to print three dimensional objects from a Digital CAD/CAM file (Wohlers and Gornet 2012). The structures are created using an incremental approach; whereby a series of layers are built successively on top of each other. This is in sharp contrast to the reductionist approach used by traditional manufacturing techniques like machining, casting, and moulding.

Figure 4. Explanatory diagram of how 3D Printing works (T. RowePrice n.d.)



Three years later, the first patent was granted for this novel invention, before the very first 3D printer (3D Systems SLA 250) became commercially available to the public in 1988 (McLellan, 2014). Several variations and improvements to additive manufacturing appeared in quick succession. This includes the introduction of Fused Deposition Modelling (FDM) in 1991 and Selective Laser Sintering (SLS) in 1992 (Wohlers and Gornet 2012).

Massachusetts Institute of Technology (MIT) entered the scene in 1993 with its 3DP; *"*a technology that spreads a thin layer of powdered material (originally ceramic) on a flat bed, solidifying successive layers with fine jets of binding agent" (Kaczynski 2000). MIT later licensed its innovation to six diverse companies. Another milestone in terms of technological improvement was reached in 2008 when a 3D printer named "Darwin" was introduced to the market along with its ability to produce its own replacement parts (McLellan 2014).

Notwithstanding 3D printing's continuous improvements, it is essential to evaluate if the technology is capable of living up to the hype and bring about a global economic upswing.

Is 3D printing a disruptive innovation?

The evaluation of whether 3D printing has the potential to bring about global economic disruption calls for a close observation of the characteristics of innovations that have caused similar impact in the past. Particularly, by looking at the most recent disruptive innovation, i.e. information technology and/or computers, the following guiding points are developed: (a) technological improvement, (b) industrial reach, (c) cost of production, and (d) governmental contributions.

To start with technological improvement, it can be argued that there has been a continuous improvement ever since the introduction of the first 3D printer to the market in 1988 (McLellan 2014). Notable examples include the transition to Fused Deposition Modelling (FDM) technique and the innovation of the first self-replicating 3D printer in 1991 and 2008 respectively (Wohlers and Gornet 2012; McLellan 2014).

Secondly, in terms of industrial reach, 3D printing is widening its target market. For instance, starting from1999, it has been widely applied in the health sector. To mention one practical example, Antony Atala and Co. at The Institute for Regenerative Medicine at Wake Forest University School of Medicine used 3D technology to develop and successfully implant an organ into a patient (McLellan, 2014). Similarly, the expansion of the technology into other industries continued in the beginning of the 21st century with the first 3D printed chocolate and robotic suit in 2011 and 2013 respectively. As Gartner's (2014) Hype Cycle states, 2011 also marks the year 3D printing technology entered the consumer market. Furthermore, other examples of 3D printing's expansion and diversification include the first 3D printed aircraft at the University of Southampton (McLellan, 2014), the first 3D printed object by NASA (Hubscher 2014) and Barak Obama becoming the first president to have his bust 3D scanned and printed (Lewis 2014).

Thirdly, implications for cost of production are clear, with conventional methods resulting in up to 90 per cent of the input materials being wasted (3D Printing Basics, 2014). This is one reason for the rapid evolution of 3D technology and the drop in price of 3D printers themselves. For instance, the price dropped from more than USD $200,000 at the beginning of 2000 (The DTM 125 & DTM SinterStation 2000) to as low as USD $29,900 in 2002 (Stratasys 2012). This decline is expected to continue even further in conjunction with increasing stakeholder collaborations and the rise in consumer demand. According to Gartner's prediction, by the year 2016 the price of an enterprise-class 3D printer will be as low as USD $2000 (Neagel 2013).

Fourthly, another interesting trend over the course of additive manufacturing's evolution is the increasing attention it has gained from governing bodies at various levels. Being well aware of the innovative technology's potential, various national and supranational entities are already devising their own 3D printing strategies. At the national level, China and Japan are two noteworthy examples. The Chinese government has been quite vocal about their aim to become a leader in the 3D printing technology industry by the year 2016 (Grace 2013). Japan is also significantly increasing its investment in 3D printing technologies. Quoting Toshimitsu Okane from the National Institute of Advanced Industrial Science and Technology: "This is a good chance to establish technological superiority over the U.S. and Europe" (METI 2013, p. 7).

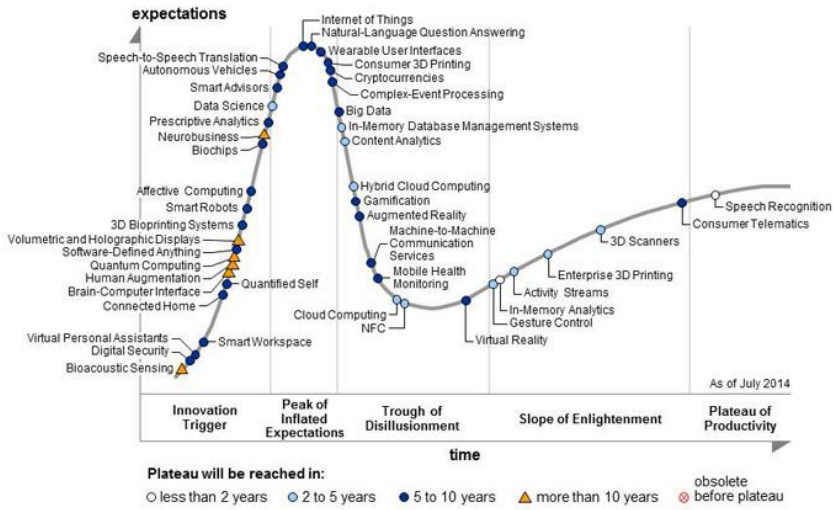
In a similar vein it can be argued that the US and European member states are equally, if not more, aware of the significance of 3D printing. While the US dominates the 3D printing market in terms of the number of metal powder additive manufacturing machines that are being produced, Germany and other European states enjoy the largest share of production of metal powder additive manufacturing machines (METI, 2013).

Supranational entities are also providing special attention to the further advancement of additive manufacturing technology. For instance, the EU has been allocating funds for 3D technologies since as far back as 1984 under the first framework program (FP1), and the supranational organization's intention to continue financially supporting R&D is loud and clear under the current Horizon 2020 initiative (European Commission, 2015).

To sum up, the above discussion makes it apparent that 3D technology is growing in sophistication of capacity and simplicity of use, while its cost of production is decreasing dramatically. In addition, the growing numbers of stakeholders involved, along with the penetration of various industries, allude to the fact that 3D printing has the characteristics of a disruptive innovation.

The aforementioned claim can further be substantiated by the Hype Cycle, developed by the consultancy firm Gartner (2014). Specifically, for additive manufacturing advancements, the Hype Cycle shows that 3D bioprinting systems, consumer 3D printing, enterprise 3D printing and 3D scanners are all making remarkable progress. Furthermore, with the chart predicting how many years it will take certain innovations to progress, the plateaus of these four 3D printing developments are estimated to be 2 to 10 years away (*Divining Reality*, 2014).

Figure 5. The 2014 Gartner Hype Cycle Chart (source: Gartner, 2014b)



How can higher education and 3D mutually reinforce each other's development?

In addition to the economic development and the evolution of 3D printing that were described above, the *Austrian Research and Technology Report 2013* contends that this field of innovation will probably contribute to the initiation and advancement of the so-called "Third Industrial Revolution" (Federal Ministry [BMWF] et al. 2013), which could also lead to a (relatively) small comeback of industrial production processes in Organisation for Economic Co-operation and Development (OECD) countries.

Therefore, large corporations that are key players in the industrial sector must adapt to this disruptive technology, remain at the forefront of its development, and not lose connections with start-ups companies. One can argue that universities face the same challenges.

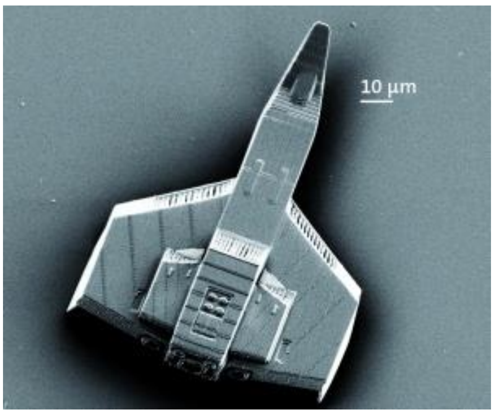
Moreover, 3D printing is seen as a full democratization of the production process. It is characterized as a digital fabrication revolution because it leads to grass-roots manufacturing—generally speaking—that can be applied anytime and anywhere by anybody. For example, there is even the possibility to purchase and assemble one's own 3D printer at home (see section 2). In the end, the consequence of this is democratization of innovation with more power and opportunities for consumers (van Lambalgen et al. 2012, p. 6; Bass 2014; BMWF et al. 2013, p. 10 and p. 85; Universität Liechtenstein 2014; Tietze 2014; MacDonald 2012, Ranaldi 2014, p. 1).

But more specifically, how is this technology used concretely in higher education and what implications does it have? In the higher education sector one can observe examples of its remarkable application across various disciplines and departments - from libraries and research groups to the disciplines of fine arts and mechanical engineering (Nicholls 2014).

Accordingly, this section provides an overview of the applications of 3D printing at universities. This encompasses a broad range of activities from educating pupils in high schools, to new teaching and learning methods, educational outreach, research projects and spin-offs.

To start with technology transfer, in the year 2007 at the Karlsruhe Institute of Technology (KIT), a spin-off was created to facilitate printing in micro- and nano-format. This creation followed the research that had been carried out since 2001 at KIT. It will also create the world's fastest 3D printer (effective date 2013). The following picture shows one of the smallest three-dimensional objects, namely a spaceship in nano-format (10 µm is smaller than the diameter of a human hair, see figure 6). By using this technology, micro- and nano-sized objects can be produced, which can then be used in optics, medicine, fluidics, electronics, and mechanics (KIT 2013; Nanoscribe 2014a; b).

Figure 6. 3D printed spaceship in nanoformat (source: KIT 2013)



Additionally, new possibilities for teaching and learning methods arise at universities, e. g. students that print out molecules to visualize difficult structures. By doing so, it also makes it easier to communicate structures to non-experts. At the same time, materials that would be usually unavailable in a university setting, or would be too fragile or expensive, like ancient artefacts such as Egyptian vases, can be shown to students (Nicholls 2014; Johnson et al. 2014, p. 40f; Johnson et al. 2013, p. 29; Donau-Universität Krems 2012a).

Furthermore, through online platforms that enable crowd sourcing such as innocentive.org, 3D printing competitions are emerged (Leitner 2014). Open calls to the wider public are also posted, which are similar to crowd sourcing; e. g. Government 2027 is a competition at the Danube University Krems in Austria to predict the future government usage of smart technology, such as the use of 3D printing to simplify government solutions, the production of driver's licenses for instance (Futurezone 2012).

Another interesting research project is a bionic bra that is developed at the University of Wollongong in Australia. This is a bra which contains sensing technologies, and the production process is facilitated through 3D printing (Australian Research Council, 2014). Furthermore, at the newly established Health Lab of the University of Applied Sciences Krems, research on health issues is carried out by professors and students; including 3D printing approaches in future health solutions (IMC FH Krems, 2014), such as assistance for elderly people (Fraunhofer-Allianz 2014).

By extension, some experts argue that the implementation of 3D printing should already take place in high schools. There are projects that exemplify this, for instance pupils that create a model of a whole city by using additive manufacturing. This type of secondary school environment is being described more and more these days with the catch phrase "educate to innovate". At the Danube University Krems research is also carried out in the field of 3D printing, for example in designing teeth components by using 3D printers (part of medical printing; for bioprinting see section 5). (Donau-Universität Krems 2012b p. 11; Donau-Universität Krems, 2013a, p. 1; Donau-Universität Krems 2013b; Donau-Universität Krems 2014, p. 14).

The whole process enables new possibilities for students and community engagement. To illustrate, the "Carleton University Discovery Centre 3-D Printing" in Canada allows students to print their own projects (Carleton University 2014). Moreover, in academic libraries this kind of service is already offered to users. These institutions provide the technology and community members can use it to print out their own projects (Nicholls, 2014). This is also the concept of fab labs (fabrication laboratories) for public use, which is seen as a type of educational outreach of universities (The International Fab 2014).

Nevertheless, sustainability should always be taken into account. This means that material should not be wasted for creating useless products (Tietze 2014) - although failure is part of the innovation process (Lutz, 2014, p. 59) and is therefore not seen as something negative. There are even 3D printers that only use waste materials to foster recycling and reuse. One also has to read the literature critically because a lot of revolution hype comes from the 3D printing industry itself. As some technology experts (Leitner 2012; Leitner et al. 2012; Johnson et al. 2014; Johnson et al. 2013; Bass 2014) suggest, despite the fast development and the endless possibilities, one has to be reserved about the future.

There are indicators that suggest 3D printing technologies, HEIs, and the open innovation movement will remain inextricably intertwined in the decades to come. However, before this point can be made, it is first necessary to establish some theoretical background information. Namely, how universities have become drivers of innovation, and defined the open innovation paradigm in particular.

With the rise of entrepreneurial universities in the second half of the 20th century, HEIs are continuing to position themselves as leaders of innovation. Etzkowitz (2003) describes this role within his Triple Helix model as it applies to the university-industry-government relationship. In short, Etzkowitz states that universities are moving passed being merely "a support structure for innovation" to increasingly become sources of innovation in cooperation with corporate firms and government research institutes (2003, p. 294). While HEIs still serve as intellectual feeders, they are also showing proficiency in spurring technology firms' research and development (R&D) along with policy formation at the local and national levels.

To be more specific, Etzkowitz outlines reasons why universities hold equal standing in the Triple Helix model. One may even say that universities have preeminent status in certain partnership arrangements, with industry and government becoming heavily reliant upon HEIs. First is that universities have a greater “flow-through” of knowledge than public research institutes or corporate laboratories (2003, p. 324). HEIs also have a revolving door of young minds that bring fresh ideas through reciprocally inspiring interactions with older students and professors. Correspondingly, spin-off companies from academic research groups have the added benefit of access to student labourers and faculty consultations. In this regard, universities act as “natural incubators” with flexible physical resources in addition to the human resources and intellectual knowledge that they provide (2013, p. 325). Ultimately, the HEIs that perform such functions assume a central role in collaborations with industry and government.

Subsequently, open innovation is a relatively new paradigm that has been gaining momentum in higher education and business sectors. First coining the term in 2003, Chesbrough describes open innovation as "the use of purposive inflows and outflows of knowledge to accelerate internal innovation and expand the markets for external use of innovation, respectively" (Teece 2006; Chesbrough 2006, p. 1). In other words, open innovation recognizes the importance of utilizing resources from both inside and outside the firm. It also allows for projects to start, enter, and/or go to market throughout the innovation process. This is in stark contrast to traditionally closed modes of innovation where knowledge and products are developed internally with projects originating in R&D departments and then selectively distributed to market by the firm in a highly protected manner.

So, how are HEIs acting as drivers of open innovation for 3D printing? Generally speaking, one only has to look as far as MIT’s OpenCourseWare or the rapidly growing list of spin-off companies that universities have launched, with the US and Europe leading the charge. Additionally, examples given in the previous sections of this paper are certainly illustrative starting points within the specific context of 3D printing. Other notable instances include University of California Fresno students developing a 3D printed prosthetic arm and making the blueprint available online for free download (Gonzalez Kotala 2014). Another is the partnership between the University of Louisville and General Electric subsidiarity FirstBuild for open innovations in 3D printing manufacturing (Karman III 2014).

These are just a few indicators as to why the future of 3D printing is tied to higher education and open innovation.

What legal and ethical challenges do HEIs and 3D printing face?

There is no denying that 3D printing has made some awe-inspiring contributions to society. Nor can its enormous potential for even greater innovations be ignored. However, it is also imperative to consider the dangers and legal ramifications of additive manufacturing. Akin to the disruptive technologies that came before it, 3D printing could result in disastrous consequences if left unchecked. This is to say that the policy implications of additive manufacturing must be examined.

Take the automobile for example. After its arrival on the scene in the early 20th century, it was widely praised as an invention that would change the world for the better. Granted that there were critics of the automobile since day one, but their voices were initially drowned out by the growth in popularity that the “horseless carriage” was receiving. Nonetheless, the legal challenges involving the automobile quickly became apparent and have gathered in greater numbers over the past 100 years: tort law for defective car parts that results in customer injury or death, punishments for driving while intoxicated, environmental pollution concerns, and the list goes on.

While not all the issues involving automobiles are applicable to additive manufacturing, they still serve as omens that the perils of disruptive technologies must be taken seriously. As 3D printing enters its maturing phase, it is important to note that legal precedents governing additive manufacturing are basically non-existent with the downstream impact of 3D printing being difficult to fully predict. Fortunately, there are experts who have begun speculating, with public safety, liability, and intellectual property rights being major areas of legal interest.

A major argument against 3D printing is the dual use dilemma. This is the philosophical perspective that a scientific discovery has the capacity to be used for both virtuous and destructive purposes. With additive manufacturing, one technology that has especially caused controversy in the past couple of years is bio printing. With many experts from around the world devoted to this particular field of research and innovation, it has been the centre of attention (Australian Research Council 2014; Koch et al. 2009, p. 853;

Gartner 2014a; Medizin 2014; Christen 2014, p. 3; Ranaldi 2014, p. 2). The following quote is illustrative: “The issue will trigger a major debate on ethics and regulation, Gartner has predicted, possibly sparking calls to ban the use of 3D printing for human and nonhuman use by 2016” (Christen 2014, p. 3). Important questions include but are not limited to quality assurance of these printed medical products, e.g. the assurance of preparing pure and non-contaminated cells. It is therefore important to rely on the research ethics committees at universities and research centres to check and approve such research projects.

Another equally controversial issue is the ability to make weapons such as plastic guns that can avoid metal detectors and other security measures. Because individual consumers can print them in the privacy of their own home, these firearms also have no serial numbers. They thus exist outside national tracking systems. In the US, Congress has responded with legislation that aims to prevent the 3D printing of guns, but arguments can be made and there are still loopholes in the laws (Wagstaff 2013).

Thirdly, yet another worry that will grow in strength as the technology develops for printing multi-material products is the potential harm of unrecognizable chemical substances. Pharmaceuticals are of interest in this regard, especially with the exorbitant cost of brand name medications likely to motivate some consumers to make their own generic drugs. The problem with these in-home factories is that miscalculations when printing the chemical compounds have the risk of leading to accidental poisoning or overdoses. Meanwhile, emergency response professionals use a pharmacological classification system that categorizes drugs and household substances. If a person ingests a new chemical mixture that is not in their database, then it becomes harder for medics and physicians to administer the appropriate treatment and save lives.

Returning to the topic of tort law, additive manufacturing opens a vast legal arena for liability cases where a 3D printed product causes injury, whether it be physical, emotional, economic, etc. Envision a situation where a defective part in a particular refrigerator model catches fire and damages many customers’ homes. The appliance manufacturing company would be at fault and have to pay compensation. Now picture a scenario where a 3D printing designer creates a blueprint for the same part in the refrigerator model and makes it available for free online. Then, a person downloads the part, prints it, and then installs it in their refrigerator. If the part malfunctions and bursts into flames, who would be to blame? The refrigerator owner, the author of the 3D printing blueprint, or the appliance manufacture? While opinions could be given for or against any of the mentioned parties depending on closer inspection of the situation, this hypothetical case shows the legal complexities that are involved in additive manufacturing.

Lastly, there is the issue of intellectual property (IP) as it pertains to 3D designs and printed objects. As Lipson and Kurman remind us, IP law is “a sword that cuts both ways” (2013, p. 226). Large businesses defend IP as a means of ensuring that they get returns on their research and development investments, while independent inventors or artists also benefit in receiving payment from people and companies that use their works. However, corporations can also be protectionist with IP by blocking the spread of their products as a means of eliminating competitors and keeping prices high. The lone inventor or artist could fall victim to having their ideas modified just enough and then sold for less, which would then take away their market niche. All in all, additive manufacturing inevitably involves discussions about how it will affect copyrights, trademarks and patents when mass production methods are coupled with empowered consumers that can print anything from the privacy of their own home.

The future of 3D printing

As shown, 3D printing is no longer science fiction. Additive manufacturing is a maturing technological breakthrough with various examples as to how it is being applied in higher education settings. 3D printing also has important implications for science and technology studies that are being considered by great intellectual minds across disciplines.

Meanwhile, the industry is certainly not without its critics who claim that 3D printing is a gimmick, overhyped, and a passing fad (Mims 2012; Blum 2013; Silverberg 2014). However, there are also advocates like the New Media Consortium whose annual *Horizon Reports* have changed their estimation about 3D printing’s time-to-adoption for educational purposes from five years to now as little as two years away (Johnson et al. 2013; Johnson et al., 2014). Consumer confidence from rising stock prices and increased sales is another indicator that 3D printing is manifesting itself and in all likelihood is here to stay for at least the foreseeable future (3D printing 2013; Lipson and Kurman, 2013; Hern, 2014). Therefore, the question now is what will the 3D printing of tomorrow look like? The future is certainly wide open with additive manufacturing being a frontier of endless possibilities.

In *Fabricated: The New World of 3D Printing*, Lipson and Kurman (2013) share the story of 3D printing's accomplishments while giving a glimpse into what the future holds for the innovative technology. By analysing past developments, recent advances, and cutting-edge areas of study, they determine one overarching trend, which is that the usability of 3D printing will continue to be simplified. Scientists and technicians are seeking ways to make 3D printing more intuitive, enjoyable and affordable for everyday consumers, while still expanding the range of its manufacturing capabilities. To achieve these ends, Lipson and Kurman (2013) identify a number of progressive areas for 3D printing. They do this by mapping the evolutionary journey in what they call "the three episodes of 3D printing" (p. 265). This is also in line with the 2014 Gartner Hype Cycle Chart plateaus for 3D printing technologies mentioned in section 3.

The first episode — and one that is still being improved upon today — is mastering the command over physical matter. While additive manufacturing technology began with plastics as the medium of construction, 3D printers today can now build with nearly any kind of material from glass, metals to various foods and even living cells. This is turning mass manufacturing into mass customization, where designers from all walks of life are making original products with greater creativity.

The second milestone is still in its initial phases. This is the ability to manipulate the compositions of matter by shaping the internal structure of materials. In this way, 3D printing technology will blend multiple raw materials at nanoscale simultaneously to create new microcomposites that perform better than the materials available today. For example, taking two weaker or fragile materials such as glass or wood and then printing them in a complex pattern that makes them stronger than steel. Scientists will also be able to discover completely new synthetic compounds with greater ease.

Then, the third era of 3D printing is when humans will have control over the behaviour of fabricated objects. Beyond moulding the shape of products and widening the possibilities of their composition, the future of 3D printing is the ability to program how products function after they are created. One case in point is the development of self-healing materials. To illustrate, picture a world where all new cars are equipped with bumpers that absorb and redirect energy upon impact while then returning to their original shape no matter how destructive the accident is. Current developments suggest that this reality is not far off from today as again identified in Figure 5 Gartner Hype Cycle Chart in section 3.

How will these 3D printing achievements be actualized in the future? One driver is the incorporation of artificial intelligence to create smarter 3D printers. At present, nearly all replicator devices are limited to being only able to make exactly what they are instructed. The next step would be encoding competencies to locate design flaws and assist designers with solving these problems. This would create a form of "interactive evolution", whereby the designer and the printer brainstorm ideas together (Lipson and Kurman 2013, p. 249). Printers would also be able to adapt and correct when they sense malformations developing in an object as it is being printed.

To a greater extent, experts predict that 3D printing will be central to the ultimate level of creation—machines creating machines. Hints of this are already being seen with such technologies as RepRap 3D printers that include blueprints for fabricating their own replacement parts (Tiefenbacher, 2012; Lipson and Kurman, 2013). Generations of machines to follow will design, build, repair, adapt, and recycle other machines along with their own self-replicating features (Lipson and Kurman, 2013). 3D printers that can construct multimaterial integrated systems will accelerate this advancement, such as being able to print electronic parts that have internal wiring already in place. While this level of sophistication is still being developed, it is only a matter of time before multimaterial integrated system products will "stroll out of the printer" (2013, p. 266).

Similarly, another route that 3D printers will take is "reactive blueprints" that adjust to the environment in real time (2013, p. 257). This dynamic and responsive form of 3D printing allows for changes that were not or could not be predicted during the initial blueprint design. This includes post-design alterations based on the specific circumstances surrounding the print job. For instance, "a house that needs to adapt to a yet unknown terrain, a bridge that needs to adapt to wind conditions, or a lampshade that needs to compensate for particular ambient lighting conditions" (2013, p. 258). This is a design space where passive parts and active systems meet.

At the moment, the range of possibilities for 3D printing is limited to humans' ability to express their imagination. As the additive manufacturing's audience becomes wider and wider, innovations will make even greater leaps and bounds. What is needed is new design implements that allow people to better convey their creative ideas. 3D printing mechanisms that are more responsive to touch and body movements will make it easier to build products with greater complexity and precision, which will then inspire new generations of products. As characterized by West, Vanhaverbeke, and Chesbrough (2006), this process is akin to planting the "seed corn for future innovations" (p. 290).

Conclusion

In conclusion, concrete examples given throughout this paper reveal the fact that 3D printing is essentially characteristic of a true disruptive innovation. What is more, it is an emerging technology that is growing in sophistication and industrial reach at unprecedented rates. Meanwhile, its production costs are rapidly on the decline. The reason for this is that additive manufacturing is receiving greater attention and investment from key stakeholders at national and supranational levels. All of these trends indicate that 3D printing has and will continue to transform society as we know it.

However, 3D printing is not without its limitations and critics. As often is the case with disruptive innovations, 3D printing requires small incremental improvements before the technology attains full maturity and bring an upswing in the global economy. Similarly, there is a lot of scepticism surrounding the ethical and responsible use of the technology as current government regulations are ill-equipped for addressing the various complications that 3D printing brings from scientific ethics to an array of legal dilemmas. As such, there is no doubt that it will take a concerted effort on the part of all three members of the Triple Helix.

Nonetheless, what roles must HEIs play in this Brave New World of 3D printing? The following are five foundational recommendations: For starters, section 4 shows how 3D printing has entered classrooms in primary and secondary schools. Additive manufacturing must continue to reach children before they get to college or university. This is essential to help prepare pupils for more technologically-advanced modes of higher education. It will also inspire them to be innovative in their daily lives regarding their learning and personal development, and not limited to classroom settings. In turn, as children become more passionate about science and technology, this will reverse the declining rate of students who major in these areas of study. One way that colleges and universities can assist in this form of bottom-up transformation is by supporting 3D printing projects at local elementary and high schools. Teacher training programs could also build in modules about using 3D printing in the classroom to teach children from an "educate to innovate" perspective as discussed above.

In addition, section 4 also gave examples of how 3D printing is being used in higher education settings. Institutions should continue working towards integrating 3D printing into classrooms across disciplines, broadening the technology's use further than the fields of engineering, science, and medicine. All current and future postsecondary students will benefit from learning how to use 3D printing if it is built into required courses for every degree path. This comes from the point of view that it is colleges' and universities' responsibility to prepare their graduates for the present age of rapidly changing technologies. Initially, this could take place in the form of free workshops under the guidance of trained lecturers and technical staff. However, the final aim must be to incorporate introductory 3D printing courses as general education requirements for all degree programs.

Correspondingly, colleges and universities must strive to build a culture of 3D printing innovation that extends to all corners of the campus. Beyond 3D printing technology courses themselves, professors in every department should seek to find ways of including additive manufacturing theories and practices in their classes. For instance, as mentioned in section 4, librarians could also take the lead by offering a 3D printer for public use that is open to the community. Meanwhile, administrators must work to use 3D printing for daily campus operations. It could begin with products as simple as those that are already being seen today, such as 3D printed lab equipment or replacement parts for various machines.

Fourth, section 4 emphasizes how HEIs can support the spread of 3D printing both for corporate and personal use with further contributions to the open innovation movement. Inspired by the open courseware and massive open online course revolutions, additive manufacturing would benefit from a coordinated higher education effort that fosters the creation of 3D blueprints and collects them in an online database that is free for everyone to share. Similar to websites such as MakerBot's Thingiverse.com, but that galvanizes more scholars to join the effort, with peer-review methods working to maintain minimum standards of quality assurance.

Finally, accomplishing the above tasks will not be possible unless colleges and universities continue to strengthen their partnerships with the other two branches of the Triple Helix. Further collaborations must be built between HEIs, industrial leaders, and government agencies towards additive manufacturing technology to even greater heights. Moreover, while research and development projects are essential undertakings, academia must also further scholarship on technical assessment for ethical uses and legalities of 3D printing. With innovations arising on a daily basis, this is an endless endeavour.

All things considered, additive manufacturing is here and it is here to stay. It is up to higher education leaders to usher in its full integration, extending from their campuses to the local community, the nation, the region, and the entire world - at what speed and to what end still remains to be seen. Nevertheless, if the heart-warming stories of 3D printing's past achievements are any indication, the future will be home to wonders beyond humankind's most fascinating dreams.

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