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3 hard realities for 3D printing

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Abstract: The enthusiasm for 3D printing is quickly spreading around the world. Technological advances in 3D printing and other techniques initially intended for rapid prototyping make it possible to produce sophisticated parts with relatively simple means. While it gives people the possibility to fabricate sophisticated (mostly) plastic objects by themselves, it comes with challenges and considerable drawbacks. 3D printers using recycled materials are still an exotic minority, and the rubbish island swimming in the Oceans is growing fast. Being able to produce almost anything anywhere and at any time will lead to changes in the way industrial manufacturing and supply chains work – reducing transportation but also efficiency. People will increasingly produce things at home or in local manufacturing communities, using both original and self-made designs. This has implications for the environment, intellectual property laws, the economy and other aspects like safety and security. Society and politicians must act before the problems get out of hand.

1 Introduction

With 3D printers becoming increasingly popular and versatile, it is time to think about the implications of personalised manufacturing, and how it may change the world we live in [14; 3; 17]. Manufacturing is not an isolated technological reality, but rather a network of interactions between engineering, society, economy and the environment.

Advantages of home manufacturing include the immediate availability of products or spare parts, the possibility of buying existing product designs online, personalising them, making them from scratch, or exchanging and discussing them with peers. From this perspective, additive manufacturing could be seen as counteracting globalisation; people would return to making many things locally, rather than buying them from far-away industry.

Ideally, undesired products could be recycled and the primary material reused for new designs. Current technology does not allow this yet, but it is certainly one of the issues to address, or else we are heading for an ecological disaster with plastic rubbish clogging lakes and oceans. One of the challenges with recycling will be how to separate different materials from each other when they were mixed in the printing process, and how to assure sufficient purity to guarantee the desired material properties.

These challenges are represented in Figure 1, together with two other hard realities for additive manufacturing and the topics they concern, namely ‘safety and security’ as well as ‘economy and innovation’. Each of these identified realities cover a number of different but related topics, with some overlaps as well. As it is, technological aspects always come together with social dimensions, as technology is made and used by and for humans, and human behaviour is influenced and often enabled by technology. The emergence of additive manufacturing as a common technology must therefore be considered and analysed as a **socio-technical system** [10]. Additionally, all considered aspects are relevant to legality, as most countries have laws concerning them.

For instance, companies and researchers making such 3D printing / home manufacturing available to a large public carry a responsibility of which they are today largely unaware. But then, it may be society who needs to address the issue, as the creators of novel technologies are probably unable to deal with their implications. Society needs to find ways to deal with the crimes associated with new technologies, be it the home fabrication of weapons or chemicals and drugs made with the help of 3D printers [11]. A new framework of regulations will be needed to deal with these new technologies, and society is going to appreciate them for their beneficial effect: freedom is positive, but it needs boundaries.

The core contribution of this paper is to clearly identify the set of challenges and dangers that come with emerging individualised manufacturing technology, and to act as a warning message that we might be running into problems unless measures are taken.

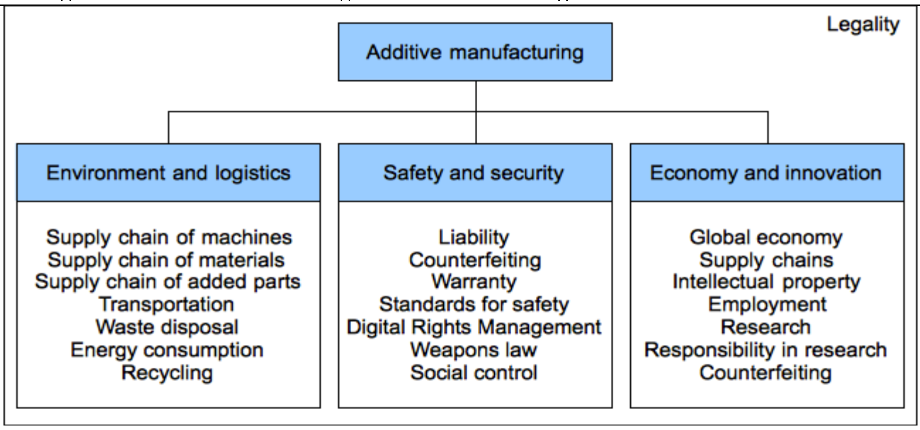

Figure 1: Three hard realities for additive manufacturing and the topics they concern

2 Technological advances in Additive Manufacturing

First forms of 3D printing were developed in the 1970s, and have become much more sophisticated ever since. The American Society for Testing and Materials (ASTM) group F42 discerns seven types: sheet lamination, vat photo-polymerisation, material jetting, binder jetting, material extrusion (often called Fusion Deposition Modelling – FMD), powder bed fusion, and directed energy deposition. For FDM, the most commonly used materials are thermoplastics (rigid or elastic) and metal alloys, but also ceramics, gypsum, plaster, wax, food and even living cells can be printed. Especially with material jetting, materials may be mixed; the transition from one material to another may be graded, random or following an elaborate microscopic pattern [14]. A further advantage is that three dimensional objects can be scanned with touch-less optical methods using suitable image integration methods [16] and replicated by additive manufacturing.

Modern **additive manufacturing technologies** [24] combine multiple materials and functions in a single manufacturing process that incrementally adds materials to build the desired structure as well as optical and electrical properties. The 3D printing of plastics is closest to ink printing as we know it, and it is also best suited for home applications. Materials like metals or ceramics come with more stringent requirements on technology due to high melting temperatures or the need to cure them in a kiln.

The applications of 3D printing technologies are widespread across numerous domains and there are almost no limitations. The currently available resolution of professional 3D printers goes down to a few micrometers, both in printed layer thickness and X-Y resolution. Household versions are cheaper and lower in resolution. While professional applications tend to require specialised computer aided design (CAD) models to print from, household applications run with simplified software, and designs are often publicly shared.

Different from other manufacturing techniques, 3D printing does neither require the creation of moulds nor any drilling, milling or turning. This implies that the production of individual parts comes at a low cost that is impossible to achieve through other manufacturing methods. As long as there is a 3D printer and a CAD model to serve as a blueprint, parts can be produced when and where required, independent from any other manufacturing facilities, enabling the Cloud Manufacturing approach [12]. This can be particularly useful in remote military operations or crisis situations when replacement parts are needed. Another advantage of 3D printing is the possibility to create complicated parts in one piece instead of having to compose them from several parts. Also, parts can be made inside other parts or be interlocked with each other; all features that are impossible to achieve with other manufacturing methods. For instance, concentric spheres can be printed in one process, one piece each. Even entire buildings can be 3D printed, including electrical connections and plumbing. When considering how to build a base on the moon, this is a solution with considerable advantages [8]: it takes lunar materials as a primary material for 90% of the structures.

Two **approaches to 3D design** exist [14]: One is Solid Modelling based on a ready-made collection of shapes (cylinders, rectangles, etc). This approach originated from engineering and computer aided design. The other is Surface Modelling / Polygonal Modelling and is based on free-form shapes, which means digitally wrapping shapes in a virtual fishing net. This approach originated from cartoons and video games and is unable to describe an object's inside.

The current industry standard for **3D printing files** is STL (Standard Tessellation Language, created in 1980s) uses a surface mesh of small interlocked polygons to describe an object; the printer's firmware then slices up the mesh to create printable layers. The new standard AMF (Additive Manufacturing Format) can handle different colours, materials, lattices and other internal structures. It uses curved instead of flat polygons for surface meshes [14].

However, the transformation of a 2D design like computer animated graphics or hand sketches into a printable 3D design is still not straight forward. Articulations and other movable joints are difficult to design for a layman. Software using surface meshes may serve as a basis for creating viable 3D shapes including kinematic components [2]. It adds ball-and-socket or hinge joint parts.

In terms of **recycling**, the Filabot[1] recycles a variety of plastic materials. The materials are shredded, molten and then used as printing filament. The process can be repeated several times. However, assuring certain material properties with a varying material mix is challenging. Apart from discarded plastic providing free primary materials, this approach also makes recycling a local instead of global affair; there is no need for transportation [19]. An additional effect of being able to fabricate customised parts is the possibility for people to replace broken components and thus repair their things instead of throwing them away.

Challenges in additive manufacturing identified by the Engineering and Physical Sciences Research Council (EPSRC), UK, include the use of biodegradable and functionalised materials (e.g. conductors and dielectrics), improving speed, resolution and repeatability of the printing process, as well as the development of polymerised structures for sensing applications at nano-scale. Furthermore, more capable design software is required to make full use of the possibilities offered by 3D printing [14].

2.1 Key applications of 3D printing

A simple yet promising application of 3D bioprinting is the deposition of cultivated cells on a wound [1], similar to skin grafting. 3D printing only needs a few cells from the patient, as they can multiply *in vitro*, whereas skin grafting requires the extraction of healthy skin tissue as large as the wound to cover.

A more advanced application of 3D printing is the creation of customised implants. This is often a three-step approach: the first is to acquire 3D imaging data (CT, MRI) of the body part in question; the second step is image post-processing using biomechanical models; and the third step is the 3D printing of the implant (or organ) to be investigated [18]. This approach allows surgeons to individually design implants and protheses rather than to use standard versions, and to have the personalised parts produced quickly and at low cost [22]. The printing resolution is fine enough to eliminate the need for polishing the implant surfaces; hence production cost are further reduced.

Printing organs like kidneys or heart valves is a much more complex application [15; 20; 1], also called computer-aided tissue engineering (among other terms) may in the future help mitigate the scarcity of organs for transplants. The cells are printed on a gel base or scaffold which allows them to grow and develop. However, printed cells tend to migrate and rearrange themselves, potentially out of the intended shape. This is why further research is needed to investigate the principles of predictable and adequate self-deformation, self-remodeling and self-organisation of printed cells [21]. The main problems with printed organs are currently their lack of resistance to mechanical stress and the absence of vascularisation to nurture the cells [14]. While printed organs are not ready to be implanted yet, they are used for repeatable research on complex tissues such as lungs. 3D printing allows researchers to reproduce any number of identical organs by printing reproduced lung cells into defined shapes [6]. Specialised printers like the BioFactory[2] generate 3D constructs of cells, proteins and extracellular matrices.
Printing replicas of natural foods like vegetables or meat is a similar challenge, whereas creating cookies is easier. Printers can use a variety of powders and liquids to create edible, nutritious and tasty foods while controlling their content [14]. Algae and insects could serve as ideal sources for the primary materials, as they are naturally abundant, consume little resources and could be sustainably cultivated. Due to the possibility to control the nutritional content of printed food, this technology might be ideal for people with special dietary requirements like diabetics. NASA is even investigating the application of 3D printing food for space missions[3].

3D printers can also be used to create small chemical reactors (a polymer gel called *Reactionware*[13]) for mixing substances handled by the printer [14]. This home chemistry factory could be used for personalised medicine [7], but also comes with considerable potential for criminal abuse [11]. Furthermore, Reactionware allows researchers to mix substances that are difficult to handle otherwise, and hence opens the door for creating new chemical compositions as well as the benefits and dangers they come with. *Tort law* untangles corporate responsibility for such technologies [14], but society must find new ways of dealing with their implications.

3 Hard reality one: Environment and logistics

One of the downsides of industrial manufacturing is the amount for **transportation**, which the current economic system heavily relies on. Due to cheaper production and assembly prices in some parts of the world - especially when manual labour is involved - parts and products often get shipped back and forth. While this may

[1] http://www.filabot.com
[2] http://www.regenhu.com
[3] http://www.nasa.gov/directorates/spacetech/home/feature_3d_food.html

make sense economically, it certainly does not ecologically. Any strategy to reduce transportation, including local and home manufacturing, would benefit the environment. Home manufacturing might bring some shortcuts, with only the primary materials needing to be prepared, packed and shipped to the clients, instead of all of these steps being necessary for parts, components and the final product as well. However, many products will still require additional parts made from other materials or with integrated electronics. This means that there will still be a **traditional supply chain** for those parts. Similarly, while some printers are self-replicable to a certain degree (e.g. RepRap), most printers will not be made locally but shipped from factories.

Another aspect is the need for **energy** while operating. If a 3D printer is powered for an hour although the actual printing only takes 10min, valuable energy is wasted. This may not make a big difference for each household, but the cumulated wasted energy in an entire city will. Industrial production may be more efficient in this aspect, as there would be only one machine producing many products. Local printing shops might offer a good compromise, possibly offering additive and subtractive manufacturing processes depending on what is more sustainable for the parts to be made [24].

Additive manufacturing needs to come with **recycling** solutions. People may be led to print several versions of their product, until it takes the desired shape, and the used material as well as discarded products should not go to waste but be fed back into the cycle to avoid adding to the plastic particles floating in the oceans [14]. Materials should either be biodegradable or printers should operate with shredded or melted recycled plastic, like the Filabot produces. Depending on the recycling solution that can be found, also discarded materials might need to be collected and treated. Ideally, unused or broken parts would be melted and reused at home. If this turns out not to be practicable for technological or economical reasons, then solutions with the providers of the primary materials will need to be found.

A possible solution for their supply and recycling might be to establish local material centers in proximity of the village printing shops. These centers would both supply people with a variety of fresh materials and collect unused or discarded materials for recycling. People returning their printing waste would be credited points which could be used for buying supplies. Recycling centers would melt or crush and shred the returned materials, purify them and make them ready for resale. With the recycling system improving and growing, the need to ship new materials in would decrease and a local ecosystem could be established. The environment would benefit from less transportation and less waste, and people would benefit from the local business and the **reinforced local community**.

4 Hard reality two: Safety and security

Most products need to conform with laws and **legal standards for safety**, which are often specific to certain countries. With the changeability of products through individualised manufacturing, the question arises if the self-made products still need to conform with the law, or if they will be exempt, and under which conditions. Again, with no manufacturing company taking responsibility, it becomes close to impossible to verify if products comply with rules or not.

Often, a certain design has multiple reasons to be the way it is. For instance, if we could home manufacture a steering wheel, somebody might be tempted to make a triangular instead of circular design. However, a triangular shape would drastically increase the risks of severe injury in case of a car collision. While in this example, the designer puts mainly himself at risk, changing external parts might put other people at risk. An industry-made car fender will correspond to standards which reduce the severity of the injuries a pedestrian is likely to suffer in case of a collision with the car. With a home-made fender, this may not be the case at all. For one, this may endanger pedestrians, and for the other, insurance companies may refuse to pay for damage done by a dangerous fender. The implications of this are manifold.

A possible solution to this problem could be to include the sale of designs with a limited range of changeability with a primary material cartridge (similar to ink cartridges, but they come with problems as well: genuine cartridges are expensive and only available in certain shops; compatible cartridges by other suppliers are cheaper and available on the internet, but then, the printers may reject them or get clogged). To limit design changeability, companies could sell design blueprints where only certain parameters can be changed within a certain range, or a certain relation to each other [4; 5]. Allowing users to make such changes while guaranteeing product safety, however, will doubtlessly lead to additional costs for product designers. It remains open if this could be economically viable.

Additionally, it is often a lengthy and costly procedure for **safety-critical products** to get approved by legal authorities. With user-changeable blueprints, this will get even worse or even impossible for design companies to achieve. Also, individual users designing their own products will probably never even attempt to get approval. The question is, why do products need to conform to laws or norms? Usually, it is about assuring certain safety standards. For instance, people trusting a nursery with their children want to be sure that their children are safe when playing with the provided toys. Hence the toys must conform with norms for toy safety. What if the nursery staff printed their own toys for the children to play with? Maybe the existing chairs are just a little too large for the space, and a narrower model could be printed to fit. How could it be assured that the modified design would still support the necessary weight, and who would be responsible?

One of the services which manufacturing companies traditionally provide is **liability**. They stand with their name for their products. People will buy a certain brand because they have experienced or heard that the products are of good quality and will withstand the stresses of intended use. Companies sell products which will fulfil certain functions for a certain time Ð thus the product warranty. If the product fails prematurely, the manufacturer will usually repair or replace the product. If the failure has drastic consequences, the manufacturer may even be sued in certain countries. When manufacturing at home, this liability most likely falls away. Even if a user buys a design file from a company, the company has only limited control over the design being used 'as-is', the composition of the material being suitable, and the manufacturing process executing properly.

One way for a manufacturing company to maintain a certain control over what is being produced at home - for instance, in case of delicate or critical products being made - is for the user to use sealed cartridges and to provide the company remote access to the home manufacturing facilities. A similar approach is chosen today when customers grant hotline staff of telecommunications companies remote access to their computers, for the company to install problematic software or rectify incorrect settings.

If we were to be allowed to change the design of cars and other potentially dangerous items, there would have to be rules to be followed, possibly enforced through **Digital Rights Management (DRM)** [14]. This means that a printer would only print items that have been paid for, or that respect certain rules. However, with technology advancing, also ways to hackers make progress. As with all technologies, DRM can be hacked or circumvented. Companies are increasingly likely to decline all responsibility, similarly to the way it is done with software nowadays [14]. Therefore, the drawbacks of individualised manufacturing include the lack of liability by a manufacturer, the risk of faulty designs and material weaknesses, etc. Intellectual property laws urgently need to change for them to be able to keep up with new technology and its implications [14].

The problem of **counterfeiting** is related. Technologies to certify physical products and virtual designs are becoming more elaborate, but ways to falsify and hack them are discovered just as fast, if not faster. The possibility to increasingly produce components locally might be of advantage when attempting to assure that all parts are genuine. It is probably easier to receive design files from trusted sources and print them out locally, than to ship parts all around the world hoping that they are not tinkered with.

Hence, other ways of enforcing certain ground rules for safety and security need to be found. How would violations be detected and sanctioned? In other words, how could society regulate its own behaviour?

Realistically looking designs for firearms to be 3D-printed have already appeared on the internet, and at first been banned by the community. While most of them may not be functional (yet), they certainly look very real. In a criminal context, carrying a realistic-looking gun is often enough to terrorise victims. Many countries have laws against people freely carrying firing weapons and require permits for them. 3D printed guns could be a very effective way around this. How would people even be able to discern a real gun from a printed one without a close-up inspection? Moreover, with technology progressing, the US government has already given a license to a private person 3D print functioning firearms and to sell them. It is only a question of time until they can be produced by everybody at home, not to speak of knives and other simpler weapons. This brings an additional level of complication to laws which control weapon possession, as it now also needs to control **weapon fabrication**. Protecting original designs from being accessible without payment or identity verification is challenging, but making sure certain individuals do not have access to any weapons-related designs - branded or open source - is almost impossible on a free market. This is already the case today (a quick search on the internet provides detailed instructions), but the difference is that nowadays it is not as easy to get access to the manufacturing equipment necessary to professionally forge firearms, whereas with advanced 3D printing, this is will be immediate. 3D printing will even allow people to make improved weapon designs which were impossible to fabricate with traditional methods. Home fabricated firearms may become a threat to national security, as it removes any barrier against cheap weapon production and unregulated procurement. Society will definitely need to evolve and find new ways to deal with public security.

Existing laws and regulations try to limit the access to weapons as a key to security. But it is a fact that the illegal business with weapons and war technology thrives. Making it possible for mentally healthy and equilibrated people to produce weapons is unlikely to pose a problem. The technology to produce powerful weapons anywhere and at any time in the hands of the mentally unstable and those with ill intentions, however, may exacerbate an already existing complex of problems. It currently seems close to impossible to make technologies inaccessible to criminal or terroristic groups. Society may have to deal with the fact that weapons will be ubiquitous, and need to find ways to protect people nevertheless. It will certainly require everybody's vigilance and collaboration; countries like UK have already started to request the population to keep their eyes open and to let the police know about suspicious activities. Engaging the crowds and giving them free access to technologies, too, may be the only way.

5 Hard reality three: Economy and innovation

Industrialisation has brought wealth to developing countries, but it also comes with many downsides and problems, for instance in a social and environmental context. Returning from a globalised to a more local manufacturing and economy might be a chance to return to a more sustainable world with more social equality. As discussed in the context of the environmental impact in section 3, individualised manufacturing will shorten and simplify certain **supply chains**. Eliminating intermediaries as well as reducing factories will eliminate certain jobs. However, just as with automation, this does not have to lead to unemployment, as other jobs will be created. Some of them will require special training, but others will be about the same as today. The home manufacturing machines will have to be produced, distributed, sold, serviced, repaired and recycled. The same also applies to the primary materials used in additive manufacturing.

The effect of such a new kind of manufacturing on **global economic situation** is difficult to predict at this speculative stage. However, it is certain that manufacturing would be transformed gradually, and society would adapt, like it adapted to increasing industrialisation. Additionally, it would probably never be possible to home manufacture all goods. Special facilities would always be needed for high precision, stringent specifications, dangerous materials, safety-critical products and systems (e.g. aircraft). These could, however, be produced in local manufacturing communities. Furthermore, local manufacturing shops might offer people customised service in collaboration with local experts. Manufacturing skills and facilities should be seen as a network acting at various levels and scales.

Nowadays, the most **fundamental research** is done at universities with government funding, but industry finances and executes a lot of the more applied research and development. This is driven by economic interest, as the companies want to gain advantages against competition on the market. If they lose the possibility of earning money with their innovations because people manufacture at home, they also lose their interest in research.

Solutions would have to be found for companies to sell licenses on their new product designs (see Digital Rights Management discussed in section 4). Nowadays, the licensing and copyrights of music, films and software are a rather leaky affair. A similar system for manufacturing designs might not be good enough to finance industrial research and innovation. However, a lot of open source software[4] has been written without a company's funding behind, and it still works. This mixed regime of protecting intellectual property and allowing people to contribute and change is likely to spread from software to manufacturing; an example is the open source 3D printer RepRap. Less intricate designs and smaller innovations might be achieved by individuals and then offered on the internet against a small fee, just as it is done with apps for smart phones. Furthermore, crowd funding might contribute to innovation requiring financial means. For bigger and more costly technologies, the issue may at least only arise later, when individualised manufacturing has gained maturity.

With the tendency for research to be done by independent individuals or consortia formed on a project basis, questions of **safety and responsibility in research** become an issue. For instance, industrial research centers or universities run chemical labs with stringent safety measures and can be held responsible if toxic or otherwise dangerous substances are accidentally released into the environment. But when people experiment with Reactionware at home, there are likely to be very few or no safety measures. Hazardous mixtures might be created without the user being aware of it. Both users and their environment could potentially be exposed to danger. Who might be responsible? The designer of the 3D printer, the designer of the Reactionware, the supplier of the chemical substances, the person divulging ideas about chemical reactions on the Internet, or the user doing the experiment? A lot of thinking needs to be done, hopefully before such technologies become mainstream commodities.

Last but not least, the problem with **counterfeiting** has mainly two aspects, both of which have economical consequences: withholding license payments from the designer / inventor, related to what was discussed above, and misguided trust in a product, related to safety and liability as explained above. The problem is basically the same, no matter if the product was manufactured in industry or at home, but the strategies to deal with it may differ. With industrial manufacturing, counterfeiting is illegal, and in many countries, selling and buying counterfeit products are as well. Nowadays, it is obvious to most people when they are offered a counterfeit product like a handbag because it is much cheaper than the original and it will be offered on the street or in a back-alley rather than a legitimate shop.

[4] An important distinction is to be made between free as in 'for zero price' and free as in 'with little or no restriction'. The former is often used for proprietary software that is distributed for free use, as it is often the case with basic versions of anti-virus programmes. The latter applies to open source software communities, where users are allowed and encouraged to contribute to the further development of the software with their own work.

The question is if the same would be true when just buying a design to fabricate at home. Would the buyer most often be aware of its authenticity (or lack thereof) and be able to take an informed decision? Being misled by a fake design sold under false pretense could have bad consequences for a consumer who relies on safety properties guaranteed by the rightful seller of the original design.

On the other hand, industrial counterfeiting is a major problem already today, as it often goes undetected. Especially Chinese companies are selling electronic components as 'new' whereas in reality, they are refurbished [9]. This induces great danger, as the parts are likely to be less reliable than newly manufactured ones. It also greatly damages the legitimate economy when IP laws are violated. Being able to produce the parts locally as and when required as well as within proper licensing conditions would eliminate this problem. It still implies, however, that such individualised manufacturing would have to come with some way of certifying original designs in a trustworthy way. New approaches to certifying the authenticity of a design or a finished product are required.

6 Application cases

The aspects discussed in the previous three sections are not of equal importance to any product. For instance, for a cooking spatula made from plastic, only a few aspects would matter:

• **Supply chain:** For a product consisting of a single part, the supply chain for industrial and individualised production is relatively similar, with the difference that in the former case, the primary material is shipped to the manufacturer who then ships the product to the distributors, who sell it to the consumer, whereas in the latter case, the primary material directly reaches the consumer, who fabricates the spatula locally.

• **Liability:** The manufacturer of a spatula will carry liability for two aspects: firstly, the material needs to be food safe and heat resistant, and secondly, the design needs to be robust enough as well as suitable for the intended purpose. This implies that it must not have sharp edges which might harm the users hand, and it must not crack under the expected utilisation force, taking into account the anisotropic mechanical properties often resulting from AM processes [23]. If the spatula is made at home, the user may either use a design of any origin, meaning that nobody carries any liability, or use a branded design. In this case, some way of assuring that the design is not unduly altered would be necessary in conjunction with a way to verify primary material properties (e.g. a sealed cartridge from the company selling the design). A related question would be if the user who printed the spatula at home could be held responsible if the spatula was given to a friend who then got hurt while using it.

• **Warranty:** The question of warranty is related to the one about liability. A manufacturer usually grants some warranty on the product sold, under the condition that it was used under proper conditions. With home manufacturing, this would only be possible with a branded design home fabricated under verified conditions.

• **Design IP:** A manufacturer is responsible for having the license to use a certain potentially branded design and to pay royalties. Distributors and consumers assume that the manufacturer assumes this responsibility, and customs offices may occasionally verify this. With a spatula made at home, it is the user's responsibility to either pay for a branded design or to potentially get it on an alternative way. Each customer using a branded design without paying royalties contributes a little damage to the economy.

• **Recycling:** Some councils now recycle plastic of several types and collect it together with PET bottles, but most traditionally fabricated spatulae are likely to end in the rubbish bin. If they were made from recyclable 3D printing material, it would be straight-forward to reuse it as spatulae are made from a single homogeneous material.

However, for a product like a firearm, there are many more implications. Table 1 compares the situations for an industry-made and a home-made gun.

	Industrially manufactured	**Home fabricated**
Machines supply chain	Several machines at the manufacturer's.	One local 3D printer.
Parts supply chain	Some parts may be produced elsewhere.	Depending on the design, a few externally produced parts may be needed or not.
Materials supply chain	Shipped to the manufacturing companies.	Shipped to the user.

Transportation	From manufacturer to distributors and dealers and finally to the customer.	None.
Disposal	Depending on the country, unwanted firearms may surrendered to police or officially deactivated and then destroyed	The question is if home manufactured firearms would be licensed in the first place; if this is not the case, their destruction will also go without paperwork.
Recycling	Firearms are typically made of metal, sometimes with components in plastics, wood and other materials. They can be recycled if separated and treated properly. Initiatives [5] for firearm recycling exist but are not very widespread.	Individualised manufacturing does not significantly change the recycling situation, apart from weapons to be more likely to be made from plastics, which are easier to print with simple means than metals.
Liability	Manufacturers are liable for malfunctions.	Difficult. It would require for the company which made the design to have means to assure that a sealed cartridge and original design files were used under correct conditions.
Warranty	Granted by manufacturers.	Difficult.
Counterfeiting	Fake components might lead to malfunctioning and potential danger.	Fake design plans might lead to malfunctioning and potential danger.
Weapons law	Licenses needed in most countries.	Difficult to enforce when design plans and manufacturing tools are openly accessible.
Social control	Some societies grant the right to carry firearms to citizens, others restrict it.	With firearms manufacturing becoming accessible to anybody, societies will need to find new ways of handling the increased danger.
Global economy	Firearms contribute to both local and global trade.	The business model would change. Manufacturers might sell designs instead of finished products, and local dealers might assist with fine-tuning rather than sales. Alternatively, they might also provide sealed cartridges for branded designs.
IP	The appropriation of designs only makes sense for people with professional manufacturing facilities.	Anybody could benefit from appropriating designs. With 3D scanner technology, the design files are not needed any more; they can be created from scans.
Employment	The entire firearms industry and supply chain benefits from firearm sales and employment is generated.	By short-cutting trade, some jobs are lost. However, material supplies as well as designs are still needed. Additionally, as the functioning of firearms is based on sensitive mechanisms, local specialists may still be needed for adjustments.
Research	The development of new models is supported by product sales.	The sales of designs and sealed cartridges is likely to be sufficient to support the development of new designs. It might, however, not be enough to fund research into radically new firearms technologies.

Table 1: Aspects of an industrially manufactured versus a home fabricated firearm

[5] e.g. http://www.collaborace.org/outreach/americas/arms-recycling

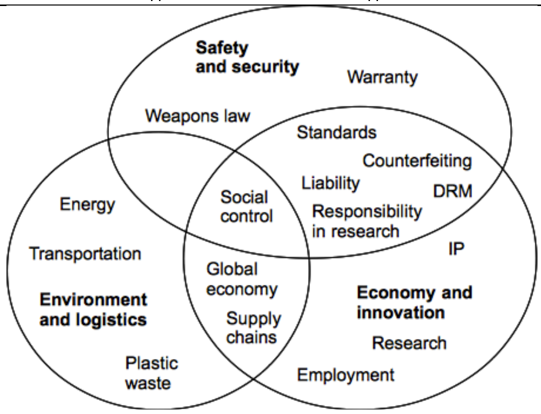

Figure 2: Critical aspects and their overlaps

7 Discussion

Similarly to how children grow up with computers nowadays and automatically become immersed in the technology, people will also get used to being able to make the parts they need in their households and daily lives. Instead of visiting shops in town to find the right product, people will browse the internet, download the desired design, and print it off using recycled plastic from discarded bottles. Sending design files around the world comes at close to no cost, whereas producing, shipping, storing and distributing products - some of which will never be sold - comes with a considerable carbon footprint.

The new trend towards home manufacturing may be considered as a development that goes back towards the production model that existed before industrialisation, when families produced goods like crockery and textiles at home or in their own workshop, when every village had their own blacksmith and carpenter. The main difference would be the new technologies which allow laymen to fabricate goods from synthetic materials and with simple means like an off-the-shelf 3D printer.

The basic idea, closest to 3D printing as we know it today, is a personal fabricator on a desk connected to a small tank feeding it raw materials and perhaps a few smaller bottles with additives. The user loads a design downloaded from the internet and then presses ‘print’, upon which the printer works for a while and then out pops a product from the flap on its front.

More advanced visions would include bigger manufacturing machines and networked devices, potentially shared between people in a community. Services could be mutually provided as and when desired, in exchange for either money, machine time, expertise or primary materials. People with expertise or specific additional skills may offer assistance to others, and manufacturing facilities may be shared locally.

The limits to the range of products that people could make are given through the availability of materials, production processes and printing facility scales, both upwards (meters and above) and downwards (micrometers and below). However, technology never ceases to evolve, and so will the home manufacturing capabilities.

Society is bound to change together with this new manufacturing paradigm. A new framework is required to deal with a multitude of critical aspects including intellectual rights as well as concerns for safety and security, at the level of individuals and communities of any scale. Figure 2 summarises them and shows some of the overlaps between the discussed topics; there may very well be more. This article reflected on the current state of technology, trends for the future, and the way society interacts with them.

Home manufacturing may be considered as a step towards a smart infrastructure for a more sustainable world, but it requires people making efforts in this direction [14]. Incentives should be created to encourage people to investigate biodegradable materials and recycling solutions. Policy makers should finally agree to raise the prices for fuel and thus transportation and wages should be more equilibrated throughout the world, the two of them making cheap manual labour at the other end of the world less appealing. A suitable approach needs to be found for Digital Rights Management, taking into account the many critical aspects including product liability and people’s individual striving for customisation of designs.

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