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Additive manufacturing as a socio-technical system

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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 objects by themselves, it comes with challenges and considerable drawbacks. 3D printers using recycled materials are still rare, and the rubbish island swimming in the Oceans is growing fast. Additive manufacturing leads to a change in the manufacturing world involving technology and society. With the integration of 3D scanning, virtual design worlds, and 3D printing, the separation between the physical and virtual worlds gradually vanishes. 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. This article analyses the trend towards personal manufacturing and its many implications. Sketching a socio-technical model of this emerging system, it makes preliminary recommendations for regulating policies.

Keywords: Socio-technical systems; Manufacturing; 3D printing; Sustainability; Recycling; Supply chain; Policy.

1 Introduction

With 3D printers becoming increasingly popular and versatile, it is time to think about the implications of personalised manufacturing at home, and how it may change the world we live in [?, ?, ?]. Manufacturing is not an isolated technological reality, but rather a network of interactions between engineering and technology, society and politics [?], 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 only allows this to a certain degree, and recycling remains 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 is 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.

One of the services which manufacturing companies traditionally provide is liability. They sell products which will fulfil certain functions for a certain time – 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. 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 [?].

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.

Possible solutions for manufacturers to still keep a certain product liability may 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 [?, ?]. 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.

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) [?]. This means that a printer would only print items that have been paid for, or that respect certain rules. However, with advances in technology, hackers will invariably make progress as well. 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?

Already today, there are designs for 3D printing guns on the internet. Whilst most of them have limited functionality, 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?

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 [?].

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. It also analyses the difference between a traditional supply chain and the one needed for individualised manufacturing.

Organisation of this article

Section 2 introduces related work. In Section 3, comparisons between traditional and personalised manufacturing are presented. Section 4 explains a possible approach to home manufacturing. Section 5 compares industrial production and home manufacturing using a case study product. A discussion on the viability of the considered solutions follow in Section 6, concluding this article.

2 Related work

A range of research areas are relevant to the subject of home manufacturing as a socio-technical and cyber-physical system, contributing to a more sustainable world.

2.1 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 [?]. A further advantage is that three dimensional objects can be scanned with non-contact optical methods and replicated by additive manufacturing, although this is more complicated regarding internal structures. A series of TED talks [?, ?, ?, ?, ?, ?, ?] shed light on various aspects of 3D printing, from miniaturisation to criminality.

Modern *additive manufacturing (AM) technologies* of industrial grade 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 applications of these technologies are widespread across numerous domains and there are almost no limitations. The currently available resolution of industrial grade AM machines goes down to a few micrometers, both in printed layer thickness and X-Y resolution. Household versions are cheaper and lower in resolution, and mostly use FDM. Therefore, they are often called *3D printing*.

Different from other manufacturing techniques, AM 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 computer aided design (CAD) model, parts can be produced when and where required, independent from any other manufacturing facilities. This is particularly useful in remote military operations or crisis situations when replacement parts are needed. Another advantage of AM 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. This newly achieved degree of manufacturing flexibility is particularly beneficial because it has been shown that manufacturing flexibility positively influences product innovation [?].

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 [?]: it takes lunar materials as a primary material for 90% of the structures.

Two **approaches to 3D design** exist [?]: One is Solid Modelling based on a ready-made collection of shapes (cylinders, rectangles, etc). This approach originated from engineering and CAD. 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 [?].

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 [?]. 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. 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 [?]. 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. However, assuring certain material properties with a varying material mix is challenging.

Challenges in additive manufacturing identified by the UK Engineering and Physical Sciences Research Council (EPSRC) 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 AM [?].

2.1.1 Medical applications of 3D printing

The probably simplest application of 3D bioprinting is the deposition of cultivated cells on a wound [?], 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 step 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 [?]. 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 [?]. 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 [?, ?, ?], 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 [?]. The main problems with printed organs are currently their lack of resistance to mechanical stress and the absence of vascularisation to nurture the cells [?]. 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 [?]. Specialised printers like the BioFactory[2] generate 3D constructs of cells, proteins and extracellular matrices.

3D printers can also be used to create small chemical reactors (a polymer gel called *Reactionware*[3]) for mixing substances handled by the printer [?]. This home chemistry factory could be used for personalised medicine [?], but also comes with considerable potential for criminal abuse [?]. Furthermore, Reactionware allows researchers to mix substances that are difficult to handle otherwise, and hence opens the door for the creation of

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[1] http://www.filabot.com

[2] http://www.regenhu.com

[3] http://www.chem.gla.ac.uk/cronin//reactionware.php

new chemical compositions as well as the benefits and dangers they come with. While *Tort law* untangles corporate responsibility for such technologies [?], society is required to find new ways of dealing with their implications.

2.2 Adaptive design with blueprints

Morphogenic blueprints [?, ?] allow designers to specify parts or systems in a way that they maintain certain properties while others are modifiable; for instance, the length of a part may be variable, but the ratio between its length and thickness must remain constant within certain boundaries. Design blueprints also establish relations between the different components of a system; for instance, one part must remain parallel to another. Taking the approach further with simulation, parts can also virtually grow into shapes that satisfy the desired specifications and incrementally correcting deficiencies [?] .

Such an approach brought to AM would enable companies to offer their designs to clients with a certain freedom to modify them, while maintaining safety critical properties as well as functional characteristics.

Design for adaptive reuse is also a topic studied in building construction [?]. If the design follows certain rules relating to invariant characteristics, other properties may be modified more easily.

2.3 Sustainability in manufacturing and technology

A spectrum of research communities investigate approaches to creating a new sustainable world of manufacturing. While their objectives are often similar, their backgrounds as well as vocabulary differ. This section reviews the most relevant approaches.

Initiatives around the vision of *Living Technology* [?] aim at creating sustainable solutions through personal technology that is based on characteristics of living systems [?, ?]. Personal embedded technology would be shared in a *personal fabricator network*. Design and fabrication are done locally, while benefitting from the creativity and shared expertise of a networked community. Furthermore, design, production, use and recycling form a never ending circle. Research in living technology includes advances in 3D printing, chemical and biological fabrication, functionalised materials and surfaces, design languages for objects, as well as social impact management (among others concerning security and safety, market development, education, health and environment).

The *Virtual Enterprises and Collaborative Networks* community [4] has identified the need to re-industrialise Europe to achieve a sustainable economy. It implies to change the focus from service-industry back to manufacturing, in a new form. This is a process with economic, social, and political perspectives. A more sustainable industrialisation would incorporate the need for addressing the products' full life cycle, including recycling and the products economical footprint, and keep a view on the global impact of local decisions. Collaborative networks can contribute to sustainability in various ways [?], considering the social, environmental and economical aspects.

Companies all over the world increasingly use dynamic forms of collaboration with changing partners. This brings a plentitude of issues, such as information sharing, confidentiality and trust. The partners both provide and request services from other partners without central control. The complexity in large-scale online collaboration stems from the back-and-forth of ideas that are exchanged through the medium and that affect the collaborators' thinking. Effects such as group-think and cognitive collapse are reinforced by collaboration tools [?].

Both in manufacturing and building construction [?], designers are increasingly concerned with the recuperation of materials at the end of a building's or product's life cycle. Parts should be made based on design practices that facilitate the separation of materials at deconstruction / disassembly. This way, materials can be recycled and hence re-enter the construction process instead of being discarded. An example of a 3D printer able to use recycled plastic is described in section 2.1.

The concept of the *Circular Economy* [?] goes further by not only reusing materials, but also components and entire products, through processes including refurbishing and remanufacturing. This requires Reverse Supply Chains [?] which feed parts and products from end consumers or any stage of the forward supply chain back into the circle of usefulness.

2.4 Socio-technical systems

An intuitive understanding of socio-technical systems is that they are composed of humans, technologies and devices including robots, sensors, actuators, machines and software. These entities interact with each other in multiple ways over time; they may collaborate, compete or provide services to each other.

The term *socio-technical system* was coined by Eric Trist in the 1950s based on a study of how technical

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[4] http://www.pro-ve.org

changes affected human performance in coal mines. As it is, technical improvements may have detrimental effects on human communication and team dynamics, which in turn eliminates the advantage gained through the technical changes. Hence the need to study systems from the aspect of how technology and humans interact with each other. For instance, it has been found that personal traits of staff like intelligence, knowledge, personality and interests have an influence on performance even on tasks like inventory management [?].

According to [?] as well as [?], socio-technical systems have the following characteristics:

1. Systems should have interdependent parts.
2. Systems should adapt to and pursue goals in external environments.
3. Systems have an internal environment comprising separate but interdependent technical and social subsystems.
4. Systems have equifinality. In other words, systems goals can be achieved by more than one means. This implies that there are design choices to be made during system development.
5. System performance relies on the joint optimisation of the technical and social subsystems. Focusing on one of these systems to the exclusion of the other is likely to lead to degraded system performance and utility.

A recent framework for *socio-technical systems engineering (STSE)* builds on research done in the areas of work design, information systems, computer-supported cooperative work, and cognitive systems engineering [?]. STSE relates organisational change to system development using two main types of activity: *sensitisation and awareness*, which means that engineering need to be persuaded that an STSE approach is beneficial; and *constructive engagement*, which is the integration of STSE methods with the processes of change in the organisation.

Socio-technical systems can be formally modelled as collective adaptive systems [?] composed of different heterogeneous parts or entities (e.g., individuals, groups, computers, robots, agents, devices, software, services, sensors) that interact collectively in a complex and largely unpredictable manner. Suitable formal methods include situation calculus, ambient calculus, and *bigraphical* reactive systems. They are used to specify, verify, and validate foundational properties at design time and while running (runtime verification). This assures that the system continues to correspond to its specifications, even when undergoing changes and exhibiting emergent behaviours.

Another way of modelling socio-technical systems of systems uses three types of 'cuts' [?]: The *Cartesian cut* refers to the difference between what is and what is not accounted for by the observer's knowledge. For instance, in an open system like individualised manufacturing as a socio-technical system, not all factors influencing the system will be known to the observer. The *Heisenberg cut* distinguishes between systems where the user may or may not predict the system's response to requests depending on if the user is part of the system or not. In an ecosystem like individualised manufacturing, the user will always be part of the system. Finally, the *Endo-exo cut* describes what the client can or cannot know about his needs. In a socio-technical system, agents may endogenously interact with each other while the system exogenously constrains the interactions.

Socio-economic systems are closely related to socio-technical systems but they focus on the aspects of how economic and institutional structures interact with human behaviours. As it is, open, embedded and resource constrained systems can be considered from the perspective of institutions for management of common pool resources (CPR) [?]. Such systems can be axiomatised using action languages used in Artificial Intelligence (AI) for reasoning about action, agency and norms. Such an axiomatisation can be used as an executable specification for systematic experiments to test whether these principles are necessary and sufficient conditions for enduring institutions [?]. Sociologically inspired computing is used for an axiomatization of six of the eight CPR principles [?]. These principles support enduring institutions, in terms of longevity and membership, and also provide insight into calibrating the transaction and running costs associated with implementing the principles against the behavioral profile of the institutional membership. Hence these principles are necessary and sufficient conditions for enduring self-organising electronic institutions to manage sustainable common-pool resources.

2.5 Society development

A strong mutual dependency exists between society and technology; they co-evolve and influence each other in multiple ways. Disruptive new technologies often lead to unexpected changes in society and the way people lead their lives; illustrative examples are the invention of letterpress printing and the computer. The availability of these technologies and their effect on society in turn increased the need for other new technologies, like mobile phones and ubiquitous Internet connectivity. Theses again have profound effects on social interactions and societal structures.

Ethics in engineering is much more important than it may seem at first. The engineering of technologies influences the safety of many different parties, including the public, consumers, operators, as well as workplaces and the environment. Ethical problems in engineering are often like design problems: complex, often ill defined; resolving them involves an iterative process of analysis and synthesis; and there can be more than one acceptable solution [?].

The teaching of ethics in engineering often focuses on the engineer as an individual but ignores the broader context [?]. Courses in *Science, Technology and Society (STS)*, as now offered by many universities, may contribute to a better preparation of the engineering students for their ethical and social responsibility. The interrelations between technology and society with regards to a sustainable world are also studied at the Oxford Martin School at Oxford University, UK, for instance within the programme on the impacts of future technology[5].

The **role of the engineer in the society** of the 21st century is to create a sustainable world, facing the global environmental, social and economic challenges [?]. To be able to fulfil their role, engineers need training in multi-disciplinary thinking and a holistic approach. The responsibilities of an engineer are manifold and often underestimated [?]. Engineering has a close relation to society and its needs; this includes peers, employers, clients and the public. Conceptually, engineering happens where the growth of scientific knowledge overlaps with the needs of society. According to [?], the responsibility of engineers includes the safety and welfare of the public and of clients; professional ethics; legal liabilities of engineers; environmental responsibilities; quality; and communications. These aspects should be included in the engineering education.

The **legal system** is made to guarantee a predictable environment on which people can rely [?] even when facing novel technologies. With many of the new technologies, including AI, which come without a clearly responsible company, one of the questions will be whom to blame in case something goes wrong. A better approach, however, is to create a legal framework in which society takes responsibility and peer-to-peer interactions regulate people’s behaviour. Enabling the crowds to take responsibility for themselves is much more powerful than relying on a few authorities to control individuals [?].

The idea to rely on **crowds** is spreading to more and more areas, including investments. For a long time, research was either funded by rich private investors, industry or governmental agencies; funding was awarded to experts and institutions. However, crowd funding[6] has opened new ways for individuals to gain funding for their creative projects. Anonymous people are encouraged to contribute financially to projects they like, without any monetary reward. This is a sign of society developing towards a configuration where inventions and technological progress can be achieved anywhere, by anybody.

However, increased consumerism can be counterproductive to other factors that affect people’s happiness; sustainable solutions are needed instead. They require a responsible citizenship throughout the generations [?]. Sustainable growth can be modelled in economic systems based on energy and resources without reducing the efficiency of the economic processes [?].

2.5.1 Social theories to model transitions

Several social theories are suitable for the study of socio-technical transitions to sustainability [?]. Each other them has a different way of modelling the actors and their behaviours.

1. *Rational choice:* Individual, self-interested actors make choices based on the available information.
2. *Evolution theory:* Agents in a population search for solutions, select the fittest and retain them
3. *Structuralism:* ‘Deep structures’ influence the beliefs of the actors and hence their views and preferences
4. *Interpretivism / constructivism:* Individual actors with individual ideas and preferences socially interact with others to create shared meaning
5. *Functionalism:* A social system where actors play roles, follow norms and fulfil tasks
6. *Conflict and power struggle:* Conflicted collective actors (groups) struggle for power.
7. *Relationism:* Focusing on networks and relations, their construction and development.

Theories 1, 3, 5 and 7 show difficulties in explaining transitions because they are focused on stability. Theories 2, 4, and 6 are designed to model dynamic processes, which makes them better suited for explaining transitions; hence the following paragraphs discuss the latter.

Conflict theory was founded by Karl Marx in the mid-1800s and focused on inequalities and power differentials, e.g. between factory owners and workers. Several modern versions of these theories exist, mostly considering groups with differing interests and resources. From this perspective, order arises from coercion, that is, one group oppressing the other. Change occurs when economic or political power shifts for some reason. There is a strong dependency between economical forces (industry) and political policy makers, as they often create favourable conditions for each other. New economical forces growing from niche markets have the potential to

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[5] http://www.futuretech.ox.ac.uk
[6] Initiated by http://www.kickstarter.com

lead to political shifts [?]. Additive manufacturing and the new business models [?, ?] might just provide such an opportunity for change. Currently, unsustainable industries hold the power, but together with the public opinion moving towards recognising the need for sustainable technologies, 3D printing might become the small force at the tipping point leading to bigger change [?].

Constructivism considers that groups construct shared knowledge and meanings, collaboratively creating culture and learning from each other. Actors first need to make sense of data, signals and situations, to then be able to take decisions and actions. Learning and sense-making are on-going activities and dynamically modify their content [?]. The social construction of technology (SCOT) approach argues that new technologies are perceived in different ways by different groups, and that transitions only advance once shared meaning is agreed on [?]. This process can be facilitated through participatory visioning exercises, multi-stakeholder learning processes, and societal debates, which are tools of transition management [?]. In terms of a transition towards sustainability, the participants will have different interpretations of the right balance between social, economic and environmental sustainability. Additionally, they will give different importance to environmental problems and hold different views about the (dis)advantages of particular solutions and the most appropriate policies to be established [?]. This is clearly the case for the situation with intellectual property rights; the current laws cannot deal with the new technologies, but the opinions about how to modify them are still scattered. Viable solutions for dealing with technologies that merge the physical with the virtual do not exist yet.

Evolution theory in sociology is based on Darwin's theory of biological evolution. *Micro-evolution* deals with change as an incremental adaption through learning. *Bounded rationality* is assumed, where information processing capacities are limiting. Therefore, actors do not search explore entire search spaces but content themselves with satisficing solutions within the possibilities of existing technology. *Macro-evolution* focuses on long-term change patterns. Evolution advances with sudden outbursts caused by disruptive innovations. Often, these are promoted by new players in the field, whereas the established ones try to uphold the existing technologies. Innovation usually makes its way from niches to mainstream market once price/performance characteristics have improved enough to compete with existing solutions [?]. *Techno-economic paradigms (TEP)* refer to manufacturing technologies and economic structures which are stable over long periods of time. New technologies are then confronted with a mis-match between the emerging techno-economical sub-system and the existing socio-institutional framework [?]. Once a breakthrough is achieved, society will change as well. Making the analogy with Darwinian evolution, in social evolution change is due to mechanisms related to innovation (R&D investments, competence building, etc.) whereas selection happens through stricter regulations or modified user preferences [?]. This emphasises the importance of a suitable policy framework, built with public support, to guide and accompany technological and economical change coming with disruptive technologies such as 3D printing.

2.5.2 Challenges in society development

Society needs to evolve to embrace novel / disruptive technology and to create suitable legal frameworks including peer-to-peer responsibility. The question is if it is possible to guide this process, and if so, how to do it. How to lead a society towards establishing and enforcing certain norms (e.g. for collective responsibility)?

Among the most critical issues are also [?]:

- How to facilitate the transition from the currently disabling rigid control and coordination structures into the necessary enabling agile policy frameworks that will transform our coercive institutional frameworks into agile, responsive and fluid ones, capable of fostering creativity and supporting innovation;
- How to design engaging control mechanisms that stimulate rather than oblige, transitioning the current work organisation processes from contract to commitment by fuelling performance through visceral engaging architectures of participation;
- How to design validation frameworks that reveal the impact of policies on the work ethics, culture and productivity in our organisations.

3 Traditional manufacturing versus personalised manufacturing

A number of issues are important in manufacturing of any kind, but need to be investigated when considering new forms of manufacturing. This sections reviews the most crucial.

3.1 Environmental impact 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 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.

Depending on the recycling solution that can be found, also discarded materials might need to be collected and treated. Ideally, unused or broken plastic parts would be melted and reused at home or in the local community. Where this is not practicable for economical or technical reasons (e.g. for metals with a high melting point), then regional solutions with the providers of the primary materials or recycling companies will need to be found.

The 3d printing community will need to find recycling solutions for all materials. 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 of usefulness. Materials should either be biodegradable or printers should operate with shredded or melted recycled materials, like the Filabot. Especially plastic waste polluting the environment is a very serious problem.

Another aspect is the need for energy. 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.

3.2 Liability

Most manufacturers hold liability for their products, even if lawsuits against them would not be accepted in every country. Nevertheless, companies 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. 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 primary material being suitable, and the manufacturing process being executed properly. Solutions to this problem may include the use of sealed cartridges, electronic access of the company to the home 3D printer for verification of design and process in the form of DRM. However, as with all technologies, these can be hacked or circumvented. Additionally, the use of sealed cartridges increases cost, enlarges the carbon footprint, and limits the creative freedom. Better solutions are required. Currently, companies are increasingly declining all responsibility, similarly to the way it is done with software nowadays [?].

3.3 Legality

Most products need to conform with laws and legal standards, 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.

As an example, 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.

3.4 Economics / Employment

Eliminating intermediaries in the supply chain 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 AM.

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.

3.5 Research / Innovation

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. 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 fund industrial research and innovation. However, a lot of open source software has been written without the financial backing of a company, and it still works. Furthermore, crowd funding might contribute to innovation requiring financial means. 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. For bigger and more costly technologies, the issue may at least only arise later, when individualised manufacturing has gained maturity.

3.6 Counterfeiting

The problem with counterfeiting has mainly two aspects: withholding license payments from the designer / inventor, related to what was discussed in section 3.5 and misguided trust in a product, related to liability explained in section 3.2. This section will focus on the consequences of the latter.

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 illegal 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.

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 pretence 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’ and genuine whereas in reality, they are refurbished or counterfeit [?]. This induces great danger, as the parts are likely to be less reliable than newly manufactured ones. Being able to produce the parts locally as and when required 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.

3.7 (National) Security

Realistically looking designs for firearms to be 3D-printed have already appeared on the Internet, and at first been banned by the community. However, with technology progressing, the US government has already given a license to a private person to 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.

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 in 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.

4 Suggestions for how to address the problematic issues

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 [?]. 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.

Environmental impact and logistics: In terms of materials used for AM, a possible solution for their supply and recycling might be to establish local material centres in proximity of the village printing shops. These centres 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 centres 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.

Solutions need to be found both for traditional and individualised manufacturing. Public policy may be required to incentivise companies to invest in finding suitable recycling technologies and collecting discarded plastic material.

Liability: 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 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.

Legality: It is often a lengthy and costly procedure for 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?

Economics and employment: Industrialisation has brought wealth, 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.

Research and innovation: With the tendency for research to be done by independent individuals or consortia formed on project-basis, questions of safety and responsibility become an issue. For instance, industrial research centres 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.

Counterfeiting: 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.

National 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.

4.1 Influencing additive manufacturing as a Complex Adaptive System

The community around additive manufacturing technology qualifies as a Complex Adaptive Systems (CAS). These are systems which emerge over time into a coherent form, and adapt and organise themselves without any singular entity deliberately managing or controlling it [?]. CAS are many-body systems, composed of numerous elements of varying sophistication, which interact in a multi-directional way to give rise to the system's global behaviour. The system is embedded in a changing environment, with which it exchanges energy and information. Variables mostly change at the same time with others and in non-linear manner, which is the reason why it is so difficult to characterise the system's dynamical behaviour. CAS often generate 'more of their kind' [?], which means that one CAS may generate another. To characterise them, researchers describe their components, environment, internal interactions and interactions with the environment.

Strategies for controlling CAS of various nature - markets, companies, business organisations and others - have been suggested [?]. As centralised top-down control cannot be imposed to CAS, the idea is to influence the environment and operating conditions of the system instead. DNA functions in a similar way for the genes to influence the development of a body. As Clark puts it: "Genes thus act as nanny and as coach: the nanny (ideally) creates and maintains an environment in which a child's own curiosity and intelligence will lead her to learn and flourish; the coach looks out for difficulties and potential sticking-points and tries various ploys and tricks to push the player onwards." Hence, management should create conditions under which the system can give flexible, self-organising responses and unfold its intrinsic dynamics. This means that the system needs to be maintained in balance between a frozen state and chaos or anarchy and decay. There should be tolerance for failure, diversity, overlap and redundancy. Instead of prescribing how an organisation is to operate, it should be maintained in conditions for exploration, decentralised adaptation, and environmental exploitation.

Helpful tools in this endeavour are tags, labels and explicit models [?]: they may play a powerful indirect role by acting as the seeds or anchor points for new organisation to form itself. Tagging and labelling can help create and maintain adaptively valuable diversity; help create and stabilise the multiple external alliances characteristic of the new organisational forms; participate in processes of diffuse control; and promote the kind of systemic self-understanding that underpins effective (albeit indirect) intervention and control.

From the perspective of biosystems, the management of CAS means making decisions about the system with the least negative side effects, or at least containing them as well as possible [?]. Diverse and integrated approaches have better chances at managing CAS than individual approaches. Multi-objectives and guide lines can better be realised than precisely formulated unique goals. A closed feedback loop for decision making is beneficial, and strategies may evolve.

Characteristics of such complex adaptive organisations include [?]:

- *The exploitation of open corporate architectures capable of making maximal use of external resources*[7]. In the case of AM, this may mean that companies active in the area collaborate with creative individuals or groups in an informal way and find new types of synergies. For instance, in the case of the RepRap, people have access to the printer's design, and are encouraged to add to it and improve it, even to take patents on their inventions. The original company, in return, becomes better known and may sell more of the original printer as well as their other services including maintenance and problem-solving.

- *The use of minimal hierarchical control structures both within individual companies and between interdependent ventures.* The decentralised manner in which 3D printing has been progressing, hand-in-hand with the Internet, would not allow for very hierarchical structures. Most companies in the field are still rather small and many independent actors contribute to new inventions and improvement as well as dissemination of the technologies. Also the advantages of localised manufacturing support independent but collaborating ventures.

- *Acceptance of waste and redundancy as the natural cost of a continuing search for productive collaborations with other ventures.* 3D printing allows for people to buy identical or similar machines, to adapt and personalise them, and to set up their small businesses in their own market niche. Depending on their skills, interests and resources, people will collaborate or compete. Due to the relatively low investments required to set up 3D printing facilities or design services, the associated risks are small and invite people to try out their ideas.

- *The development of complementary, symbiotic or co-specialised skills and assets as a stable and productive mode of extended organisation.* The 3D printing community has already developed structures where people focus on different parts of the process and different specialisations. They will collaborate as and when required. Some of them meet regularly at conventions to exchange experience and expertise, whereas others use the Internet for this purpose.

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[7] A strategy increasingly used by successful organisations is *dovetailing*, referring to dynamic collaborations (*collaboration niches*) between multiple companies and organisations where each participant contributes necessary but not sufficient expertise and resources. Success then depends on the coordination of these in a changing environment. An advantage is that each company only carries a share of the risk and responsibility, while still benefiting from the results.

5 Manufacturing case study

To illustrate the difference between traditional industrial manufacturing and localised manufacturing, this section introduces a small case study on mobile phone accessories.

Mobile phone data transfer and charging cables have a tendency to break, to stop functioning, or to simply get lost. Replacing them with original equipment can be costly; for instance, an original iPhone 30-pin to USB cable costs GBP 15 at the Apple store. Non-original cables ordered on the Internet or bought in local high street shops cost a fraction of this price, but then, the risk of them not being supported by the mobile phone is considerable. Additionally, connecting a new charging cable and discovering that it does not work is annoying, inconvenient and a waste of resources.

Besides their brand-specific plugs, such cables are relatively simple. These reasons make mobile phone data transfer and charging cables ideal candidates for home manufacturing. However, with current 3D printing technologies, it is not yet possible to print cables due to the very different melting temperatures of plastic and metal. Technological solutions to this problem are yet to be found, but they might include the elaboration of plastic conductors [?] suitable for 3D printing.

Subsequently, we compare the industrial manufacturing and distribution of such phone cables to the alternative of home manufacturing. Manufacturing always exists within the context of a supply chain or supply network linking the primary materials to the end customer through an ensemble of connections and entities.

A cable typically consists of a copper wire in a rubber insulation, a phone specific plug made from stainless steel, a generic USB plug made from stainless steel, and a plastic housing for each of the plugs. The connection of the wire to the plugs is relatively simple and may be clipped, screwed or soldered, depending on the design. For 3D printing, we assume conductive polymers are used instead of copper and a mixture between the conductive polymers and plastic instead of stainless steel.

A simpler example for a case study would be mobile phone cases which usually consist of one or two materials only, mostly plastics. Through personalised manufacturing, the user would gain much more freedom in terms of design options, and the monetary savings would be considerable. Phone cases are often sold for princes in the range of GBP 5-25, whereas production cost are usually very low. Figures 1 and 2 equally apply for phone cases, considering only the plastic / rubber parts.

Industrial manufacturing and distribution: Figure 1 schematically represents the industrial production of a mobile phone data transfer cable with its many steps and involved parties. In reality, there may very well be a few steps more or less, a few involved parties more or less. In essence, each component comes with a chain of companies handling it. For the sake of simplicity, the facilities needed for each step were not considered.

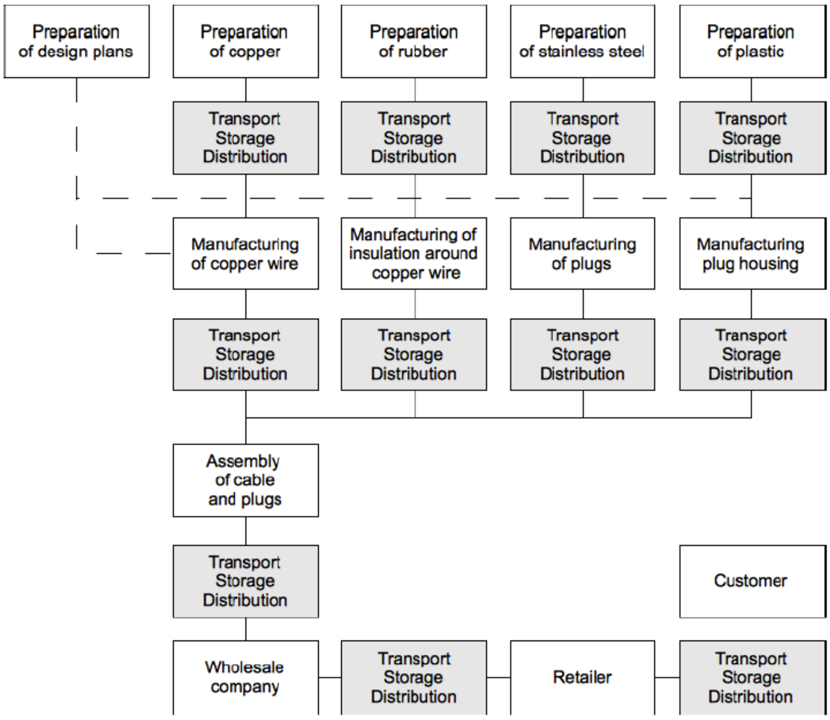

Figure 1: Schematic representation of the industrial production of a mobile phone data transfer cable. Transportation plays a major role.

Home manufacturing: The design would ideally be bought online from the original manufacturer, but the open market would certainly provide a range of cheaper alternatives for the customer to download. Different from buying a finished product, which takes time and causes inconvenience, home manufacturing would allow the user to produce a selection of different cables and test them. Those not functioning could be recycled.

Figure 2 schematically represents the home manufacturing of a mobile phone data transfer cable with its many steps and involved parties. For the sake of simplicity, the facilities needed for each step were not considered.

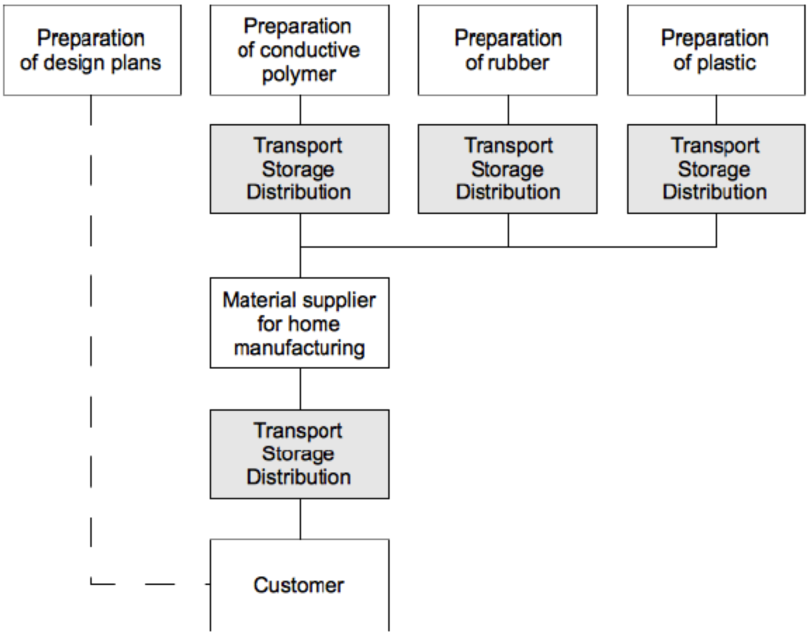

Figure 2: Schematic representation of the home manufacturing of a mobile phone data transfer cable. Transportation is considerably reduced.

Discussion: It is quite clear that manufacturing at home or in a local shop or community centre saves big proportions of the shipping, storage and distribution. The supply chain is much shorter. However, this does not necessarily mean that it is more efficient; improving supply chains [?] and analysing their cost [?] are complex undertakings. Mass production is trimmed for being lean, and the economy of big masses is lost when working with small quantities of 3D printing materials. This needs to be considered when creating logistic systems for individualised manufacturing.

It may certainly be very attractive that the customer gets more autonomy and is able to influence the design of the product, although this also comes with dangers, as discussed previously. People experimenting with different designs will doubtlessly lead to additional waste due to failed attempts at printing, but there is no unsold stock at shops. Nevertheless, solutions for recycling need to be found, and political pressure may be required for achieving this.

6 Conclusion

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. However, with individualised manufacturing, the economy of masses is lost and efficiency may be very low in terms of energy usage and transportation.

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.

The potential dangers coming with 3D printing must not be disregarded. There will be no boundaries to people producing functioning and/or real-looking weapons and mixing harmful chemicals. Critical parts in machinery and vehicles may be replaced by self-made designs, and people may be harmed in accidents nobody can be held responsible for. Furthermore, with 3D scanning technology, designs can be reproduced effortlessly, and unless they are drastically changed, intellectual property laws will become both unenforceable and ineffective. Moreover, plastic waste discarded in the environment is bound to increase with individualised manufacturing, and it is a real threat to the ecosystem unless technologically and economically viable recycling solutions are found.

Society is bound to change together with this new manufacturing paradigm, and people must take responsibility before things get out of hand. A new framework is required to deal with intellectual rights as well as concerns for safety, security, and the environment – at the level of individuals and communities of any scale. This article reflected on the current state of technology, trends for the future, and the way society interacts with them.

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