United Nations Conference on Trade and Development

Note on a proposed

UN CENTRALISED DATABASE OF OPEN-SOURCE APPROPRIATE TECHNOLOGIES

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A substantive draft of the note was prepared by Joshua M. Pearce. The note was finalized by Liping Zhang and reviewed by Angel Gonzalez Sanz.

Xiahui Xin designed the cover. Malou Pasinos provided administrative support.

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For further information, please contact: stdev@unctad.org

EXECUTIVE SUMMARY

Open source allows users the freedom to control their technology while sharing knowledge and encouraging commerce through open exchange of designs. Open licenses contain a viral restriction and changing existing designs requires re-sharing the new design within the same license. This well-established method encourages rapid innovation and is regarded as a mainstay in software development. The same concept is now used for physical products and the open-source technical development method is in exponential growth in hardware development. Millions of open-source products are shared by the global community from consumer goods to scientific and medical equipment. New digital manufacturing and recycling techniques enable individuals and communities to fabricate their own products for less than the price of purchasing them. This model has been proven to be effective for emergency manufacturing during the COVID-19 pandemic.

One area particularly ripe for open-source development and knowledge sharing is "appropriate technology". Appropriate technologies encompass technological choices and applications that are small-scale, economically affordable, decentralised, energy-efficient, environmentally sound and easily utilized by local communities to meet their needs. Therefore, the trend in appropriate technologies is towards relatively simple and non-complex technologies, such as solar cookers.

One way the appropriate technology movement is modernizing to overcome intellectual property (IP) barriers is to blend with the open-source approach to technology development in order to overcome many of appropriate technologies' shortcomings as a technology change model and completely breaking away from IP restrictions. Open-source appropriate technology (OSAT) is an appropriate technology that contributes to the achievement of sustainable development goals (SDGs) while being designed in ways synonymous with free and open-source software (FOSS) and free and open-source hardware (FOSH).

Free and open-source software (FOSS) is software that is both free software and open-source software. Unlike proprietary software, FOSS is available in source code (open-source) form, and can be used, studied, copied, modified and redistributed without restriction, or with restrictions that only ensure that further recipients have the same rights as those under which it was obtained. Today free and open-source software (FOSS) plays the dominant role in software development globally and there is burgeoning rise in digital manufacturing, which make free and open-source hardware (FOSH) not only physically possible, but economically advantageous. The innovation cycle in open-source technology is much more rapid than the conventional intellectual property (IP)-focused process.

Both FOSS and FOSH go beyond open access, granting users substantial freedoms to build on the intellectual work of others. FOSH provides the "source code" for physical hardware including the bill of materials, schematics, computer aided designs (CAD), and other information such as detailed instructions needed to recreate a physical item.

The OSAT approach, even in areas such as medical research, radically reduces the costs even in the upfront investment and can be funded publicly, while earning a high return on investment.

<u>Examples of how open-source can contribute to SDGs</u>

To meet the SDGs, it is imperative that developing countries have access to a broad knowledge base. Access to relevant knowledge can significantly improve the quality of life in developing communities and solve the challenge of sustainable development. Examples of how open-source including FOSS and FOSH can contribute to SDGs include:

- **SDG 2.** An automatable, field camera track system for phenotyping crop lodging and crop movement **SDG 3.** Osmar, an open-source autosampler. Commercial microsyringe manipulation is common for automated sampling of liquids or gases and normally costs over $30,000. Osmar is a viable technically-accessible alternative that can be adapted and expanded for more general liquid handling tasks and be built for under $1,000. Loss of life could be prevented by known technologies whose availability is restricted by causes such as paywalls on articles under copyright, which restrict the free flow of information or companies leveraging patents to restrict the manufacturing of medical products (e.g. restricting the sale of antiretroviral drugs to treat HIV).

- **SDG 4.** The OpenFlexure Microscope is a 3-D-printed laboratory-grade motorized microscope, which was co-developed between the University of Bath, UK and the Tanzanian engineering company STICLab. It replaces commercial tools that cost over $30,000 for under $100.

- **SDG 6**. An open-source, programmable pneumatic setup for operation and automated control of single- and multi-layer microfluidic devices.

- **SDG 7, SDG 2**. Sharing technology of solar cookers or solar bakeries can be advantageous in terms of having no recurring costs, the potential to reduce drudgery, the improvement of indoor air quality, the high nutritional value of food they produce, and high durability.

- **SDG 8.** OpenDesk which is a global platform for local making, uses a business model for open-source furniture made with distributed on-demand manufacturing. Anyone can download the design files and cut it out on their own open-source CNC (computer numeric controlled) mill. Local economic development occurs because of local manufacturing and sales.

- **SDG 15**. ImageJ which is an open-source image processing and analysis software package originally developed to look at microscopic organisms. Because it is open source and highly adaptable, it is even being used for remote sensing work carried out by aerial drones over enormous land areas.

- **SDGs 1, 2, 3, 4, 11**. OSAT development has already reached sophisticated devices such as open-source 3-D printers used for both the design, but also the production of OSAT in a wide range of areas. For example, RepRaps can be used for manufacturing tools for organic farming, to make microscopes for medical clinics or for full optical labs in schools and research facilities in developing communities for far less cost than conventional means. Open-source 3-D printers are used to create thousands of free 3-D printed hands and arms for those in need of an upper limb assistive device from open-source designs, with significant cost reduction.

The need for a centralised open-source database

A database of OSAT could have potential to accelerate discovery and innovation across all sectors associated with the SDGs, while minimizing legal or financial impediments. Technical information made available via open-source methods can overcome barriers to the building and dissemination of the global stock of knowledge, particularly in developing countries.

Currently, there is no comprehensive repository or central database of OSAT, including technologies with expired patents, patented technologies that are freely licensed (with conditional or unconditional use), and free and open-source technologies. Many organizations, non-profits and for-profit companies are developing OSAT and maintaining existing small-scale databases. While many OSAT are available, they are scattered in various databases for particular technologies. Meanwhile, there remains a distinct need for increasing the use rate of OSAT. Therefore, there is an urgent need for a trusted, global centralised open-source database (COSD).

Being global in scope, a COSD repository would provide a one-stop-shop that everyone can access to solve local challenges. Appropriate technologies that are relevant to the SDGs would be expected to make up the core of the COSD. COSD would thus cover all technical areas. In addition, the COSD will not be limited to specific sectors or applications, as open-source technologies can often solve problems far outside the scope of their intended use. For example, ImageJ is an open-source image processing and analysis software package originally developed to look at microscopic organisms. Because it was open source and highly adaptable, now it is being used for remote sensing work carried out by aerial drones over enormous land areas. In the COSD, all information, data, plans, full digital design and manufacturing files, instructions for assembly and use, etc. are available and free.

UN is rightly positioned to host the COSD

The United Nations (UN) is well placed to take a lead in the establishment of a COSD given its well established role in advocating open-source technology through various intergovernmental forums and publications. In particular, the 2030 Connect is a UN online technology platform that was developed as part of the work of the UN Inter-Agency Task Team. The COSD could enhance it by being incorporated into the 2030 Connect. The success of the COSD depends on support from the UN Member States as well as collaboration and cooperation among UN agencies including United Nations Conference on Trade and Development (UNCTAD), UN Department of Economic and Social Affairs (DESA), United Nations Development Programme (UNDP) and UN regional commissions. Private sector engagement in COSD is equally important. For example, companies that already belonging to organizations like Open-Source Hardware Association may find it beneficial to share their own designs with the COSD.

ABBREVIATIONS & ACRONYMS

ASME	American Society of Mechanical Engineers
CAD	Computer aided designs
CNC	Computer numeric controlled
COSD	Centralised Open-source Database
DESA	Department of Economic and Social Affairs
DIY	Do-it-Yourself
DRAM	Distributed Recycling and Manufacturing
E4C	Engineering for Change
FDA	Food and Drug Administration
FOSH	Free and open-source hardware
FOSS	Free and open-source software
FPF	Fused Particle Fabrication
GIAN	Grassroots Innovation Augmentation Network
ICT	Information and Communication Technology
IEEE	Electrical and Electronics Engineers
IP	Intellectual Property
NIH	National Institutes of Health
OSAT	Open-source appropriate technology
OSE	Open-source Ecology
OSHWA	Open-source Hardware Association
PPE	Personal Protective Equipment
ROI	Return on Investment
SDGs	sustainable development goals
TAP	Tech Access Partnership
UN	United Nations
UNCTAD	United Nations Conference on Trade and Development
WHO	World Health Organization

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1. INTRODUCTION

The United Nations has been discussing for some time the use of open-source technologies, such as free and open-source software (FOSS) and open access to knowledge to drive sustainable development. The United Nations Conference on Trade and Development (UNCTAD) has focused on this area in the *E-Commerce and Development Report 2003*[1] and concluded "*The advantages for developing countries of promoting policy that will provide a positive environment for open-source IT are manifold*." Later, the Information Economy Report 2012[2] summarized the benefits of open-source for use in the public sector as follows: (i) lower costs and local value creation, (ii) promotion of local learning with universal information and communication technology (ICT) access, (iii) less dependence on specific technologies or vendors (e.g. no lock-in), (iv) easy adaption to meet local needs with customizability to local languages and cultures, and (v) addresses concerns of national security and long-term availability. The 2012 report concluded:

> *Rather than purchasing software licences and services abroad, local FOSS[3] development, sales and services can help keep resources within the local economy, avoid dependency on specific vendors and provide opportunities for income generation and employment. When based on FOSS, local software companies may be in a better position to develop innovative and cost-effective solutions that are customized to meet specific needs in the domestic market. As noted earlier, such capabilities are essential to seize full development benefits from improved access to ICTs.*

Today, free and open-source software (FOSS) plays a dominant role in software development globally. There is also a burgeoning rise in digital manufacturing activities, which make free and open-source hardware (FOSH) not only physically possible, but economically advantageous. The innovation cycle in open-source technology is much more rapid than the conventional intellectual property (IP) focused process.[4] The COVID-19 pandemic has made the use of accelerated open-source and distributed manufacturing approach apparent. As highlighted in the intergovernmental deliberations at the 15th session of the UN Commission on Science and Technology for Development (CSTD) in 2012[5], there is now consensus that technical information made available via open-source methods can help overcome barriers to the building and dissemination of the global stock of knowledge, particularly in developing countries. Today, millions of open-source technologies are scattered across various websites and there is no comprehensive repository of free and open technologies. Therefore, a platform of public domain technologies could potentially accelerate discovery and innovation across all sectors associated with the SDGs[6], while minimizing financial and IP-related barriers.

This technical note provides: (a) a background on open source technologies, (b) describes the proposed database, (c) catalogues existing initiatives, (d) provides a means of calculating the value of open-source technologies and the return on investment for financing them, and (e) discusses why the UN should take a leadership role in providing a global universal database.

2. BACKGROUND TO OPEN-SOURCE TECHNOLOGIES

The open-source technical development method has grown to dominate software, and it is now in exponential growth in hardware development. New digital manufacturing and recycling techniques enable individuals, organizations and communities to make their own products for less than purchasing them, and this model has just proven effective as an emergency manufacturing response during the COVID-19 pandemic. This is the right time to harness the international *Maker movement*[7] and formulate an open database to avoid intellectual bottlenecks for sustainable economic development.

2.1 Free and open-source software

Free and open-source software (FOSS) is software that is both free software and open-source software.[8] FOSS is available in source code (open-source) form, and can be used, studied, copied, modified and redistributed without restriction, or with restrictions that only ensure that further recipients have the same rights as those under which it was obtained.

With the majority of large companies contributing to open-source software projects,[9] it has become a dominant form of technical development.[10] All supercomputers[11] and 90% of cloud servers run open-source operating systems. Effectively, every click on Facebook, Twitter, Walmart, Wikipedia, Yahoo, YouTube or Amazon uses a machine running FOSS.[12]

FOSS is increasingly embraced by the business world with 90% of the Fortune Global 500 companies now using the open-source Linux operating system.[13] In addition, over 84% of the global smartphone market is open-source, using Google's Android operating system,[14] and more than 80% of the "internet of things" devices use FOSS.[15] In the FOSS ecosystem, there are equivalent software packages for the vast majority of proprietary programs.[16] For example, Libre Office, a free office suite, is used on hundreds of thousands of computers across the world. In particular, it is used by the government of France, the government of the Spanish autonomous region of Valencia and Italy's Ministry of Defense. In Brazil, Universidade Estadual Paulista uses it as part of a larger migration towards FOSS.[17]

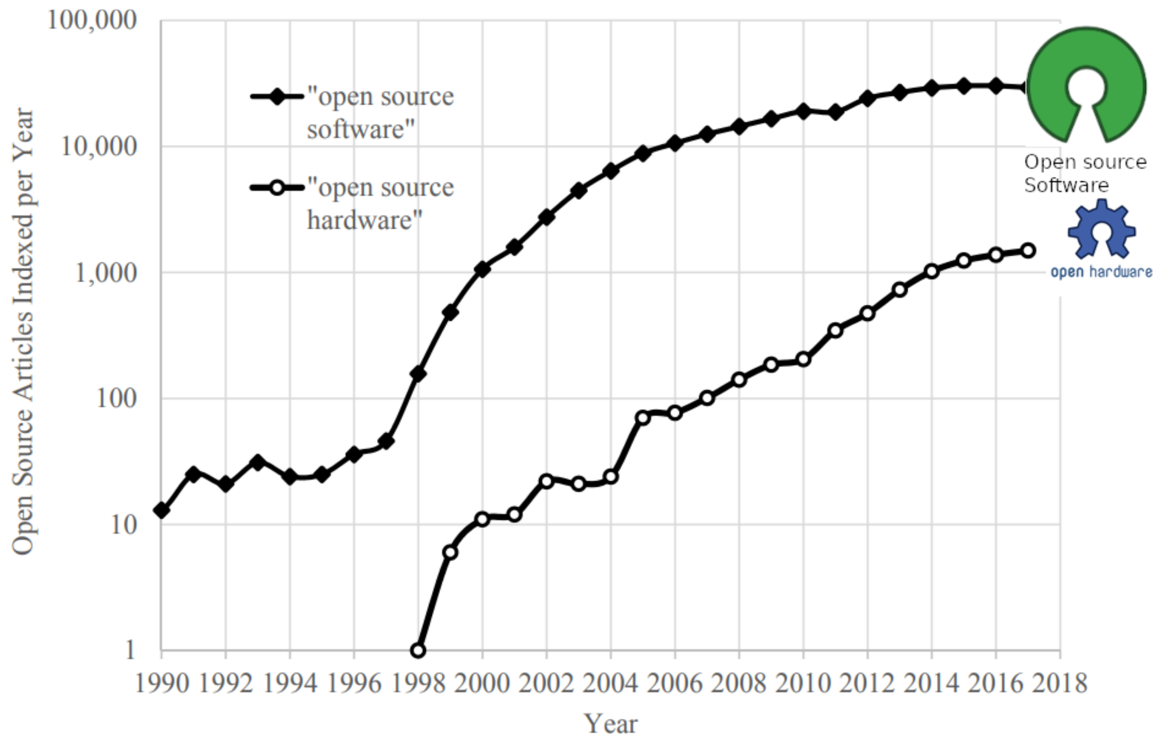
These countries and regions are not alone. A growing number of governments worldwide have embraced the use of FOSS.[18] For example, China developed its open-source Kylin operating system. By 2019, the NeoKylin version of this operation system has been made compatible with over 4,000 software and hardware products and was pre-installed on most computers sold in China.[19] Together, Kylin and NeoKylin have 90% of the domestic operating system market share in the government sector.[20] Similarly, other countries are embracing this approach to FOSS operating systems and programs. Some European countries like Finland[21] have open-source policies, the Indian government announced a policy on adoption of FOSS,[22] as has Peru,[23] Brazil[24] and South Africa.[25] Ecuador[26] has encouraged distribution of low-cost computers running Linux and uses Libre software in the public sector. In the U.S., the federal government has a policy that mandates a percentage of custom source code be released as open-source.[27]

2.2 Free and Open-Source Hardware

Free and open-source hardware (FOSH) builds on the same sharing philosophy and rights of users that underlies the success of FOSS[28]. As defined[29] by the Open-source Hardware Association (OSHWA), a FOSH design is shared publicly, so that anyone can study, modify, distribute, make, and sell the design or hardware based on the design. Thus, both FOSS and FOSH go beyond open access, granting users substantial freedoms to build on the intellectual work of others. FOSH provides the "source code" for physical hardware including the bill of materials, schematics, CAD, and other information such as detailed instructions needed to recreate a physical item. As well-established in FOSS development, research-related FOSH is now demonstrating improved product innovation.[30,31] FOSH is rapidly gaining momentum and trails behind the historical rise of FOSS by about 15 years (*see Figure 1 below*).

There has been a consistent increase in the emergence of FOSH-based electronics, even if at a rate that is slower than free and open-source software. It is now possible, for example, to automate and control almost any electronic device using open-source microcontrollers like the Arduino.[32] The Arduino is a family of microcontrollers, whose functionality has been built up by a global open-source community on a wide range of thousands of projects,[33] from automated irrigation systems,[34] to nitrate testing for optimal crop fertilization,[35] to low-cost baby monitors in Africa.[36]

Figure 1. Articles indexed by Google Scholar on FOSS and FOSH
(a logarithmic scale is used because of the orders of magnitude changes)



Source: Pearce, J.M. Sponsored Libre Research Agreements to Create Free and Open-source Software and Hardware. Inventions 2018, 3, 44.[37]

Even in relatively mature open hardware areas like open-source electronics, the designs are separated in many locations. There are many scattered repositories open to any global citizen to download for free various open-source electronics including: Open Electronics,[38] Open Hardware Repository,[39] Open Circuits Institute,[40] Open Circuits Wiki,[41] Hackster,[42] Codemade[43] and Hackaday.[44] All these websites allow both users and developers to discover and share open-source projects. In addition, the catalogues of open-source electronics companies, which contain the full source code for their thousands of products, are also de facto repositories including Sparkfun,[45] Adafruit,[46] Tiny Circuits[47] and Seeed Studio.[48]

Users are free to download and manufacture the electronics using open-source printed circuit board mills.[49]

Access to open-source electronics has been an enabling technology that allowed the growth in FOSH, which is now being driven by the open-source distribution of three primary classes of digitally distributed (to the point of ‘at-home’) manufacturing: 1) 3D printers, 2) laser cutters and 3) computer numerical control (CNC) mills. Each of these three technologies has accessible starting points in the open-source ecosystem, yet they also have evolved enough that new users can fabricate sophisticated tools that can match product available from an industrial manufacturer. It has been suggested that digital distributed manufacturing is poised to unleash a new paradigm shift equivalent to an industrial revolution.[50] Yet, the OS growth of these technologies proves the potential for this industrial revolution to be democratized, which holds incredible promise for developing communities.[51]

Although 3D-printing and additive manufacturing are now an old technology, it has gained popular attention only recently when the open sourcing of the technology dropped the costs so that they became accessible to most of the world’s population.[52] Today, the most popular desktop 3D printer, Creality Ender 3, made in China, is open-source and can be purchased for under $200.[53] Yet these low-cost and open-source 3D printers derived from the self-

REPlicating RAPid prototyper (RepRap) project[54] are capable to produce parts as mechanically functional in applications as those from commercial 3D printers (costing over $20,000).[55]

A recent development of open-source 3D-printers makes the scaling of mass-distributed additive manufacturing of high-value objects technically feasible for much of the world from open-source plans.[56] RepRap solutions hold promise in the developing countries.[57] They can fabricate many of their own parts, so can be fixed without access to supply chains. They are open source so they can be upgraded easily. They literally have been evolving under the open-source paradigm.[58]

Selecting from millions of free designs, communities can radically reduce costs for a wide range of products by 3D printing them for themselves. They include children's toys,[59] learning aids,[60] drones,[61] photovoltaic racking,[62] and medical equipment, such as braces for clubfoot,[63] and prosthetics (*see Box 1*),[64] self-adjustable glasses,[65] and adaptive aids for arthritis sufferers.[66] The free and open-source designs for these products are growing exponentially,[67] already numbering in the millions, and are currently scattered throughout dozens of online repositories.[68] *Thus, by combining open-source designs with digital distributed manufacturing, it is possible for consumers throughout the world to manufacture their own products for lower costs than can be mass manufactured.*[69]

Box 1: Custom Prosthetics for <1/100th of the cost for SDG 3

The e-NABLE Community (http://enablingthefuture.org/), with more than 10,000 volunteer members in 140 Chapters and hundreds of schools from all over the world, are using their 3D printers to create thousands of free 3D-printed hands and arms for those in need of an upper limb assistive device from open-source designs. Prosthetics are customized for the children and can be produced for about $25 - reducing the commercial costs by orders of magnitude.

Caption: Photographs of children using e-NABLE hands made by a global network of volunteers, including 12-year-old Musa, a survivor of the Boko Haram attacks in Adamawa State, Nigeria.

Open-source designs have even entered areas that have been historically used as examples of the need for traditional IP such as pharmaceuticals.[70] For example, Open-source Pharma's[71] mission is to create an alternative, comprehensive, open-source pharmaceutical system driven by principles of openness, patient needs, and affordability. This includes initiatives such as (*a*) Open-source Pharma Foundation that has commenced a multicentric phase 2b clinical trial for an adjunct therapy for tuberculosis, reaching this stage nearly a decade faster and for less than 1% of the cost of the conventional IP-intensive pharmaceutical approach[72]; (*b*) Open-source Malaria[73] and the Malaria DREAM Challenge[74], which are using open-source principles to discover new Malaria drugs; (*c*) the Nipah Virus Open Research Collaborative, which are doing the same to find cures for the deadly outbreak of the Nipah virus in India[75], and (*d*) the CRI in Paris[76], which is developing a safe model microbe E. coli as a proxy organism to express and target essential metabolic enzymes from other species.

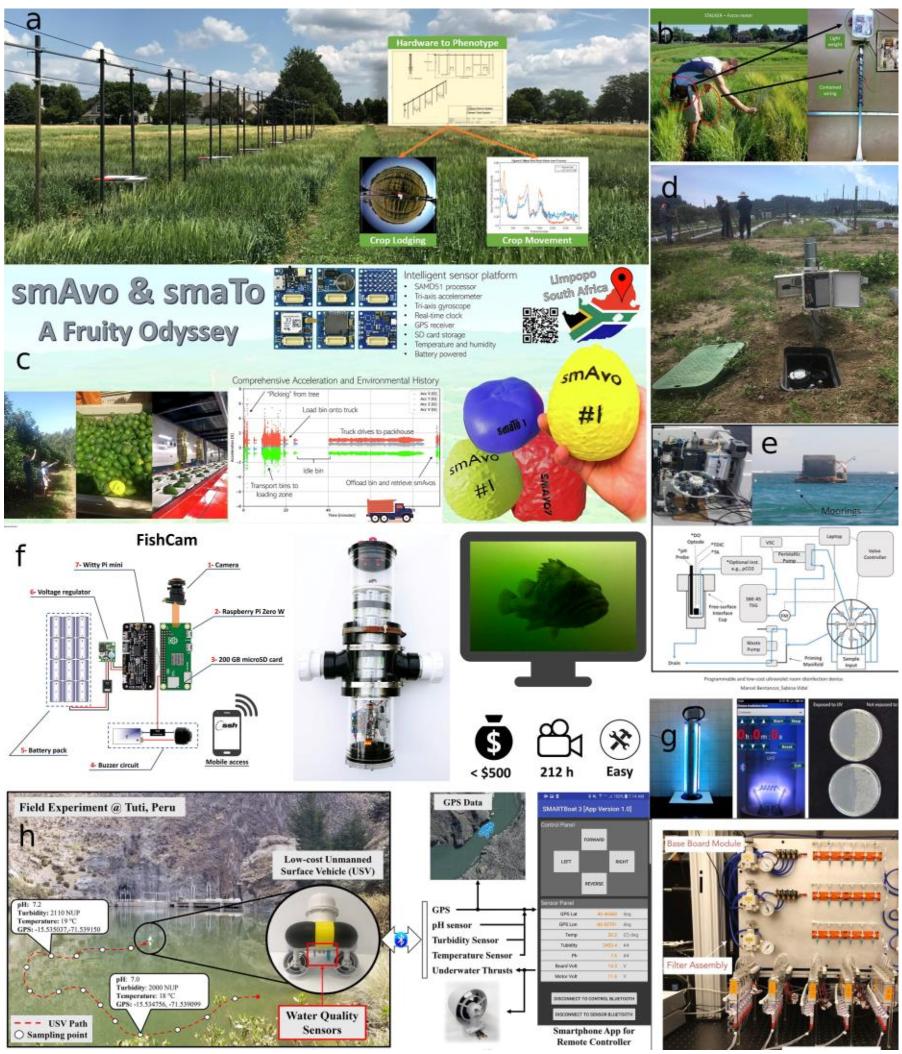
By developing inexpensive, simple and safe drug discovery tools, Open-source Pharma hopes to greatly expand the number of people and places that can participate in the discovery process. Much medical research is already publicly funded, which could be made open source. Research has shown[77] that the competence for scientific breakthrough innovation and the competence for "operational excellence" for corporations are conflicting. This means that innovation creates forced obsolescence of existing products, corporate processes, and threatens the organizational fabric of some companies – all of which reduce innovation rates. As such, the open-source model can offer[78] a chance to restore the balance by locating disruptive innovation outside of corporations, where it can thrive without any constraints.

Distributed digital manufacturing of FOSH has shown promise among scientists[79] for developing custom scientific tools[80] (*see Box 2*). There are now journals specifically dedicated to scientific FOSH such as *HardwareX*[81] and the *Journal of Open Hardware*[82], as well as the *Public Library of Science Open-source Toolkit*.[83]

Box 2: Examples of low-cost scientific FOSH for SDG 2 and SDG 6

The following examples of low-cost scientific FOSH are from *HardwareX*, an open access journal dedicated to free and open-source hardware, which uses a template format to ensure that all of the source code needed to recreate the device is accessible. Savings are observed for fabrication, however, even during use and maintenance, open-source approaches have significant advantages as costs depend on local labor costs, which in developing countries provide an advantage for exploitation. The examples are from agricultural and environmental science instruments (specifically related to water quality) on the large and small scale:

a) An automatable, field camera track system for phenotyping crop lodging and crop movement (10.1016/j.ohx.2018.e00029);
b) The Stalker: An open-source force meter for rapid stalk strength phenotyping used for plant breeding (10.1016/j.ohx.2019.e00067);
c) smAvo and smaTo: A fruity odyssey of smart sensor platforms in Southern Africa for agricultural engineering (10.1016/j.ohx.2020.e00156);
d) A low-cost Arduino-based datalogger with cellular modem and FTP communication for irrigation water use monitoring to enable access to CropManage (10.1016/j.ohx.2019.e00066);
e) Automated multiport flow-through water pumping and sampling system (10.1016/j.ohx.2020.e00147);
f) FishCam: A low-cost open-source autonomous camera for aquatic research (10.1016/j.ohx.2020.e00110);
g) Programmable and low-cost ultraviolet room disinfection device (10.1016/j.ohx.2018.e00046), which can be used to sterilize rooms in the agriculture industry as well as for R&D and medical applications;
h) A low-cost and small USV platform for water quality monitoring (10.1016/j.ohx.2019.e00076);
i) An open-source, programmable pneumatic setup for operation and automated control of single- and multi-layer microfluidic devices (10.1016/j.ohx.2017.10.001);



Caption: Open-source hardware courtesy of *HardwareX* (CC-By). https://www.sciencedirect.com/journal/hardwarex

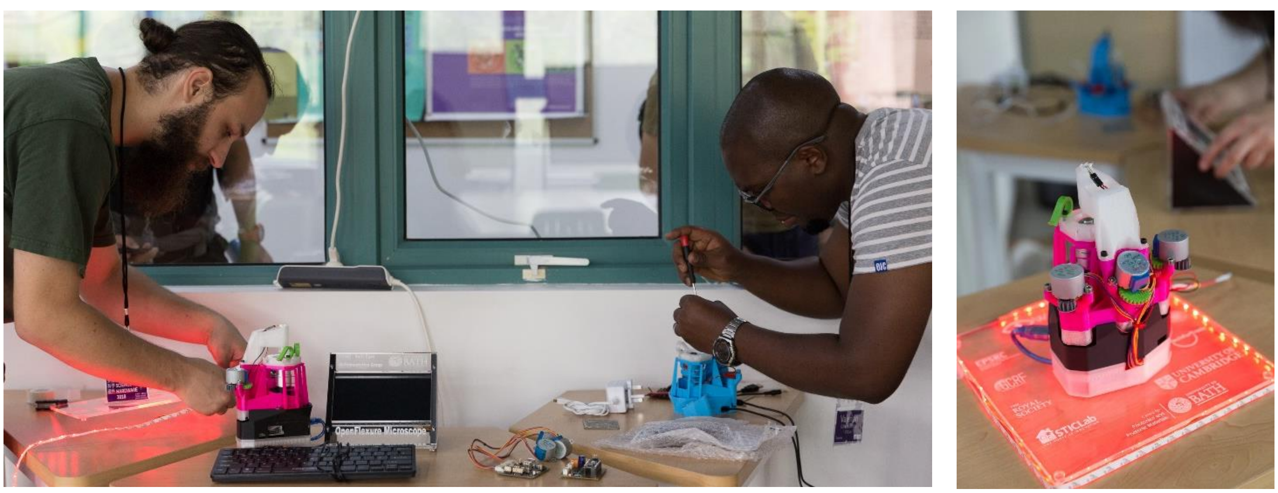
FOSH not only provides customized products for doing state-of-the-art experiments but makes them more accessible to developing world scientists because of significant cost discounts.[84] A 2020 review article[85] found that the average material costs from the aggregate of the bill of materials for the open-hardware scientific devices were under $1,500, yet they were able to replace proprietary devices with equivalent (or lesser) functionality that cost over $20,000 (i.e. FOSH saved 87% compared to proprietary scientific tools).

These economic savings increased slightly to 89% for those that used Arduinos, to 92% for those that used RepRap-class 3D-printing, and 94% when both Arduino and 3D printing were used. These savings were over 99% for sensors,[86] reactors,[87] analytical equipment[88] and digital manufacturing equipment.[89] The latter type of equipment, which is used for the automation of experiments or further custom scientific experiments generally saved a large percentage over commercial products (e.g., laser sintering additive manufacturing system[90] or an autosampler[91]). The profit potential for *do-it-yourself* (DIY) digital manufacturing is so high that $20 for a kg of commercial plastic filament can 3D-print 20 products that exceed the value of a desktop printer itself and can be printed in a weekend.[92]

A good example of a high-quality scientific tool that slashes the costs of conventional equipment is the OpenFlexure Microscope.[93] Optical microscopes are essential tools for both disease detection in medical clinics and for scientific analysis (see Box 3). The OpenFlexure is built upon a clever adaptation of flexure technology, which gives <100nm alignment[94] and even super-resolution imaging.[95]

Box 3: Open Flexure Microscope for SDG 4

The OpenFlexure Microscope (https://openflexure.org) is a 3D-printed laboratory-grade motorized microscope, which was co-developed between the University of Bath, UK and the Tanzanian engineering company STICLab (https://sticlab.co.tz). It can be built using either inexpensive webcam optics for use in the classroom and non-demanding applications or lab quality, RMS threaded microscope objectives for state-of-the-art science. It replaces commercial tools that cost over $30,000 for under $100. The majority of the expense is in the Raspberry Pi (https://www.raspberrypi.org) and its camera module; the design requires only around 200g of plastic and a few parts that are easy to source in most places.



Caption: OpenFlexure Microscopes being set up left and detail (right) (CC-BY) courtesy of the GOSH community (the Gathering for Open Science Hardware) http://openhardware.science

Such economic savings are possible because of the proliferation of enabling FOSH such as distributed direct digital production with 3D printers[96] as well as the rise of FOSH-based electronics such as the Arduino microcontroller for designing new hardware[97] and keeping old hardware running.[98] This can be accomplished in-house, or by the proliferation of small and medium sized 3D-printing businesses manufacturing and selling products to consumers or other businesses in their communities (*see Box 4*).[99]

Box 4: Distributed Manufacturing for SDG 8

OpenDesk is a global platform for local making. It uses a business model for open-source furniture made with distributed on-demand manufacturing. It is an online marketplace that hosts independently-designed furniture and connects its customers to local makers around the world. OpenDesk designs are largely under creative commons licences and available to download. Designers can choose whether to make downloads available for free (which will increase distribution and uptake and is a nice way to provide value to individuals, charities, students and schools without impacting commercial revenue), or to charge for the download. For example, the Lift Desk shown below is an adjustable height workbench that goes from seated, to a bar, to a standing desk height. Anyone can download the design files and cut it out on their own open-source CNC (computer numeric controlled) mill. CNC devices are used to fabricate physical objects with a high degree of precision, and if they are mills, they do it with subtractive manufacturing, i.e., cutting away what you do not want in your object from a block of material, in this case wood. For those without their own CNC mills, they can order the product from local makers that are part of the OpenDesk network. In this way, everyone benefits from high quality design shared globally, yet local economic development occurs because of local manufacturing and sales.

Caption: Lift Standing Desk designed and shared by Joni Steiner and Nick Ierodiaconou under creative commons licence on OpenDesk. *See* https://www.opendesk.cc/lean/lift-standing-desk#make-it-yourself (CC-BY-SA-NC)

2.3 Distributed Recycling and Manufacturing

One of the most promising sustainable development opportunities that open hardware has enabled recently is distributed recycling and additive manufacturing (DRAM).[100] Several technologic pathways[101](see Box 5) have matured to allow individuals to recycle waste plastic directly by 3D-printing it into valuable products.[102] DRAM starts with waste plastic that is produced everywhere from packaging to broken products. It is washed, dried and then ground or cut into particles using a waste plastic granulator[103] or office shredder. Next, the particles are either converted to 3D-printing filament using a recyclebot[104] or printed directly. Filament made with a recyclebot costs less than 10 cents per kg, whereas commercial filament costs $20/kg or more. This can produce valuable products at remarkably low costs. For example, using a recyclebot/3D-printer combination can produce over 300 units (e.g., camera lens hoods) for the price of one such item listed on Amazon.com.[105]

This process can also be solar-powered directly, making it accessible even to those without reliable electricity.[106] The second approach skips making filament and uses fused particle fabrication (FPF) or fused granule fabrication to directly 3D print waste plastic into products at the large scale[107] and on the desktop.[108] Both approaches work over a wide range of plastics, including the most common one, PET (e.g., water bottles).[109] Lastly, 3D-printed waste molds[110] can be used to recycle composites or hard-to-print plastics.[111] Overall, both recycling[112] and 3D printing[113] via DRAM is better for the environment. With a pandemic interrupting global supply chains[114], making products at home from waste is even more appealing.

Box 5: How DRAM works for SDG 12

Below are two approaches to turning waste plastic into consumer goods with DRAM. On the left, waste plastic is first converted to filament in a vertical recyclebot and then 3D-printed into components for a camera tripod using fused filament fabrication (FFF), which is also referred to in the proprietary process of fused deposition modeling (FDM). On the right, the shredded waste plastic is directly 3D-printed using fused FPF to make a skateboard deck, which was converted into an electric-skateboard (as shown) using open-source plans.

FFF-based recycling on desktop Lulzbot 3D printer

FPF-based recycling on industrial-sized GigabotX 3D printer

2.4 What we learned about intellectual property and open source from COVID

Rapid access to high-quality information was of critical importance during the COVID-19 pandemic, yet conventional approaches to intellectual property (IP) hindered scientists, engineers and medical doctors from access to designs and clinical data trials, as well as the utilization of technologies such as respirators, diagnostic kits, therapeutics and vaccines that could have scaled to meet the demand. Scientific collaboration during the pandemic put aside copyright restrictions and has greatly relied upon open access to knowledge for research as major publishers such as Springer-Nature,[115] Elsevier,[116] and the *New England Journal of Medicine*[117] provided free access to COVID-19 articles. Perhaps most surprisingly, OS technologies have enabled engineers to rapidly design medical devices for domestic distributed production. There was an explosion of free and open-source designs meant to help others – everything from open-source ventilators[118] to personal protective equipment (PPE) like face shields[119] and masks. [120] In the U.S., the National Institutes of Health, for example, used their open-source 3D Print Exchange to review free designs for clinical and community use.[121]

All different kinds of makers are fabricating PPE for their local hospitals and helping each other in their communities. To see how widespread this type of sharing and caring is, consider just one group of “Helpful Engineers”.[122] They have congregated to aid in the COVID-19 pandemic response by developing both FOSS and FOSH of a wide range of medical devices, to create solutions that can be quickly reproduced and assembled locally worldwide. Although just starting out, they have over 2,500 registered volunteers, and their Slack team has grown quickly to over 9,000 by March 2020. These makers are largely professional engineers, but other non-professional maker volunteers sewed thousands upon thousands of face masks to help shield doctors, nurses and everyone else from the coronavirus.[123] This is just one group of dozens throughout the world.

2.5 Harnessing the Maker Movement

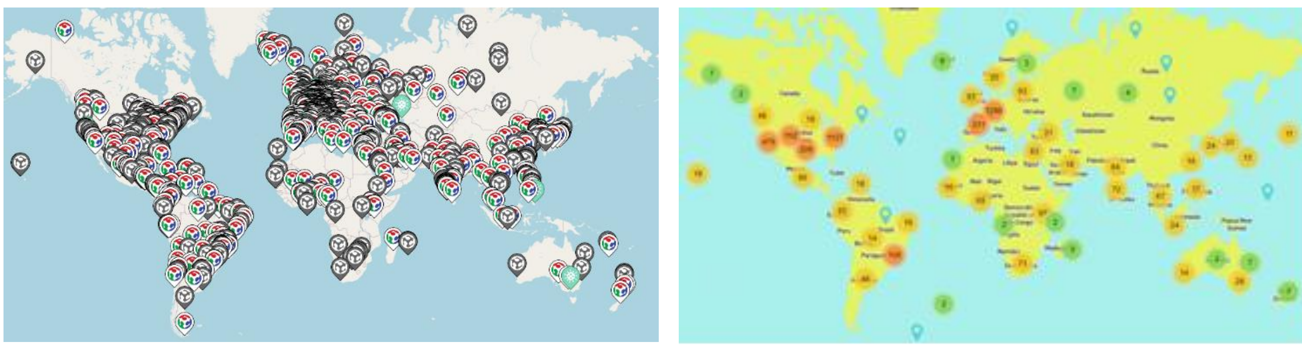
The *Maker movement,*[124] which encourages local manufacturing (i.e., making) for self-consumption are long been proponents of FOSH. Makers have a mutual expectation of collaboration.[125] Makers stress a cut-and-paste approach to standardized hobbyist technologies, and encourage cookbook re-use of freely published designs, which make local production far easier and convenient than replicating a proprietary product from an expired patent. A positive maker attitude is often a necessity in the developing world, where networks of grassroots innovation abound.[126] Even in the developed world, makers flourish. An estimate[127] by *USA Today* suggests the

U.S. has over 135 million makers, which is well over half (57%) of the American adult population. The maker movement itself is a relatively new subculture that represents a technology-based extension of the more traditional DIY culture.

Every family does not yet have both the capital and technical expertise to operate DRAM out of their homes (although this is possible). In larger systems, for DRAM to be a path to the circular economy, these tools could be housed in neighborhood-level enterprises like small local businesses, makerspaces, fab labs, and to a growing extent, schools, community centers and libraries. The return on investments (ROI) for small companies or fab labs making custom products, even one at a time, this way is substantial.[128] France is already investigating making small businesses that collect plastic waste at schools to make 3D filament.[129]

A growing number of community-operated physical places where people can meet, share skills and work on their projects using both analogue and digital manufacturing tools are spread out globally. Examples of such physical spaces include local hackerspaces,[130] fab labs[131] and makerspaces[132] (*see Figure 2*).

Figure 2. Geographical spread of global fab labs (left) and makerspaces (right) as of January 2021



Source: https://www.fablabs.io/labs/map

Source: https://www.nationofmakers.us/find-a-makerspace

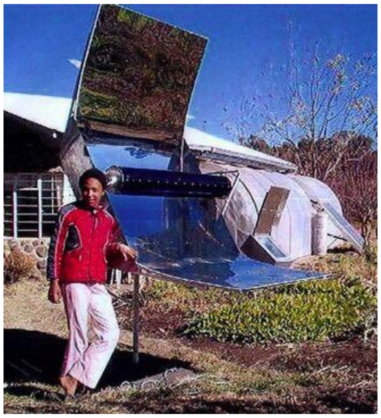
3. A CENTRAL OPEN-SOURCE DATABASE FOR SUSTAINABLE DEVELOPMENT GOALS

In order to meet the SDGs, it is imperative that those in the developing world have access to a broad knowledge base. Access to relevant knowledge can significantly improve the quality of life in developing communities and solve the challenge of sustainable development.[133] Some common examples include access to weather and sea conditions, crop and product valuation, micro-credit loan and financial tracking, government services and records, health care information, and transportation services.[134] Free and open-source technologies of all kinds eliminate the national-level economic loss resulting from duplication of work, which is why a *Central Open-source Database (COSD)* needs to be global in scope. One area particularly ready for open-source development and knowledge sharing is "appropriate technology" and would be expected to make up the core of an COSD. This area encompasses all of the SDGs and covers all technical areas.

Appropriate technologies[135] encompass technological choices and applications that are small-scale, economically affordable by locals, decentralised, energy-efficient, environmentally sound, and that enable local autonomy.[136] Thus, appropriate technologies are made up of technologies that are easily and economically utilized from readily available resources by local communities to meet their needs.[137] Appropriate technologies are normally discussed in terms of sustainable development for "*intermediate technologies*" that are viewed as stepping stones to enable people to escape poverty (SDG 1).[138] Therefore, the bias of appropriate technologies is towards relatively simple and non-complex technologies. For example, solar cookers[139] have been identified as appropriate technologies because of numerous advantages such as no recurring costs, the potential to reduce drudgery, the improvement of indoor air quality, the high nutritional value of food they produce, and high durability.[140]

There can be challenges (e.g., sunlight may be intermittent, space may be limited, initial capital costs too high, it may be perceived to be inconvenient of socially unacceptable[141]) but solar cookers can even be used at the retail scale (*see Box 6*). Appropriate technologies such as a solar cooker might be used by a family as an intermediate technology between cooking with a fire indoors until family capital accrues to use a more capital-intensive technology (e.g., a microwave oven) that enables more rapid cooking.

Box 6: Solar Bakery for SDG 2 and SDG 7



Caption: A solar trough baking oven along with a solar box cooker in the background (left) powers a solar bakery making bread (right) and other baked goods run by the Bethel Business and Community Development Centre in Lesotho in southern Africa. The design reports are available on the Solar Cookers International Wiki (CC-By-SA)(https://solarcooking.fandom.com/wiki/Solar-Trough-Baking-Oven) The BBCDC is both a commercial and technical school located in a remote rural district of Lesotho that was developed on barren land.

Even much of the research that is related to SDGs is unavailable to those who need it due to intellectual property law such as patents and copyrights.[142] It is argued that the results of this restricted and closed model of technological development creates socially-constructed scarcity[143](i.e., human social systems create a scarcity where physically it does not exist[144]) that is not conducive to addressing continued poverty and social challenges observed globally.

For example, the World Health Organization (WHO) reports that 5.2 million children under the age of five died from treatable causes.[145] This loss of life could be prevented by known technologies, many of which are simply not available due to socially-constructed reasons to those who need them. Availability is restricted by indirect causes, such as paywalls on articles under copyright, which restrict the free flow of information and by direct causes like companies leveraging patents to restrict the manufacturing of medical products (e.g., restricting the sale of antiretroviral drugs to treat HIV in Africa[146]). One way the appropriate technology movement is modernizing to overcome these IP-related barriers is to blend with the open-source approach to technology development[147] in order to overcome many appropriate technologies' shortcomings as a technology change model[148] and completely breaking away from IP restrictions. The OSAT approach, even in areas such as medical research, radically reduce the costs even in the upfront investment and can be funded publicly, while earning a high return on investment.[149]

An open-source appropriate technology (OSAT)[150] is a technology that provides for the SDGs while being designed in ways synonymous with FOSS/FOSH.[151] OSAT can also be used to empower communities,[152] as people create value for themselves.[153] When using the open-source design paradigm, the OSAT must meet the traditional appropriate technology boundary conditions.[154] There are numerous groups, non-profit organizations, universities, companies and individuals that have embraced the open-source paradigm when working on an appropriate technology because of the growth of the Internet even to the least developed areas of the world (*see* next section for examples).[155] Following the OSAT paradigm, anyone can learn how to make and use appropriate technology free of IP concerns while simultaneously adding to the collective open-source knowledge commons[156] by contributing ideas, designs, observations, experimental data, deployment logs, wish lists, etc. The primary current challenge is that these contributions are spread over hundreds of websites, often in different contexts and languages. Thus, not only there is duplication of efforts but people cannot easily find solutions. For example, open-source designs needed by an impoverished community in Honduras for a community renewable-energy microgrid exist and would help drive economic development in the area, but these are behind a paywall at the Institute of Electrical and Electronics Engineers (IEEE).[157] Another version of the designs is freely accessible, but it is only in English and not-tagged or searchable on Engineering for Change.[158] A COSD repository would solve this problem and provide a one-stop-shop for the community in Honduras along with for everyone else in the globe to find the OSAT they need to solve the problems they prioritize. It is thus imperative that the COSD is global in scope.

In addition, the COSD should not be limited to specific sectors or applications as open-source technologies can often solve problems far outside the scope of their intended use. For example, consider ImageJ[159] which is an open-source image processing and analysis software package originally developed to look at microscopic organisms. Due to its being open-source and highly adaptable, it is now being used even for remote-sensing work carried out by aerial drones over vast land areas.[160] OSAT development has already reached sophisticated devices such as open-source 3D printers used for both the design and the production of OSAT in a wide range of areas.[161] For example, RepRap can be used for manufacturing tools for organic farming,[162] to making microscopes[163] (*see Box 3*) for medical clinics or for full optical labs in schools and research facilities in developing communities for far less cost than conventional means.[164] In order to ensure 3D printing and other distributed digital manufacturing tools are actually an appropriate technology,[165] communities must be able to choose out of the millions of free designs what they want to manufacture, as well as what they can add to them. In addition, they must also have access to the Internet and to electricity (e.g., solar-powered 3D printers[166]). Such distributed manufacturing with appropriate local feedstocks like waste plastic can be used to make a sustainable OSAT system for the circular economy (*see Box 5*).

With OSAT, all the information, data, plans, full digital design and manufacturing files, instructions for assembly and use, etc. are all freely available. This is in contrast to patents, which have been the primary means of technical deployment in the past. Patents generally only contain the idea and demand a licence agreement or commercial sale to disperse. With OSAT, these barriers to diffusion are lifted. Community members themselves decide what OSAT to deploy based on their own priorities. The community, however, needs to know it is there to meet their needs and they need a mechanism and the capacity to do it. OSAT often involves some investment and communities need to be assured that the devices will work before they take the risk with the investment. This is where there is a critical need for a centralised trusted database of vetted OSAT.

Most OSAT work focuses on a specific technology, such as low-tech off-grid wind turbines,[167] often from a technical or engineering perspective. There have been efforts on learning models,[168] as well as service learning,[169] yet there is a need to better tie an appropriate technology to technology diffusion.[170] This need exists because the development and diffusion of an appropriate technology and OSAT was largely pursued by the not-for-profit appropriate technology movement and was largely conducted by engineers.[171] Stated simply, professional engineers and amateur makers can provide solid OSAT for any location to meet any given need. People throughout the world, however, need to be able to easily access this information. Thus, there remains a distinct need for increasing the rate of OSAT, which is why there is a pressing need for a trusted, global Centralised Open-source Database.

4. EXISTING DATABASES AND POTENTIAL PARTNERS

Fortunately, the creation of a COSD does not demand starting from scratch as there are many organizations, non-profits and for-profit companies developing OSAT and maintaining existing small-scale databases. This section will not attempt to review all of them as they are extremely diverse in (*i*) technical focus areas, (*ii*) application targets, and (*iii*) national origin and language. Instead, several examples will be given for representative organizations that would be natural partners for the COSD and how they might work with the UN in mutual benefit to meet the SDGs.

Many OSAT are available, but are found scattered in databases for particular technologies. For example, the RepRap wiki maintains a list of databases that house 3D printable OS designs.[172] As of January 2021, there are 48 databases, many of which contain thousands of designs, and some that maintain millions of designs. Similarly, there are dozens of databases that cater to those with access to other technical tools like CNC mills or laser cutters with OS designs. In addition, there are organizations that are dedicated to specific application areas, such as over 80 organizations focused on SDG 6 for water and sanitation that are operating in more than one country.[173] Similarly to the FairCap,[174] which develops digitally manufacturable low-cost activated carbon filters to clean drinking water, many single technology organizations are not included in any database. In addition, other complementary organizations focus on specific applications, like MANDATE, which is assembling an inventory of technologies commonly used to save maternal, fetal, and neonatal lives globally.[175] Substantial work is needed to get these database owners to enable SDG categorization as well as single technology NPOs to enable record importation of all of the OSAT into a central easily searched database.

The COSD has natural partners in the open-source community, like the OSHWA,[176] which aims to foster technological knowledge and encourage research that is accessible, collaborative and respects user freedom. OSHWA provides an Open-source Hardware certification,[177] which allows the community to quickly identify and represent hardware that complies with the community definition of open-source hardware.[178] The certified open hardware is organised by country, type and licence and is primarily from commercial open hardware vendors.

There are also many natural partners for the COSD from different countries. An example is Village Earth,[179] which is a U.S. non-profit that works to achieve sustainable community-based development by connecting communities with global resources through training, consulting, and networking with organizations worldwide. Village Earth leads communities through a series of workshops where participants create a community vision, identify obstacles or constraints, and create an actionable plan. Village Earth members then provide links to outside resources and knowledge through a variety of information sources that have been created within the organization including a digitized Appropriate Technology Library. Having a multilanguage updated database would accelerate Village Earth's mission and they could provide access to their Appropriate Technology Library to be indexed in the COSD. In addition, as their partner communities deployed OSAT, they could feed this back into the COSD to help provide vetting and ranking. There is already evidence that organizations like Village Earth are amenable to such partnerships because they have joined forces with Appropedia,[180] a website for collaborative development of solutions, focused on sustainability, poverty reduction, and international development. Appropedia is a wiki-based website where a large number of participants are allowed to create and modify the content directly from their web browsers.

Appropedia offers insight into the benefits of a full COSD. It has enormous potential to assist in sustainable development because it takes on the administration of collaboratively organizing information, project examples, and best practices, thus allowing sustainability, appropriate technology, social entrepreneurship, service learning and international development organizations and individuals to focus on what they do best. Appropedia has already become the appropriate technology venue of choice for other organizations like Engineers Without Borders – Australia[181] (a community organization that creates social value by developing skills, knowledge and appropriate engineering solutions), Demotech[182] (an organization in the Netherlands that Re-designs concepts, tools, methods, ideas to make them accessible and affordable to everybody in the world), and the Full Belly Project[183] (an organization dedicated to empowering people in developing countries with the ability to achieve independent and sustainable economies by facilitating the design and distribution of appropriate technologies). It is set to expand rapidly as other organizations utilize its information transfer capability. Appropedia, combined with recent advances in semantic MediaWiki, can be viewed as the foundation for COSD as it allows users to add structured data to wiki pages and thus be easily organised and searched. The COSD could either directly partner with Appropedia to expand their offerings or partner with them as a content provider.

There are other organizations, like Open-source Ecology[184] (OSE), which has the goal to provide 'open-source blueprints for civilization' itself. These is perhaps an ambitious goal, but they are doing this by providing extremely practical innovations. OSE is providing the open-source plans for a Global Village Construction Set[185] (*see Box 7*), which is fifty of what OSE has identified as the most important devices for modern society. Each open-source device is meant to be modular, able to be built by anyone, and low-cost. Overall, the idea is to have a high-performance platform that allows for the easy fabrication of the fifty industrial machines that it takes to build a small, sustainable civilization with modern comforts. Their open-source solutions are at a fraction of commercial costs.

Box 7: Offerings at the Open-Source Ecology

Caption: The fifty open-source devices in the Global Village Construction Set (left) being developed by Open-source Ecology and an example (right) is the 27-horsepower open-source LifeTrac tractor (CC-BY-SA). OSE uses a modular design so that components can be re-used or swapped. So, for example, the "power cube", which is a modular, universal, self-contained power unit, consisting of an engine coupled to a hydraulic pump, provides power from hydraulic fluid at high pressure through quick connect hoses. It can be used to power the tractor and can also be taken off to power other OSE machines.

There has been steady development of these fifty tools with help from specific open-source communities, like those working on laser cutters and 3D printers. OSE, however, has taken the lead on many tools like a tractor, backhoe, trencher, ironworker, rototiller, soil pulverizer and compressed earth block press, and has already prototyped and, in several cases, the technology (e.g., the tractor) has been replicated all over the world.

Some of the OSAT databases are businesses. For example, Wikifactory[186] is a hybrid social platform with an embedded hardware product development workspace that enables multi-person CAD collaboration. Wikifactory has over 70,000 members from 190 countries. Almost half of the projects on Wikifactory are aligned with the UN's Sustainable Development Goals and is their fastest growing project cluster.[187] It supports projects like Dronecoria, which is an open-source drone platform for aerial sowing of seed balls, for the efficient large-scale forest reforestation[188] and the 3B version (Bare Bones Build) of the Nextfood Aeroponic vertical farming system.[189] There are several databases that are commercial but contain some OSAT, like MyMiniFactory[190], which is a 3D-printing repository that sells some designs, but also has a vast quantity of free, easily-replicated open-source content. Websites like these would agree to partner as long as the COSD could provide them with more users.

Another example is Engineering for Change (E4C),[191] developed by the American Society of Mechanical Engineers, the IEEE and Engineers Without Borders USA, and includes many collaborators including the United Nations Major Group for Children and Youth. E4C helps develop affordable appropriate technologies. The most relevant E4C resource is the Solutions Library,[192] a curated database of products that meet basic needs and SDGs. In the Solutions Library, products are arranged by technological category, searchable, able to be found by price, the region and the units distributed. Although very useful, many of the products do not have open-source documentation and are not amenable to local manufacturing. E4C operates as a searchable database that sends users out to partner companies offering the products. E4C solutions would need to be screened for full OS documentation to be included in the COSD.

There are similar initiatives and websites centered in different countries. For example, in India, the Society for Research and Initiatives for Sustainable Technologies and Institutions (SRISTI)[193] maintains several databases of interest, including Common Property Resource Institutions (CIPRI) Database,[194] which is a database consisting of 138 cases of indigenous resource Institutions from across the world. SRISTI is also partnered with the HoneyBee Network[195], a collection of traditional knowledge, low-cost practices, medicinal plants, and grassroots innovations where the creators are acknowledged. Another example, Techpedia[196] has a database of 200,000 engineering projects by 550,000 students, mainly from India. In addition, the Grassroots Innovation Database GRID[197] maintained by the UNDP India and the HoneyBee Network currently has over 1,500 innovations. Similarly to many of the existing databases developed in the U.S., the quality of the documentation, as well as the ability to be replicated, varies widely and would benefit from a COSD quality-assurance approach.

One of the HoneyBee Network institutions is Gujarat Grassroots Innovation Augmentation Network (GIAN),[198] which is India's first technology business incubator focused on commercializing grassroots innovations (solutions generated by people at the grassroots levels to solve persistent problems, which are either not available or not affordable to the consumer masses in developing countries). GIAN maintains a database of U.S. patents that are no longer in force,[199] which is similar to the Free Inactive Patent Search[200] developed in the U.S. for open-source technology development.[201]

There are databases at the World Intellectual Property Organization[202] in their Patentscope and Global Design Database for existing patent searches as well as more complicated data analytics at Lens,[203] which serves global patent and scholarly knowledge as a public good to inform science and technology enabled problem solving. Unfortunately, patent-related information is not nearly complete enough to meet the standards of modern OS documentation, particularly for distributed digital manufacturing. In the OS model, users can simply download complete design files, modify or customize them if needed and then digitally fabricate functional replicas of the technology. Even with complete access to a patent and a legal licence, replicating the technology from Patentscope or similar offerings is far more complicated, time consuming and costly. It should also be pointed out patent information explicitly does not include an open licence and thus is not appropriate for inclusion in the COSD until it has entered the public domain.

The Lens Cooperative is attempting to address some of the friction and delays caused with IP licensing for social enterprises (starting in 2021), however, the quality and completeness of the documentation based on patents is inadequate for OS-style digital replication.[204] There are other academically-focused databases, like Google Scholar, which can also be used to obtain information about technologies that can help with SDGs**.** There is, however, a major difference between a patent document that is primarily legal and rarely contains all the necessary information for fabricating a product, or a scholarly article which often minimizes the 'method' for making a technology and the far more comprehensive OS model that provides complete design files to enable users to make modifications to designs in their native OS software (and thus accessible) format.

The WHO has published a compendium of new and emerging technologies that address global health concerns targeted at low-resource settings.[205] Such independent and neutral vetting of technologies is needed for those developed by organizations like PATH that re-invent medical devices as reliable and easy-to-use tools that work in places where resources are limited (e.g., money, power and trained health care workers).[206] It should be stressed that OSAT can be sophisticated high-tech and normally expensive products such as autosamplers[207] for rapid biomedical research (*see Box 8*).

Box 8: Osmar, an open-source autosampler for SDG 3

Caption: Commercial microsyringe manipulation is common for automated sampling of liquids or gases and normally costs over $30,000. Osmar, is a viable technically-accessible alternative that can be adapted and expanded for more general liquid handling tasks and be built for under $1,000 (CC-By).

5. DOWNLOADED SUBSTITUTION VALUE AND RETURN ON INVESTMENT

The return on investment (ROI) for the development of FOSH can be calculated from the downloaded substitution value (discussed in the annex. To understand how powerful this approach is, consider a simple open-source syringe pump library design[208] and example derivative[209] (*see Box 9*), which may be government funded for scientific innovation acceleration, but also have applications in STEM education and medicine. Currently, the repositories the open-source syringe pump is housed on do not allow tracking of uptake by country, which is a feature that could be integrated into the COSD to help quantify the value for developing countries of FOSH designs.

Box 9: Open-Source Syringe Pumps

Low-cost open-source pumps are completely customizable allowing both the volume and the motor to scale for specific applications including carefully controlled dosing of chemical reagents, pharmaceuticals, and other applications. The design, bill of materials and assembly instructions are globally available to all for free.



The pump library was designed using open-source and freely available OpenSCAD, which is a script-based, parametric CAD package enabling users to customize the design for themselves. The majority of the pump parts can be fabricated with an open-source RepRap-class 3D printer and readily available parts such as a stepper motor and steel rods. The pumps can be used as wireless control devices attached to an open-source Raspberry Pi computer (middle image). Thus, one can control the pumps from any internet-connected device like a laptop or smart phone. Performance of the syringe pumps generated by the open-source library were found to be consistent with the quality of commercial syringe pumps.

The cost to purchase a traditionally manufactured syringe pump, Cp, ranges from $260-$1,509 for a single pump and $1,800-$2,606 for a dual pump (left and center images). Cf for the materials for an open-source syringe pump is $97 and $154 for the single and double pump. As of December 2020, the designs for the open-source pump, have been downloaded from two digital repositories a total of ND = 10,646 times (2,177: Thingiverse 8,469: Youmagine). The time to assemble either the single or double pump is less than an hour and can be accomplished by a non-expert. The assembler hourly rate is assumed to be $10/hour as no special skills are needed. P was assumed to be 1, as although 3D printer owners may view many designs, they only download the STL files (STereoLithography is a file format used for 3D printers) of the designs they intend to print. This provides a savings for substituting the open-source pump for a commercial one of $153 to $1,402 for a single and $1,636 to $2,442 for the double pump. Thus, following equation 1, the value VDT of the pump library in December of 2020 ranged from over $1.6m to over $25.9m. The value actually increases far more when considering the additional secondary benefits of enhanced research, derivations such as the Y-struder (right image) that allows for material testing for additive manufacturing, enhanced education (for students that can now afford to use a syringe pump) and any secondary values from improved medical care when the pump is used. The ROI based on an I of $30,000 by equation 2 is over 5,000% at the minimum. (CC-BY-SA)

The ROI for even modest use would be expected to be many times the investment as the COSD would be expected to drive more use than any single repository and if adopted widely far more than the aggregate all of the current scattered repositories.

6. WHY THE UN SHOULD TAKE THE LEAD

As summarized in the introduction, the UN already has established a leadership role in advocating open-source technology for the member countries through the UNCTAD E-Commerce and Development Report 2003, the Information Economy Report 2012, the intergovernmental deliberations since the 15th session of the CSTD in 2011-2012.

Critics may point out that the private sector could potentially provide this solution, as for example, there are 3D design search engines like Yeggi, and companies like Google or Amazon, that are well positioned to make a search engine to cover OS designs for SDGs, or a database of SDG-relevant products. There are, however, major issues with having central OS repositories owned by private companies. For example, GitHub, the largest FOSS repository in the world, was purchased by Microsoft. An engineer at Blockstack,[210] which posts its open-source software on GitHub explains: "GitHub doesn't compete with most companies, but Microsoft is a potential competitor or acquirer for a huge percentage of smaller companies in the tech industry. Giving your competitor access to your company's most valuable secrets understandably makes people uneasy."[211] This indicates the risk with having the COSD run by either a single nation (that could potentially exclude or limit participation from its geographic rivals), or a company (that could exclude the best work of its business rivals). There are two examples that demonstrate the real risk of operating a central open-source database from a private company or attempting to profit from it by restricting access.

First, even an open-source 'champion' company is vulnerable to changes in policies because of conflicts with funders. This occurred with MakerBot, which was previously a model open hardware 3D-printing company. It was the largest and most successful prosumer 3D-printing company up to 2012, literally helping build the Maker Movement in the United States. MakerBot was purchased in 2013 by a conventional IP-focused additive-manufacturing company, Stratasys. With the change in ownership, MakerBot abandoned the open-source ethos and largely lost the support of the maker community. Supporters and customers were outraged by the sudden change in licensing of their files on the MakerBot online service Thingiverse, as the company attempted to patent designs which were freely uploaded, deleting previously-supported documentation, and only releasing new printers and software as proprietary.[212] Many users pulled their designs in protest (Occupy Thingiverse) and the majority of designs became 'private.'[213] The previously exponential increase in open designs observed in Thingiverse[214] slowed to less than a million a year in 2020. This number now stands at only 4.6m designs in total, many of which are personalizations or have been deleted by the designers. MakerBot's initial proprietary designs failed[215] and their "Smart Extruder" was so poor that it resulted in a class action lawsuit from investors against Stratasys for purchasing MakerBot. Compounding failures have largely destroyed Makerbot as their 3D printer sales have plummeted, resulting in laying off its entire manufacturing force in the U.S.[216] This same risk is present if a country suddenly changes its political preferences and thus radically changes their international collaboration and foreign policy.

In areas where the open-source ethos is mature, IP closure to extract a profit from freely given information risks losing the best developers. This was apparent when thousands of the top machine learning and artificial intelligence (AI) researchers[217] boycotted the *Nature Machine Intelligence* journal because it was not open access. Machine learning has been at the forefront of the movement for free and open access to research. For example, in 2001, the Editorial Board of the *Machine Learning* Journal resigned *en masse* to form a new zero-cost open access journal, the *Journal of Machine Learning Research* (*JMLR*).[218] Quoting from the 2001 resignation letter:

> *"...journals should principally serve the needs of the intellectual community, in particular by providing the immediate and universal access to journal articles that modern technology supports, and doing so at a cost that excludes no one."*

Today, the closed *Machine Learning* journal has an impact factor of 2.672, while the open *JMLR* has an impact factor about double at 5.310.[219] The impact factor is a scientometric index that reflects the yearly average number of citations that articles published in the last two years in a given journal received and is generally used as proxy for the relative importance of a journal within its field. This indicates that the best developers favor an open-source approach and that the IP-restricted venues to extract profit will not house the highest-quality information.

For these reasons, the COSD should be operated by a non-profit entity from an international and highly-trusted organization. The UN is rightly positioned.

A trusted centralised database or repository of high-quality open-source designs can accelerate the diffusion of the technologies. Currently, there is no such database available. Databases focusing on technology like the patent databases do not provide the level of detail required. The efficacy of this approach on a limited scale was witnessed by the COVID-19 PPE shortage in the U.S. that was solved in part by an agreement[220] by the National Institutes of Health (NIH) and the Food and Drug Administration (FDA) within the U.S. Department of Health and Human Services, and Veterans Health Administration within the U.S. Department of Veterans Affairs to accelerate distributed manufacturing of 3D-printed protective gear for COVID-19 response.[221] The successful process began with the existing NIH's 3D Print Exchange, which is used to share and find 3D models that are clinically relevant and readily compatible with distributed digital manufacturing. The maker community submitted their open-source designs relevant to COVID-19 to the repository, and then the Veterans Health Administration, NIH and FDA evaluate and test the submitted designs. For hospitals, many of which had no (or little) prior 3D printing experience, having a trusted source and a point of contact to address questions about 3D-printable medical devices and products such as PPE, was critical to enable the FOSH to be used in hospitals by the tens of thousands to overcome the shortage. This worked despite the U.S. medical system being largely private for-profit hospitals, highly fractured and competitive. Similarly, for a global Central Open-source Database to be most effective, it needs to be housed in a trusted central authority like the UN.

The UN is experienced and highly-qualified at forging partnerships, essentially mirroring the NIH example in the U.S. for the whole world with the Tech Access Partnership (TAP) program initiated by the UN Technology Bank that supports developing countries to scale up local production of critical health technologies needed to combat COVID-19 and ensure equitable access to essential health technologies. Because TAP does not provide the actionable designs as the NIH does, the COSD would provide direct access to needed information to produce OSAT and thus fill the gap.

The DESA's Division for Sustainable Development Goals and the UN Office for Information and Communication Technology released 2030 Connect jointly with UNCTAD and WIPO in July 2020. This is an online tool intended for entrepreneurs, innovators, students and leaders from around the world to exchange ideas and technology, build networks, and work to advance the SDGs.[222] At present, the information on technologies currently available in 2030 Connect is not specific and concrete enough to allow a producer in a developing country to manufacture an OSAT that is relevant to a SDG or several SDGs, as one could use the disclosed information by Harvard on making ventilators and by Switzerland on the WHO's website on making hand sanitizer. The 2030 Connect tool is primarily focused on forming partnerships and the information on the 2030 Connect provides contact information of innovators for a particular technology but does not provide sufficient information (i.e. a complete recipe) to produce the technology.

The COSD, on the other hand, will contain detailed information and steps on how to fabricate and use an OSAT that is relevant to a SDG or several SDGs, and in some cases the digital designs to directly replicate it. However, there is no need to create the COSD from scratch. The 2030 Connect could be enhanced in the direction to fulfill the tasks of the COSD.

The success of the COSD depends on support from the UN Member States as well as collaboration and cooperation among UN agencies including UNCTAD, DESA, UNDP and regional commissions. Private sector engagement in COSD is equally important. For example, companies that already belonging to organizations like Open-Source Hardware Association may find it beneficial to share their own designs with the COSD.

7. CONCLUSIONS

Technologies that are appropriate to the needs of developing countries in achieving SDGs are badly needed. Commercially available technologies are often too costly for many users in developing countries to afford or too difficult for local adaptation and adoption. Financial and intellectual property constraints also make traditional technology transfer a serious challenge for many developing countries.

The open-source approach to technology diffusion is a fast-developing model to provide developing countries access to technologies. OSAT are increasingly seen as key to supporting these countries' efforts to achieve SDGs.

Many initiatives, including several within the UN system, have been created to facilitate transfer of technology including FOSS. The current deficiencies in relation to these initiatives, such as narrow or sector-specific coverage of technologies, lack of or insufficient technical information and scattering of technologies among various database make it difficult for producers and consumers in developing countries to locate OSAT easily.

A COSD to be hosted by the UN could address these existing deficiencies. Joint efforts from relevant UN agencies, support from the UN Member States and the private sector are necessary to make it a success.

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[8]8 "*Free*" here refers to a user's freedom to use, copy, study, and change the software in any way as well as sell it (https://www.gnu.org/philosophy/free-sw.html) because of the "Open-source" or access to the source code. To be open-source, software must meet several requirements (*see* https://opensource.org/osd). Free software focuses on the fundamental freedoms it gives to users, whereas open-source software focuses on the advantages of peer-to-peer technical development model. FOSS is used here to avoid bias towards either political approach.
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