Heikkinen, Ismo; Savin, Hele; Partanen, Jouni; Seppälä, Jukka; Pearce, J.M.

Towards national policy for open source hardware research: The case of Finland

Published in:
Technological Forecasting and Social Change

DOI:
10.1016/j.techfore.2020.119986

Published: 01/06/2020

Document Version
Peer-reviewed accepted author manuscript, also known as Final accepted manuscript or Post-print

Please cite the original version:
Heikkinen, I., Savin, H., Partanen, J., Seppälä, J., & Pearce, J. M. (2020). Towards national policy for open source hardware research: The case of Finland. *Technological Forecasting and Social Change*, *155*, Article 119986. https://doi.org/10.1016/j.techfore.2020.119986

Towards National Policy for Research Open Source Hardware:

The Case of Finland

I. T. S. Heikkinen[1], H. Savin[1], J. Partanen[2], J. Seppälä[3], J. M. Pearce[1,4*]

[1] Department of Electronics and Nanoengineering, School of Electrical Engineering, Aalto University, Espoo, Finland.

[2] Department of Mechanical Engineering, Aalto University, Espoo, Finland.
[3] Department of Chemical and Metallurgical Engineering, School of Chemical Engineering, Aalto University, Espoo, Finland.
[4] Department of Materials Science & Engineering and Department of Electrical & Computer Engineering, Michigan Technological University, Houghton, MI USA.

*Correspondence to: pearce@mtu.edu 1400 Townsend, Houghton MI 49931 USA

Abstract

Free and open-source hardware (FOSH) is rapidly gaining momentum because it provides customized research hardware with over 90% savings compared to the costs of proprietary tools. However, the focused skill sets of researchers who aim to facilitate their own research limit FOSH complexity. The most expensive research equipment normally requires an interdisciplinary team. To overcome this complexity barrier and obtain large returns on investment for research funders by replacing the most expensive research equipment with FOSH, new development funding mechanisms are needed. To guide such research policy, this paper provides the first analysis of the strategic national benefit of applying the FOSH approach to major research equipment for any nation. The results of an example analysis for a single nation indicate Finland's science funders could save between 2.84-27.7m€/year directly on scientific equipment purchases if research hardware is converted to FOSH and the nation would likely garner the well-established concomitant benefits of increased research innovation within their economy. Finally, a detailed generalized model for determining national research policy in hardware development is derived and research policy mechanisms for accelerating FOSH deployment and greater accessibility to research equipment are discussed.

Keywords: economics of science; equipment; research tools; open source; open source hardware; research expenditures

1. Introduction

The inflated costs of highly-specialized proprietary scientific equipment restricts access to research tools for experimentalists throughout the world (Pearce, 2014). This challenge is most acute in regions with low scientific expenditures as the countries that spend the most on scientific tools and researchers to use them have the highest scientific outputs (May, 1997; Man et al., 2004). However, even in the wealthy countries of Europe (Man et al., 2004) and the United States (National Science Board, 2012), rarely do research labs have unrestricted access to the best research tools or as many of them as necessary to optimize their rate of discovery and innovation. Lack of access to the optimal research tools because of costs thus slows the rate of scientific and technical development in every field (Pearce, 2014;2017).

Free and open-source hardware (FOSH) (Powell, 2012; Gibb, 2014) builds on the same sharing philosophy and rights of users that underlies the success of free and open source software (FOSS)[1]. FOSH is hardware whose design is shared publicly so that anyone can study, modify, distribute, make, and sell the design or hardware based on the design (OSHWA, 2018). Thus, both FOSS and FOSH go beyond open access, granting users substantial freedoms to build on the intellectual work of others[2]. FOSH provides the "source code" for physical hardware including the bill of materials (BOMs), schematics, computer aided designs (CAD), and other information such as detailed instructions needed to recreate a

---

[1] The superiority of FOSS method for software development is well-documented (Raymond, 1999; Zeitlyn, 2003; Lakhani & Von Hippel, 2003; Weber, 2004; Comino et al., 2007; Lee et al., 2009; Herstatt & Ehls, 2015).

[2] It should be noted that the FOSH definition from OSHWA demands these freedoms, however, in the open source software community there is a splitting of the freedoms, which are only available in pure FOSS while not necessarily for licenses in some open source software listed by the Open Source Initiative (OSI) (https://opensource.org/licenses). Some of the licenses allowed by OSI are not FOSS (e.g. some code is only free for non-commercial usage, but cost for commercial purposes or can not be commercialized) (FSF, 2016).

physical item. As well established in FOSS development,[1] research-related FOSH is now demonstrating improved product innovation (Dosemagen, et al., 2017; Yip & Forsslund, 2017). FOSH is rapidly gaining momentum because it provides customized research hardware for cost generally 90-99% less than similar commercialized proprietary tools (they thus can be produced for 1-10% of their commercial counterparts).[3] These savings are possible because of the proliferation of enabling FOSH such as distributed direct digital production with 3-D printers (Jones et al., 2011; Bowyer, 2014) as well as the rise of FOSH-based electronics such as the Arduino microcontroller (Pearce, 2012; Baden et al., 2015; Coakley and Hurt, 2016).

Hundreds of FOSH research tools already exist (Pearce, 2014; Baden et al., 2015) as researchers design (Oberloier & Pearce, 2018), share and build on one another's work (Harnett 2011). Similar to FOSS (Subramanyam & Xia, 2008), most FOSH is developed by scientists to "scratch an itch" – i.e. solve a problem for themselves in their own labs (Pearce, 2012). In practice, this has resulted in wide coverage of relatively simple tools[4], which have purchase costs less than 10,000€. The complexity of FOSH is currently limited by the focused skill sets of researchers, who know how to use the tools, but not necessarily how to design them. The most expensive equipment normally requires an interdisciplinary team of scientists, engineers and computer programmers, which are not frequently available in all laboratories. This complexity barrier represents a significant opportunity cost to the scientific community. It has already been shown that investing in FOSH development of even modestly complex tools (e.g. syringe pump (Wijnen et al., 2014)) in the 100€-1,000€ range, can create a return on investment (ROI) more than 1,000% in only a few months (Pearce, 2016).

To overcome this complexity barrier for FOSH development and obtain similar ROIs on the most expensive research equipment, funding mechanisms are needed at the national level. In this paper, the theoretical approach to fostering national FOSH developed proposed by the U.S. National Academy of Engineering (Pearce, 2017) is applied to Finland. The main contribution of this study is a new method that is developed and demonstrated on an example nation to determine the best strategic investments for a nation for FOSH development. The method follows five steps: i) the most-representative university in the country is selected for a detailed analysis of research equipment purchases greater than 10,000€ over the past 20 years; ii) the equipment is classified into four categories ((1) characterization, (2) electronics, (3) processing and (4) space improvements) and then refined to sets of instruments; 3) these are compared to available FOSH; iv) evaluated for future FOSH development; and v) the origin of the equipment classes are determined to investigate balance of trade impacts. Using this approach national research priorities are recommended for Finland. Finally, the Finnish example is made useful for those in other countries using a detailed generalized model is derived for determining national research priorities in hardware development and appropriate research policy mechanisms are investigated.

2. Background on Finland

This paper specifically targets policy improvements for Finland, which are based on the National Systems of Innovation (Lundvall, 2010) or National Innovation Systems (Sharif,

---

[3] There are many studies that document enormous economic savings with FOSH (Fisher and Gould 2012; Pearce 2012;2017; Murillo and Wenzel, 2017; Damase et al., 2015) and argue for open source science (Willinsky, 2005; Hope, 2009; Robertson et al., 2014; Friesike et al., 2015; Nosek et al., 2015).

[4] Examples include: handheld micropumps (Bravo-Martinez, 2017), turbidimeters (Kelley et al., 2014), optics equipment (Zhang, et al. 2013; Salazar-Serrano et al., 2017) or automatic feeders for animal experiments (Oh et al., 2017).

2006) approach. This approach argues that technological flows and technology development interactions are often more frequent within national boundaries (Niosi, et al., 1993; Edquist, 2010; Lundvall, et al., 2002; Lundvall, 2010). These national systems of innovation can be at least in part a function of government at the national level (Nelson, 1988; Nelson and Rosenberg, 1993). National economies are enhanced by science as both innovation draws on science as well as the demands for innovation force the creation of science (Rosenberg and Landau, 1986; Caraça, Lundvall, and Mendonça, 2009). Thus, with FOSH showing both an innovation and direct economic benefit, this national example attempts to determine the best FOSH investments for Finland to support their national system of innovation within university-industry-government interactions.

2.1 Background on Finland and University Selection

Finland, a sparsely populated northern European country with about 5.5 million people, has taken a holistic and systematic approach to education (Sahlberg, 2012) that resulted in a reputation as one of the best education systems in the world (Morgan, 2014). Finland has 15 universities (*yliopisto),* which provide free education to all qualified citizens, which are selected in a fully transparent, merit-based, and objective process (e.g. no human factors, extracurricular, or application essays). Universities put a lot of effort towards research, which provide some of the highest per capita outputs globally (Man, 2014; Oksanen et al., 2003). Students obtain a theoretical education and the most talented students are encouraged to join research groups.

In addition to Finland's clear commitment to educating their citizens, Finland is an early and aggressive adopter of telecommunication technology and one of the most wired nations (based on mobile phone and Internet usage) (Ibrahim, 1997; Cooper, 2016). The appeal of advanced communication is clear as Finnish values include a devotion to equity and cooperation (Sarjala, 2013) – even being called "a nation of cooperators" (Leonard, 2000). It is thus not surprising that a Finnish university student developed an operating system (Torvalds & Diamond, 2001) and then shared it with the world in a way that provided the origin of the open source movement (Bonaccorsi & Rossi, 2003;2006). Linux, the resultant free and open source operating system, now dominates proprietary rivals with 94% of the world's top 500 supercomputers (Noyes, 2012), 75% of the top 10,000 websites and 98% of enterprises using open-source software (Rosenberg, 2010). In addition, Android, a Linux-based operating system accounted for 84% of the smartphone market in 2016 (Gartner, 2016) and is now making inroads in smart TVs, thermostats, Amazon's Kindle e-reader, drones, and self-driving cars (Finley, 2016). This spirit of cooperation responsible for birth of the open software movement is the reason Finland is selected as the example country. In addition, previous empirical findings in Finland indicate that the adoption of technologically advanced strategies requiring complex legal and managerial knowledge, such as those using an open source strategy, demands relatively highly educated people (Harison & Koski, 2010) that Finland's education system can provide. Researchers operating in Finland already have a high degree of cooperation and productivity and thus would appear to be primed to take advantage of the benefits of FOSH in research.

The University of Helsinki is the largest and makes up more than 20% of the Finnish higher education system. Aalto University and the University of Turku both make up more than 10% and the remaining universities are smaller than 10% of the student population. Due in part to data access, Aalto University was chosen over Turku University as medium-large university, which is heavily technology focused as the best representative of the research equipment infrastructure of Finland.

2.2 Background and Description of Aalto University

Aalto University (Finland's second largest with 17,500 students) is a relatively new university established in 2010 as a merger of the Helsinki University of Technology (established 1849), the University of Art and Design Helsinki (established 1871) and the Helsinki School of Economics (established 1904). The merger was intended to foster close collaboration between the scientific/engineering, design and business communities for multi-disciplinary education and research, which appears ideal for FOSH development and deployment.

Aalto University has defined four fundamental competence areas (Aalto University, 2018): 1) ICT and digitalization, 2) Materials and sustainable use of natural resources, 3) Art and design knowledge building and 4) Global business dynamics. In addition to these areas, the university invests in three integrative multidisciplinary themes that focus on solving challenges that are important globally and for the Finnish economy (Aalto University, 2018): 5) Advanced energy solutions, 6) Human-centered living environments and 7) Health and wellbeing.

Aalto University showcases Finland's experiment in higher education with several internationally known innovations including: The Aalto Design Factory, Aalto Ventures Program and Aalto Entrepreneurship Society (Aaltoes) as well as the digital fabrication facilities at the Design Factory, A-Space, the Learning Centre's Fab Lab and the ADD lab (specializing in additive manufacturing research and development). Combined these multidisciplinary initiatives have contributed substantially to the emergence of Helsinki as a hotbed for at least 500 startups (Kennedy, 2017). This multi-disciplinary approach as well as ready access to digital fabrication tools are essential ingredients to advanced FOSH development.

3. Materials and Methods

3.1 Data Source and Frame of Analysis

This paper evaluates the research expenditures over the last 20 years at Aalto University. Aalto University Procurement provided raw data in Finnish including the type, supplier, price and purchase date for all instruments priced over 10,000 € purchased by Aalto University in the last 20 year. The economic analysis is from the position of the nation of Finland scaling the results from Aalto University to the country scale for the reason described in Section 2. The goal of the analysis is to maximize the value of the return on FOSH investment for Finland by offsetting research equipment costs.

3.2 Procedure

The text data was translated from Finnish into English. Then, the type of instrument was classified into the following categories: (1) characterization, (2) electronics, (3) processing and (4) space, building, or room improvements. Next the three non-space constrained categories were further refined into their top two sub-categories (1a) characterization nonimaging and (1b) characterization imaging and (2a) electronics-specialty and (2b) electronics-IT and (3a) bulk processing or (3b) nanoscale processing and finally lasers, which can be used for both characterization and processing.

All sub-classes were evaluated in detail with the research expenditures for major equipment being compared to what is available or under development in the FOSH community now.

3.3. Calculations

The highest value of future FOSH opportunities in Finland, $V_{Finland}(j)$, was identified for in the two major classes (characterization and processing) for all instruments (j) using:

$$V_{Finland}(j) = d_{FOSH} \sum_{i=1}^{L_{Finland}} c_j(i) \times n_j(i) \qquad (1)$$

$L_{Finland}$ is the total number of research labs in Finland, c_j is the cost per unit of j instrument, and n_j is the number of j instruments in i lab. d_{FOSH} is 1 minus the expected discount from replacing a proprietary tool with FOSH and is taken as a range of savings from 90-99% (Fisher and Gould 2012; Pearce 2012;2017; Murillo and Wenzel, 2017; Damase et al., 2015).[5] This can be calculated as the sum of the lab equipment at each university and the sum of all universities:

$$V_{Finland}(j) = d_{FOSH} \sum_{k=1}^{U_{Finland}} \sum_{i=1}^{I_{University}} c_j(k) \times n_j(k) \qquad (2)$$

This is further approximated by using data from a single representative university:

$$V_{Finland}(j) \approx d_{FOSH} \times S_r \times \sum_{i=1}^{I_r} c_j(k) \times n_j(k) \qquad (3)$$

Where $U_{Finland}$ is the total number of universities in Finland (15), $I_{university}$ is the total number of labs at university i. For a specific representative (r) university a scaling factor (S_r) can be determined based on the ratio of total expenditures. Here S_r is estimated to be ~6.6 for Aalto University using data based on ratio of research funds at Aalto University (196 m€) and the total sum of all Finnish universities (1,294 m€) in 2016 (Vipunen -- Education Statistics Finland, 2018).

In addition, to determine national economic impacts, the nationality of firms supplying the equipment was evaluated. Using this approach and data for Aalto a generalized model for determining national research priorities is derived and discussed.

4. Results and Discussion

In the past 20 years Aalto University has invested 49.146m€ items in 625 individual of scientific equipment costing more than 10,000€ per item. The average expenditures for the last ten years was 4.3m€/year and was generally limited to no more than three tools over 0.5m€ per year. Using the semi-quantitative estimated based on the literature that FOSH costs only 1-10% (see footnote 3) of proprietary tools, it is calculated that if all major research infrastructure were converted to FOSH, Aalto University would save between 0.43m€ and

---

[5] This range is dependent on the proportion of the equipment that can be digitally manufactured by researchers. As the proportion increases the costs near those of the materials and the savings approach 99% or more (Hietanen, et al., 2018). It should also be noted that this is the most common range of savings, savings can be less and far greater savings have been demonstrated with FOSH on individual components (e.g. a USD$4,000.00 slot die can be replaced with one that costs USD$0.25 (Beeker et al., 2017)).

4.2m€ annually on research equipment expenditures. Similarly, following equation (3), Finnish science funders could save between 2.84m€ and 27.7m€ annually. Ideally, such savings would be reinvested in research to provide access to more and better equipment for more of Finland's researchers.

The results of the percent classification of high-value research expenditures is shown in Figure 1. The most expensive tools, which cost more than 1m€, were for magnetic resonance imaging (MRI) and transmission electron microscopy (TEMs) in the classes of characterization and imaging.

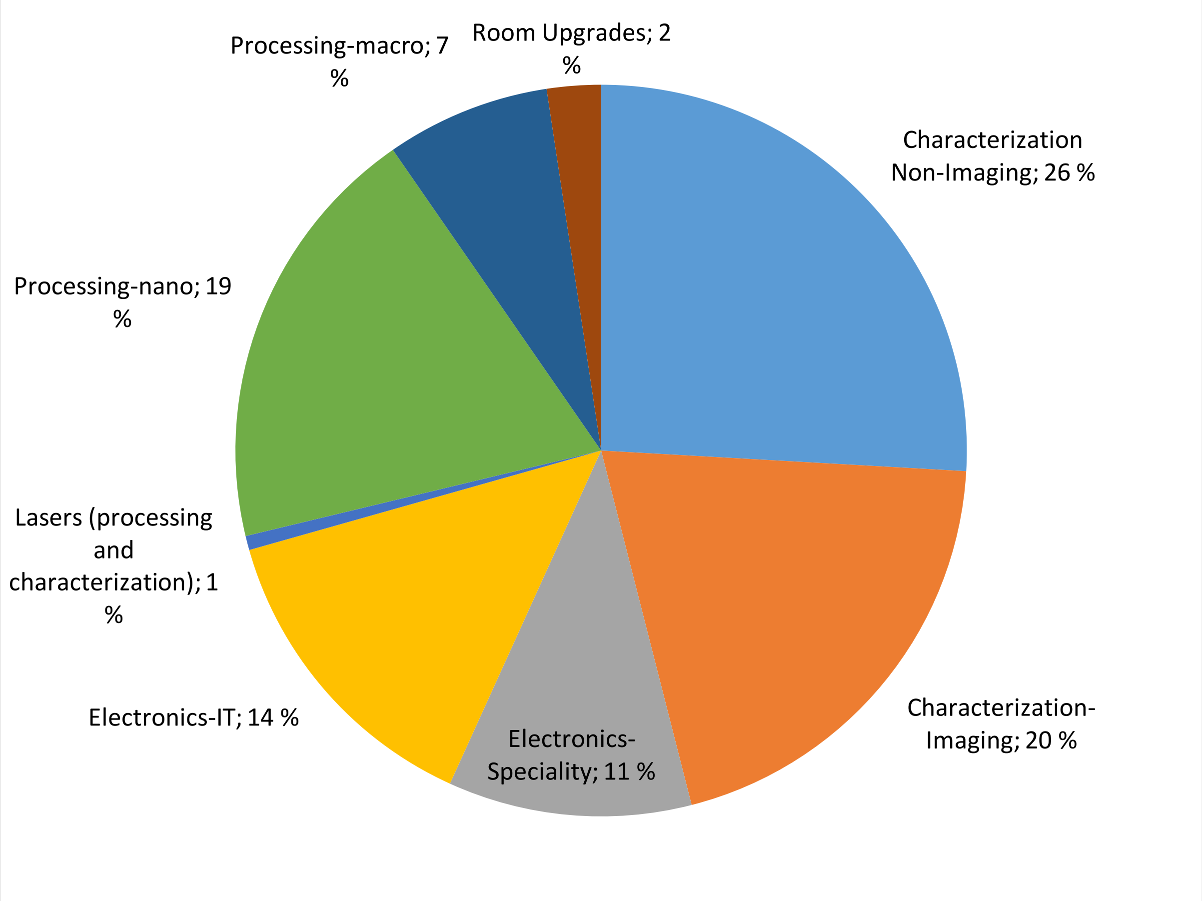

Figure 1. Distribution of Aalto University research expenditure in percent of the classes of research tools costing more than 10,000€.

As can be seen in Figure 1, characterization equipment dominates expenditures at 46% with over 22.6m€ invested. Within characterization, nearly half of the equipment is for imaging. Many FOSH imaging tools have been developed for the low and medium-end microscopy work. including: a one-piece 3-D printed flexure translation stage for open-source microscopy (Sharkey et al., 2016), light-sheet microscopes and optical projection tomography (Gualda, et al., 2013), automated 3-D microscopes (Wijnen, et al., 2016), fluorescence microscopy (Chagas, et al., 2017), microscope-based cytometry (Gordon et al., 2007), and two photon microscopy (Roseneggar, et al., 2014). Although there was some optical microscopy purchases in the data set[6], the largest investments for imaging is for nanoscale

---

[6] Most optical microscopes and their accessories cost less than 10,000€.

imaging using transmission electron microscopes (TEM) at 4.5m€, scanning electron microscopes (SEM) at 2.4m€ and scanning probe microscopes like atomic force microscopes (AFM) and scanning tunneling microscopes (STM) at 0.7m€. Several research groups have developed their own AFM/STMs and thus a high-quality FOSH AFMs and STMs can be expected in the near term (Babu et al., 2014; Kang, 2015; Li et al., 2016; Loh et al., 2017; Open AFM, 2018). However, the development of both SEM and TEM technologies come with significant hurdles because of the complexity of the technologies and there is thus an opportunity for Finland to benefit from developing FOSH versions of these technologies. Conservatively assuming that the FOSH SEM and TEM would cost 10% of the cost of current commercial offerings, 0.69m€ would provide the same technology abilities as has already been invested by Aalto University thereby saving 6.2m€. Using equation (2) if these two FOSH tools could be developed, Finland as a whole could save over 40m€ to obtain the equivalent level of nano-scale imaging. Thus, relatively modest investments to design the FOSH SEM and TEM (on the order of a few million €) would result in a substantial ROI directly (Pearce, 2016). In addition, there has been considerable progress on the development of open source software (e.g. the Gnome X Scanning Microscopy (GXSM) software (Zahl, et al., 2010), Gwyddion (Nečas & Klapetek, 2012), and the X-windows based microscopy image processing package (XMIPP) (Sorzano, et al., 2004), which could be leveraged to accelerate these projects. Finally, the public domain imageJ software program could be used for the image analysis (Collins, 2007; Schneider, et al., 2012) providing a completely open source toolchain.

Electronics and processing both make up about a quarter of the expenditures at around 12m€ each. Within electronics, mass produced items with dual uses in information technology sectors (e.g. servers) make up 6.8m€ investment, while specialty electronics only accounts for 5.3m€. Providing open source solutions that can directly compete with mass manufactured IT equipment is more challenging than directly targeting open source specialty electronics, thus specialty electronics makes a better target for FOSH developed scientific tools. One of the earliest successful FOSH projects was the Arduino electronics prototyping platform (Banzi & Shiloh, 2014), which enables research applications including: behavioral experiments (D'Ausilio, 2012), electrophysiology (Newman, et al., 2012), traps and data loggers for arthropods (McMunn, 2017), pressure monitoring (Russell et al., 2012), lab rotator/mixers (Dhankani et al., 2017), drop velocity measurements (Fobel, et al., 2013), microscopy (Gualda, et al., 2013), Skinner boxes (Pineño, 2014), low-cost UAVs for oceanographic research (Busquets, et al., 2012), and multi-spectral in-vivo optical image acquisition (Sun et al., 2010). Finally, the Arduino-enabled self-replicating rapid prototyper can be converted to a printed circuit board mill (Anzalone, et al., 2015); so that FOSH circuit designs can be fabricated using only FOSH tools. In addition, there is already a robust open source electronics industry and well-developed business models (Seidle, 2012;Pearce, 2017b).

The majority of processing technologies purchases were for nanotechnology related processing for more than 9.3m€, while macroscale processing was only 3.6m€. Nanoscale processing technologies offer more opportunities for FOSH development because of the relative impact of the materials costs on nanoscale vs macroscale development. In addition, there are only a few examples of FOSH development of macroscale technology (Macul & Rozenfeld, 2015; Osunyomi, et al., 2016), which are primarily based on agriculture and not research. Within the nanoscale processing technologies, atomic layer deposition (ALD) systems or components were the most numerous. This is particularly interesting as ALD was first developed independently in Finland and today Finland has a strong leadership presence in the scientific community as the technique has expanded around the globe (Puurunen, 2014). ALD is a thin film deposition method in which a film is grown on a substrate by exposing its surface to alternate sequential gaseous precursor pulses. In each of these pulses the precursor molecules react with the surface in a self-limiting way, providing unprecedented control of material growth. ALD can thus be used to tailor interface properties by depositing high-quality thin films with precise thickness control, very good uniformity over large areas and excellent step coverage on non-planar surfaces (George, 2009). ALD has already proven itself as an enabling technology for the miniaturization of transistors (Kim, et al., 2009), which enables it to play a major (and growing) role in the semiconductor industry. ALD also has other rapidly expanding applications including flexible electronics (Maydannik, et al., 2014), OLED displays (Park, et al., 2011; Choi, et al., 2014), energy conversion and storage (Meng, et al., 2017; Yersak, et al., 2018), and solar cell fabrication (Niu, et al., 2015). In particular, Aalto University publishes aggressively in the field: according to Google Scholar more than 135 articles per year in the past 5 years including demonstrating the use of ALD for passivation of high-efficiency "black silicon" solar photovoltaic cells with incredible promise (Savin et al., 2015) and close to ideal photodiodes with a high conversion efficiency over a wide spectral range (Juntunen et al., 2016).

Although, Aalto University has many more ALD systems than a typical research university, it still suffers from innovation delays caused by restrictions on machine availability.[7] Essentially, all institutions working on ALD would benefit from having access to more machines. As these ALD tools are already manufactured in Finland, funding for Finnish industry in collaboration with universities to create an open source desktop ALD specifically targeted at researchers may be an appropriate mechanism for accelerating the deployment of ALD applications throughout the world in industry.

As shown by the results, Finnish science funders could save between 2.84m€ and 27.7m€ annually on scientific equipment purchases if all major research hardware purchases are converted to FOSH. However, it should be pointed out here that these values although quantified are themselves extremely conservative as they do not account for any internal (e.g. in-house or learning-by-using following Rosenberg (1982)) or external (e.g. learning by interacting following Lundvall (2010)) learning effects. Moreover, there is already convincing research that has shown that firms that adopt FOSS benefit from increased productivity (Nagle, 2018). This would be similarly expected of the companies that adopt the FOSH developed to directly support research although quantification of this benefit is left for future work. In addition, science (which historically was unhindered by intellectual property concerns) and technology that is patented are no longer being separated (Nelson, 2004). This can restrict innovation, slow science and be detrimental to the economy.[8] Thus by encouraging the development of new open source research tools, not only does the university

---

[7] ALD is in general a slow process (e.g. a few nm per minute), so to make one sample takes more time than using other tools in research environments where in general batch processing is not used.

[8] Many authors have argued that intellectual property restricts innovation and that science itself should be an open source collaboration (Eisenberg, 1996; Heller and Eisenberg, 1998; Takalo and Kanniainen, 2000; Nelson, 2003;2004; Forero-Pineda, 2006; Boldrin and Levine, 2002;2004;2008; Pearce, 2012b;2013; Pagano, 2014; Biddle, 2014; Osborn et al., 2015).

save research funds, they also enable others to innovate faster. This moves research closer to what Pénin (2008;2011; Pénin and Wack 2008) describes as an 'open source innovation' model that goes beyond the confines of the business focused 'open innovation' (Santos, 2015; West and Bogers, 2017). Research on the impacts of FOSS on economic growth (Greenstein and Nagle, 2014) provide some idea of how these values would dwarf direct savings. Overall, the increased network effect catalyzed by FOSH would be expected to increase research productivity and have economic benefits far outside of the labs either funded to do FOSH or that use it.

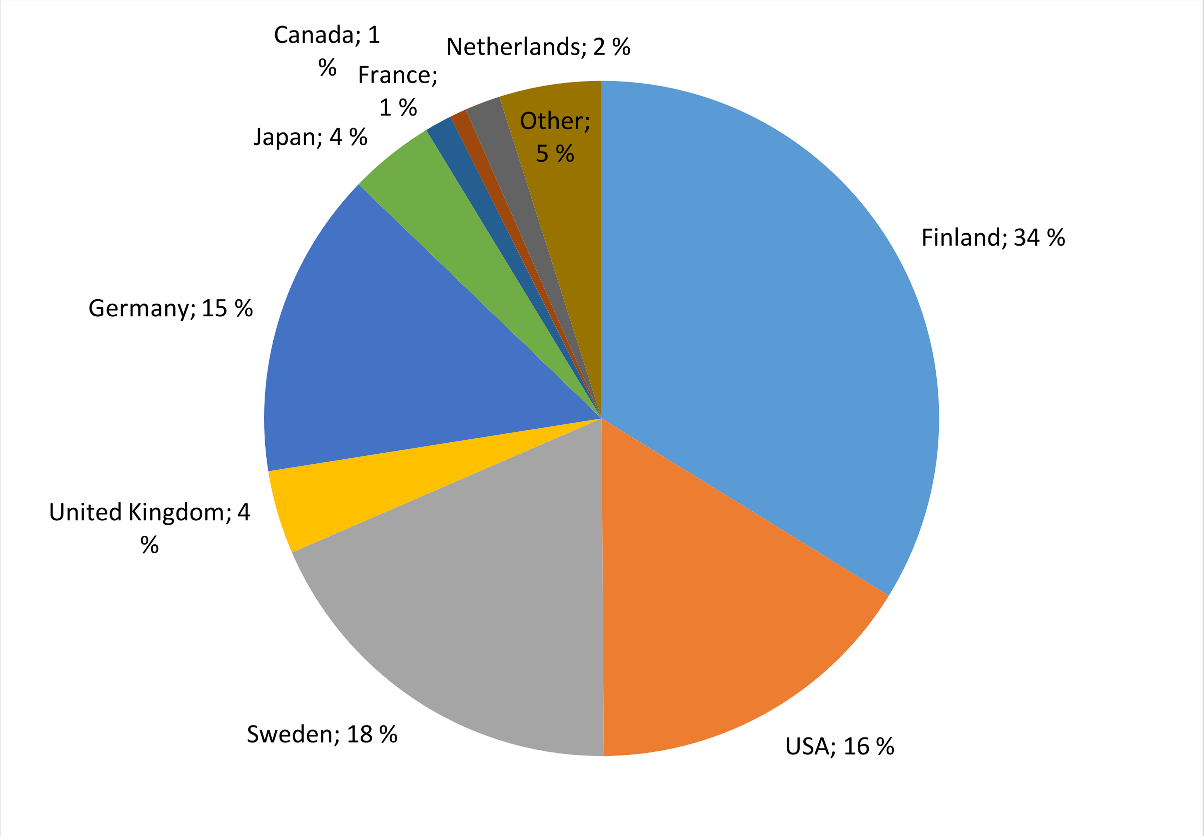

Figure 2. Distribution of Aalto University research expenditures in percent of the countries of origin for research tools costing more than 10,000€.

There are also direct national economic benefits that can be approximated. As can be seen in Figure 2, only 34% of research tools are purchased from Finnish companies, with the majority of equipment coming from outside of the country most notably from the USA, Sweden and Germany. Thus if all high-cost equipment were to be transitioned to FOSH, about 2/3rds of this would 'on shore' production currently carried out by equipment manufacturers in other countries and about 1/3 outside of the European Union. However, even these values are somewhat misleading. For example, the majority of the SEM equipment was supplied by JEOL, which although having offices and sales points in Germany and Sweden and other countries throughout Europe is actually a Japanese company. For example, JEOL (Germany) GmbH is a subsidiary of JEOL Ltd. Tokyo. By 'on shoring' production of FOSH in Finland, Finland balance of trade stands to benefit as it would decrease the trade deficit with Germany and Sweden, while strengthening Finland's trade advantage with the United States (Statistics Finland, 2018).

5. Generalizable National Policy

5.1 Steps Towards National Research FOSH Policy

Understanding that FOSH can both accelerate innovation and reduce costs and following the National Systems of Innovation approach discussed in Section 2, a generalizable five step process for fostering FOSH can be followed. Here the National Academy of Engineering model in the US (Pearce, 2017) was adapted for Finland. This adaptation would be necessary for any specific region based on the funding and organization structure present.

First, a country should establish a task force or panel to identify the best opportunities to realize strategic national goals and a high ROI for the creation of FOSH. These goals can be directly related to obtaining more research for the funds invested in research, but as shown above could also have an impact on the balance of trade.

Second, a country's largest past research equipment expenditures of high-cost (>10,000€) equipment should be determined along with likely future expenditures (e.g. the European Strategy Forum on Research Infrastructures (ESFRI) or Academy of Finland's Roadmap for Research Infrastructure (FIRI)). The targets for FOSH can be ordered following equation (1). For large countries, doing this nation-wide without an existing database could cause unnecessary bureaucratic hardship. Most universities maintain their own databases of high-value research equipment so equation (2) can be used. Where data availability or database analysis is limited, a subset of universities can be analyzed as was demonstrated here with Aalto University and then scaled up to determine national impact with equation (3). In addition, funders may want to collect this information for future grants to make more-informed decisions on priorities in the future. Thus, the method outlined in this paper can be directly applied to small countries or it will need to be scaled up for larger countries to ensure a representative quantity of purchasing data is used.

Third, existing national research funding mechanisms should be identified for the development of FOSH research equipment and then specific calls for proposals should be issued for strategic innovations. This can be accomplished with a combination of traditional calls for proposals: e.g. Academy of Finland FIRI, Business Finland funding for small and large companies cooperating with research organizations, EU H2020 and FP9's funding for enabling technologies, and to some degree also the Strategic Council for Research and the Foresight activities of Prime Minister's Office. In addition, funding agencies may wish to sponsor contests like the XPRIZE or "first to make" can promote progress toward specific technical goals by offering "bounties."

Fourth, governments can directly assist market development for FOSH by i) prioritizing funding for FOSH scientific equipment design over purchasing proprietary offerings, ii) ensuring that grant award guidelines direct PIs to consider lower-cost FOSH and iii) create a purchasing preference for all of Finland's more than 70 government research centers (e.g. VTT), universities, 25 universities of applied science and other teaching institutions.[9]

---

[9] It is clear that FOSH must exist before strong guidance for acquisitions for FOSH research equipment is put in place. However, FOSH is available for significant numbers of tools today and (particularly) at the low end can be effectively used as STEM teaching tools (Herger et al., 2015; Schelly, et al., 2015).

Fifth, create a free online database of tested, -vetted, and validated FOSH, with the bill of materials, digital designs, instructions for assembly and operation, and source code for all software and firmware. Funding for this vetting is needed to eliminate the technical risks for labs to adopt the use of the FOSH, while simultaneously making the research equipment future proof (in contrast to proprietary equipment that can become obsolete when a company loses key personnel, discontinues a product line, or goes out of business). The database would be equivalent to the digital twin model used in industry (Sierla, et al., 2018). There have been efforts on this front with for example in the US. NIH 3-D Print Exchange[10], which provides a portal for custom labware (Coakley et al. 2014; Coakley and Hurt 2016). Three scientific publishers have also started to do the same: 1) Public Library of Science's Open Source Toolkit[11], 2) Elsevier's *HardwareX* journal for publishing validated studies of scientific FOSH and 3) Ubiquity Press's broader *Journal of Open Hardware.*

Following these five steps will encourage entrepreneurs to scale production of manufactured components that are not easily digitally distributed (e.g., microcontrollers, -sensors, actuators) often called "vitamins" as they are necessary to make a piece of FOSH research equipment.

5.2 Limitations

There are several limitations to this study. First, it only evaluated data from a single university. Although the university was carefully selected to be the most representative of research investments within the nation, future studies could add to the robustness of the example country by studying more or even all of the purchasing data from other universities in Finland. This would be approachable because Finland is a relatively small country. However, it is a single country, which is the second limitation of this study. There are significant differences between countries in terms of their national strategies, research priorities, available funding, etc., which limit the results of this study from being universally applicable. Finland is also well positioned to implement pro-FOSH policy because the already has a large focus on cooperation using a network approach (Schienstock and Hämäläinen, 2001) and a relatively strong national innovation system (Godinho et al., 2005; Castaldi, 2009). Other countries may be less receptive as well as may be lacking the require infrastructure. For example, Woodson et al. finds that 3-D printing is not an overly inclusive innovation tool in Brazil because of lack of government support and lack of access at the individual level (2019). In the case of Finland, 3-D printing is routinely found at public libraries, and is already accessible within the university system so it may represent an outlier in terms of personal access. However, as this study is specifically focusing on the high-end research tools, it can be assumed that most labs purchasing those tools would have access to digital manufacturing technologies that cost less. In addition, future work is needed to determine the impact on the overall scientific equipment industry. If a large amount of open hardware begins to flourish in the scientific community could it reduce the number or quality of commercial products or would the increased competition drive innovation?

5.3 The Dilemma of Innovation Parasites and Profiting from FOSH

Although benefits for developing and using FOSH equipment are clear (e.g. increased researcher control, lower costs, more customizability and novel experiments, future proofing,

---

[10] https://3dprint.nih.gov/

[11] https://channels.plos.org/open-source-toolkit

avoiding vendor lock in, shorter lead times, etc.) a nation may be tempted to wait for others to invest in FOSH and simply be pure users. Similar to parasites in nature that utilize resources from a host (the open source community) but never benefit it, some users or even nation states may be tempted to forgo their own FOSH (or FOSS) development. In the open source community, this is often referred to as the "free loader" dilemma. This section will address the question: Why should a small country or one with a limited scientific budget invest in FOSH?

In addition, to the well-established economics of research and development of all kinds (Evenson, et al., 1979; Griliches, 1991; Salter & Martin, 2001; Bilbao-Osorio & Rodríguez-Pose, 2004), freeloading on FOSH development loses the national benefits of 1) an accelerated National Systems of Innovation and 2) from increased business opportunities directly related to FOSH.

Businesses that are close to academic research have a major advantage over those located at a distance (Mansfield & Lee, 1996). It is highly likely, for example that a FOSH project developed at a university results in one or several businesses to provide the FOSH commercially or the vitamin kits to make it. For example, Italy benefits materially from Arduino having been developed there first, where it continues to be manufactured profitably despite not being a major national player in microelectronics manufacturing (Arduino, 2018). Similarly, companies are beginning to offer FOSH for specific research applications spun out of research groups such as OpenTrons for fluid handling, Pax Instruments for temperature monitoring, OpenQCM for quartz crystal microbalances, OpenPCR for thermocycling, and RedPitaya for FPGA (field programmable gate arrays).

Li et al. (2017) identified five economic motivations for FOSH companies, which can be applied to nations wanting to capitalize on the opportunity that open source affords: 1) reduce research and development costs as discussed above, 2) reduce recruiting costs using open source records of researcher skills, 3) eliminate patent intellectual property costs, 4) build a platform (e.g. Arduino) or 5) provide a related service (e.g. RedHat). Defying conventional wisdom open source innovators can profit handsomely from sharing with for example, RedHat earning more than $2 billion per year on a version of Linux that is technically free although they invest heavily to develop it (Callaway, 2017). FOSH business models have also been successfully applied in the scientific hardware sphere for both selling hardware directly as well as services around them in addition to using low-cost FOSH to provide outsourcing services for researchers (Pearce, 2017b).

Researchers are particularly well-positioned as potential customers interested in a reliable open hardware option as they have the capacity to improve them. Empirical studies of innovation have found that end users frequently develop important product and process innovations (von Hippel, 1976;1986;2005; Shaw, 1985; Franke and Shah, 2003; Shah, 2000; Harhoff, et al. 2003), which can be major benefits to a FOSH-based company. Everyone benefits from the free sharing including users that can reproduce the innovation and benefit from using it and the original innovator and manufacturers are in a position to refine the innovation and sell it to all users (Harhoff, et al. 2003). Even before the open source movement, innovating users often did not sell or license their innovations to manufacturers and instead freely reveal details of their innovations to other users and to manufacturers (von Hippel and Finkelstein, 1979; Allen, 1983). In addition, some of the technical communities such as high energy physics have already have an established open access system through publishing preprints with arXiv (Gentil-Beccot, et al., 2010). This free sharing of "open source" information is critical to the success of both FOSS and FOSH. Firms that benefit from this approach can add to it without being 'pure' in terms of libre. Hippel and Krogh, for example, detail the benefits of a "private collective" innovation model (2003), which still provides real free and open source contributions from members. For a nation, to take the largest potential advantage of FOSH development of research tools, it is necessary to be active participants in the development itself.

6. Conclusions

In the example country presented in this article, Aalto University was used as a representative university in Finland and strategic FOSH design targets were discovered. The analysis of the national FOSH research priorities for Finland include developing open source TEM and SEM microscopes and ALD systems. Conservatively, FOSH development of the two electron microscopy tools would save Finland over 40m€ to obtain the equivalent level of nano-scale imaging. Similarly, millions of Euros would be saved nation-wide, while significantly strengthening Finland's ALD-related research excellence by strategically releasing a FOSH lab-scale ALD. Overall, the results indicate Finnish science funders could save between 2.84m€ and 27.7m€ annually on scientific equipment purchases if all hardware costing over 10,000€/item is converted to FOSH. Furthermore, about 2/3rds of this would 'on shore' production currently carried out by equipment manufacturers in other countries and 1/3rd outside of the European Union. It should be noted, that the economic benefits quantified here are minimums because none of the benefits of open innovation were determined. The literature supporting these benefits is well developed and the catalytic effect increased innovation in the lab that FOSH produces would be expected to catalyze economic growth similarly to standard scientific innovation.

The results of this example country analysis provide not only clear potential positive impacts for policy interventions to support strategic FOSH development in Finland, but they also provide generalizable directives for other nations. First, the method used in this study can be directly replicated in other highly-educated, scientifically and industrially advanced nations. All the nations with some form of national innovation systems in place can immediately benefit from support for FOSH development and deployment for domestic high-technology products used in research (e.g. similar to the open source ALD potential for Finland). In larger and more diverse nations, it may be appropriate to apply this model over smaller geographic areas (e.g. states within the U.S. or by funding agencies focused on a specific discipline or set of problems such as the NIH). Also with increased resources, a large country (e.g. China) or entity like the European Union could perform a study over representative research institutions to enjoy the benefits of increase FOSH deployment domestically. In conclusion, the model used for Finland here can be generalized and could be used by any nation for determining national research policy and research policy mechanisms for accelerating FOSH deployment in research.

7. Funding

Fulbright Finland supported this work. Ismo T. S. Heikkinen acknowledges the financial support of Walter Ahlström foundation and Aalto ELEC Doctoral School.

8. Acknowledgements

The authors would like to thank Antti Laakso and Jukka Stenroos for access to Aalto University equipment data, Ella Bingham and Matti Kaivola for helpful discussions.

9. References

Aalto University. (2018). Key research areas. http://www.aalto.fi/en/research/strengths/

Aalto University. (2018b). Key figures and annual reports http://www.aalto.fi/en/about/reports_and_statistics/

Allen, R. C. (1983). Collective invention. *Journal of Economic Behavior & Organization*, *4*(1), 1-24.

Anzalone, GC, Wijnen, B and Pearce, JM (2015). Multi-material additive and subtractive prosumer digital fabrication with a free and open-source convertible delta RepRap 3-D printer. *Rapid Prototyping Journal* 21(5): 506–519.

Arduino. (2018). How to spot a counterfeit Arduino. https://www.arduino.cc/en/Products/Counterfeit

Babu, S. K., Singh, J. S., Moni, D. J., & Devaprakasam, D. (2014). Design and Development of a Nanoscale Multi Probe System Using Open Source SPM Controller and GXSM Software: A Tool of Nanotechnology. *arXiv preprint arXiv:1410.2709*.

Baden T, Chagas AM, Gage G, Marzullo T, Prieto-Godino LL, Euler T. (2015). Open labware: 3-D printing your own lab equipment. *PLoS Biology* 13(3).

Banzi, M., & Shiloh, M. (2014). *Getting started with Arduino: the open source electronics prototyping platform*. Maker Media, Inc.

Beeker, L. Y., Pringle, A. M., & Pearce, J. M. (2018). Open-source parametric 3-D printed slot die system for thin film semiconductor processing. *Additive Manufacturing* 20: 90–100.

Biddle, J.B., (2014). Can patents prohibit research? On the social epistemology of patenting and licensing in science. *Studies in History and Philosophy of Science Part A*, *45*, pp.14-23.

Bilbao-Osorio, B., & Rodríguez-Pose, A. (2004). From R&D to innovation and economic growth in the EU. *Growth and Change*, *35*(4), 434-455.

Boldrin, M. and Levine, D., (2002). The case against intellectual property. *American Economic Review*, *92*(2), pp.209-212.

Boldrin, M. and Levine, D.K., (2004). Lawrence R. Klein lecture the case against intellectual monopoly. *International Economic Review*, *45*(2), pp.327-350.

Boldrin, M. and Levine, D.K., (2008). *Against intellectual monopoly*. Cambridge: Cambridge University Press.

Bonaccorsi, A., & Rossi, C. (2003). Why open source software can succeed. *Research Policy, 32*, 1243–1258.

Bonaccorsi, A., & Rossi, C. (2006). Comparing motivations of individual programmers and firms to take part in the open source movement: From community to business. *Knowledge, Technology & Policy*, *18*(4), 40-64.

Bowyer, A. (2014). 3D printing and humanity's first imperfect replicator. *3D Printing and Additive Manufacturing*, *1*(1), 4-5.

Bravo-Martinez, J. (2017). Open source 3D-printed 1000 µL micropump. *HardwareX.* https://doi.org/10.1016/j.ohx.2017.08.002 (in press).

Busquets, J, Busquets, JV, Tudela, D, Pérez, F, Busquets-Carbonell, J, Barberá, A, Rodriguez, C, Garcia, AJ, Gilabert, J (2012). Low-cost AUV based on Arduino open source microcontroller board for oceanographic research applications in a collaborative long term deployment missions and suitable for combining with an USV as autonomous automatic recharging platform. *Autonomous Underwater Vehicles (AUV)*, September 2012 2012 IEEE/OES: 1–10. IEEE.

Callaway, T. (2017). To the Moon and Beyond: Open Source and Open Innovation. *The Bridge* 47(3): 46-47.Caraça, J., Lundvall, B.Å. and Mendonça, S., (2009). The changing role of science in the innovation process: From Queen to Cinderella?. *Technological Forecasting and Social Change*, *76*(6), .861-867.

Castaldi, C., (2009). The relative weight of manufacturing and services in Europe: An innovation perspective. *Technological Forecasting and Social Change*, 76(6), 709-722.

Chagas, A. M., Prieto-Godino, L. L., Arrenberg, A. B., & Baden, T. (2017). The€ 100 lab: A 3D-printable open-source platform for fluorescence microscopy, optogenetics, and accurate temperature control during behaviour of zebrafish, Drosophila, and Caenorhabditis elegans. *PLoS Biology*, *15*(7), e2002702.

Cesaroni, F. and Gambardella, A.,(2003). Research productivity and the allocation of resources in publicly funded research programmes. *Chapters*. Available: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=163309

Chesbrough, H.W., (2006). *Open innovation: The new imperative for creating and profiting from technology*. Harvard Business Press..

Choi, H., Shin, S., Jeon, H., Choi, Y., Kim, J., Kim, S., Chung, S., and Oh, K. (2014) Fast spatial atomic layer deposition of Al2O3 at low temperature (<100°C) as a gas permeation barrier for flexible organic light-emitting diode displays. *Journal of Vacuum Science and Technology A*, 34(1), 01A121.

Coakley, M. F., Hurt, D. E., Weber, N., Mtingwa, M., Fincher, E. C., Alekseyev, V., ... & Yoo, T. S. (2014). The NIH 3D print exchange: a public resource for bioscientific and biomedical 3D prints. *3D Printing and Additive Manufacturing*, *1*(3), 137-140.

Coakley M, Hurt DE. 2016. 3D printing in the laboratory: Maximize time and funds with customized and open-source labware. *Journal of Laboratory Automation* 21(4):489–495.

Collins, T. J. (2007). ImageJ for microscopy. *Biotechniques*, *43*(1 Suppl), 25-30.

Comino, S., Manenti, F. M., & Parisi, M. L. (2007). From planning to mature: On the success of open source projects. *Research Policy*, *36*(10), 1575-1586.

Cooper, L. (2016). The 20 most wired countries in the world. Transferwise. https://transferwise.com/us/blog/the-20-most-wired-countries-in-the-world-infographic

Damase TR, Stephens D, Spencer A, Allen PB. (2015). Open source and DIY hardware for DNA nanotechnology labs. *Journal of Biological Methods* 2(3):e24.

D'Ausilio, A (2012). Arduino: A low-cost multipurpose lab equipment. *Behavior Research Methods* 44(2): 305–313.

Dosemagen, S., Liboiron, M., & Molloy, J. (2017). Gathering for Open Science Hardware 2016. *Journal of Open Hardware*, *1*(1).

Dhankani, K. C., & Pearce, J. M. (2017). Open source laboratory sample rotator mixer and shaker. *HardwareX*, 1, 1-12.

Edquist, C., (2010). Systems of innovation perspectives and challenges. *African Journal of Science, Technology, Innovation and Development*, *2*(3), 14-45.

Eisenberg, R.S., (1996). Public Research and Private Development: Patents and Technology Transfer in Government--Sponsored Research. Va. L. Rev., 82, p.1663.

Evenson, R. E., Waggoner, P. E., & Ruttan, V. W. (1979). Economic benefits from research: an example from agriculture. *Science*, *205*(4411), 1101-1107.

Finley, K. (2016) Linux Took Over the Web. Now, It's Taking Over the World. Wired. https://www.wired.com/2016/08/linux-took-web-now-taking-world/

Fisher D, Gould P. (2012). Open-source hardware is a low-cost alternative for scientific instrumentation and research. *Modern Instrumentation* 1(2):8–20.

Fobel, R**,** Fobel, C**,** Wheeler, AR (2013). DropBot: An open-source digital microfluidic control system with precise control of electrostatic driving force and instantaneous drop velocity measurement. *Applied Physics Letters* 102(19): 193513.Forero-Pineda, C., (2006). The impact of stronger intellectual property rights on science and technology in developing countries. *Research Policy*, *35*(6), 808-824.

Franke, N., & Shah, S. (2003). How communities support innovative activities: an exploration of assistance and sharing among end-users. *Research Policy*, *32*(1), 157-178.

Free Software Foundation (FSF). Why "Free Software" is better than "Open Source" [WWW Document], 2016. URL https://www.gnu.org/philosophy/free-software-for-freedom.en.html (accessed 11.18.19).

Friesike, S., Widenmayer, B., Gassmann, O. and Schildhauer, T., (2015). Opening science: towards an agenda of open science in academia and industry. *The Journal of Technology Transfer*, *40*(4), 581-601.

Gartner, (2016). Gartner Says Worldwide Smartphone Sales Grew 3.9 Percent in First Quarter of 2016. https://www.gartner.com/newsroom/id/3323017

George, S.M., (2009). Atomic layer deposition: an overview. *Chemical Reviews*, *110*(1), 111-131.

Gentil-Beccot, A., Mele, S., Brooks, T.C. (2010). Citing and reading behaviours in high-energy physics. *Scientometrics* 84, 345–355.

Gibb, A. (2014). *Building open source hardware: DIY manufacturing for hackers and makers*. Pearson Education.

Godinho, M.M., Mendonça, S.F. and Pereira, T.S., 2005. Towards a taxonomy of innovation systems. , https://www.repository.utl.pt/handle/10400.5/2682

Gordon, A., Colman-Lerner, A., Chin, T. E., Benjamin, K. R., Richard, C. Y., & Brent, R. (2007). Single-cell quantification of molecules and rates using open-source microscope-based cytometry. *Nature Methods*, *4*(2), 175-181.

Greenstein, S. and Nagle, F., 2014. Digital dark matter and the economic contribution of Apache. *Research Policy*, *43*(4), pp.623-631.

Griliches, Z. (1991). *The search for R&D spillovers* (No. w3768). National Bureau of Economic Research.

Gualda, EJ**,** Vale, T**,** Almada, P**,** Feijó, JA**,** Martins, GG Moreno, (2013). OpenSpinMicroscopy: an open-source integrated microscopy platform. *Nature Methods* 10(7): 599–600

Harhoff, D., Henkel, J., & Von Hippel, E. (2003). Profiting from voluntary information spillovers: how users benefit by freely revealing their innovations. *Research Policy*, *32*(10), 1753-1769.

Harison, E., & Koski, H. (2010). Applying open innovation in business strategies: Evidence from Finnish software firms. *Research Policy*, *39*(3), 351-359.

Harnett C. (2011). Open source hardware for instrumentation and measurement. *IEEE Instrumentation & Measurement Magazine* 14(3):34–38.

Heller, M.A. and Eisenberg, R.S., (1998). Can patents deter innovation? The anticommons in biomedical research. *Science*, 280(5364), 698-701.

Herger, L. M., & Bodarky, M. (2015, March). Engaging students with open source technologies and Arduino. In *Integrated STEM Education Conference (ISEC), 2015 IEEE* (pp. 27-32). IEEE.

Herstatt, C. and Ehls, D., 2015. *Open Source Innovation: The Phenomenon, Participant's Behaviour, Business Implications*. Routledge.

Hietanen, I., Heikkinen, I.T., Savin, H. and Pearce, J.M., (2018). Approaches to open source 3-D printable probe positioners and micromanipulators for probe stations. *HardwareX*, *4*, p.e00042.

Hippel, E.V. and Krogh, G.V., (2003). Open source software and the "private-collective" innovation model: Issues for organization science. *Organization science*, *14*(2), pp.209-223.

Hope, J., (2009). *Biobazaar: the open source revolution and biotechnology*. Harvard University Press.

Ibrahim, Y. M. (1997). As Most Wired Nation, Finland Has Jump on 21st Century. *New York Times, January*, *20*.

Jones R, Haufe P, Sells E, Iravani P, Olliver V, Palmer C, -Bowyer A. 2011. RepRap: The replicating rapid prototyper. Robotica 29(01):177–191.

Juntunen, M., Heinonen, J., Vähänissi, V., Repo, P., Valluru, D., and H. Savin. (2016) Near-unity quantum efficiency of broadband black silicon photodiodes with an induced junction. *Nature Photonics*, 10, 777-781.

Kang, Q. Y. (2015). *Development of Low-Cost Precision Scanner System for Scanning Probe Microscopy Application* (Doctoral dissertation, UTAR).

Kelley, C. D., Krolick, A., Brunner, L., Burklund, A., Kahn, D., Ball, W. P., & Weber-Shirk, M. (2014). An Affordable Open-Source Turbidimeter. *Sensors*, 14(4), 7142-7155.

Kennedy. J. (2018) 15 of Helsinki's hottest start-ups worth sussing out. Silicon Republic. https://www.siliconrepublic.com/start-ups/helsinki-startups

Kim, H., Lee, H., and Maeng, W. (2009) Applications of atomic layer deposition to nanofabrication and emerging nanodevices. *Thin Solid Films*, 517, pp. 2563–2580

Lakhani, K. R., & Von Hippel, E. (2003). How open source software works:"free" user-to-user assistance. *Research Policy*, *32*(6), 923-943.

Lee, S. Y. T., Kim, H. W., & Gupta, S. (2009). Measuring open source software success. *Omega*, *37*(2), 426-438.

Leonard, A. (2000). Finland — the open-source society. Salon. https://www.salon.com/2000/04/20/chapter_six_part_1/

Li, Y., Zhang, L., Shan, G., Song, Z., Yang, R., Li, H., & Qian, J. (2016). A homemade atomic force microscope based on a quartz tuning fork for undergraduate instruction. *American Journal of Physics*, *84*(6), 478-482.

Li, Z., Seering, W., Ramos, J. D., Yang, M., & Wallace, D. R. (2017). Why Open Source?: Exploring the Motivations of Using an Open Model for Hardware Development. In *ASME 2017 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* (pp. V001T02A059-V001T02A059). American Society of Mechanical Engineers.

Loh, S. H., & Cheah, W. J. (2017). Optical Beam Deflection Based AFM with Integrated Hardware and Software Platform for an Undergraduate Engineering Laboratory. *Applied Sciences*, *7*(3), 226.

Lundvall, B.Å. ed., (2010). *National systems of innovation: Toward a theory of innovation and interactive learning*. Anthem Press.

Lundvall, B.Å., Johnson, B., Andersen, E.S. and Dalum, B., (2002). National systems of production, innovation and competence building. *Research Policy*, *31*(2), 213-231.

Macul, V., & Rozenfeld, H. (2015). How an open source design community works: the case of open source ecology. In *DS 80-3 Proceedings of the 20th International Conference on Engineering Design (ICED 15) Vol 3: Organisation and Management, Milan, Italy, 27-30.07. 15*.

Man, J. P., Weinkauf, J. G., Tsang, M., & Sin, J. H. D. D. (2004). Why do some countries publish more than others? An international comparison of research funding, English proficiency and publication output in highly ranked general medical journals. *European Journal of Epidemiology*, *19*(8), 811-817.

Mansfield, E., & Lee, J. Y. (1996). The modern university: contributor to industrial innovation and recipient of industrial R&D support. *Research Policy*, *25*(7), 1047-1058.

May, R. M. (1997). The scientific wealth of nations. *Science*, *275*(5301), 793-796.

Maydannik, P., Kääriäinen, O., Lahtinen, K., Cameron, D., Söderlund, M., Soininen, P., Johansson, P., Kuusipalo, J., Moro, L., and Zeng, X. (2014). Roll-to-roll atomic layer deposition process for flexible electronics encapsulation applications. *Journal of Vacuum Science and Technology A*, 32(5), 051603.

Meng, X., Wang, X., Geng, D., Ozgit-Akgun, C., Schneider, N., and Elam, J. (2017) Atomic layer deposition for nanomaterial synthesis and functionalization in energy technology. *Materials Horizons*, 4, pp. 133-154.

Morgan, H. (2014). Review of research: the education system in Finland: a success story other countries can emulate. *Childhood Education*, *90*(6), 453-457.

McMunn, M. S. (2017). A time-sorting pitfall trap and temperature datalogger for the sampling of surface-active arthropods. *HardwareX*, *1*, 38-45.

Murillo, L. F. R., & Wenzel, T. (2017). Welcome to the Journal of Open Hardware. *Journal of Open Hardware*, *1*(1). p.1. DOI: http://doi.org/10.5334/joh.3

Nagle, F., 2018. Open source software and firm productivity. *Management Science*. 65(3) https://doi.org/10.1287/mnsc.2017.2977

National Science Board, (2012). *Science and Engineering Indicators 2012.* Arlington VA: National Science Foundation (NSB 12-01).

Nečas, D., & Klapetek, P. (2012). Gwyddion: an open-source software for SPM data analysis. *Open Physics*, *10*(1), 181-188.

Nelson, R.R., (1988). Institutions supporting technical change in the United States. *Technical change and economic theory*, 312-329.

Nelson, R.R. and Rosenberg, N., (1993). Technical innovation and national systems. *National innovation systems: A comparative analysis*, *322*.

Nelson, R.R., (2003). The advance of technology and the scientific commons. *Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences*, *361*(1809), 1691-1708.

Nelson, R.R., (2004). The market economy, and the scientific commons. *Research policy*, *33*(3), 455-471.

Newman, JP, Zeller-Townson, R, Fong, MF, Desai, SA, Gross, RE, Potter, SM (2012). Closed-Loop, Multichannel Experimentation Using the Open-Source NeuroRighter Electrophysiology Platform. *Front Neural Circuits* 6: 98.

Niosi, J., Saviotti, P., Bellon, B. and Crow, M., (1993). National systems of innovation: in search of a workable concept. *Technology in Society*, *15*(2), 207-227.

Niu, W., Li, X., Karuturi, S., Fam, D., Fan, H., Shrestha, S., Wong., L., Tok, A. (2015) Applications of atomic layer deposition in solar cells. *Nanotechnology*, 26, 064001.

Nosek, B.A., Alter, G., Banks, G.C., Borsboom, D., Bowman, S.D., Breckler, S.J., Buck, S., Chambers, C.D., Chin, G., Christensen, G. and Contestabile, M., (2015). Promoting an open research culture. *Science*, *348*(6242), 1422-1425.

Noyes, K. (2012) 94 Percent of the World's Top 500 Supercomputers Run Linux. Available online: https://www.linux.com/news/enterprise/high-performance/147-high-performance/666669-94-percent-of-the-worlds-top-500-supercomputers-run-linux

Oberloier, S. & Pearce, J.M. (2018) General Design Procedure for Free and Open-Source Hardware for Scientific Equipment. *Designs*, 2(1), 2; doi:10.3390/designs2010002

Oh, J., Hofer, R., Fitch, W. T. (2017). An open source automatic feeder for animal experiments. *HardwareX*, *1*, 13-21.

OpenAFM. (2018). https://openafm.com/

Open Source Hardware Association (OSHWA). 2018. Definition. https://www.oshwa.org/definition/

Oksanen, T., Lehvo, A., Nuutinen, A. (2003). *Scientific research in Finland: a review of its quality and impact in the early 2000s*. Academy of Finland. http://www.aka.fi/globalassets/awanhat/documents/tiedostot/julkaisut/10_03sutieng-verkkoversio.pdf

Osborn, L.S., Pearce, J.M. and Haselhuhn, A., (2015). A case for weakening patent rights. . *John's L. Rev.*, *89*, p.1185.

Osunyomi, B. D., Redlich, T., Wulfsberg, J. P. (2016). Could open source ecology and open source appropriate technology be used as a roadmap from technology colony?. *International Journal of Technological Learning, Innovation and Development*, *8*(3), 265-282.

Pagano, U., 2014. The crisis of intellectual monopoly capitalism. *Cambridge Journal of Economics*, *38*(6), 1409-1429.

Park, J., Chae, H., Chung, H., Lee, S. (2011) Thin film encapsulation for flexible AM-OLED: a review. *Semiconductor Science and Technology,* 26, 034001.

Pearce, J.M., (2012). Building Research Equipment with Free, Open-Source Hardware. *Science* 337(6100): 1303–1304.

Pearce, J.M., (2012b). Physics: Make nanotechnology research open-source. Nature, 491(7425), p.519.

Pearce, J.M., (2013). Open-source nanotechnology: Solutions to a modern intellectual property tragedy. *Nano Today*, *8*(4), 339-341.

Pearce, J.M., (2014). *Open-Source Lab: How to Build Your Own Hardware and Reduce Research Costs*, Elsevier, Amsterdam.

Pearce, J.M., (2016). Return on investment for open source hardware development. *Science and Public Policy* 43(2):192-195.

Pearce, J.M. (2017). Impacts of Open Source Hardware in Science and Engineering. *Bridge* 47, 24–31.

Pearce, J. M. (2017b). Emerging Business Models for Open Source Hardware. *Journal of Open Hardware*, *1*(1). DOI: http://doi.org/10.5334/joh.4

Penin, J., (2008). More open than open innovation? Rethinking the concept of openness in innovation studies. *Bureau d'Economie Théorique et Appliquée, Working Paper*, *18*(33), 1-20.

Pénin, J. and Wack, J.P., (2008). Research tool patents and free-libre biotechnology: A suggested unified framework. *Research Policy*, *37*(10), 1909-1921.

Pénin, J., (2011). Open source innovation: Towards a generalization of the open source model beyond software. *Revue d'économie industrielle*, (136), 65-88.

Pineño, O (2014). ArduiPod Box: A low-cost and open-source Skinner box using an iPod Touch and an Arduino microcontroller. *Behavior Research Methods* 46(1): 196–205

Powell, A. (2012). Democratizing production through open source knowledge: from open software to open hardware. *Media, Culture & Society*, *34*(6), 691-708.

Puurunen, R.L., (2014). A short history of atomic layer deposition: Tuomo suntola's atomic layer epitaxy. *Chemical Vapor Deposition*, *20*(10-11-12), pp.332-344.

Raymond, E. (1999). The cathedral and the bazaar. *Philosophy & Technology*, *12*(3), 23.

Robertson, M.N., Ylioja, P.M., Williamson, A.E., Woelfle, M., Robins, M., Badiola, K.A., Willis, P., Olliaro, P., Wells, T.N. and Todd, M.H., (2014). Open source drug discovery–a limited tutorial. *Parasitology*, *141*(1), 148-157.

Rosenberg, D. (2010) Survey: 98 Percent of Enterprises Using Open Source Software, Interrupted–CNET News. Available online: http://news.cnet.com/8301-13846_3-20013258-62.html

Rosenberg, N., (1982). Learning by using. *Inside the black box: Technology and economics*, 120-140.

Rosenberg, N. and Landau, R. eds., (1986). *The Positive sum strategy: harnessing technology for economic growth*. National Academies Press.

Rosenegger, D. G., Tran, C. H. T., LeDue, J., Zhou, N., & Gordon, G. R. (2014). A high performance, cost-effective, open-source microscope for scanning two-photon microscopy that is modular and readily adaptable. *PloS one*, *9*(10), e110475.

Russell, L, Steele, AL, Goubran, R (2012). Low-cost, rapid prototyping of IMU and pressure monitoring system using an open source hardware design. Instrumentation and Measurement Technology Conference (I2MTC). May, IEEE International: 2695–2699. IEEE.

Sahlberg, P. (2013). Teachers as leaders in Finland. *Educational Leadership*, 71 (2), 36-40.

Salazar-Serrano, L. J., Torres, J. P., & Valencia, A. (2017). A 3D Printed Toolbox for Opto-Mechanical Components. *PloS one*, *12*(1), e0169832.

Salter, A. J., & Martin, B. R. (2001). The economic benefits of publicly funded basic research: a critical review. *Research Policy*, *30*(3), 509-532.

Santos, A.B., (2015). Open Innovation research: trends and influences–a bibliometric analysis. *Journal of Innovation Management*, *3*(2), 131-165.

Sarjala, J. (2013). Equality and cooperation: Finland's path to excellence. *American Educator*, 37 (1), 32-36.

Savin, H., Repo, P., von Gastrow, G., Ortega, P., Calle, E., Garín, M. and Alcubilla, R., 2015. Black silicon solar cells with interdigitated back-contacts achieve 22.1% efficiency. *Nature nanotechnology*, *10*(7), pp.624-628.

Schelly, C., Anzalone, G., Wijnen, B., & Pearce, J. M. (2015). Open-source 3-D printing technologies for education: Bringing additive manufacturing to the classroom. *Journal of Visual Languages & Computing*, *28*, 226-237.

Schienstock, G. and Hämäläinen, T., (2001). *Transformation of the Finnish innovation system: A network approach*. Helsinki: Sitra.

Schneider, C. A., Rasband, W. S., & Eliceiri, K. W. (2012). NIH Image to ImageJ: 25 years of image analysis. *Nature Methods*, *9*(7), 671-675.

Seidle, N. (2012). IP Obesity. Sparkfun.com, January 8 2012 https://www.sparkfun.com/news/963

Sierla, S., Kyrki, V., Aarnio, P., & Vyatkin, V. (2018). Automatic assembly planning based on digital product descriptions. *Computers in Industry*, *97*, 34-46.

Shah, S. (2000). Sources and patterns of innovation in a consumer products field: Innovations in sporting equipment. *Sloan School of Management, Massachusetts Institute of Technology, Cambridge, MA, WP-4105*.

Sharif, N., (2006). Emergence and development of the National Innovation Systems concept. *Research policy*, *35*(5), 745-766.

Sharkey, J. P., Foo, D. C., Kabla, A., Baumberg, J. J., & Bowman, R. W. (2016). A one-piece 3D printed flexure translation stage for open-source microscopy. *Review of Scientific Instruments*, *87*(2), 025104.

Shaw, B. (1985). The role of the interaction between the user and the manufacturer in medical equipment innovation. *R&D Management*, *15*(4), 283-292.

Sorzano, C. O. S., Marabini, R., Velázquez-Muriel, J., Bilbao-Castro, J. R., Scheres, S. H., Carazo, J. M., & Pascual-Montano, A. (2004). XMIPP: a new generation of an open-source image processing package for electron microscopy. *Journal of Structural Biology*, *148*(2), 194-204.

Statistics Finland. (2018). Trade. http://www.stat.fi/tup/suoluk/suoluk_kotimaankauppa_en.html

Subramanyam, R., & Xia, M. (2008). Free/Libre Open Source Software development in developing and developed countries: A conceptual framework with an exploratory study. *Decision Support Systems*, *46*(1), 173-186.

Sun, R, Bouchard, MB, Hillman, E (2010). SPLASSH: Open source software for camera-based high-speed, multispectral in-vivo optical image acquisition. *Biomedical Optics Express* 1(2): 385–397.

Takalo, T. and Kanniainen, V., (2000). Do patents slow down technological progress?: Real options in research, patenting, and market introduction. *International Journal of Industrial Organization*, *18*(7), 1105-1127.

Torvalds, L., & Diamond, D. (2001). *Just for fun: The story of an accidental revolutionary*. Harper.

Vipunen -- Education Statistics Finland (2018). University research funding 2016. https://vipunen.fi/en-gb/_layouts/15/xlviewer.aspx?id=/en-gb/Reports/Yliopistojen%20tutkimusrahoitus%20-%20yliopisto_EN.xlsb

Von Hippel, E. (1976). The dominant role of users in the scientific instrument innovation process. *Research Policy*, *5*(3), 212-239.

Von Hippel, E. (1986). Lead users: a source of novel product concepts. *Management science*, *32*(7), 791-805.

Von Hippel, E. (2005). Democratizing innovation: The evolving phenomenon of user innovation. *Journal für Betriebswirtschaft*, *55*(1), 63-78.

Von Hippel, E., & Finkelstein, S. N. (1979). Analysis of innovation in automated clinical chemistry analyzers. *Science and Public Policy*, *6*(1), 24-37.

Weber, S. (2004). *The Success of Open Source*. Harvard University Press.

West, J. and Bogers, M., (2017). Open innovation: current status and research opportunities. *Innovation*, *19*(1),43-50.

Wijnen B, Hunt EJ, Anzalone GC, Pearce JM. (2014). Open-source syringe pump library. *PLoS One* 9(9):e107216.

Wijnen, B., Petersen, E. E., Hunt, E. J., & Pearce, J. M. (2016). Free and open-source automated 3-D microscope. *Journal of Microscopy*, *264*(2), 238-246.

Willinsky, J., (2005). The unacknowledged convergence of open source, open access, and open science. *First Monday*, *10*(8).

Woodson, T., Alcantara, J.T. and do Nascimento, M.S., (2019). Is 3D printing an inclusive innovation?: An examination of 3D printing in Brazil. *Technovation* 80-81, 54-62.

Yersak, A., Sharm, K., Wallas, J., Dameron, A., Li, X., Yang, Y., Hurst, K., Ban, C., Tenent, R., and George, S. (2018) Spatial atomic layer deposition for coating flexible porous Li-ion battery electrodes. *Journal of Vacuum Science and Technology* A, 36(1), 01A123.

Yip, M. C., & Forsslund, J. (2017). Spurring Innovation in Spatial Haptics: How Open-Source Hardware Can Turn Creativity Loose. *IEEE Robotics & Automation Magazine*, *24*(1), 65-76.

Zahl, P., Wagner, T., Möller, R., & Klust, A. (2010). Open source scanning probe microscopy control software package GXSM. *Journal of Vacuum Science & Technology B, Nanotechnology and Microelectronics: Materials, Processing, Measurement, and Phenomena*, *28*(3), C4E39-C4E47.

Zhang, C., Anzalone, N. C., Faria, R. P., & Pearce, J. M. (2013). Open-source 3D-printable optics equipment. *PloS One*, *8*(3), e59840.

Zeitlyn, D. (2003). Gift economies in the development of open source software: anthropological reflections. *Research Policy*, *32*(7), 1287-1291.