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ISSUES IN OPEN HARDWARE

On the Economic Value of Open Source Hardware – Case Study of an Open Source Magnetic Resonance Imaging Scanner

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Increasing maturation and dissemination of easy-to-use and affordable means of digital production (e.g. 3D printing), access to these in makerspaces and FabLabs as well as powerful tools and online platforms for virtual and collaborative product design enabled the highly efficient and innovative mode of open source to spill over from software to hardware. Open source technology has enormous potential to spur innovation and enhance technological literacy and thus contribute to socioeconomic and ecological sustainability. Like in software, open source hardware (OSH) projects and online communities have evolved in a broad range of technologies and applications. In these communities, people from all over the world with diverse backgrounds (students, researchers, consumers, users etc.) gather online to jointly develop, revise, improve and freely share hardware designs and documentation. Additionally, people may build, adapt, use and sell physical artefacts based on these designs in accordance with the notion of open source. The (potential) economic impact and value of open source hardware is hard to quantify as contributors usually do not get paid and users do not necessarily buy products from vendors. Nonetheless, value is created as in the case of Linux or Wikipedia. We applied established valuation methods for open source hardware to quantify cost savings and as a result the value of an open source magnetic resonance imaging device (MRI) currently under development by the Open Source Imaging Initiative (OSI²). Depending on the scenario and the valuation method, we found that savings for healthcare systems from US$1.8 million up to US$222 million per year are possible in the near future making the case for public funding and private investment in open source technology development.

Keywords: open source hardware; MedTech; open source innovation; open hardware; healthcare

1. Introduction

Innovation in medical technology (MedTech) is crucial to prevent, diagnose, treat and manage conditions, diseases, illnesses and disabilities and, thus, to save lives and improve people's health all over the world. To reach its full potential, these technologies need to be *Available*, *Accessible*, *Appropriate* and *Affordable* (*4 As*) (World Health Organization, 2010; 2011a). The evidence we have, however, demonstrates how difficult it is to realize this potential: "Persistent and growing inequalities in health are increasingly evident, both between and within countries." (World Health Organization, 2011b). Increasing costs of MedTech for healthcare systems due to high safety standards and regulations as well as oligopolistic industry structures are just two factors that fuel this development and prevent improvements around the *4 As* (European Commission, 2018). For developing countries, the situation is even more dramatic having in mind that 70–90% of all donated medical devices cannot be properly operated due to missing documentation, lack of technical training, machine failures or missing spare parts (Malkin and Oldenburg Beer, 2013; Richards-Kortum and Oden, 2013).

This is where the open source hardware (OSH) movement comes into play: With increasing maturation and dissemination of easy-to-use and affordable means of digital production (e.g. 3D printing), access to these in makerspaces and FabLabs as well as powerful tools and online platforms for virtual and collaborative product design the highly efficient and innovative mode of open source spilled over from software to hardware (Raasch, Herstatt, and Balka, 2009; Anderson, 2012; Pearce, 2012b; Gibb, 2014; Moritz et al., 2016). Hundreds of projects and online communities have evolved around physical artefacts and technologies ranging from cars, computers and electronics to environmental tech, robotics and drones as well as machine tools and MedTech where thousands

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of people from all over the world with very diverse backgrounds (students, researchers, consumers, users etc.) gather online to jointly develop, revise, improve and freely share hardware designs and documentation (Raasch, Herstatt, and Balka, 2009; Bonvoisin et al., 2016; Moritz, Redlich, and Wulfsberg, 2018). Starting from some of these projects, firms have evolved too that capture value by selling and distributing ready-to-use products or kits, components and spare parts or by offering service and building workshops (e.g. Arduino, Ultimaker, Sparkfun) (Raasch and Herstatt 2011; Moritz et al., 2016).

The design and documentation (such as bill of materials, schematics, assembly instructions) of the products, however, can be freely accessed online by anyone to study, build, repair, adapt and sell products based on these designs and enable users to have full control of the technology (Open Source Hardware Association, 2018). Beyond potentials for rapid and low-cost product design and development, this decentralized and collaborative model of value creation which is based on openness (also known as *bottom-up economics*) offers opportunities for social, economic and ecological sustainability by empowering people all over the world to participate in a system of democratized value creation with ubiquitous access to knowledge and technology (Pearce, 2012a; Basmer et al., 2015; Redlich and Moritz, 2016).

In MedTech too a range of open source hardware projects can be found that aim to provide low-cost, adaptable and patient-specific alternatives to proprietary products for private use, e.g. myoelectric prostheses (e-Nable, MyOpen), CT scanners (Tricorder project), echo-stethoscopes (echOpen (Jonveaux, 2017)), infusion pumps (OpenPump), physiological monitoring systems (openBCI), diabetes treatment (Diabeto, openAPS) (Niezen, Eslambolchilar and Thimbleby, 2016; Moritz, Redlich, and Wulfsberg, 2018). For commercialization of these products, however, approval of authorities of the corresponding markets would be required regarding the safe use of a product. At this point incorporation and financial resources are necessary.

Lately, another promising open source hardware project in the field of MedTech was launched: The Open Source Imaging Initiative (OSI²) focusing on magnetic resonance imaging (MRI) (Winter et al., 2016; Arndt et al., 2017). MRI is a crucial diagnostic tool for a wide and growing range of clinical applications and perfectly fitting the scope of open source due to several reasons: Most of the patents around MR technologies have expired allowing anyone to use them for commercialization; most innovations in the field originate from publicly funded research communities; the market is dominated by very few corporate suppliers with minimal variety of products; on a global scale, only few regions have sufficient access to MRI services; the total cost of ownership (TCO) for users is enormous including expensive lock-in service contracts for maintenance and training; and, finally, the technology is safe to use as it operates without ionizing radiation (World Health Organization, 2011a; Schmitt, 2015; European Commission, 2018).

Open sourcing MRI technology has the potential for cheaper products, faster innovation cycles and more competition with a global community involved. Transparency of the technology improves the ease of maintenance, repair and service and allows anyone to study and build MRI technologies and, finally, modularity facilitates customized and appropriate design to regional or patient-specific needs (Pearce, 2012a; Pearce, 2012b; Niezen, Eslambolchilar and Thimbleby, 2016). Still, these aspects even though well-known from other open source projects are rather vague, and the question arises whether it is possible to determine the monetary value and impact of an open source MR device in terms of cost savings compared to commercially available products.

Quantifying this value is not easy because contributing users and researchers are not necessarily being remunerated thus far. There is no registered contribution to the gross domestic product (GDP) that would allow us to derive the value being generated. Similar observations were made in the field of user innovation: von Hippel et al. (2012) found that around 3 million consumers in the UK regularly engage in innovation activities in the household sector resulting in product innovation expenditures that exceed the combined R&D expenditures of all firms in the UK. This value, however, is not included in economic analyses.

Nonetheless, scholars have tried to quantify the economic value of open source projects, e.g. RepRap (Wittbrodt et al., 2013), Linux (McPherson, Proffitt, and Hale-Evans, 2008). Pearce et al. (2015) applied different evaluation methods with focus on open source hardware. They calculated the value of a simple syringe pump and found that millions of dollars of savings could be created by substituting proprietary products with the open source version, by avoiding costs of redesign by a freely shared design or by having access to cheaper products in the market due to lower marginal costs. We assume a similar potential of value of an open source MR scanner. Subsequently, our goal was to apply these valuation methods on an open source MR scanner and be able to quantify the value of such a device for healthcare systems worldwide, but also to provide more data on the economic value of open source innovation. For realistic calculations, we relied on data from an ongoing project of OSI², specifically the COSI extremity MR scanner.

2. Methods and Case Setting

2.1. Valuation Methods

Pearce et al. (2015) proposed different approaches to calculate the value and cost savings of open source hardware respectively. We applied three valuation methods of these that are strongly related to the product itself with different perspectives among them (substitution of proprietary products, avoided cost of redesign, market impact) where data was available and validity high. For reasons of simplification and a short-term perspective, inflation effects were neglected.

First, *Downloaded Substitution Valuation* (DSV) takes into account that once the design of a product is freely accessible, basically anyone could download the design, build the product and sell it. Thus, economic savings (V_D) result from a substitution of commercially available products with open source hardware within a time t depending on the number of downloaded designs and products resulting from these by means of distributive manufacturing:

$$V_D(t) = (C_p - C_f) \cdot P \cdot N_D(t) \quad (1)$$

C_p is the total cost of ownership of a similar proprietary product, whereas C_f represents the marginal cost of producing an open source product with access to means of digital fabrication, e.g. in a FabLab, makerspace or research laboratory. *P* stands for the share of downloads that will eventually result in a manufactured product. We have to keep in mind that *P* is hard to determine as one download might result in multiple products via file sharing, but also the opposite might happen meaning that many people download it without the intention to build it. The number of downloads for a given time *t* is indicated by N_D. Note that C_f is very likely to decrease over time if more and more people rebuild the product, improve the design and share their improvements with the community.

Second, *Avoided Reproduction Valuation* (ARV) captures savings V_R (for a single firm or society as a whole) by not having to replicate the design of the product as with open source it is freely available, accessible and reproducible. It is calculated by adding up the design hours *h* (electronics, mechanics etc.) multiplied by the hourly wages *w* of experts that are required to design and test the different components *J* resulting in the final version of the design. With *P* and the number of downloads N_D within a given time *t*, V_R adds up to:

$$V_R(t) = \sum_{n=1}^{J} h_n \cdot w_n \cdot P \cdot N_D(t) \quad (2)$$

Third, *Market Savings Valuation* (MSV) anticipates a moment in the future where open source hardware might capture an entire market of a product with ever increasing access to means of distributive manufacturing and products superior to proprietary alternatives in terms of cost, quality and customizability. We have to take into account the value of the market *M* of a product in year *t* and subtract the marginal cost $C_f(t)$ multiplied by the number of products $N_M(t)$ that would meet the entire demand of that market resulting in market savings $V_M(t)$:

$$V_M(t) = M(t) - (C_f(t) \cdot (N_M(t)) \quad (3)$$

In addition to these established valuations, we also elaborate on secondary effects that indirectly emerge via open sourcing the hardware (designs).

2.2. Case Setting: COSI Extremity MR

The Open Source Imaging Initiative (OSI[2]) was founded in 2016 and these days comprises about 100 researchers in the field of MRI and other related disciplines from more than 50 institutions from all over to world who joined to advocate open source science and open source development of MR technologies (Winter et al., 2016; Arndt et al., 2017). The goal is to address existing challenges of reproducible research and make medical (MRI) devices more available, accessible, appropriate and affordable. An open source policy facilitates these efforts. One ongoing project among many others is the development of a cost-effective open source imaging (COSI) MR scanner which follows a modular design, is scalable for different applications and is easily reproducible.

A concept and prototype of an extremity MR is currently under development (**Figure 1**). It is based on a permanent magnet Halbach design comprised of multiple small octagonal neodymium magnets generating a magnetic field strength of $B_0 = 0.3T$ for imaging (Winter et al., 2016). Two software defined radios (SDR) are used to generate RF and gradient pulses (Blücher, 2017). The SDRs are compatible with an open source software framework to enable hardware independent development of MRI techniques (Hasselwander, Cao and Grissom, 2016). The software for operation, imaging and evaluation is open source. Estimated material cost of the complete system is about US$ 15,000. Potential clinical applications

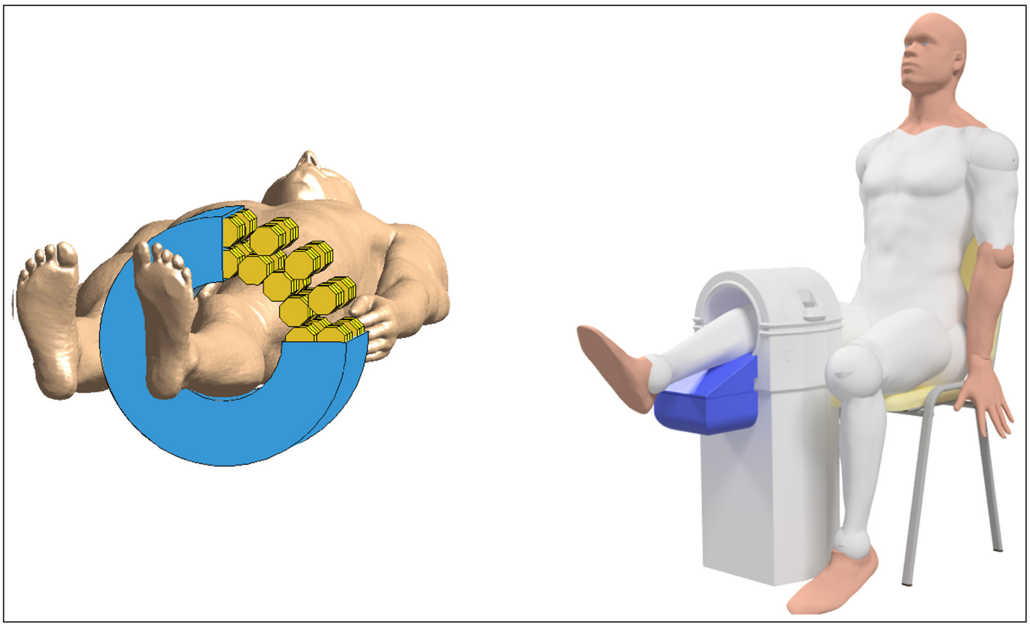

Figure 1: Concept of the COSI extremity MR scanner. Reproduced with permission of OSI[2].

are musculoskeletal imaging of extremities such as knee, foot, wrist or elbow. The system is low-cost, smaller and lighter (total weight: ~100 kg) than commercially available extremity MR devices which makes it also interesting for mobile applications.

3. Results

3.1. Downloaded Substitution Valuation

The design of the COSI extremity MR is still under development and not available online yet. Thus, we cannot determine the number of downloads N_D at this stage. Instead, we rely on numbers from an open source CT scanner (the Tricorder project), which might serve as a reference product. This design was first uploaded to the online design repository Thingiverse in 2014 and since then has been viewed 10,000 and downloaded around 1,600 times as of now following an exponential growth. For the number of downloads per year at an early stage once the design will be uploaded, we set a realistic number ranging from $N_D = 10$ to 100, also having in mind the lack of access to MR technology in many regions and the fact that most of donated medical devices cannot be operated in developing countries due to missing documentation and training.

P reflects the percentage of designs that will eventually be converted into a physical product. Insights from interviews with makers led Pearce et al. (2015) to set $P = 1$ which means that on average one downloaded design will lead to one product built (while some downloads might not be converted into a physical product, others might be shared, and multiple products potentially be realized from a single download). This assumption might be prone to error, so we set a broader range with $P = 0.5$ to 2.

As a proprietary reference product in the area of extremity MRI, we found the Esaote O-Scan 0.31T to be suitable (for comparison of the technical specifications, see **Table 1**). It costs about US$230,000 plus additional costs of US$43,333 for installation, training etc. as well as US$13,800 per year for service (assuming 6% of purchasing prize) (Sferrella, 2012; Schock, 2015; Esaotemri, 2017). C_p adds up to US$411,333 total cost of ownership assuming 10 years of operation.

In comparison, material costs of the COSI extremity MR add up to US$15,000 (magnets: US$3,000; RFPA: US$2,000; spectrometer: US$2,000; gradients: US$3,000; other components: US$5,000). For service, maintenance and development, similar to the Esaote O-Scan we assume 6% of the total price per year to be realistic considering a higher effort in total, but lower cost e. g. with inhouse technicians or independent contractors. Additionally, we also have to take into account the assembly cost of the system, certification costs (e.g. CE) in case of a non-human commercial application and additional cost for approval by a regulatory body (e.g. FDA or EU medical device directive) for human clinical application. We looked into two specific use cases for an open source MR that vary among these factors resulting in different values of C_f.

3.1.1. Use Case 1: Research Institutions

In this case, researchers will download the design and documentation, buy the parts and assemble the MR scanner themselves or with the help of students for research and educational purposes. Cost for assembly and certification can be neglected here assuming a mature state of the open source project (e.g. exhaustive testing, thorough documentation). For 10 years of operation, the total cost of ownership of the open source MR scanner adds up to C_{f1} = US$24,000. Substituting only one proprietary MR scanner with the open source version results in savings for a research institution of €387,333 (factor 15).

Following Equation 1, we are now able to calculate savings within one year once the design will be uploaded. For a very pessimistic scenario S_1, very likely in the first year, we set $P = 0.5$ and $N_D = 10$ meaning that design will be downloaded 10 times and only 5 machines will be built and operated. In this case, savings would add up to $V_{D1;1}$ = US$1.9 million within one year. A more optimistic view S_2 with $P = 2$ and $N_D = 100$ considering 50 research institutions that are already part of the OSI[2] network and assuming a high demand for low-cost and modular MR technology that rapidly spreads around the world would result in savings of $V_{D1;2}$ = US$77 million per year.

3.1.2. Use Case 2: Hospitals and Firms

Beyond the realm of research, an open source product with full access to the technology also empowers professional users such as hospitals to build and operate MR scanners on their own (e.g. with inhouse technicians). Alternatively, new professional actors could step in that independently assemble open source MR scanners and supply users with them.

In this case, we have to consider additional costs in our valuation. Costs for certification of a regulatory body (e.g. FDA or EU medical device directive) are estimated to be around US$3,000 per device assuming a fully approved documentation and extensive testing results of the fully assembled system. For assembly, we estimate the work load to be about 4 weeks for two technicians to build and

Table 1: Comparison of a proprietary and the open source COSI extremity MR scanner (Mr-Tip.com, 2018).

Specifications	Esaote O-Scan	COSI extr. MR
Magnetic field strength	0.31 T	0.3 T
Magnet type	Permanent NdFeB	Permanent NdFeB
Weight	1,240 kg	~100 kg
Gradient amplifier	5 kW	2.4 kW
RF power	1.5 kW	1.4 kW

Table 2: Cost savings per year by substituting proprietary extremity MR scanners with an open source device.

Downloaded Substitution	Cost savings per year	
	Use Case 1: Research Institutions	**Use Case 2: Hospitals and Firms**
1 MRI substituted	US$387,333	US$364,333
5 MRI substituted (S_1)	US$1,9 million	US$1,8 million
200 MRI substituted (S_2)	US$77 million	US$73 million

test the magnet system and the same work load for a team of two technicians for the power electronics. Other hardware components and overall testing can be performed within 4 weeks by one technician. The average wage of a technician was set to US$25 per hour with 40h per week resulting in total cost for assembly of US$20,000 and C_{f2} = US$47,000 subsequently. With the same two scenarios S_1 and S_2, cost savings are $V_{D2;1}$ = US$1.8 million and $V_{D2;2}$ = US$73 million per year (**Table 2**).

Table 3: Cost savings per year by using an existing open source hardware design instead of redesigning an extremity MR scanner from scratch.

Avoided Reproduction	Cost savings per year
1 firm makes use of OS design	US$1.11 million
5 firms make use of OS design (S_1)	US$5.6 million
200 firms make use of OS design (S_2)	US$222 million

3.2. Avoided Reproduction Valuation

To calculate the cost of design of or rather the necessary investment for the COSI extremity MR, we first need to subdivide the system into its major components (magnet, amplifiers and other components) and estimate the effort to design, test, integrate and prototype the subsystems. We estimate the workload for an overall functional prototype as follows: magnet (1 person-year for each an electrical engineer and a mechanical engineer); amplifiers (1 person-year for an electrical engineer); gradient system (2 person-years for an electrical engineer); other components (1 person-year for an electrical engineer); software (0.5 person-year for a software engineer). Furthermore, we have to add another 1.5 person-years for 3 electrical and 1 software engineers to advance the prototype to a ready-to-build product that complies with safety and regulatory standards for medical devices and to prepare proper documentation of the project according to OSH standards and licences including the bill of materials and instructions for assembly, installation and maintenance. The average annual salary for an engineer of each discipline was set to US$89,000 (Pearce, 2015).

The total design costs for the COSI extremity MR adds up to US$1.11 million. Applying the scenarios S_1 (5 firms make use of the design) and S_2 (200 firms or startups make use of the design) from above on Equation 2 would result in savings (for society) of V_{R1} = US$5.6 million within one year and V_{R2} = US$222 million, respectively (**Table 3**).

3.3. Market Savings Valuation

Market savings in our context means healthcare cost savings by cheaper MR scanners available for sale on the market. We therefore assume that, after the release of the design, start-ups would take on the design, commercialize new products, enter the market and put pressure on incumbents leading to a strong market penetration within five years due to lower cost and thus selling price (Pearce, 2015). To calculate the cost savings, we relied on data from Germany where market growth was about 4% per year from 2007 to 2014 (Eurostat, 2016). 88 new MRI scanners were sold per year on average (demand in 2022: 107). We also know that about 30% of all MRI examinations are scans of extremities (Statista, 2009). The vast majority of these are carried out on whole body systems in hospitals and practices. Having in mind though that the number of MRI examinations and waiting time especially for non-urgent cases are further increasing tells us that very likely there will be an additional demand for cheaper low-field extremity MR devices.

Assuming a market share of 10% for low-field extremity MR scanners within the overall market for MR scanners leads to a demand for N_M = 11 devices and a market volume *M* of around US$2.7 million in Germany in 2022 (reference purchasing price of an Esaote O-Scan 0.31T in 2022: US$247,798; inflation: 1.25%). The marginal cost of the COSI extremity MR for 2022 would be C_f = US$40,435. Market savings V_M for the German market along Equation 3 add up to US$2.25 million within one year in case the entire demand would be met by an open source MR scanner. In this calculation, new applications and markets or a substitution of other scanning devices with MRI due to the reduced price was neglected (section 3.4.2 discusses some of these issues).

3.4. Secondary Effects

The previous calculations focused on costs directly related to the design, manufacturing and marketing of a MR device. Monetary savings and thus the value of an open source MR device could be derived based on available data. Beyond these calculations, however, additional benefits arise from open source innovation, and value may be generated that is very hard if at all to quantify but still might have an enormous impact on markets and society as a whole (Aksulu and Wade, 2010). Examples like Wikipedia, the RepRap project, Arduino or the e-Nable initiative are just a few representatives among many open source projects that point the way. In the following, we will elaborate on some effects on healthcare in general, on markets and innovation as well as on research and education that open source MR technologies might cause in the long run.

3.4.1. Reducing Healthcare Costs

The COSI extremity MR is a very useful device for many clinical applications. However, it is based on low field magnet technology whereas most clinical MR systems are whole body scanners that are based on superconducting magnets with higher magnetic field strengths of $B_0 = 1.5T$ or above. Reducing the production costs of these systems via open source is far more difficult to achieve and seems not viable in the short term. However, there is still a huge potential for savings by reducing the service costs via open source designs.

Again, we look into data from Germany that has a publicly funded healthcare system with about 2,800 MR scanners in use these days (Statista, 2016). Most of these are 1.5T (~70%) and 3.0T systems (~20%). A 1.5T whole body MRI costs around US$1.2 million which leads to service costs of US$72,000 per year and device (6% of the purchasing price according to experts from the field). Assuming all MR systems having an average price of a 1.5T system (averaging out the higher cost of 3.0T and even higher field systems and the lower cost of low-field <1.5T scanners) the total cost per year on service contracts for the healthcare system is US$202 million. It has been reported that in-house service can cut down maintenance costs by more than half as compared to OEM service contracts (Sferrella, 2012). In reality however, these solutions are mainly for bigger hospitals with many devices as the knowledge about the device is not readily available. Transparent open source MedTech would change that and either enable in-house service or create a competitive service market with lower prices.

Cutting down service costs by only 1% from 6% to 5% thus would generate savings of US$34 million per year or US$340 million for 10 years. If service costs could be further reduced to 3% by applying the open source model, cost savings for the public healthcare system may easily reach US$101 million per year and up to US$1 billion after 10 years (**Table 4**). In addition to cost savings, the off-time of an MR scanner during malfunction can be reduced due to faster repair by in-house service.

Table 4: Service cost savings for the public healthcare system in Germany by using open source MR technology.

Reduction of service cost	Cost savings	
	1 year	**10 years**
from 6% to 5%	US$34 million	US$340 million
from 6% to 3%	US$101 million	US$1 billion

3.4.2 Impacts on Markets and Innovation

Beyond the potential for massive savings for existing users of MRI devices, the overall market would increase too, if low-cost and modular open source MR devices were available that could be configured and scaled for regional and patient-specific needs and applications such as mobile MR, veterinary, material testing or engineering applications. New markets would emerge in regions and countries that until now have no or limited access to MR devices. A substitution of other imaging technologies that utilize harmful ionizing radiation such as CT or X-ray would also be likely if the costs were comparable.

In addition, general benefits of open source do apply for MedTech, too: Transparency of and ubiquitous and unrestricted access to technology spurs research, competition and innovation; it reduces dependencies from monopolistic suppliers and leads to the emergence of new (local) business ecosystems with tech start-ups, suppliers and third-party service providers. A global (online) community will evolve bringing together patients, medical professionals, manufacturers, students and researchers to share and exchange knowledge, to learn, to give feedback and to jointly improve MR technologies leading to better and cheaper products and services and, in the end, globally enhanced education, patient safety and healthcare.

4. Discussion

Our goal was to estimate the value of an open source MR scanner compared to today's industry standards in terms of cost savings and additional benefits. We calculated these monetary savings with three different perspectives (substitution, avoided redesign and market savings) ranging from US$1.8 million to US$222 million per year. We applied different scenarios to increase the robustness of the results. **Table 5** gives an overview of the values determined for each method. In addition, secondary effects of a global open source MedTech ecosystem were discussed with even more value potentially generated.

The *Downloaded Substitution Valuation* (DSV) method is straight forward and was found to be powerful in different contexts before (Wittbrodt et al., 2013; Pearce, 2015). In our analysis, we took into account that users such as hospitals, research institutions or manufacturing start-ups will build and operate MR scanners themselves based on the designs available for download and thus would not have to buy expensive proprietary products. The cost structures of both products are based on available data. The estimates of the number of downloads and the number of products cannot be determined yet. Still, looking at similar open source projects in MedTech where data is available and keeping in mind the global demand for

Table 5: Overview of the value generated by an open source MR scanner.

Method	Validity	Reference	Min. cost savings	Max. cost savings
Downloaded Substitution	Year of release	Worldwide	US$1.8 million p.a.	US$77 million p.a.
Avoided Reproduction	Year of release	Worldwide	US$5.6 million p.a.	US$222 million p.a.
Market Savings	5 y. after release	Single market		US$2.25 million p.a.

low-cost and accessible MR technology tells us that once the design and relevant documentation will be online, people will start using it. Scenario 1 therefore considers a very slow adoption at an early stage nonetheless leading to savings of millions per year. With increasing dissemination, operation and improvements by an evolving global community, scenario 2 is more likely to happen. This development will also be fuelled by cost optimization and optimization for digital and distributive manufacturing (e.g. as many 3D printed parts as possible).

The *Avoided Reproduction Valuation* (ARV) determines the value for firms and society overall by not having to reinvent the wheel. Once the design is mature and freely accessible online, anyone can use and build on it. In this case too the numbers are reliable in terms of development costs. Regarding both scenarios, the same assumptions as with DSV apply. This method is a very powerful means to showcase the value and potential return on investment of publicly funded open source R&D. In contrast to the patent system, knowledge immediately enters the public domain and may freely circulate to speed up innovation cycles, diffuse technology and enhance technological literacy worldwide. From a firm's perspective too, it can be reasonable to share knowledge and collaborate with external actors (communities, users, customers) to increase the resource base and be very close to customers (Baldwin and Hippel, 2011).

Finally, we calculated potential savings five years from now with the *Market Savings Valuation* (MSV) in case a superior and cheaper open source extremity MR device would enter the market (in this case Germany where data is available) and put pressure on incumbents. Our assumptions for a strong market position within that period are rather optimistic. The product is still in a prototype status, testing and certification is missing and firms need to be founded as well as operations set up. However, we should keep in mind that this data is based on a single market only. We did not account for a general market growth due to cheaper products, for a substitution of other imaging devices or the emergence of new (regional) markets and applications due to access to low-cost technology. Furthermore, an open source documentation and transparent certification process has the potential to harmonize MedTech regulations globally and function as an important safety guideline in MedTech markets that are unregulated (Ettinger et al., 2016). And finally, innovation cycles will speed up with a growing global community of researchers and users involved. Hence, we expect a much higher value in the long run adopting on a global perspective and potentially new applications based on open source MR technology. Today's 3D printing market is a good example to demonstrate how an open source hardware project (RepRap) may boost technology and innovation with a wide range of applications and turn it into a billion-dollar global market within 15 years (Bowyer, 2014).

5. Conclusion

We demonstrated how an open source approach could lead to major improvements and cost savings in healthcare towards more available, accessible, appropriate and affordable MedTech. MRI in particular with its huge benefits for patients and a broad range of applications on the one hand, but high TCO and thus limited availability on the other hand is a very promising case for open source innovation. By applying different valuation methods, it was possible to derive potential cost savings for healthcare systems and patients worldwide of up to hundreds of million dollars per year that could be realized with a simple small-scale and low-cost MR device whose design and documentation will be available for anyone to build, adapt, improve and repair MR systems independently. Beyond reduced costs of the MR systems itself, additional benefits will arise with unrestricted access to knowledge and a global collaborative effort. Having in mind the broad range and enormous number of other open source hardware projects, one can easily imagine the magnitude of value being generated overall. To reach its full potential, however, public funding and investments by the public or private sector are necessary stage to support the democratization of technology.

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Competing Interests

LW is co-initiator and spokesperson of the non-profit Open Source Imaging Initiative on voluntary basis. All other authors have no competing interests.

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