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Democratizing Manufacturing – Conceptualizing the Potential of Open Source Machine Tools as Drivers of Sustainable Industrial Development in Resource Constrained Contexts

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Abstract

Similar to open source software, the open source hardware (OSHW) movement is seen as a technology driver which can enable developing economies to leapfrog their industries. While machine tools are a subset of OSHW, they have received relatively little academic attention compared to electronic OSHW. This study applies an explorative research approach and analyses open source designs for machine tools freely available on the internet. By coining, the term open source machine tools (OSMT), it determines their applicability in low resource contexts and identifies the potential of OSMTs in democratizing manufacturing technologies. OSMTs thereby encourage diversification, entrepreneurship, and inclusive industrial development, thus contributing to the implementation of Sustainable Development Goal no. 8 which aims to promote inclusive and sustainable economic growth. Specific areas for OSMT application in low-resource contexts and factors and barriers affecting their success are singled out.

Keywords

Open Source Hardware; Democratizing Manufacturing; Open Source Machine Tools; SDG; Technology Driver; Resource Constrained Contexts; SME; Sustainability

1. Introduction

In the developing and least developed countries (LDCs), more than five billion people live in resource constrained contexts [1]. The global digital divide exacerbates this phenomenon: On the one hand, industrialized nations witness the evolution of industry 4.0, artificial intelligence, and associated technologies at a rapid pace; on the other hand, there is a persistent lack of technical know-how, digital infrastructure, and lack of scientific research capacities in developing countries and LDCs. As a consequence, this last group is left behind in global development. This has recently become even more evident as resource constrained environments have been hit hard by the disruption of globalized supply chains due to the COVID-19 pandemic [2]. People at the bottom of the socioeconomic spectrum, the so-called bottom of the pyramid, are affected most by this. These dynamics can be seen not only on the international but also on the national level.

To mitigate these inequalities, development theorists have frequently called for faster and more comprehensive inclusion of developing and LDCs into the global network of industrialized nations as well as for the creation of competitive environments to stimulate innovation and boost productive capacities[1] [3]. This is vital for sustainable and equitable economic growth that localizes production and explicitly includes communities and individuals at the bottom of the pyramid [2], especially as traditional developmental approaches such as dissemination of technology have often not yielded the intended successes.

Developments in the field of open source economics have recently offered opportunities to contribute to this goal. Not only are many software programs freely available for anyone to access, use, modify, distribute, and sell, but open source principles are increasingly applied to all kinds of tangible products in the form of open source hardware (OSHW). OSHW is a broad term that includes virtually any kind of tangible item that is produced based on information that is freely accessible, from toys and furniture to farming machinery. Research on OSHW has focused primarily on products such as medical devices [5,4], laboratory equipment [6,7], renewable energy systems [8,9] and also on improving education through OSHW [10,11]. However, even though it is precise about open source aspects, the OSHW definition makes no differentiations between the many different types of hardware that can be built based on open source principles. This paper advocates for the need of subclassifications catering to the particularities of the different kinds of products included in the OSHW definition and proposes the conceptualization of open-source machine tools (OSMT) as a distinct subdomain of OSHW. On the basis of this definition, this paper furthermore identifies OSMT's potential and challenges to democratize manufacturing and to contribute to the implementation of the SDGs and to enable emerging countries to leapfrog their economies through cost-effective, sustainable, and inclusive capacity building.

2. Background

2.1 The limits of traditional production technology

In industrial production technology practice, the innovation process has generally been closed source. As this innovation requires a high input of knowledge and capital, the process is largely barred to most SMEs in developing countries as they lack the necessary human and financial resources to carry out research and development [28]. Closed source production technology thus is a cohesive circle that hinders the dissemination of knowledge and capital to developing countries [12]. Many industrialized countries have in the last decades developed a consciousness for the intrinsic inequalities of traditional production technology and have put forward developmental efforts aimed at making advanced technologies available in developing contexts [13]. However, this top-down developmental aid has not always yielded the anticipated results [15,14]. Based on this observation, bottom-up economics utilizing the concept of co-creation enabled by participation and collaboration such as open source economics can be used as a means to achieve inclusive and sustainable development [16].

2.2 Open Source Hardware (OSHW)

With its roots in open source software (OSS), OSHW applies the open source principles to tangible objects such as machines, devices, or other physical artifacts [17]. The miniaturization of microcontrollers and electronics, coupled with increased accessibility to digital fabrication technologies lowering the barriers to rapid prototyping, have accelerated the evolution of OSHW technology. The democratization of the internet has allowed makers and creators to freely share their designs and know-how, while communities around the world replicate these designs, build upon them, and further improve them [18]. To qualify as OSHW, the design files required to reproduce the machine or device must be made openly available for anyone to study, modify, distribute, make, or sell [19]. Simple replication of an object only requires a bill of materials (BOM)

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[1] Productive capacities are defined as "the productive resources, entrepreneurial capabilities and production linkages that together determine the capacity of a country to produce goods and services and enable it to grow and develop." [2].

and build instructions; editable documents such as computer-aided design (CAD) files in the native format are furthermore necessary to make modifications of OSHW projects. Other instructions such as assembly guidelines, drawings, or electrical schematics can also be made available. Based on this information, a user can either replicate a design, further develop it, or simply extract ideas for other projects [20]. In contrast to OSS, which relies exclusively on computers, OSHW requires tools, machines, and raw materials for replication. This increases OSHW's transaction costs and complexity compared to OSS [10].

In OSHW, two general domains can be distinguished, namely hedonic and utilitarian. With a majority of OSHW projects being hobbyist gadgets, DIY projects in the developed world can be classified as being predominantly hedonic in nature [21]. In contrast, in emerging economies, DIY machines mostly serve a utilitarian purpose [22]. Given that a majority of the OSHW projects are developed in industrialized countries and are designed according to their local resources, needs, and requirements, exact replications of these projects can be inefficient, uneconomical, or even unfeasible in the developing world [23]. Based on this observation, the concept of open source appropriate technology (OSAT) has emerged [24,18] which is based on the argument that advanced technologies are not appropriate for the contexts of developing nations. Instead of exporting the technologies of industrialized countries, technologies should be developed to fit the specific cultural, environmental, socioeconomic, and educational contexts in which they are to be applied [25]. Appropriate technology is characterized by having low capital demands, being locally controlled, decentralized, small-scale, labour-intensive, and energy-efficient [26]. OSAT's goals to adapt technology to human needs and specific socioeconomic and cultural contexts are nowadays also often seen in relation to sustainable and environmentally sound technologies [27].

3. Building on the Shoulders of Giants: Conceptualizing Open Source Machine Tools (OSMT)

One category of items that has in recent years increasingly been built based on open source principles are machine tools. The term machine tools has varying definitions but has generally referred to forming, milling, or grinding machines with a focus on metal processing. Machine tools are directly or indirectly used to make every modern human-made object and with their ability to produce the components required to make other machines, machine tools are aptly known as "mother machines" [28]. Microelectronics and computer technology have allowed the digital control of machine tools, introducing the nowadays widely used Computer Numerical Control (CNC) systems. "Digital fabrication machines" is another umbrella term that includes all machines that can be digitally controlled, whereby laser cutters and 3D printers are also included along with conventional CNC machine tools [27]. For the sake of conciseness and to allow for a certain degree of generalization, we will refer to all these machines – CNC controlled or not, hobbyist or industrial grade – that enable the production of products simply as machine tools.

With their importance for different industries and their potential to bridge sectors, technological developments in machine tools are regarded to generally have the highest impact on the productivity of economic systems compared to innovations in other fields [29,30]. However, only a few industrialized nations are the sole producers of machine tools and manufacturing technologies [31]. Many developing countries lack the resources and know-how to invent and produce such technologies themselves thus rely on buying them abroad. This, however, requires not only high upfront capital investments, but these machine tools are often difficult and expensive to import into low-income countries due to high shipping costs, customs taxes, and administrative hurdles. A lack of technical know-how and low technological literacy[2] further exacerbate these challenges. Taken together, the cost of purchasing and using a high-tech machine tool is prohibitively high in resource constrained contexts; this confirms the assumptions of appropriate

[2] The ability to work with technology in different ways, from understanding over accessing and using to managing it, is called technological literacy or technology literacy. For an individual to obtain technological literacy, a certain degree of digital literacy is an important precondition. Via digital devices such as computers, said individual is enabled to make use of digital information in various forms that is accessible on the internet [32].

technology. Therefore, even though machine tools can be regarded as decisive technology drivers for economic growth that have the potential to leapfrog developing economies, high-tech machine tools are often unattainable in developing contexts.

The OSHW movement offers a potential solution to this problem: By applying OSHW principles to machine tools and making build instructions, BOMs, electronic schematics, and CAD files for machine tools freely available on the internet, the divide in their accessibility between industrialized and developing economies could be bridged and bottom-up, community-driven developmental approaches could be strengthened. While open source machine tools already exist in myriad forms, they have, however, not previously been defined as such. The concept of open source machine tools was first used by Pat Delany, who designed and developed OSHW projects focused on machine tools for "do-it-yourself global development" [33]. Recent years have also seen collective efforts such as Open Source Ecology's Global Village Construction Set [34], which is a set of 50 open source industrial machines and machine tools required to build a small but sustainable civilization, as well as individual efforts from the maker community such as the PrintNC open source CNC mill [35] and the Voron, an open source 3D printer [36]. By applying OSAT design principles and open collaboration, these projects have been able to develop machine tools for a fraction of the cost of their commercial counterparts, and they have been successfully replicated by the community [37]. Online repositories like the Open Hardware Observatory have compiled a list of self-built machine tools collected from the internet by means of a crawlerbot[3] using keywords such as 'DIY' and 'homemade', and have sorted them into various machine tool categories [39]. These DIY or homemade machine tools range from desktop machines weighing a few kilograms to large scale industrial machines. Out of the thousands of designs online, only a handful (10 – 20 machine tools per category) fulfil the OSHW requirements as most do not publish any blueprints to allow replication [40].

However, despite open-source machine tools' great potential for inclusive economic growth and their popularity among the maker community, they have hitherto been neglected in academic OSHW research. This paper therefore proposes the introduction of open-source machine tools (OSMT) as a distinct concept under the domain of OSHW to reflect their importance, to encourage research and standardization efforts in the field and to foster dissemination. To meet the minimal requirements to qualify as OSMT, an item must be a machine tool as defined above. Parallel to the OSHW definition, a machine tool can be considered to be open source if all the plans and instructions that are needed to reproduce it are publicly available under free terms and for anyone. Furthermore, the project source files should be easily accessible to allow for community collaboration in the development, replication, and feedback processes. Due to the open development process of these products and the holistic and dynamic involvement of stakeholders in all stages from ideation over production to modification, OSMT can be considered a disruptive innovation.

Considering the complexity of machine tools, the design sharing function is a key differentiator of OSMT from proprietary machine tools, whereby end users can save tremendous research and development efforts by building on the experience or findings of other users, thus avoiding constant reinventions [41]. Since OSMT are built by the end-users, they are then also able to maintain and fix any issues that could arise during the lifetime of the machines. Production occasionally requires custom machine tools for which there might not be an ideal solution on the market and that is when a self-built machine tool can optimally use available workshop area and be built according to user's specific needs and requirements. With most open source practitioners being individuals working from their homes or garages, the parts and resources for these machines are often cheaper options compared to their industrial counterparts, which can sometimes cause reliability issues. Moreover, as many of the designers are no engineers, there is also often a lack of engineering best practices, which can lead to either under- or overengineered solutions. However, through standardization efforts and focused research in these fields, in the future, OSMT have the potential to attain

[3] Webcrawling is the technical term for automatically accessing a website and obtaining data via a software program [38].

the reliability, performance, and quality normally associated with commercial machine tools. Projects like the Helmut Schmidt University's Open Lab Starter Kit, which aims at designing meticulously documented and globally replicable open source machine tools that comply with industry norms hence prioritizing user safety, can help this process.

4. OSMTs' role in implementing the SDGs

OSHW can constitute a sustainable developmental alternative for developing industries by fulfilling the criteria of OSAT which combines the principles of appropriate technology with open source characteristics. Especially the subdomain of OSMT has great potential for this as it is able to "meet the boundary conditions set by environmental, cultural, economic, and educational resource constraints of the local community" [18]. OSMT developed under OSAT principles – by making use of locally available resources, using off the shelf components, offering customization towards specific user needs as well as expandability or upgradability, integrating community support to answer technical questions – are affordable, easily accessible, and flexible. This democratization of machine tool access can lead to more inclusive and sustainable economic growth by offering opportunities for new business models. It is therefore directly related to the implementation of the Sustainable Development Goals (SDGs) [42]. Moreover, OSMT can be the key to building local production capacity which is vital to realize the goals of achieving a circular economy by localizing production [43].

OSMT can be regarded as a key enabling technology that lowers the barriers to manufacturing in developing countries. By opening up opportunities to prototype, design, create, and invent products that are intimately adapted to local markets and needs, local entrepreneurship is strengthened. As machine tools, that would normally have been imported, can be produced locally based on OSHW principles, local economies become more resilient and less vulnerable to economic shocks through reduced import dependency. It eliminates the need for high upfront capital investments and facilitates a quick return on investments as OSMT are cheaper compared to conventionally produced machine tools [37]. This further encourages economic diversification by offering more business opportunities with less risk, especially for SMEs with little human and capital resources, all the while strengthening resilience by offering options for circular economic models. In this, OSMT contribute to the implementation of SDG no. 8, and especially target 8.2, which aims at promoting "sustained, inclusive, and sustainable economic growth […]" by achieving "higher levels of economic productivity through diversification, technological upgrading and innovation" [44].

Next to bridging differences in the economic development on an international level, the adoption of OSMT also has the potential to bridge national inequalities. In this, it helps to achieve SDG no. 10, which targets the reduction of "inequality within and among countries", by contributing to sub-target 10.2. ("[…] empower and promote the social, economic and political inclusion of all, irrespective of age, sex, disability, race, ethnicity, origin, religion or economic or other status") [44]. Xenophobic national economic policies can disadvantage certain groups of the society and exclude them from equitable economic development [45]. Here, OSMT can empower marginalized communities that are failed by conventional development policies to become self-reliant and pursue bottom-up economic growth, thus making inclusive and fair development a reality. To realize this potential of OSMT and to use them to address the SDG implementation, there is an additional need for new educational models and incentives.

5. Potential Challenges to OSMT Adoption

While further research is necessary to determine the barriers to OSMT adoption in specific local, resource-constrained contexts, some general challenges can already be anticipated. One basic factor hindering the adoption of open-source technology is the lack of awareness of OSHW in general and particularly OSMT. Limited access to the internet and low digital literacy decrease accessibility as OSHW projects are often strewn over the internet across various forums, social media platforms and online repositories [46]. To meet this challenge, it has been suggested that a global centralized open source database be created to house all OSHW projects that are relevant to the UN Sustainable Development Goals (SDGs) [46].

A further challenge is the replicability of OSMT projects. Encompassing the fields of mechanics, electronics, and software, building a machine tool can be a complex endeavour requiring proficiency in various domains such as precision fabrication, high voltage electrical wiring and software configuration. In contrast to OSS, where replication mostly involves downloading and running a code, the replicability of OSMT depends on more pre-requisites such as required manufacturing tools, accessibility of parts and raw materials, as well as considerably more technical know-how, digital literacy, money, and time. An OSMT project can be considered replicable if a functional version of the project can be built by builders in their respective locations, which is also a key characteristic of the OSHW definition [47]. As user requirements and access to parts, raw materials, and manufacturing capability differ in different regions of the world, developing globally accessible designs that are also locally adaptable remains a challenge. Language barriers and cultural differences are further factors that potentially hinder replicability.

OSMT need to moreover be designed in a way that people with little formal education are also able to access, manufacture, assemble, and use the machine tools. The local unavailability of building materials and machine tools to manufacture components in the context of limited resources could potentially hinder the replication of a product that could easily be built in non-constrained circumstances. This is especially likely for electronic components and precision machined components. The arising need to import the building materials from elsewhere counteracts many of the advantages of OSMT described earlier. However, the increase in locally built OSMT could potentially create a market pull for local suppliers of machine tool components to emerge, which creates the possibility of new supplier networks and corresponding business models.

A further challenge lies in the fact that many projects are also outdated, provide insufficient instructions, or lack robustness and quality, thus hindering replication. Without meticulous documentation of the fabrication methods and assembly guidelines, the machine tool might turn out imprecise or unusable or the process could pose hazards to the safety of the builder. One aspect that is specific to the design of proprietary machine tools for industrial use is that the machines are designed with design standards and norms such as the CE certification that ensures compliance with the EU machinery directive (2006/42/EC) and hence the safety of the end user. With no regulatory requirements to abide by, the user safety aspect is commonly neglected in the development of OSMT, since they are often designed for personal use in provisional workshops and therefore do not need to conform to any industry norms. Without the need to commercialize the machine, there is often no incentive to invest resources, time, and money on the extra development effort required to build industry-compliant machines. Organizations such as the open hardware repository have developed a community-based OSHW certification process which is carried out by experts who check designs for user safety and reliability, thus aiming to develop quality standards for OSHW [48]. A similar process to verify the safety and reliability of OSMT is paramount to safe diffusion of these technologies, but the complexity of the machine tools is likely to make this a challenge. Moreover, new business models need to be derived that gives OSMT practitioners sufficient incentive to develop well-documented OSMT that also take user safety and industry standards into consideration.

6. Conclusion and Future Works

Coining the concept of OSMT shows the potential and necessity for subclassifications under the domain of OSHW. This is hoped to stimulate future research specifically on machine tools' particularities in open source contexts as well as encourage further conceptualizations of other types of OSHW. By defining OSMT as a distinct concept, it is also possible to analyse their specific potential for sustainable, context-appropriate, and inclusive development and their ability to contribute to the implementation of the SDGs.

As disruptive innovations, OSMT are here not intended as a competition to industrial machine tools whose technological efficiency and precision have evolved over decades, but rather as a means of making machine tools more accessible and affordable to communities and individuals who would otherwise not be able to use machine tools at all, thus democratizing manufacturing. This, in turn, can strengthen the local job market, re-shore manufacturing, lower import dependence, and create more resilient, equitable, and inclusive economies in emerging contexts. By doing so, OSMT allow developing, resource constrained economies to leapfrog their industries in a sustainable and inclusive way, making the innovations of Industry 4.0 accessible to them, and helping to close the ever-widening technological gap.

However, the successful adoption of OSMT requires more than just engineering innovation. Technology adoption and diffusion in developing economies are complex socio-technical issues which demand a multi-disciplinary approach that incorporates the diverse perspectives of engineering, social sciences, developmental economics, and governance. Such holistic approaches, in which the roles of various stakeholders, public values, and technological innovations are taken into account [49], are important because, even with the right intentions, innovation applied wrong can potentially lead to social exclusions and increased inequalities [50,51]. While being wary of falling into the traps of paternalism [4], policy-driven top down approaches as well as community-aligned bottom up approaches need to be considered to truly facilitate inclusive capacity building in emerging economies [16]. To further evaluate the potential of OSMT and determine barriers and challenges associated with their adoption, pilot projects and associated research such as the Open Lab Starter Kit [40] will need to be carried out and monitored in the long term.

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