Design Science

Designing for replicability: a qualitative empirical study on the replication of open-source machine tools

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Abstract

By making building instructions freely accessible to everyone, open-source machine tools (OSMTs) promise to democratize manufacturing by enabling users in marginalized settings to build machines tools by themselves. There is, however, a lack of empirical evidence of the replicability of OSMT designs in low-resource contexts. This article explores OSMT replicability through qualitative and empirical methods to answer the central research question: Are designs that are fully open source also globally replicable? A comparative experiment was carried out by replicating an open-source 3D printer in two different locations: in Germany (resource-rich) and in Oman (resource-poor). The experiment aimed to determine the barriers faced with the replication in each location. It was significantly more challenging to replicate the 3D printer in Oman, primarily due to difficulties in sourcing and manufacturing, necessitating extensive modifications, which demanded greater skills and dexterity from users compared to those in Germany. Qualitative interviews found that limited digital literacy posed a significant barrier for microenterprise owners in replicating OSMT. Finally, design guidelines were proposed to enhance the global replicability of contextualized OSMT designs.

Keywords: SDG, Open-source hardware, Resource-constrained contexts, Sustainability, Replicability

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1. Introduction

Open-source machine tools (OSMTs) have emerged as a pivotal technology in the democratization of production modes, by offering low-cost access to advanced technologies, especially in resource-constrained settings. Despite their potential, there is a lack of empirical research on the replicability of OSMT in such environments. This article addresses this gap in the literature by presenting the findings derived from the replication of an open-source 3D printer design procured online. The replication process was carried out twice, in two distinct locations: Germany, characterized by ample resources, and Oman, emblematic of a resource-constrained environment with unique socioeconomic considerations.

In Germany, the replication was conducted in a home setting and under conditions deemed to be representative of most OSMT practitioners in the global north. Alternatively, the Omani context focused on local migrant-run microenterprises, a demographic considered a critical beneficiary of OSMT. Through a comprehensive comparative analysis of these replication experiences, supplemented by qualitative interviews among potential OSMT users in Oman, this article explores the inherent challenges in both settings as representative of the global north and global south.

This dual methodology highlights the distinctive design requirements warranting attention when designing OSMT for resource-constrained settings. These findings inform the development of guidelines for the design and documentation of OSMT to enhance their replicability under varying circumstances and not just those prevalent in the global north.

2. Aim and significance

This research article tries to answer two critical questions:

- Is a fully OSMT design globally replicable?
- What challenges and barriers do users in low-resource contexts encounter when attempting replication of OSMT?

It is important to note that most research concerning the replicability of open-source hardware (OSH) has been conducted with OSH practitioners or users primarily from the global north (Antoniou *et al.* 2021, 2022). While the principle behind OSH suggests universal replicability due to the unrestricted availability of instructions and blueprints (Bonvoisin & Mies 2018), the adoption of OSH designs in developing contexts has been modest (Reinauer & Hansen 2021). Moreover, empirical research investigating these assumptions remains limited. This article aims to fill this gap by examining how geographical contexts, particularly in industrialized versus developing settings, influence the feasibility of replicating OSH designs, specifically OSMT designs. Additionally, the study qualitatively assesses the practical extent to which microentrepreneurs in low-resource environments can successfully replicate OSMT projects. The design guidelines outlined within this work offer best practices for enhancing the replicability of OSMT projects, emphasizing diverse facets of design and documentation. Moreover, this study aims to encourage development organizations to actively pursue the adoption of OSMT initiatives to facilitate the dissemination of cost-effective production technologies to microenterprises in resource-constrained settings.

3. Background

3.1. Machine tools – Key enablers of manufacturing

The term “machine tools” encompasses various definitions, but most often describes forming, milling, or grinding machinery primarily used in metal and wood processing. Widely recognized as pivotal in crafting nearly every modern human-made object, these tools hold a unique distinction as “mother machines” for their capability to produce components essential for constructing other machines (Mori, Hansel & Fujishima 2014). The advent of microelectronics and computer

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technology ushered in the era of digital control for machine tools, introducing the ubiquitous computer numerical control (CNC) systems. The umbrella term “digital fabrication machines” encompasses all equipment controllable via digital means, including laser cutters and 3D printers (Gershenfeld 2012). For the sake of brevity and allowing a level of generality, we will refer collectively to these machines—be they CNC-controlled, hobbyist-oriented, or industrial-grade—as machine tools, acknowledging their role in enabling the production of goods.

Given their significance across industries and their ability to bridge sectors, technological advancements in machine tools are widely acknowledged to exert the greatest impact on economic system productivity (Hall & Rosenberg 2010; Saxena & Sharma 2014). Yet, the production of machine tools and manufacturing technologies is concentrated in only a handful of industrialized nations, while many developing countries lack the resources and expertise to independently innovate and develop such technologies (Békés & Harasztosi 2020). Consequently, these nations rely on importing these tools, which entails substantial initial capital investments and obstacles such as exorbitant shipping costs, customs tariffs and administrative complexities. Consequently, their substantial initial price tags, often reaching several thousand US dollars (USD), alongside additional shipping expenses, place them beyond the financial means of microenterprises operating within tight budget constraints. Moreover, navigating this avenue can be complex, demanding expertise and experience to discern the suitable machines at the right prices (Békés & Harasztosi 2020). Furthermore, machine tools designed for the global north are often overengineered for the requirements of small microenterprises with limited workshop space and production capacities in the global south. Hence, while they are crucial drivers of technological progress capable of propelling the growth of developing economies, accessing modern machine tools remain elusive within these contexts.

3.2. Open-source machine tools

Applying principles akin to open-source software (OSS), OSH presents a potential solution: making both software and firmware freely available online, including build instructions, bill of materials (BOM), electronic schematics and computer-aided design (CAD) files, could potentially bridge the accessibility gap between industrialized and developing economies. OSMT is a subdomain of OSH with a focus on machine tools and was coined to encourage research focused on their design and replicability (Omer *et al.* 2022). The democratization of the internet has empowered creators to freely disseminate designs, fostering global communities that replicate, refine and enhance these innovations (Balka 2011; Hansen & Howard 2012). For a hardware design to qualify as open-source, design files must be openly accessible for study, modification, distribution and commercialization (Open Source Hardware Association 2021). Additionally, both OSH and OSMT heavily rely on user involvement and community cooperation (Grames, Redlich & Wulfsberg 2011; Li & Seering 2019) exceed traditional forms of design, development and quality control of conventional mass-produced industrial goods (Bonvoisin, Mies & Boujut 2021; Thomas, Evrard-Samuel & Troxler 2023).

As end users procure, fabricate and assemble the machines themselves, factoring in solely the cost of materials, self-built OSMT, like most OSH designs offer a significant cost advantage over their commercial counterparts (Pearce 2015; Open

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Source Ecology 2022). This lowers the threshold of acquiring advanced production machines that would normally be unattainable for marginalized communities in resource-constrained contexts. Especially 3D printing, often described as a disruptive force in manufacturing (Bonneau & Yi 2017), has gained considerable traction as the most frequently replicated OSMT accessible through online platforms (Jones *et al.* 2011). This innovative process enables the production of intricate components without the need for traditional jigs and tools and significantly reduces the learning curve for end users, making it a pivotal facilitator in sustainable and developmental initiatives (Pearce *et al.* 2010).

Unlike OSS, which remains confined to computers, OSH involves tools, machines and raw materials for replication, elevating its complexity and transactional costs (Abdelkafi, Blecker & Raasch 2009). This complexity in their physical replication is more pronounced for OSMT compared to generic OSH projects, due to their high requirements of precision during the manufacturing and assembly process. This consequently increases the requirements of end-user skills, domain knowledge and dexterity to achieve a functioning machine (Rayna, Striukova & Fauchart 2023). Additionally, CNC-capable OSMTs that constitute a combination of mechanical, electronic and software components within the design, add an additional layer of complexity. These intricacies make the design and documentation required for the successful replication of OSMT inherently more challenging.

3.2.1. Replicability of OSMT

The replicability of an OSH design refers to the ability of an individual builder to construct a functional hardware version in their respective settings. It stands as a fundamental aspect of OSH that distinguishes it from proprietary hardware, where designers and manufacturers typically aim to inhibit design replication (Open Source Hardware Association 2021). With the availability of all source files to replicate an artifact being one of the core principles of OSH, some studies have focused on openness as a key criterion for successful OSH projects (Bonvoisin & Mies 2018; Mies, Häuer & Hassan 2022). However, openness alone does not ensure that a design can be replicated; instead, it is also vital to capture the design rationale and reasoning in OSH documentation to enable successful replications and further adaptations by users (Antoniou *et al.* 2021).

Projects like the “Mostly Printed CNC” (MPCNC) exemplify instances where OSMT designs, while not entirely open source due to limitations such as withheld CAD files or restrictive licensing, have been extensively replicated (UltiMaker Thingiverse 2015). The prevalence of replication suggests that other factors beyond complete openness also influence the replicability of designs. The commercialization of OSH is frequently pursued and studied as a means for the widespread adoption of OSH projects among end users (Li & Seering 2019; Rayna *et al.* 2023). However, an inherent consequence of this pursuit is the counterproductive impact it exerts on the design principles aimed at enhancing replicability within OSH. It drives OSH designs toward optimization for mass production rather than catering to individualized production processes. OSH entrepreneurs who emphasize design tend to focus on product design and R&D, outsourcing manufacturing. In contrast, those entrepreneurs focusing on manufacturing primarily commercialize and sell their products as kits. For both groups, industrial efficiency is essential (Thomas *et al.* 2023). This shift in focus presents a notable challenge, as it may inadvertently

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compromise the intrinsic characteristics that facilitate easy replication within the OSH domain for individual end users.

Conventional engineering product design centers on end users who act as consumers, receiving fully manufactured, assembled and ready-to-use products. However, within the OSMT context, the consumer assumes a dual role as both the manufacturer and end user—a concept often termed as "prosumer" (Lang *et al.* 2021). Consequently, the traditional design strategies focused on "Design for Manufacture" and "Design for Assembly" optimization tailored for mass production become impractical within the OSMT framework.

Reinauer & Hansen (2021) found that despite the transformative potential of OSH, technology diffusion has remained slow. As existing studies concerned with replicability of OSH tend to be limited to intrinsic factors of OSH projects and only focus on people who already are experienced OSH practitioners from the global north (Antoniou *et al.* 2022), this suggests the importance of external factors to OSMT replicability. There is a lack of research that considers the socioeconomic position of the user, and the external environment in which an OSH project is built, as factors affecting replicability. These are, however, key considerations that need to be addressed in designing for different users in a wide variety of contexts. Despite the potential of OSMT for microenterprises in the global south, the factors affecting their replicability have not been explored empirically within resource-constrained contexts, where their diffusion could bring the highest impact toward sustainable and inclusive industrialization.

3.3. Sustainable industrial development and microenterprises

Engineering endeavors that align with the UN sustainable development goals (SDGs) aimed at "peace and prosperity for people and the planet" (UN 2016) prominently center on essential sectors like sanitation, infrastructure, water and energy. However, it is important to note that SDGs 8 and 9, which aim to foster livelihoods through sustainable industrialization, are often underrepresented in these initiatives. In academia, the concept of industrialization mostly falls within the purview of economics research, focusing on structural transformation that guides policy recommendations. This transformation, defined as shifting resources from low to high-productivity activities (Monga & Lin 2019), boosts labor productivity and, through access to better technologies, enhances worker skills over time (McMillan & Rodrik 2011).

Structural transformation holds immense potential for increasing productivity in developing countries, particularly due to their limited high-productivity zones (UNCTAD 2017). However, existing policies often target larger industrial entities, inadvertently sidelining smaller microenterprises (Radic 2019). These microenterprises, constituting a substantial portion (80%–90%) of total employment in low- and middle-income countries (LMICs), receive minimal attention (Radic 2019; Suhaili & Sugiharsono 2019). Consequently, development economists advocate redirecting focus toward microenterprises, highlighting their capacity to leverage policy interventions for profound and pervasive economic impacts (Seitz 2017; Achkar 2023), thereby acknowledging their potential to serve as catalysts for inclusive and equitable economic progress.

Microenterprises primarily differ from the more commonly known and studied small and medium enterprises (SMEs) in terms of number of employees and

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annual revenue (DIW Berlin 2023). In Oman, microenterprises are businesses with up to 10 employees and yearly earnings below 390,000 USD. Small enterprises have up to 50 workers and 3,250,000 USD, while medium enterprises can employ 150 workers and generate annual revenues of almost 13 million USD (Oman News Agency 2022). In many developing countries, microenterprises are exemplified by small roadside shops selling or manufacturing various kinds of goods. Each proprietor functions as a microentrepreneur (Seitz 2017). Despite often only generating subsistence income, microenterprises hold the potential for expansion and job creation when provided with appropriate equipment and investments, which could significantly accelerate economic growth in LMICs (Seitz 2017). Given the spillover effects linked to advancements in the manufacturing sector and the extensive participation of microenterprises across various manufacturing domains, this sector emerges as an ideal beneficiary of technology diffusion and industrial upgrading (Haraguchi, Cheng & Smeets 2017; Monga & Lin 2019).

Cost-effective and accessible technologies are crucial for the socioeconomic growth of microenterprises because they can enable them to modernize their production capabilities, gain access to new technologies to diversify their businesses and allow them to become self-sufficient in a sustainable and cost-effective way (Verma 2021). However, they face several obstacles, including limited access to finance, markets, digital infrastructure, skills training and government support, hampering their growth and sustainability (Achkar 2023). Addressing these obstacles is pivotal for unlocking the full potential of microenterprises and fostering their meaningful contribution to economic development.

3.4. Case study

For this research, migrant-run microenterprises in Muscat, Oman, were examined as a case study. While Oman is not an LMIC but a high income country, it is affected by one of the world's most unequal wealth distributions: over 60% of total income is concentrated in the top 10% of the population (Harris 2017). Oman hosts a substantial migrant population, primarily from South Asia (de Bel-Air 2015). These migrant workers predominantly engage in low-paying job sectors such as agriculture and manufacturing, typically performing laborious tasks that compromise their safety (Hassan & Jureidini 2020). Considered as transient laborers, migrants face minimal prospects for citizenship in their host country, effectively barring their integration into the socioeconomic fabric (Weeraratne 2020). Trapped in low-skilled occupations with meager wages and facing exclusionary national policies, some migrants venture into microenterprises for improved economic prospects (Rahman 2018). These microenterprises focus mostly on manufacturing-related activities since these can be carried out by renting small shops, and they are often regarded by locals as low status jobs (Al-Hashmi 2019).

The many manufacturing microenterprises center around low-skilled, labor-intensive tasks using manual machine tools, notably in sectors such as metal fabrication, construction and carpentry. Migrant entrepreneurs lack access to government SME financing initiatives, exclusively reserved for citizens, compelling heavy reliance on personal savings or borrowing from acquaintances to launch new ventures or invest in machinery (SMEF 2014; Rahman 2018). These financial limitations hamper their ability to modernize, expand, or diversify their businesses,

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rendering them more susceptible to economic shocks (UNCTAD 2021). Operating within severely resource-constrained environments, migrant microentrepreneurs in Oman face challenges in fostering business growth that are representative for most marginalized microenterprises operating with limited resources.

4. Methodology

4.1. Replication experiment

This article analyses the factors affecting global replicability of open-source projects through a physical replication experiment of an open-source 3D printer design. The 3D printer is used as a case study in this work because of its ubiquitousness among OSH communities and its disruptive potential (Bonneau & Yi 2017). As a fully CNC machine, it represents the complexity involved in replicating an OSMT design, while the relatively high precision required during the building process is a characteristic shared with conventional machine tools. The 3D printer design was chosen from an online OSH repository, considering some key factors in the choice of project:

- Openness: The project must be fully open source; design blueprints must be available and usable without any commercial restrictions.
- Cost: The design must be realistically attainable for users with limited financial resources.
- Number of replications by other users: This user-reported metric was derived from the respective design repositories. Designs with higher numbers of successful replications are deemed more complete and more reliably replicable.
- Presence of community support groups: The vibrant exchange on social media platforms can facilitate troubleshooting during the building process by discussing challenges with other builders interested in the same project.

After some suitable open-source projects had been located in online repositories such as Thingiverse, Instructables and GitHub via internet searches, they were evaluated according to the above criteria. In addition, online reviews of the designs were consulted to identify a project that would meet the requirements of this research. Several projects seemed appropriate to replicate in the Omani context but were discarded because they did not entirely fulfill the criteria for openness, such as a metal laser-cut redesign of the Prusa i3 3D printer (irobri 2013) and other projects that did not provide all necessary build resources under open-source licensing (dcorb 2015; Laaribi 2019). Ultimately, the Hypercube Evolution design was chosen, an open-source 3D printer project by user Scott3D on Thingiverse (Scott_3D 2017). Even though the design was missing a clear BOM and build instructions, the design was found to be the most committed to open-source criteria as it not only made the native CAD files available for users but also had no restrictions on commercial use. The project used a structurally robust yet simple construction while remaining affordable. This 3D printer had also been successfully replicated by several other users, and large community groups on social media existed to discuss potential problems. Overall, this design was deemed to be the most ideal in the context of this research.

Upon choosing the project, the first iteration of building the 3D printer was implemented in Hamburg, Germany. This represents the replication in an industrialized country with no resource restrictions. The printer was built in a home office to emulate the fact that most OSH projects in the global north are built by individuals in home settings (Tanenbaum *et al.* 2013). Since the project was missing a clear BOM and build instructions, after the first successful build, a comprehensive pictographic build manual was created to facilitate further replications by other users using guidelines from the works of Agrawala *et al.* (2003). This modified and updated printer design was uploaded as a redesign of the original on the open science repository with a comprehensive assembly manual and accompanying wiki (Omer 2023).

Subsequently, the same 3D printer was built a second time in Muscat, Oman. Here, the replication was attempted in the workshop of a migrant-owned manufacturing microenterprise. The country's migrant microenterprises mostly operate under circumstances of severely constrained resources – in terms of know-how, education, finances, space and time. This setting therefore represents the replication in a resource-constrained context.

4.2. Qualitative interviews

In the third step, the comparative building methodology was supplemented by qualitative interviews. As the authors replicating the 3D printer had high levels of digital and technology literacy as well as a formal education in the engineering domain, they were representative of users with high general, digital and technological literacy levels. The same characteristics are not, however, typical of the envisioned OSH users in the global south. Therefore, qualitative semistructured interviews among the large community of migrant workers in Oman served to assess the ability of potential OSMT practitioners to replicate complex designs. Seven South Asian microentrepreneurs were interviewed who worked in steel fabrication and manufacturing microenterprises in the Wadi al Kabir industrial cluster in Muscat. They were representative of microentrepreneurs working in the informal sector with limited capital and resources and often low levels of general and digital literacy. In the first phase, questions were tested to determine the optimal interview duration, the format of questions and the balance of structured and unstructured interview questions to develop the interview guide. In the second stage, the interviews, which lasted approximately 25 minutes on average, were implemented with the respondents. They were conducted in Bangla, the native language of the interviewees. The interviews were transcribed in Bangla and subsequently translated into English by a native speaker of both languages. They were analyzed in the software MaxQDA 2022 according to the principles of qualitative content analysis formulated by Kuckartz & Rädiker (2022): first, a set of deductive codes was developed with the help of the interview guide. This code system was used in an initial coding cycle. Next, inductive codes were developed and added to the existing code system. In three reiterative cycles, the interview transcripts were then coded, and the code system was revised. The final code system comprised 41 codes in six categories: knowledge of OSMT, build/buy decision, ability to build, steps in the building process, preferred instructions and digital literacy.

The interviews aimed to assess the interviewees' degrees of digital literacy (for example, their usage of computers or laptops at home or the workplace, whether they knew any online marketplaces and their proficiency to order goods online, to

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look up a design repository on the internet and download the required data), their ability to fabricate parts according to fabrication drawings and correctly assemble them according to picture-based build instructions, their understanding of electronic wiring schematics and their proficiency in setting up the software for the machines and installing the required firmware. Throughout the interview sessions, respondents were presented with diverse blueprints essential for replicating an OSMT project, showcased on a laptop. These blueprints encompassed the BOM, assembly manuals, wiring schematics, CAD model and similar documentation (Omer 2023). Participants' comprehension levels and their capacity to execute the replication process were evaluated through interactive engagement with these blueprints.

These interviews further investigated the feasibility of replicating OSMT in resource-constrained environments in the global south with standard open-source documentation. Through this, a deeper understanding was developed of the challenges when designing for the usage and application of OSMT by marginalized groups in resource-constrained environments.

5. Results

The following subsections describe the experiential observations and outcomes from replicating a 3D printer in the two distinct contexts. The comparative analysis focuses exclusively on the physical facets of replication, commencing postdesign selection and acquisition of requisite blueprints. The physical replication process, depicted as a flowchart in Figure 1, initiated with the procurement of raw materials, hardware and electronic components specified in the BOM. Raw materials, such as shafts or enclosure panels, necessitated cutting or processing to precise dimensions as outlined in fabrication drawings or specified lengths within the BOM. Certain components required manufacturing from scratch via distinct processes, including milling or 3D printing.

Subsequently, fabricated parts and off-the-shelf components were integrated during the assembly. An electrical wiring diagram depicted the wiring of the individual components such as motors, sensors, power supply and peripheral electronics to the controller board. During the software setup, the firmware that controls the machine was flashed on the machine controller board and necessary software to use the machine on a computer. The final phase involved calibration, entailing comprehensive functional testing and readiness for initial use.

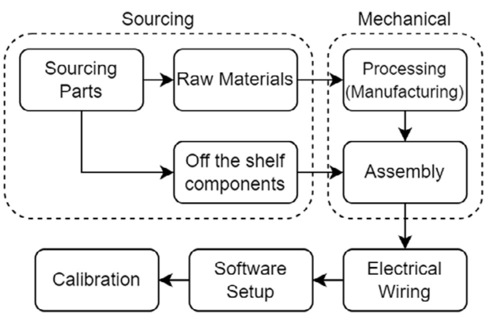

Figure 1. General replication process of OSMT postdesign selection.

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5.1. Replication in Hamburg

The BOM is typically provided in the form of an Excel sheet or text-based document and includes links to online marketplaces to purchase the necessary parts. The Hypercube Evolution, like many other OSH projects designed in the global north, provided links primarily to resellers located in these countries as well such as eBay, Amazon or local shops. Parts purchased from local sellers arrived at the home workshop after only two to three days. Procuring specific parts at favorable prices posed a challenge, often requiring bulk purchases leading to surplus parts. Variability in dimensions and model numbers occasionally resulted in incorrect orders or defective parts, although returns were feasible at no extra expense.

Small electronics items and mechanical hardware were also bought from international online marketplaces such as AliExpress. These parts had longer delivery times, 12 to 17 days on average, but they were also considerably cheaper. Moreover, all metal structural members, motion guides and enclosure panels, which would require either access to CNC machine tools or high levels of user skills with hand tools to fabricate to the necessary dimensions, were ordered online from local shops, pre-manufactured to the required dimensions. This access to manufacturing as a service during the sourcing phase eliminated the need for the user to possess any experience with such fabrication processes and made the final assembly of the printer relatively simple, precise and quick. Overall, the sourcing, purchase and shipping of the parts was straightforward for the replication in Germany.

Once all necessary parts and materials were obtained, several functional components were manufactured using 3D printing, which is a manufacturing process often used in open-source designs. Access to desktop 3D printers was available in various public spaces, makerspaces and online marketplaces such as Etsy, where complete kits of 3D-printed parts could be purchased. The author utilized a personal 3D printer at home to produce the required parts. Figure 2 shows all parts of the printer before and after assembly.

Following mechanical assembly, wiring the electrical components, along with soldering sensors and connectors, was necessary. Learning the required skills

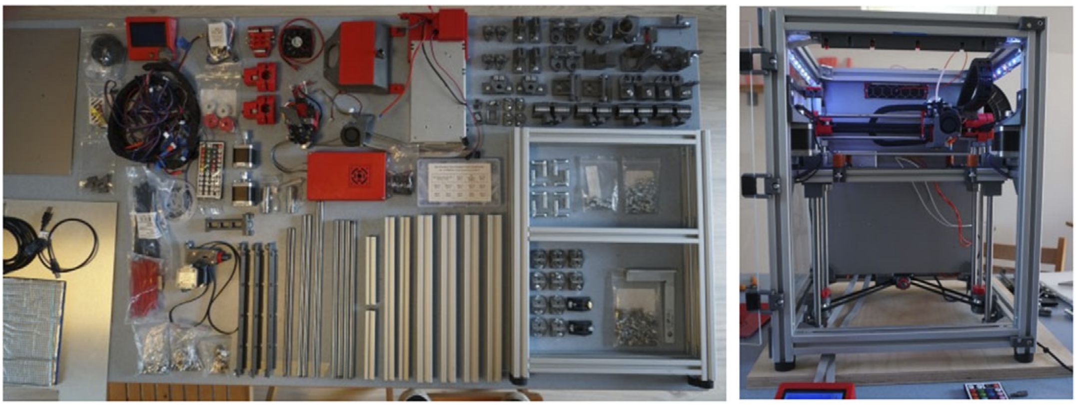

Figure 2. Left – All parts of the printer (prepared for assembly). Right – Fully assembled printer.

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involved watching YouTube tutorials and practicing. Ensuring robust electrical wiring also demanded extensive testing and seeking guidance from experienced users on community forums. For the software setup, Marlin, a prevalent open-source CNC firmware, need to be flashed onto the microcontroller board. When utilizing the original firmware without machine modifications, direct flashing onto the microcontroller is feasible. This can often involve trivial copying of a firmware. bin file onto an SD card and inserting it into the controller board, after which the firmware is automatically installed when the board is first powered up. However, alterations to the machine design or use of alternate electrical components can necessitate firmware modifications, particularly challenging without prior domain knowledge and extensive online research. Although resource limitations were not a hindrance in Germany, achieving accurate assembly and smooth operation of electronics and software proved to be complex, despite the author's engineering expertise. Accurate assembly is critical as misalignments in the assembly can cause the motion of the finished printer to suffer from binding and result in stick-slip motion. The lack of smooth motion would result in printing defects such as layer splitting and surface defects. An inaccurately assembled frame could also cause the XY axes plane to be tilted, which can make calibration challenging and also adversely affect print quality. Therefore, precision fabrication and assembly of the 3D printer frame are integral for the realization of a functioning machine.

5.2. Replication in Muscat

Considering the potential of OSMT for resource-constrained microenterprises, for the second replication cycle, a local partner willing to cooperate in the replication of the 3D printer was needed. In exchange for providing the working space, the local partner would be able to benefit from this cooperation by gaining access to new 3D printing technologies after project completion. A local steel fabrication microenterprise, Abu Usra Trading Co. LLC, agreed to provide the working space for this, whereby they saw the potential of diversifying their business by offering new 3D printing services. The microenterprise is situated in the Wadi al Kabir industrial cluster – an area in Muscat in which many migrant-owned microenterprises working in the steel and wood fabrication sectors are located.

Sourcing the necessary components for the printer build presented considerably more challenges in Oman. The absence of local online vendors offering the required parts, particularly specialized components such as electronics and mechanical hardware added significant hurdles to the procurement. This scarcity stemmed from the significantly smaller size of hardware required for desktop 3D printers compared to components used in automotive or plant machinery. Notably, unlike the latter, Oman lacks a local market catering to these smaller components for machine tools. Acquiring them from international online marketplaces also posed a substantial challenge as delivery times to Oman typically ranged from one to two months. As a result, multiple visits to various local physical stores were required to inquire about materials, significantly impeding and elongating the sourcing process.

Procurement was furthermore complicated by the fact that residences and companies in Oman often lack conventional postal addresses. Instead, individuals or entities need to register for a postal address at a communal post office with an annual fee of 140 USD, which most microenterprises do not possess. Overall, the

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long waiting periods and challenging conditions associated with ordering internationally significantly impeded the building process.

Sourcing aluminum slotted profiles (ASPs), crucial for constructing the printer's frame and precisely mounting functional components, posed a significant challenge. These ASPs, also known as T-slot extrusions, are commonly used in industrial automation and machine building. They offer flat surfaces for accurate assembly and feature T-slots facilitating precise manual component mounting within the printer frame. Ensuring high precision in frame construction and part mounting is pivotal for a functional 3D printer, demanding adherence to a minimum precision of at least 0.05 mm throughout the assembly process. Unfortunately, ASPs were unavailable in Oman. Importing them from international online platforms incurred exorbitant shipping costs, nearly tripling the original part expenses. This conflicted with the project's objective of maintaining cost-efficiency and sourcing materials locally.

This posed a major challenge for replication, requiring a different design approach to avoid redesigning all components. Locally available materials for the frame were chosen to avoid making complex modifications to subassemblies or mounted functional components. Thin-walled steel square hollow sections (SHSs) were the best local alternative resembling the ASP, which were commonly used in fabrication jobs by the microenterprise. Initially, welding was chosen for fabricating the frame due to its simplicity, cost-effectiveness and the familiarity of the microenterprise workers with this manufacturing method. Given that the user possesses the required skills and dexterity to fabricate the design, a welded frame similar to the one documented by dcorb (2015) was a feasible design variant for achieving an accurate frame under the conditions witnessed in Oman.

The microenterprise technicians preferred a single 3D drawing showing key dimensions of the frame for fabrication. 3D drawings were made of the frame with the representative dimensions to be considered during fabrication. Considering the lack of precision tools, the manufacturing tolerances were kept similar to that provided for the ASP build (+-0.05 mm.) However, despite using the dimensional drawings, the final product exhibited warping and significant dimensional deviations. The resulting frame required extensive post-processing to reduce warp and achieve non-binding linear motion. The microenterprise's limited precision fabrication capabilities, including the absence of flat surfaces and welding jigs, hindered achieving the required accuracy for constructing the 3D printer via a welded frame.

As an alternative, a bolted design was developed in 3D CAD to address warping issues, utilizing locally fabricated angle brackets to reinforce the frame (seen in green on Figure 3, right). This design necessitated 31 custom metal brackets and the drilling of 370 holes. This task demanded a considerable degree of proficiency and expertise and increased manufacturing time. Only a limited number of microenterprise workers possessed the requisite skills to precisely drill the holes, and even these workers did not employ precision tools such as vernier calipers and precision marking tools. Furthermore, the accuracy of other power tools utilized by the workers, such as disc cutters for profile cutting, was compromised due to wear and tear, resulting in irregular end shapes. Consequently, measurements taken with these imperfectly cut edges as a reference introduced additional errors. Additionally, several postassembly adjustments were necessary for squareness, but without welding-induced warping and with flexible bolted joints, precise frame assembly was possible.

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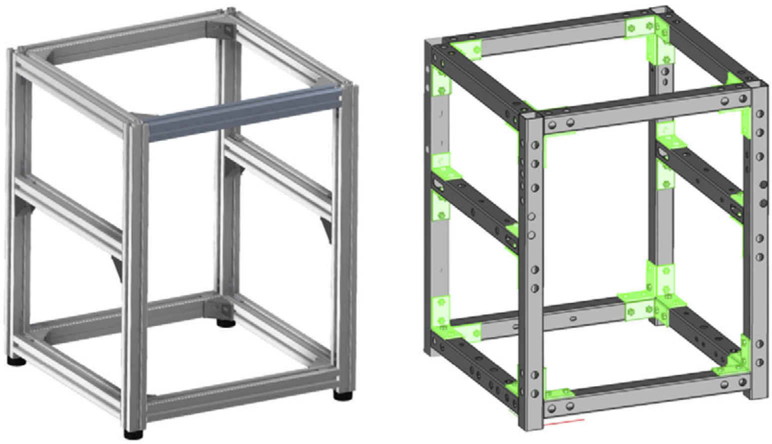

Figure 3. Left – Original aluminum profile frame. Right – Modified steel SHS frame with brackets.

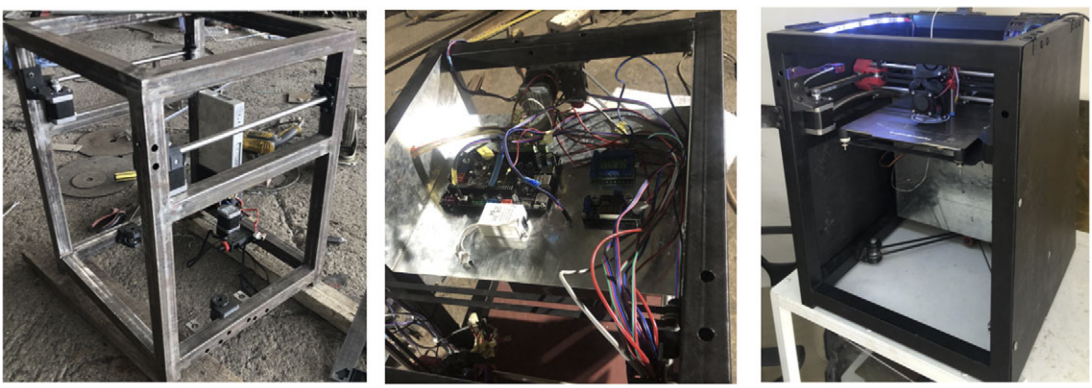

Figure 4. Left – Manufacturing the printer frame, Center – Electrical wiring and Right – Finished 3D printer.

After the frame was manufactured (see Figure 4), the functional components and brackets that were to be installed on the frame needed to be 3D printed. Compared to their abundance in Hamburg, local makerspaces or other 3D printing facilities were scarce in Muscat. While a few startups provided 3D printing services, their pricing rendered the printing of parts financially prohibitive. Moreover, the absence of local 3D printer vendors necessitated importing one. Despite their relatively affordable prices, the substantial shipping costs could significantly inflate the total expense. Consequently, acquiring a 3D printer to manufacture another 3D printer appeared counterproductive, lacking justification for the added expenditure. By seeking assistance from a university laboratory, the parts were finally printed. However, this was only possible in the context of a research project. Producing 3D printed parts therefore poses a potential impediment to the replication of OSH projects in developing contexts in general, as 3D printers are not common in Oman compared to their ubiquity in industrialized nations.

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5.3. Qualitative study of replicability

The qualitative interviews among potential OSMT practitioners from the community of migrant entrepreneurs highlighted further challenges when designing for resource-constrained contexts. The landscape of migrant microentrepreneurs largely presents a distinct profile, characterized by individuals mostly with minimal literacy skills, often informally apprenticed in family businesses, lacking proficiency in digital tools, and often devoid of English language abilities. Contrasting this, a younger generation is currently emerging—with higher literacy levels, good English skills and typically children of these small business owners, joining the family trade after high school or university.

All respondents interviewed expressed confidence in their capacity to source parts and raw materials from local shops and execute the mechanical aspects of the build, including part fabrication and mechanical component assembly. This confidence was contingent upon the availability of detailed part lists, fabrication drawings and a comprehensive pictographic build manual. However, tasks demanding high digital literacy and technological proficiency, such as firmware code modification or design adaptation utilizing 3D CAD software, proved beyond the capabilities of most interviewees. Notably, only one younger respondent, a mechanical engineering graduate, exhibited proficiency in all domains of the replication. Another respondent, acknowledging limited expertise, mentioned asking an acquaintance possessing IT skills for help with potential firmware modifications.

Some microentrepreneurs from the older generation expressed apprehension regarding electrical wiring due to a lack of experience with electronics and challenges with reading diagrams. Conversely, younger respondents conveyed confidence in accomplishing electrical wiring tasks with assistance from local electricians, given comprehensive wiring schematics. The availability of local expertise in the form of electricians was noted as likely to be utilized during electronics-related tasks. Microentrepreneurs, lacking formal education and computer familiarity, would face obstacles in replicating steps demanding digital literacy. Tasks like finding OSMT designs online and installing necessary software would serve as barriers to replication for these users. They would require external assistance to navigate the digital aspects of OSMT replication.

Upon reviewing the comprehensive steps involved in replicating an OSMT design, certain respondents expressed interest in obtaining fully assembled machines or comprehensive kits, mirroring prevalent models observed in OSMT project business models (Thomas *et al.* 2023). This inclination highlights a demand for local suppliers capable of providing these options, in line with market trends where kits encompass all necessary components and let end users skip the time-consuming sourcing process. This preference signals a potential market niche, emphasizing the need for local suppliers to accommodate these demands. The emergence of such suppliers could foster a symbiotic relationship between demand and supply within the microenterprise ecosystem, meeting the specific needs of these entrepreneurs. However, sustaining the cost advantage of low-priced machine tools to suit the limited purchasing power of microenterprises could pose difficulties.

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6. Discussion

The replication of the 3D printer in resource-constrained migrant-run microenterprises in Muscat differed significantly from the replication in Hamburg. Conducting parallel replications under comparable conditions (by the same user, with the same build instructions, etc.) enabled an examination of OSMT replication steps while revealing context-specific challenges. The initial printer design was outdated, requiring modifications such as a modern microcontroller and noise-resistant endstop sensors. These changes demanded complex firmware adjustments, and a new electrical wiring setup often challenging for those lacking electronics or programming experience. Additionally, issues such as poorly soldered joints, loose connectors and faulty electronics frequently hindered progress, adding further potential for error during custom wiring and cable assembly. Consequently, achieving flawless functionality demanded significant time and effort, regardless of the location of replication. The design's openness facilitated adaptation of the design to local resources, a significant advantage inherent in OSMT. However, these modifications were highly time-consuming and complex, which would be impossible for users without proficiency in 3D CAD skills and access to the native CAD files. This highlights the fact that while an OSMT design might be entirely open source, its global replicability is not guaranteed.

During the replication of the 3D printer in Oman, sourcing of the parts and building the machine structure posed the primary challenges, compounded by limited access to 3D printing technology for manufacturing the functional parts. This highlights a key difference in OSMT replication between the global north and the global south: While 3D printing is often seen as an easy and affordable way to manufacture specific necessary parts in the former, the limited access to 3D printing technologies in the global south poses significant challenges to the replicability of OSMT projects designed in the global north. Precise manufacturing of custom parts was also a challenge due to substandard machinery and a lack of automated machine tools. Achieving precise assembly posed a further challenge, as this requires different tasks, including mounting multiple parts with utmost accuracy, which is contingent on the user's prior experience and skill with similar tasks.

Another hurdle was identified in the fact that the goods typically manufactured by the microenterprises in Oman were significantly larger in size and did not require precision fabrication. The welded design thus posed challenges as the workers, while understanding the need for precise frame construction, found it challenging to translate their existing experience to the much smaller frame design of the 3D printer. Therefore, local skills, experiences and manufacturing infrastructure can become barriers to replicability.

6.1. Designing for replicability

The experiment revealed distinct challenges in OSMT replicability. First, physically replicating OSMT designs demands high precision during fabrication and assembly, elevating the requisite user skills, domain knowledge and dexterity required to achieve a functional machine. To enhance precision and efficiency in machine construction, designs may leverage CNC machines for manufacturing tasks, which is the chosen means of fabrication in OSMT projects whereby complex shapes are avoided to enable even laypeople with limited production capabilities to build them

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(Bonvoisin *et al.* 2021). With the increased affordability of fiber-laser cutters in global markets, some workshops now offer metal laser cutting services in the industrial cluster in Oman. Employing a 2D laser-cut metal sheet design (such as the laser-cut design of the Prusa i3 3D printer published by irobri (2013)) could address the challenges encountered during the printer frame replication in Oman, stemming from the absence of necessary jigs and tools, substandard inhouse machinery and limited worker skills in precision fabrication. The design, featuring precut slots, tabs and mounting holes, can ensure precise component alignment and simplifies frame assembly for users with diverse fabrication skills. Although outsourcing frame fabrication entails a slight cost increment over manual construction, the efficiency and machine build precision gained justifies this expense within the OSMT design context. This viewpoint was corroborated by the microenterprise workers in discussions. This highlights the need for context appropriateness in open-source design (Hazeltine & Bull 2003; Pearce 2012) as the resource requirements make it unfeasible to exactly replicate the OSMT printer designed in the global north in a vastly different setting (Tanenbaum *et al.* 2013). Instead, technologies should be designed to be adaptable to different socioeconomic, cultural and environmental contexts (Akubue 2000). In the context of OSMT, this was first promoted by Pat Delany, who developed machine tools for "do-it-yourself global development" (Delany 2000). This approach was adopted by more recent efforts such as Open Source Ecology's Global Village Construction Set (Moritz *et al.* 2016) and could provide a basis for the appropriately designed OSMT aimed at microenterprises.

The integration of electrical and software dimensions into the mechanical assembly in CNC-capable OSMT introduces an added layer of complexity. Successful design adaptations of CNC-capable OSMT necessitate proficiency across multiple domains: 3D CAD, electronics and software. While users with high literacy levels can learn these skills online, it becomes an insurmountable challenge for those with low digital and overall literacy. The replication of the software setup phase of OSMT is not dependent on location, but more on end-user digital literacy levels. However, for non-IT professionals or users without some form of coding experience, it can be a steep learning curve. Simplifying firmware modifications for OSMT adaptations, using Graphical User Interface (GUI-based) software abstraction, can reduce the complexity of manually altering specific lines of code across multiple nested files. This approach would lower the barriers to adapting OSMT designs requiring firmware modifications.

During the OSMT design phase, specific steps taken in the machine tool structure design can enhance its replicability potential. For example, it is mostly the heavier and larger portions of the design that would incur the most costs when imported. Since shipping costs rise dramatically with increased weight or volume of shipped goods, these are also the parts that would require intermediate manufacturing steps to transform the raw materials into the final form. In this article, this problem was exemplified by the difficulties in obtaining the aluminum profiles to fabricate the frame according to the initial design. While the lack of aluminum profiles is a problem that is specific to Oman and they might be accessible in other countries of the global south, this example showed how the lack of one specific part can severely hinder the replication of an OSMT project. It is the design of these structural components that stands to benefit most from context-appropriate design that harnesses local raw materials.

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Utilizing the advanced design automation capabilities within various 3D CAD systems empowers designers to create adaptable designs that seamlessly cater to end-user requirements without complex modifications. Leveraging design configurations enables end users to select the most suitable design variant aligned with their local resources and manufacturing capacities. Simultaneously, employing parametric design allows for scalable designs, enabling users to automatically adjust the size of the machine tool by specifying their specific workspace dimensions. Using parametric design is, however, time-intensive and complex for large assemblies and therefore less common in OSMT projects. One straightforward application of parametric design that does not require advanced CAD skills involves using a spreadsheet calculator that automatically adjusts the size and length of members listed in the BOM based on user-specified machine dimensions, as seen in the original Hypercube Evolution 3D printer design repository (Scott_3D 2017). Notably, this feature is applicable to parametric design but not design configurations, where a CAD model would be required.

The use of modular design can enable modifications to independent parts without impacting others, thus streamlining and facilitating the design adaptation process (Gavras & Kostakis 2021). Modularity is a fundamental characteristic of OSMT that is frequently cited as a crucial factor in facilitating openness and is essential for do-it-yourself production (Bonvoisin, Galla & Prendeville 2017). Although these methods have been employed in the machine tool industry for years (Ahuett, Aca & Molina 2005), their complexity for large assemblies has limited their implementation in OSMT projects (Table 1). However, more recently, similar approaches have also emerged within the OSMT domain, with one example being the rapid prototyping of machine tools using cardboard (Peek *et al.* 2017).

Table 1. Recommendations to facilitate the replicability of OSMT designs and their implications for the building process

Design recommendations to increase replicability	Implications
Context-appropriate design of structural components	• Reduces the need to import at high cost • Adaptability in different socioeconomic settings
Leveraging CNC manufacturing for precision tasks	• Possibility of outsourcing precision tasks at slight cost increment for greatly increased precision and efficiency. Eliminates user related errors during fabrication and assembly
Simplifying firmware modifications through GUI-based software abstraction	• Reduces need for coding experience to make modifications to an OSMT design • Can facilitate adaptations for users with low levels of digital literacy
Including conditions for design adaptability and knowledge-based parametric design	• Facilitates modifications by end users to account for different material and spatial resource requirements
Modular design	• Streamlines modifications of individual modules or components without having to change the entire machine design

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Table 2. User profiles and their abilities

User context	Examples	Abilities	Minimum documentation
User context 1: • High digital and general literacy • Low technological proficiency • No design knowledge or prior build experience	Educated users with a high school education or university degree or professionals with nonengineering background (majority of users in global north)	• Can search designs on internet and access design documentation for replication • Can source parts online from international markets • Can fabricate parts and assemble the machine • Wire electronics and setup software • Can *outsource* manufacturing with CNC processes like 3D printing, milling, laser cutting machines, etc.	• BOM • Fabrication drawings • Assembly instructions • Wiring schematics • Software (firmware) along with installation instructions
User context 2: • High digital and general literacy • High technological proficiency • Possess design domain knowledge • Prior build experience	Engineers or makers (most experienced OSH practitioners in the global north)	• Can do all of the above steps • Can carry out manufacturing with CNC processes such as 3D printing, milling, laser cutting machines, etc. • Can modify design or firmware code to adapt the design to local needs	• All of the above • (Optional) Native CAD files, or at least CAD files in STEP format • (Optional) document detailing the design rationale
User context 3: • Low general and digital literacy • Very low technological proficiency • Build experience with mechanical artifacts	Manufacturing microenterprise owners/workers with no formal education	• Can only fabricate parts and assemble the machine (mechanical replication) independently	• Language agnostic build documentation • Video guides • Browser-based text documentation for automatic translation

These additional procedures, however beneficial, are complex and time-consuming, making them impractical for individual users who often design OSMT projects for personal fulfillment or to address their specific needs (Hausberg & Spaeth 2020; Hippel 2010). Additionally, designers based in the global north face significant challenges in creating designs suited for resource-constrained settings without a thorough understanding of local needs, user requirements, constraints and capabilities. Nevertheless, sharing the machine designs as transparently and openly as possible offers capable users in developing economies the opportunity to adapt the design to their specific requirements.

The vast differences in local resources and manufacturing capabilities between the global north and south mean that there will probably not be 'one design that fits

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all' contexts. For global replicability, new design approaches need to be considered that take differences in global resources into account and specifically target the needs of local users and markets – this could mean creating appropriate designs that employ frugal design principles (Murphy, McBean & Farahbakhsh 2009; Bihouix 2020; Agarwal & Brem 2021) coupled with human-centered design (Giacomin 2014). It is also advisable to create designs that allow modifications catering to the needs and preferences of individual microenterprises and their employees (Gregg *et al.* 2020). This also underscores the need for concerted efforts by academic institutions, NGOs and development organizations to foster projects generating OSMT designs tailored for low-resource contexts, accounting for local resource constraints and low literacy levels.

6.2. Designing for user context

To enhance the global replicability of OSMT designs, best practices should also consider the context of end-user abilities. As a result of the qualitative interviews, three basic end-user profiles were outlined with their key differences being in their literacy levels (general, digital and technological). Even though these terms have various definitions in the literature, this article defines digital literacy as the ability to work with computers, access the internet, search for specific terms and copy and paste items on a windows GUI (Ali, Raza & Qazi 2023). General literacy refers to formal education. Technological proficiency refers to the ability to work with design software such as 3D CAD software and, on the higher end of the spectrum, modify and adapt software code (Table 2).

End users from user contexts 1 and 2 with formal education and good digital literacy levels are most likely to be able to replicate properly documented OSMT. Should any critical parts from the BOM list be inaccessible, requiring modifications or a complete redesign of the machine tool, access to native CAD files becomes imperative. Optionally, a supplementary document detailing the design rationale proves beneficial, enabling end users to navigate potential modifications while considering the original design's logic, thereby safeguarding against alterations that might compromise the design's robustness and functionality. Such modifications, however, are likely feasible only for the most advanced users, specifically those in user context 2. While not overly common, such users can also be found in resource-constrained contexts, exemplified by one respondent who was confident about his abilities to implement all stages of the OSMT replication process, including further modifications to the design. This shows that replication is possible if all necessary user and design conditions are fulfilled to not only build an OSMT but also modify it for context appropriateness. However, aiming for replicability among only user context 2 bears the risk that OSMT remains inaccessible to the more widespread user contexts 1 and 3 in low-resource contexts.

The most disadvantaged user segment, exemplified by migrant microentrepreneurs lacking formal education, user context 3, encounters formidable obstacles when replicating OSMT designs. Their limited digital literacy complicates access to and extraction of replication documents from text-based web pages. Instead, these users, accustomed to instructional content on platforms like YouTube, would benefit more from video-based guides illustrating the replication process. Simplified assembly instructions, such as pictorial or language-agnostic manuals akin to IKEA guides, could also enhance comprehension. Furthermore, for users lacking

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proficiency in English, browser-based build guides allowing automatic translation to the local language would be advantageous. This is consistent with the findings of Austin-Breneman & Yang (2013), which suggest that educating users and enabling them to become emancipated prosumers is integral to the successful adoption of products in the context of microenterprises. However, such approaches may prove insufficient for complex OSMT tasks requiring advanced technological capabilities, such as microcontroller firmware flashing and machine calibration. Consequently, independent replication of CNC-capable OSMT remains unattainable without external support for this user segment. However, these users demonstrate proficiency in the fabrication and assembly process, which are the most time-consuming and labor-intensive steps of the replication process. Conversely, tasks demanding high digital literacy, although complex and unattainable for this user segment, are relatively straightforward and swift for individuals with advanced digital skills.

While these user contexts are not unique to the global south and can be distinguished in industrialized settings as well, they provide a framework for the successful dissemination of open-source technologies that are appropriate for different user segments. By suggesting to design OSMT projects to be adaptable to the abilities and requirements of different user segments, such a framework can also help to mitigate the phenomenon of lacking quality controls in OSH designed for hobbyist settings impeding the adoption in professional contexts identified by Reinauer & Hansen (2021).

Moritz, Redlich & Wulfsberg (2018) found that OSH usage greatly benefits from ecosystems that create synergies for open-source value creation. Collaboration between local microenterprises and universities, makerspaces or NGOs could thus play a pivotal role in bridging the digital divide and facilitating OSMT adoption. Furthermore, the findings confirm known general challenges of technology transfer to the global south for OSMT: Similar to other technologies, OSMT transfer is hampered by a lack of formal education, prevalent digital illiteracy, weak research and development capabilities and general infrastructure (Danquah 2018), a lack of financing opportunities and limited access to international markets (Reinauer & Hansen 2021). These challenges are not unique to OSMT technologies, and similar conclusions have, for example, been made by Arancio (2023) with regard to open science hardware. However, compared to this, OSMT replication need precision fabrication on a much larger scale. Furthermore, while open science hardware targets scientists and people with generally very high literacy levels, the OSMT end-user base is much more diverse and also includes people with low general and technical literacy. The need to attain skills in relatively different domains and for access to certain infrastructure to successfully replicate an OSMT design, including international procurement, precision fabrication, electronics, firmware adaptation and software implementation, makes the case of OSMT particularly challenging. Furthermore, different to common challenges associated with technology transfer of mechanical artifacts (such as wind turbines or agricultural machines) to resource-constrained settings, the replication of CNC-capable OSMT requires both hardware and software skills.

7. Conclusions

While countless OSMT projects are available online nowadays, a large majority of them are designed in the global north. Existing research has routinely stressed the

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merits of OSMT for global sustainable development, but the feasibility of this has hitherto remained empirically uncertain. The initial hypothesis that an OSMT project designed in the global north would be challenging to replicate without considerable modifications in a setting of the global south can now be confirmed. The example of the Hypercube Evolution, an open-source 3D printer designed by and thus implicitly aimed at users in the global north, stresses the important influence of geographic and socioeconomic factors on OSMT replicability. Against a baseline replication in Hamburg, Germany, the second replication attempted in Muscat, Oman, highlights the intricate challenges of designing OSMT for resource-constrained contexts.

The contrast in replication difficulties between the global north and global south is most pronounced in the procurement and manufacturing dynamics. Procurement of parts and materials was relatively uncomplicated in Hamburg, where access to diverse local and international markets is readily available. In Muscat, on the other hand, sourcing parts was more complicated, and some materials could not be bought, for which replacements had to be found. Some solutions, such as the considerable design modifications that were necessary to build the machine frame, were difficult to implement and did not yield the same machine performance compared to the original design.

For OSMT to be able to make a meaningful contribution to sustainable industrial development in countries of the global south, the design process must consider different resource challenges that users might encounter. For this, designs must be versatile to be easily adaptable to diverse types of constraints. This could be achieved by providing variations that use different materials or manufacturing techniques. Making the design parametric scalable to individual user needs and spatial resources and designing subassemblies to make the build more modular could help to enable advanced users to make independent modifications more easily.

When designing OSMT projects, different user demographics need to be considered as well. This includes different language capabilities and levels of general and digital literacy. The technological capabilities of users are also vastly different, and designs need to consider the fact that most end users will not be able to make considerable modifications to existing projects. In this, it is imperative to also consider that the user demographics among marginalized communities are not homogenous, but varying degrees of literacy and capabilities exist here too. For example, from the analyzed interviews, it became apparent that more mechanical artifacts had a higher chance of successful replication and eventual adoption due to their reduced complexity. Future studies are needed to compare the replicability of mechanical machines versus partly or fully automated tools in Oman.

The results of this study are somewhat limited by the small sample size of interviewees because many microentrepreneurs were not willing or did not have the time to participate in the interviews. The lack of female entrepreneurs is a further limitation to the generalization of the findings. Furthermore, it is noteworthy that several replication challenges witnessed in Oman are specific to the country. The global south is diverse, and income levels and access to international markets as well as supply on local markets greatly vary. For example, while the aluminum profiles for the frame construction had to be replaced with a custom solution, they are available in other countries of the global south. The encountered challenges therefore merely serve as examples that illustrate how the lack of specific parts can severely hinder the replication of an OSMT project when resource

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constraints are not sufficiently considered in the initial design. Arguably, the fact that the first iteration of the replication experiment was implemented in Germany might further have introduced a bias to the project choice toward a design suited for replication in a high-resource setting. An advisable next step would therefore be a reversed experiment, whereby the first replication would be implemented in a low-resource context.

In general, the great diversity between countries and milieus as well as the internal heterogeneity of regions makes a "one-size-fits-all" approach unrealistic in OSMT design. Projects that do not take this into account cannot reasonably be considered to help sustainable industrial development in contexts other than the ones in which they were designed. To ensure replicability in resource-constrained settings, greater design varieties and the consideration of different socioeconomic environments are necessary. Adaptations to specific local contexts can be implemented either by the end users or local practitioners with advanced skills; not every possibility needs to be included in the initial project, but the preconditions for a variety of adaptations need to be made in the design stage. This includes fully open souring all source files, such as CAD files and assembly guides, along with providing troubleshooting and maintenance guides for instances where local services are not available (Omer 2023). Additionally, incorporating parametric design elements and documenting the original design reasoning will enable users to make working adaptations based on their specific requirements such as budget or workshop space while preserving functionality and stability, thus guiding users on permissible changes.

OSMT, if designed appropriately, can create opportunities for cash-strapped microenterprises and budding entrepreneurs by enabling them to build the production machines they need for upgrading their businesses themselves. However, beyond the technical feasibilities of OSMT, their actual adoption within such microenterprises is a complex socio-technical topic and needs more interdisciplinary research. Advancements in the field of OSMT replicability for resource-constrained contexts can directly contribute to SDG objectives 1, 8, 9 and 10 and thus help to reduce poverty, provide decent work, promote sustainable industrialization and reduce inequalities.

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References

Abdelkafi, N., **Blecker, T.** & **Raasch, C.** 2009 From open source in the digital to the physical world: A smooth transfer? *Management Decision* **47** (10), 1610–1632; doi: 10.1108/00251740911004718.

Achkar, S. E. 2023 *Micro and Small Enterprises: Engines of Job Creation.* ILOSTAT, online document (downloadable on December 23rd 2023) https://ilostat.ilo.org/micro-and-small-enterprises-engines-of-job-creation/.

Agarwal, N. & **Brem, A.** (Eds.) 2021 *Frugal Innovation and its Implementation*. Springer International Publishing.

Agrawala, M., **Phan, D.**, **Heiser, J.**, **Haymaker, J.**, **Klingner, J.**, **Hanrahan, P.** & **Tversky, B.** 2003 Designing effective step-by-step assembly instructions. *ACM Transactions on Graphics* **22** (3), 828–837; doi:10.1145/882262.882352.

Ahuett, H., **Aca, J.** & **Molina, A.** 2005 A directed evolution modularity framework for design of reconfigurable machine tools. In *Cooperative Design, Visualization, and Engineering. Second International Conference, CDVE 2005, Palma de Mallorca, Spain, September 18-21, 2005 Proceedings*, vol. 3675 (ed. L. Yuhua), pp. 243–252. Springer (Lecture Notes in Computer Science, 3675).

Akubue, A. 2000 Appropriate technology for socioeconomic development in third world countries. *The Journal of Technology Studies* **26** (1), 33–43; doi:10.21061/jots.v26i1.a.6.

Al-Hashmi, J. S. H. 2019 *Rifts in Omani employment culture. Emerging joblessness in the context of uneven development*. Master's Thesis, Harvard University.

Ali, A., **Raza, A.A.**, **Qazi, I.A.**, 2023 Validated digital literacy measures for populations with low levels of internet experiences. *Development Engineering* 8.

Antoniou, R., **Bonvoisin, J.**, **Hsing, P.-Y.**, **Dekoninck, E.** & **Defazio, D.** 2022 Defining success in open source hardware development projects: A survey of practitioners. *Design Science* **8**, e8; doi:10.1017/dsj.2021.30.

Antoniou, R., **Pinquié, R.**, **Boujut, J.-F.**, **Ezoji, A.** & **Dekoninck, E.** 2021 Identifiying the factors affecting the replicability of open source hardware designs. In *Proceedings of the International Conference on Engineering Design (ICED21)*, Gothenburg, Sweden, pp. 1817–1826.

Arancio, J. 2023 From inequalities to epistemic innovation: Insights from open science hardware projects in Latin America. *Environmental Science & Policy* **150**, 103576; doi: 10.1016/j.envsci.2023.103576.

Austin-Breneman, J. & **Yang, M.** 2013 Design for micro-enterprise: An approach to product design for emerging markets. In *Volume 5: 25th International Conference on Design Theory and Methodology; ASME 2013 Power Transmission and Gearing Conference. ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, Portland, OR. American Society of Mechanical Engineers.

Balka, K. 2011 *Open Source Product Development. The Meaning and Relevance of Openness*. Hamburg-Harburg, Techn. Univ., Institut für Technologie- und Innovationsmanagement, Diss., 2011. 1st ed. Gabler (Forschungs-, Entwicklungs-, Innovations-Management), checked on 1/8/2022.

Békés, G. & **Harasztosi, P.** 2020 Machine imports, technology adoption, and local spillovers. *Review of World Economics* **156** (2), 343–375; doi:10.1007/s10290-019-00365-y.

de Bel-Air, F. 2015 *Demography, Migration, and the Labour Market in Oman*, online document https://cadmus.eui.eu/handle/1814/37398.

Bihouix, P. 2020 *The Age of Low Tech. Towards a Technologically Sustainable Civilization*. English language edition. Bristol University Press.

Bonneau, V. & **Yi, H.** 2017 *The Disruptive Nature of 3D Printing. Offering New Opportunities for Verticals*. European Commission (Digital Transformation Monitor).

Bonvoisin, J., **Galla, J. K.** & **Prendeville, S.** 2017 Design principles for do-it-yourself production. In *Sustainable Design and Manufacturing 2017* (ed. G. Campana), vol. **68**, pp. 77–86. Springer.

Bonvoisin, J. & **Mies, R.** 2018 Measuring openness in open source hardware with the open-o-meter. *Procedia CIRP* **78**, 388–393; doi:10.1016/j.procir.2018.08.306.

Bonvoisin, J., **Mies, R.** & **Boujut, J.-F.** 2021 Seven observations and research questions about open design and open source hardware. *Design Science* **7** (22); doi:10.1017/dsj.2021.14.

Danquah, M. 2018 Technology transfer, adoption of technology and the efficiency of nations: Empirical evidence from sub Saharan Africa. *Technological Forecasting and Social Change* **131**, 175–182; doi:10.1016/j.techfore.2017.12.007.

dcorb 2015 *Steel Frame 3D Printer.* Openbuilds, online document (downloadable on April 25th 2024) https://openbuilds.com/builds/steel-frame-3d-printer.2853/.

Delany, P. 2000 *Do-It-Yourself Global Development.* Open Source Machine Tools, online document (downloadable on January 14th 2024) http://opensourcemachinetools.org/wordpress/open-source-tools-diy-global-development/.

DIW Berlin 2023 *Microenterprises in Developing Countries: Is there Growth Potential?*, online document (downloadable on September 5th 2023) https://www.diw.de/de/diw_01.c.566881.de/publikationen/roundup/2017_0114/microenterprises_in_developing_countries__is_there_growth_potential.html.

Gavras, K. & **Kostakis, V.** 2021 Mapping the types of modularity in open-source hardware. *Design Science* **7**, e13; doi:10.1017/dsj.2021.11.

Gershenfeld, N. A. 2012 How to make almost anything. The digital fabrication revolution. *Foreign Affairs* **91** (6), 43–57.

Giacomin, J. 2014 What is human centred design? *The Design Journal* **17** (4), 606–623; doi:10.2752/175630614X14056185480186.

Grames, P. P., **Redlich, T.** & **Wulfsberg, J. P.** 2011 Revolution of production systems through value co-creation. *Zeitschrift für wirtschaftlichen Fabrikbetrieb* **106** (5), 314–320; doi:10.3139/104.110561.

Gregg, E. S., **Colton, J.**, **Matin, M. A.** & **Krupnik, T. J.** 2020 Efficient and participatory design of scale-appropriate agricultural machinery workshops in developing countries: A case study in Bangladesh. *Development Engineering* **5**, 100046; doi:10.1016/j.deveng.2019.100046.

Hall, B. H. & **Rosenberg, N.** 2010 In *Handbook of the Economics of Innovation: Handbook of the Economics of Innovation*, Vol. **1**. North-Holland.

Hansen, A. & **Howard, T. J.** 2012 The current state of open source hardware: The need for an open source development platform. In *Icord'13* (ed. A. Chakrabarti & R. V. Prakash), pp. 977–988. Springer (Lecture Notes in Mechanical Engineering).

Haraguchi, N., **Cheng, C. F. C.** & **Smeets, E.** 2017 The importance of manufacturing in economic development: Has this changed? *World Development* **93**, 293–315; doi:10.1016/j.worlddev.2016.12.013.

Harris, K. 2017 Divergent histories and converging inequalities in the Middle East and Latin America. In *Middle East Report* (284/285), online document (downloadable on December 16th 2021) https://merip.org/2018/04/divergent-histories-and-converging-inequalities-in-the-middle-east-and-latin-america/.

Hassan, S. F. & **Jureidini, R.** (Eds.) 2020 *Migration and Islamic Ethics. Issues of Residence, Naturalization and Citizenship*. Brill (Studies in Islamic ethics, vol. 2).

Hausberg, J. P. & **Spaeth, S.** 2020 Why makers make what they make. Motivations to contribute to open source hardware development. *R&D Management* **50** (1), 75–95; doi:10.1111/radm.12348.

Hazeltine, B. & **Bull, C.** 2003 *Field Guide to Appropriate Technology*. Academic Press.

von Hippel, E. 2010 Open user innovation. In *Handbook of the Economics of Innovation: Handbook of the Economics of Innovation, Vol. 1* (ed. B. H. Hall & N. Rosenberg), pp. 411–427. North-Holland, online document (downloadable on April 25th 2024) https://www.sciencedirect.com/science/article/pii/S0169721810010099.

irobri, 2013 *P3Steel - Prusa i3 3mm Steel Laser cut (aka Leonardo).* UltiMaker Thingiverse, online document (downloadable on April 25th 2024) https://www.thingiverse.com/thing:157303/files.

Jones, R., **Haufe, P.**, **Sells, E.**, **Iravani, P.**, **Olliver, V.**, **Palmer, C.** & **Bowyer, A.** 2011 RepRap – The replicating rapid prototyper. *Robotica* **29** (1), 177–191; doi:10.1017/S026357471000069X.

https://doi.org/10.1017/dsj.2024.35 Published online by Cambridge University Press

Kuckartz, U. & **Rädiker, S.** 2022 *Qualitative Inhaltsanalyse. Methoden, Praxis, Computerunterstützung*, 5th ed. Beltz Juventa (Grundlagentexte Methoden).

Laaribi, I. 2019 *Steel Frame 3D Printer.* GrabCAD Community, online document (downloadable on April 25th 2024) https://grabcad.com/library/steel-frame-3d-printer-1.

Lang, B., **Dolan, R.**, **Kemper, J.** & **Northey, G.** 2021 Prosumers in times of crisis: Definition, archetypes and implications. *Journal of Service Management* **32** (2), 176–189; doi: 10.1108/JOSM-05-2020-0155.

Li, Z. & **Seering, W.** 2019 Does open source hardware have a sustainable business model? An analysis of value creation and capture mechanisms in open source hardware companies. In *Proceedings of the 22nd International Conference on Engineering Design (ICED19)*, Delft, Netherlands, pp. 2239–2248, checked on 8/12/2021.

McMillan, M. S. & **Rodrik, D.** 2011 *Globalization, Structural Change and Productivity Growth.* NBER Working Papers, online document https://ideas.repec.org/p/nbr/nberwo/17143.html.

Mies, R., **Häuer, M.** & **Hassan, M.** 2022 Introducing readiness scales for effective reuse of open source hardware. *Procedia CIRP* **109**, 635–640; doi:10.1016/j.procir.2022.05.306.

Monga, C. & **Lin, J. Y.** 2019 *The Oxford Handbook of Structural Transformation*, 1st ed. Oxford University Press.

Mori, M., **Hansel, A.** & **Fujishima, M.** 2014 Machine tool. In *CIRP Encyclopedia of Production Engineering* (ed. Laperrière L. & Reinhart G.), pp. 792–801. Springer.

Moritz, M., **Redlich, T.**, **Grames, P. P.** & **Wulfsberg, J. P.** 2016 Value creation in open-source hardware communities. Case study of open source ecology. In *2016 Portland International Conference on Management of Engineering and Technology (PICMET)*, Honolulu, HI, USA. 9.4.2016-9.8.2016. IEEE, pp. 2368–2375.

Moritz, M., **Redlich, T.** & **Wulfsberg, J.** 2018 Best practices and pitfalls in open source hardware. In *Proceedings of the International Conference on Information Technology & Systems (ICITS 2018), 721)*, pp. 200–210. Springer.

Murphy, H. M., **McBean, E. A.** & **Farahbakhsh, K.** 2009 Appropriate technology – A comprehensive approach for water and sanitation in the developing world. *Technology in Society* **31** (2), 158–167; doi:10.1016/j.techsoc.2009.03.010.

Oman News Agency, 2022 *Ministerial Decision Amends Classification of SMEs per Workforce, Revenues*, online document (downloadable on April 15th 2024) https://omannews.gov.om/topics/en/79/show/3482/light.

Omer, M. 2023 *Remocube – An Open Source 3D Printer.* With assistance of Center for Open Science, online document (downloadable on February 27th 2024) https://osf.io/4kw25/.

Omer, M., **Kaiser, M.**, **Moritz, M.**, **Buxbaum-Conradi, S.**, **Redlich, T.** & **Wulfsberg, J. P.** 2022 Democratizing Manufacturing – Conceptualizing the Potential of Open Source Machine Tools as Drivers of Sustainable Industrial Development in Resource Constrained Contexts, in: *Proceedings of the Conference of Production Systems and Logistics (CPSL 2022)*, University of British Columbia, Vancouver. 17.05.2022 - 20.05.2022. publish-Ing., pp. 256–266.Editors are Herberger, David, and Hübner, Marco,

Open Source Ecology, 2022 *GVCS Cost Comparison to Industry Standards – Open Source Ecology*, online document (downloadable on April 26th 2024) https://wiki.opensourceecology.org/wiki/GVCS_Cost_Comparison_to_Industry_Standards.

Open Source Hardware Association, 2021 *OSHW Definition*, online document (downloadable on September 1st 2024) https://www.oshwa.org/definition/.

Pearce, J. M. 2012 The case for open source appropriate technology. In *Environment, Development and Sustainability, Vol. 14*, pp. 425–431, online document (downloadable

https://doi.org/10.1017/dsj.2024.35 Published online by Cambridge University Press

on December 17th 2024) https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2043509.

Pearce, J. M. 2015 Quantifying the value of open source hard-ware development. *Modern Economy* **06** (01), 1–11; doi:10.4236/me.2015.61001.

Pearce, J. M., **Blair, C. M.**, **Laciak, K. J.**, **Andrews, R.**, **Nosrat, A. H.** & **Zelenika-Zovko, I.** 2010 *3-D Printing of Open Source Appropriate Technologies for Self-Directed Sustainable Development*.

Peek, N., **Coleman, J.**, **Moyer, I.**, **Gershenfeld, N.** 2017 Cardboard machine kit. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems. CHI '17: CHI Conference on Human Factors in Computing Systems, Denver CO, USA, 06/05/2017–11/05/2017* (ed. G. Mark, S. Fussell, C. Lampe, M.C. Schraefel, J. P. Hourcade, C. Appert & D. Wigdor), pp. 3657–3668. ACM.

Radic, D. 2019 *Small Matters. Global Evidence on the Contribution to Employment by the Self-Employed, Micro-Enterprises and SMEs*. International Labour Organization.

Rahman, M. M. 2018 *Development of Migrant Businesses in Saudi Arabia*, ISAS Working Papers No. 281.

Rayna, T., **Striukova, L.** & **Fauchart, E.** 2023 Commercialization strategies of large-scale and distributed open innovation: The case of open-source hardware. *California Management Review* **65** (2), 22–44; doi:10.1177/00081256231161628.

Reinauer, T. & **Hansen, U. E.** 2021 Determinants of adoption in open-source hardware. A review of small wind turbines. *Technovation* **106**, 102289.

Saxena, P. K. & **Sharma, A.** 2014 Role of machine tool industry in economic development. *ISSN* **3** (5), 188–193.

Scott_3D 2017 *HyperCube Evolution*, online document (downloadable on December 5th 2024) https://www.thingiverse.com/thing:2254103.

Seitz, H. 2017 *Microenterprises in developing countries: Is there growth potential?* In *DIW Roundup: Politik im Fokus*.

SMEF 2014 *SME Development Fund Oman*, online document (downloadable on April 24th 2024) https://www.smefoman.com/vision-mission.html.

Suhaili, M. & **Sugiharsono, S.** 2019 Role of MSME in absorbing labor and contribution to GDP. *Economics Development Analysis Journal* **8** (3), 301–315. doi:10.15294/edaj.v8i3.35229.

Tanenbaum, T. J., **Williams, A. M.**, **Desjardins, A.** & **Tanenbaum, K.** 2013 *Democratizing Technology. Pleasure, Utility and Expressiveness in DIY and Maker Practice*, online document (downloadable on December 13th 2024) https://dl.acm.org/doi/pdf/10.1145/2470654.2481360.

Thomas, L. M., **Evrard-Samuel, K.** & **Troxler, P.** 2023 Building open source hardware business models. In *Business Models and Strategies for Open Source Projects: IGI Global (Advances in Systems Analysis, Software Engineering, and High Performance Computing)* (ed. Vijayan Sugumaran & Francisco José Monaco), pp. 50–79.

UltiMaker Thingiverse, 2015 *Mostly Printed CNC "MPCNC" BURLY C-23.5mm OD*, online document (downloadable on April 18th 2024) https://www.thingiverse.com/thing:724999/makes.

UN, 2016 *THE 17 GOALS | Sustainable Development*, online document (downloadable on December 30th 2024) https://sdgs.un.org/goals.

UNCTAD, 2017 *Trade and Development Report: Beyond Austerity: Towards a Global New Deal*. UNCTAD.

https://doi.org/10.1017/dsj.2024.35 Published online by Cambridge University Press

UNCTAD, 2021 *Building Productive Capacities Critical for Least Developed Countries*, online document (downloadable on January 1st 2024) https://unctad.org/news/building-productive-capacities-critical-least-developed-countries.

Verma, P. A. 2021 Why technology is the only path to sustained growth for MSMEs. *Economic Times*, 1/15/2021, online document (downloadable on April 19th 2024) https://economictimes.indiatimes.com/small-biz/sme-sector/why-technology-is-the-only-path-to-sustained-growth-for-msmes/articleshow/80281133.cms?from=mdr.

Weeraratne, B. 2020 *Return and Reintegration without Assimilation: South Asian Migrant Workers in the Gulf during COVID-19*, online document https://www.isas.nus.edu.sg/wp-content/uploads/2020/06/327.pdf.

https://doi.org/10.1017/dsj.2024.35 Published online by Cambridge University Press