

# Community-based replication of Open Source Machine Tools

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**Abstract** – The number of developments of open-source hardware (OSH) has rapidly increased within the last years. One special form of OSH are machine tools, which are developed in an open-source manner, so called Open Source Machine Tools (OSMTs). OSMTs enable the manufacturing of hardware artefacts within open labs, fab labs and open production networks. Additionally, the distributed design and development as well as the replication process of OSMTs are aimed on increasing the technological literacy of its users within a community.

The research presented in this paper focusses on the replication process of OSMTs within community-based workshops in the field of Fab City Hamburg. The current state of replication processes of already developed and prototyped OSMTs has been outlined based on interviews, observations and document analyses. First insights were gained whilst participating in community-based workshops as well as through conversations with the workshop participants and instructors along with OSMT designers and engineers. Subsequently the replication process of OSMTs was analysed and areas of improvement have been detected with regards to enhancing the technological literacy of the workshop participants. The authors conclude that OSH build workshops bare great potential of a new, holistic approach to achieving technological literacy within a short period of time.

With this paper, the authors identify important interconnections of OSMT replicability and technological literacy through replication workshops and form a basis for further research within this area.

**Keywords** – *Technological Literacy, Open Source Machine Tools, Open-source Hardware, Build workshops*

## NOMENKLATUR

|      |                          |
|------|--------------------------|
| OSMT | Open Source Machine Tool |
| OSH  | Open-source Hardware     |
| OSS  | Open-source Software     |
| CAD  | Computer Aided Design    |
| BoM  | Bill of Material         |

## I. INTRODUCTION

The recent societal, environmental and economic challenges lead to a need of a rethinking our current value

creation model. Open-source software and hardware are currently attracting more and more attention in politics [1], research and industry [2]–[4]. Open-Source Hardware (OSH) shows possible new ways of technical innovation, business models and development processes [5], [6]. Since the first patents of 3D printers have run out in the early 2000s, the development, modifications and replications of 3D printers has increased rapidly [7]. This development has influenced other OSH product categories, especially electronics (e.g. Arduino) medical devices [8]–[10], biology (e.g. open flexure microscope) and even the automotive industry (e.g. local motors).

One main difference between open-source software (OSS) and hardware is the replication of the collaboratively developed information and knowledge. In software, the user merely needs a computer system to replicate OSS code [11]. In open-source hardware there is a need of a physical infrastructure and an existing production system in terms of space, machines, material and organization of these components as wells as knowledge and skills to execute the replication processes. To minimize the threshold of replicating hardware by local communities, the demand for machines developed and documented in an open-source manner has increased within the last years [12].

Projects within the Hamburg community are focusing especially on the development of easy usable and replicable Open Source Machine Tools (OSMTs), which subsequently form the basis for starting an open lab anywhere in the world on a low budget and building up an open production landscape. The replication hereby is operated through educational workshops, so called build workshops, in which different types of OSMTs are replicated by different user groups. With the provision of assembly kits, consisting of pre-assembled parts and under the guidance of instructors and technical documentation, the components are assembled to a ready to use machine tool.

This new phenomenon of community-based replication processes offers a great chance to increase the scope of open-source hardware as well as increasing participants technological literacy. However, not much research has been performed in this field. Therefore, the replication workshops are studied and analyzed.

The researchers are analyzing the OSMT replication workshops in order to understand how OSH replication workshops should be designed to optimize their potential for OSH replicability and participants' technological literacy.

## II. THEORETICAL BACKGROUND

The theory part of this paper aims to generate an overview on the context of open-source hardware, open-source hardware documentation, Open Source Machine Tools, open-source hardware replicability and technological literacy.

### A. OPEN-SOURCE HARDWARE

The concept of *open production* comprises a comprehensive value creation framework, describing new forms of value creation in a bottom-up economy in which collaborative, distributed and self-organized processes throughout the entire value creation lifecycle are conducted from individual or organizational actors. The principle of openness, which describes the open interaction of sub-components within this system, is an essential element of the open production framework [13].

The principles of openness in terms of knowledge and information components is accessed in the development of open-source hardware which itself is a fragment of open-source [7], [13]. The open-source hardware association (OSHWa) defines open-source hardware as follows: “Open-source hardware is hardware whose design is made publicly available so that anyone can study, modify, distribute, make, and sell the design or hardware based on that design.” [14]. Similar to open-source software in the 90s, open-source hardware is now being developed and refined throughout the whole world simultaneously, whilst the results are shared online with communities all over the world [7].

### B. OPEN-SOURCE HARDWARE DOCUMENTATION

In order to use the potential of OSH, technical documentation of the hardware is of elementary importance [15]. Therefore, a description of its documentation in form of a standardization has been outplayed in the DIN SPEC 3105 [16], [17]. This DIN specification describes a first community-based standard and certification of documentation content of OSH projects. The requirements for the documentation fully apply the rights of OSH, especially to modify, reuse and create hardware. The special feature of the DIN SPEC 3105 certification lies in its community-based assessment and its open-source license which allows modification and attestation by different communities [18]. The documentation of OSH mainly consists of its design files - primarily engineered with Computer Aided Design (CAD) tools and its Bill of Material (BoM) describing which material and components the hardware consists of. The OSH documentation is often shared in publicly accessible online repositories. An additional crucial part of the documentation, but not (yet) postulated by the DIN SPEC 3105, is an assembly guideline describing how the hardware is manufactured and assembled, to achieve the desired function of the design.

### C. OPEN SOURCE MACHINE TOOLS (OSMTs)

In the last years, global production systems have been fundamentally reshaped. The increasing availability of electronics hardware such as microcontrollers, driver units, stepper motors, and sensors has accelerated the development of computer-controlled machines and digital fabrication [7]. However, currently only a minority of actors benefit from these machine tools, which are at the heart of this fast-paced development and are largely developed under closed source premises.

With the aim to increase the accessibility and availability of affordable and adoptable machine tools, Open Source Machine Tools (OSMT) have recently gained momentum [19]. Besides 3D printers, machines for laser cutting, grinding, milling, and metal forming have been developed according to open-source principles and contribute to widen the capability spectrum of the open production infrastructure. Through open design and collaborative development, modification, and adoption, the amount of OSMT designs continually increases [19].

### D. COMMUNITY-BASED REPLICATION OF OSH

An open production system is characterized not only by openly available documentation of products and machines, but also by the replicability of designs. The factor of replicability is a significant difference from OSH to OSS. Unlike OSS, where only a PC-based environment is required to achieve replication of software code, OSH requires physical infrastructure such as material, energy as well as tools and skills [15]. A first analysis of the necessary factors for the replicability of OSH has been carried out by Antoniou et.al [20]. These factors describe an initially necessary provision of structural information, as well as requirements for the physical environment where the OSH artifacts are replicated.

These factors are summarized below:

- **Quality of documentation:** The quality of documentation increases with standardization of documentation (e.g. according to DIN SPEC), its accuracy, rigor and completeness as well as its dynamics which describes the collaboration and synchronization of documentation to current hardware design versions [20].
- **Completeness of documentation:** A complete documentation should also include a sufficient description of possible critical error events and troubleshooting measures. Additionally, there should be enough information stored to train a person to build the hardware version [20].
- **Accessibility to documentation, tools and material:** This point comprises the accessibility of OSH project documentation, also automated through metadata integration, the accessibility of the necessary materials and components as well as the required tools and equipment [20].
- **Ease of Manufacturing:** This factor determines what knowledge and skills are necessary, which materials and tools are necessary and which processes must be carried out for the assembly of the OSH design [20].

This set of factors is a first systemic approach to define dependency parameters of the replicability of OSH designs. Documentation factors as well as local physical requirements are mentioned.

### E. TECHNOLOGICAL LITERACY

Technological literacy is a term which has been defined in various ways [21]. One definition which is often used and that the authors find most suiting and comprehensive is the definition by Hansen (2003): “technological literacy is an individual's ability to adopt, adapt, invent, and evaluate technological solutions to positively affect his or her life, community, and environment [22].

Randall S. Davies has developed a framework for understanding technological literacy where he defined three successive levels of technology literacy:

#### 1) Level 1: Awareness

Level 1 mainly focuses on the question “*What can this technology do?*” [21]. When reaching this level, learners are able to talk about the technology and understand what it does, however they are not yet able to use it [21].

#### 2) Level 2: Praxis

At this level, the learners actually learn how to use the technology and will be able to complete simple tasks [21]. The lead question at this level is “*How do you use this technology?*” [21].

#### 3) Level 3: Phronesis

The third level rather concerns the meta level and questions such as “*Why do I use or not use technology in this specific situation?*” [21]. It’s mainly about the appropriate or inappropriate use of the technology, also depending on the context and situation.

These levels describe different stages of technological literacy and according to Davies those levels are sequential and require an “authentic context” in order to reach each of them [21].

In general, community-based OSH and OSMT replication workshops can be seen as a great potential to learn about hardware design, functionality, assembly and maintenance and repair possibilities. This project is focused on the research of how these replication workshops can be improved to fulfil this potential.

### III. PROJECT DESCRIPTION AND METHODOLOGY

To put the research in context, the following section provides an in-depth project description as well as a detailed presentation of the planned methodology and research methods.

#### A. Concept and Research Design

The research regarding the OSMT build workshops takes place within the Fab City Hamburg. Fab City is a concept that originated in Barcelona and combines a network of cities with the common goal to produce nearly all goods the city consumes itself, by 2054 [23]. This thought is pushed forward by the help of strong local communities within the participating cities, which are connected globally. This concept of local production but global knowledge sharing is based on the already successful and influential open-source software movement [23].

The Fab City Hamburg is one of the first German cities to join this global network in 2019. This joining set the starting point of a community building process in which various actors like SMEs, non-profit organizations, fab labs, universities and individual persons and communities have been engaged to participate and form the legal entity “Fab City Hamburg e.V.”. One output of this community is the execution of various workshops in the field of innovation consultancy and building OSMTs and other OSH prototypes. The conducted OSMT build workshops build the data foundation for this paper.

#### B. Methodology

Since research within this field is still at the very beginning, a qualitative and explorative research approach is chosen and presented in this paper [24].

This research is based on data collection through semi-structured expert interviews, observations and document analysis of OSMT documentation.

In a first step, interviews with trainers and workshop conductors had been carried out. These interviews were designed to gain a first understanding on the actual procedure of the workshops as well as possible pitfalls and problems that occur during the workshop. Subsequently, the build workshops were being observed. A special focus was set on the participants’ questions that came up during the workshop, as well as other issues hindering to the process flow.

Furthermore, the participants of the workshops were asked for feedback, after the workshops had been conducted. Through this feedback process, the researchers enabled an anonymous comment on the events. This was important to create a space for also negative and constructive feedback as well as an understanding of the actual benefit of the workshops.

Additionally, a document analysis was carried out. This analysis mainly focussed on the build guidelines and design documentation which are stored in publicly accessible repositories. The documents were analysed and compared to the actual outcomes of the observations and the interviews.

An overview on the gathered data is shown in TABLE I.

TABLE I: OVERVIEW ON DATA.

| <i>Interviews</i>           | <i>Observations</i>            | <i>Document analysis</i>            |
|-----------------------------|--------------------------------|-------------------------------------|
| 4 OSMT workshop instructors | 3 3-D printer build workshops  | Open source 3-D printer repository  |
| 3 OSMT developers           | 2 Laser cutter build workshops | Open source laser cutter repository |

Through this method triangulation the internal and external validity of this research project is strengthened.

### IV. ANALYSIS AND RESULTS

After gathering the data, it was analysed, with regards to a standard workshop setup. Additionally, a focus was set on the intersections between the build workshop and acquiring technological literacy.

#### A. Build Workshop Phases

At present, workshops are carried out for an OSH laser cutter as well as an OSH 3D printer. The build workshops usually take two to four days, depending on the OSMT built as well as on the technical knowledge background of the participants. Each workshop is accompanied of minimum one instructor, depending on the number of participants as well as community mentors who have a broader understanding of the OSMTs design.

A first analysis has led to a preliminary outline of the recent build process. For a standard build workshop, six sequential phases have been observed, as shown in FIGURE 1.

##### 1) Phase 1: Introduction

Phase 1 of the OSMT build workshops is aimed at creating a welcoming atmosphere as well as giving the participants a short introduction to the fields of open-source and OSMTs. During the interviews with the workshop conductors this phase was often emphasised: “They need the theory before this [the workshop]. A theory introduction into what are the parts

that need to be considered or how that machine exactly works”.

This phase sets the theoretical basis for the following workshop. By understanding these concepts, participants are also sensitised for possible minor errors that can happen during the process. Additionally, the participants are encouraged to be part of the open-source movement by coming up with improvement ideas during the actual build phase.

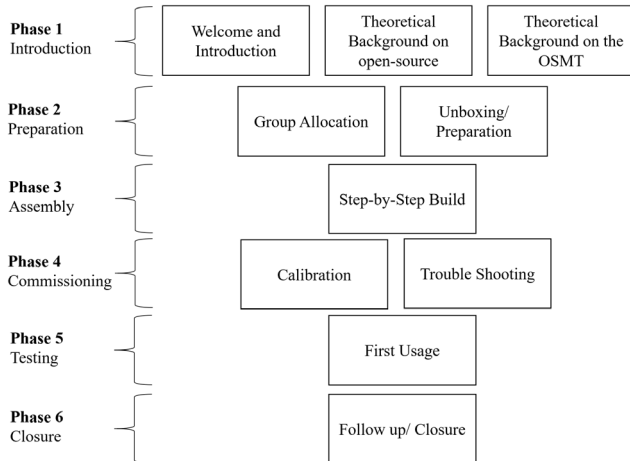


FIGURE 1: BUILD WORKSHOP PHASES.

## 2) Phase 2: Preparation

Phase 2 comprises the preparation of the actual building process as well as a suitable group allocation. Setting up all the required components and checking the BoM is not only essential for the later success of the build process. It also helps the participants to gain an overview on the actual parts and possible complexity of the OSMT they are building. During this phase, the participants often express their excitement about the whole workshop and the task that lies ahead.

For the group allocation, instructors should ensure, that a comfortable setting with mixed levels of expertise is reached for each group. In general, speaking from instructors' experience, the groups should not be larger than 3-4 participants for a 3D printer and up to 6 participants for a laser cutter build workshop.

## 3) Phase 3: Assembly

Phase 3 is the actual build process. This phase takes up the majority of time during the OSMT build workshops. During this phase, the participants are exposed to the whole assembly process in a step-by-step guidance from the mechanical frame assembly all the way to electronics wiring, sometimes even including soldering and installing high voltage components, such as a laser head. This phase is the core of the build process and takes up by far the most time. Hereby it is important that the participants can count on the support of a qualified instructor, as well as a conclusive build manual. Depending on the pre knowledge of the participants, the level of required support from the instructor can vary. One instructor described it as follows: "They're amateurs and they build it, so sometimes the result is not as good as expected. And then they're a bit frustrated. But then that's why we [the instructors] come in". This phase is also the phase which is most interesting from a research perspective in terms of learning experience, replication process and group dynamics.

## 4) Phase 4: Commissioning

After the assembly is completed, the OSMTs are mechanically calibrated. Especially with the laser component, this process is very challenging. In order to reach safety and quality requirements, the process has to be repeated several times. With a finished mechanical and electrical assembly, the software configuration takes place. The software parameter settings are dependent on the performed mechanical assembly and calibration and can therefore not be fully preconfigured.

Additionally, the trouble shooting process is included in this phase. The commissioning phase is the phase, where the instructors and mentors are supporting the most with their experience and knowledge. However, during this phase the participants already learn a lot about the machine's functionality and purpose as well as possible options for later maintenance and trouble shooting. After calibration, the machine tool is tested and occurring errors within the hardware and firmware are being addressed and fixed.

## 5) Phase 5: Testing

When calibration and troubleshooting are completed, participants can use their machines for the first time. Often this is perceived as the highlight of the workshop. Manufacturing something on a machine that itself has just been built is an important step to understanding the OSH replication concept. Unfortunately, time often runs out towards the end of a workshop, so that this part of the process needs to be considered with a time buffer to achieve the best learning experience.

## 6) Phase 6: Closure

Providing a proper closure and end to the workshop is important. By summing up the learnings and the pros and cons of each workshop, the participants are encouraged to reflect their individual learnings. It is often in this phase, that participants actually start realizing how much experience they have gained during the workshops and how much they actually have learned.

## 7) Follow up

After the workshops, a follow up is suggested. Reaching out to the participants a few weeks after the workshop is helpful to understand their personal perspective on the workshop. A follow up helps gathering possible improvement ideas as well as learnings the participants took away from the building process.

## B. Additional Factors

Some additional, more general factors influencing the workshop flow and learning results of the participants could be observed during the analysis: workshop preparation, self-organized forming of sub-groups, the detail level of background information, quality check points and instructors' competency.

### 1) Workshop preparation

One vital aspect, for a successful workshop flow, is a thorough workshop preparation with regards to manufacturing and pre-assembling of sub-components, location and time planning. Especially when parts of the sub-manufacturing and sub-assembly are being outsourced to external companies or organizations who are not familiar with the OSMT design, a thorough quality check prior to the workshop is required.

An inadequate preparation can disrupt the flow of the workshop and discourage participants from an early stage on.

### 2) Self-organized sub-groups

During the workshops, it could be observed, that small sub-groups had formed within the allocated workshop groups. Especially in those groups with four or more participants, sub-groups had formed with regards to their prior knowledge and skills. This formation of sub-groups has also had an impact on the process flow as such. Whilst the groups were able to work faster by parallelising some of the process steps, the final outcome was more error prone.

Whilst teams that had not divided into sub-groups were communicating together “Could you please check what step has to be done next?”, the teams which had formed sub groups were mostly unaware of the overall project status: “I don’t know what we need this for, but I’ll get started on it anyways”

By working “side-by-side” the internal group communication had changed and participants were not aware of what the other sub-group was doing. Hence, the final assembly was not always functioning as originally anticipated and re-work had to be done.

### 3) Background Information

One aspect that arose during all the workshops was the importance of detailed assembly guideline information. The participants often asked for further background information on the assembled components functionality and purpose. Questions such as “what does this component do?” were quite common. Therefore, the importance of interlinking technical background information of sub-components within the assembly guideline became apparent. During the interviews a workshop conductor and machine developer highlighted the importance of easy-to-understand guidelines as follows: “If you want actually people to repeat what you did, you should not think that the users are you. You should consider that the users are not knowledgeable at all and consider beginners.”

### 4) Quality check points

In general, “quality check points” during the workshops are suggested, to detect errors, that cannot be corrected later, at an early stage. One example occurred during one of the 3D-printer build workshops. The printer bed had been installed in the wrong orientation. This error was discovered too late and the participants had to deconstruct major parts of the printer and restart again. Of course, this was not only time critical but also had a huge impact on the participants’ motivation. Such occurrences could be prevented through intermediate “quality check points”. Additionally, critical phases (such as the mentioned installation of the printer bed) should be specially marked in the assembly guideline documentation.

### 5) Instructor competency and effect on workshop flow

Especially in the parts of the replication workshops with higher technical complexity, the presence of a skilled instructor was essential for the flow of the workshop and the quality outcome of the assembled machine. Whenever the instructors were present, the dynamic within the group had also changed. Participants rather relied on the comments of the instructor and were not reflecting by themselves. This also led to an increased need of help in the later steps of the assembly since some of the basic information had not been perceived by the group. It was also interesting to see how the groups’ sense of self-affirmation changed with the increased help of the

instructors. If the instructor was offering a lot of support, the groups would also tend to ask more questions later on, rather than thinking for themselves first. This is an important aspect to keep in mind, when it comes to a further analysis of the individual learning journeys during these workshops.

During the later phases of the workshop, including the trouble shooting and the calibration, the experience of the instructors is especially needed. The part of the software configuration is the trickiest and requires more knowledge and skills to understand the software and to properly configure the respective parameters. Therefore, it is of advantage to use pre-tested software units, which can be transferred in a standardized way. If wanted and needed, the software configuration can also be “taught” separately. During the trouble shooting, very specific and detailed understanding of the replicated hardware is needed, which the participants often do not yet have. To improve the workshop flow, especially during this phase, the “accuracy, rigor and completeness” of documentation mentioned by Antoniou et.al [20] are crucial.

### C. Intersections to technological literacy

When describing the six phases of a build workshop, it appears obvious to try to connect these six phases of the workshop to each of the levels of technology literacy. However, it quickly becomes apparent that it is not that simple. Whilst Davies [21] as well as Hansen [22] see technological literacy rather as a skill which should be acquired in a specific order, the build workshops pursue a more holistic approach.

When looking at the participants at the end of the workshops it can well be said that they have reached all three levels of technological literacy, the *Awareness*, the *Praxis*, as well as the *Phronesis*.

However, the holistic learning approach of the build workshops does not specifically distinguish between the single levels, technological literacy is rather reached as a whole. Even though *Phase 1 – Introduction* and *Phase 2 Preparation* largely take place at the *Awareness* level, they also already contain important aspects of the *Praxis* and *Phronesis* level. And whilst the main *Praxis* part takes place in *Phase 5 – Testing*, the participants already gain a lot of understanding on the use and functionality of the machine during *Phase 3 – Assembly* and *Phase 4 – Commissioning*.

By the end of all the build workshops, participants were not only able to understand what e.g., a 3D printer does and how it can be used, they also grasped the meaning of open-source, open production, collaborative replication and the general concepts of the technology’s capabilities. One of the workshop instructors described this learning journey as follows: “... the first day they had some trouble and so on. And by the end of the last day, they were already solving all the problems that were happening with the machine.”– This totally reflects the third level of *Phronesis* and the accompanying understanding of “effective use of technologies capabilities” [21].

## V. DISCUSSION AND CONCLUSION

The six phases of the build workshop that have been outlined in this paper form a basis for further research within the field of OSH documentation and replication. Based on the knowledge gained from this project, future build workshops can be adjusted and optimized to evaluate the potential of OSH replication workshops. The authors suggest a more in-depth analysis of the single phases in future workshops. Especially

the build and commissioning phase offer a lot of potential for future analysis.

The six phases have been based on the replication of OSMT. In the further course of this project, this framework will be further investigated during additional OSH build workshops. These should not only comprise OSMTs but also with regards to the transferability of this concept to other contexts such as OSH in general.

The authors anticipate that this first overview will lead to more structured research approaches of future OSMT build workshops and subsequently to an incremental improvement of these workshops so that they can eventually form an important contribution to the spread of OSMT and the open-source hardware concept. Additionally, this paper also bears important inputs for OSH replicability in general.

With regards to the participants' learning journeys towards obtaining technological literacy: of course, the hypothesis of a holistic approach strengthening technological literacy to a different level has yet to be further pursued and validated. However, first results show that the workshops are already highly successful when it comes to participants using their built machines at the end of the workshops and coming up with their own suggestions of improvements.

However, the authors also suggest future research to focus more specifically which phases mainly refer to which level of technological literacy in order to be able to specifically target certain aspects of technological literacy within the build workshop and to specifically adapt the workshops to certain target groups.

Also, the follow up of the learnings and takeaways from the workshops should be further institutionalized to gain a deeper understanding on the interconnection of the workshop flow and individual learning journeys.

This paper is merely a first step of grasping the OSMT replicability and community engagement. Within the further course of this project, the workshops will be analyzed and depicted more thoroughly to further enhance the understanding of OSH replication process and its effect on participants' technological literacy.

#### ACKNOWLEDGEMENT

This Paper is funded by dtcc.bw – Digitalization and Technology Research Center of the Bundeswehr which we gratefully acknowledge [project “Fab City Hamburg”].

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