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Research Hardware Definition

A report by the RDA FAIR4RH Interest Group, Subgroup 1 on FAIR4RH-Definition

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There's a (low-volume) mailing list to follow our work-in-progress:
https://sympa.cms.hu-berlin.de/sympa/subscribe/fair4rh-def_moa

Please join the RDA group FAIR Principles for Research Hardware - FAIR4RH to get your contribution recognized and/or follow our work. The group is free to join and we would love to have you with us.

Abstract & Executive Summary: This publication documents the work of the Research Hardware definition subgroup of the FAIR4RH (Fair for Research Hardware) RDA (Research Data Alliance) interest group. The following definition is proposed:

> ***Research Hardware is a physical object developed as part of or for a research process.***

Other hardware that is used in research but has not been developed for this research process should be called *"hardware in research"*. Research hardware encompasses scientific hardware (the research process acquires knowledge and evidence not necessarily complied with the scientific, hypothetico-deductive method).

A wide range and number of hardware has been developed in research and some may have lost their dedication to research. Research hardware can result from research outside academia, for instance as the result of citizen science, commercial or military research. In all these cases, we may speak of research hardware, and projects should ascertain objects as research hardware at their own discretion.

Hardware is often specified by design files and enhanced by further documentation. Some research hardware is interdependent with software, requires firmware, and/or other hardware to function.
This definition does not require openness as many others do. Reusability is also not included, as FAIR principles pertaining to Research Hardware are being developed by the FAIR4RH IG.

Keywords: research hardware, open-source software, free software, open hardware, scientific hardware, FAIR principles

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Background

The equipment and hardware used for research could be both the result of, and the means for scientific research. To date the majority of hardware is qualified and produced by companies and has thus not been part of discussions as research output. However, the growing trend towards research-led development of bespoke hardware, together with the growing interest from the Open Hardware community, is challenging the existing status quo.

To avoid any possible misconception, we provide a distinct differentiation between research hardware and scientific hardware based on the available definitions of scientific and non-scientific research, and based on the relevant literature that addresses both. The main scientific research characteristic is the scientific method, which is used to acquire knowledge and find solutions to research problems through systematic observations, predictions, and empirical testing [49]. Research, in general, acquires knowledge and evidence and does not necessarily follow the scientific method [50]. Accordingly, research hardware is, in this document, related to all research practices and techniques, and may or may not be related to scientific research. It may be publicly or privately funded, or both.

Scope of this definition

The main aim of the FAIR4RH RDA IG (FAIR principles for Research Hardware Research Data Alliance Interest Group) is to assess research hardware. For appropriate assessment of research hardware and its compliance with the FAIR (Findable, Accessible, Interoperable, and Reusable) principles [56], definition of research hardware is required. This was the initial motivation for introducing the definition provided in this document, but it can be used for any other purposes. Organizations may have developed, used, or sold research hardware. Use cases of research hardware are likely to include (but not limited to) commercial, military, academic research, and citizen science.

Research Hardware Definition

Research hardware is a physical object developed as part of or for a research process.

Extended Definition of Research Hardware

Research hardware is a physical object developed as part of or for a research process.
This process may happen in academia, citizen science, commercial or military research.

Research hardware is specified by documentation packages that may contain design files, software, further documentation (bill of materials, build and operation instructions, as well as validation and verification reports), and branding.

Hardware that is used for research but is not dedicated to research is hardware in research.[1]

RH performs specific functions. It is often interdependent with software and may require firmware to function.

— END of extended definition —

Research process should be understood as …

Relevant aspects for RH definition

List of different aspects for RH definition from FAIR4RH-Definition subgroup meeting on July 11, 2023	
Type of definition	Hardware definition (Moritz, Julien) Add possible applications and explain what is documentation (Moritz) Short and concise (Alexander, Ana, Vladimir, Nadica)
Physical equipment	Included (Moritz, Nadica)
Differentiation between	To include (Moritz, Julien, Alexander, Robert)

[1] A distinction based on dedication has also been made in research software definition proposed by the FAIR4RS WG [57] that distinguishes between research software and software in research. Similarly, FDA (Food and Drug Administration) in the USA made differentiation between software in medical device and software as a medical device [75].This differentiation may vary among disciplines.

List of different aspects for RH definition from FAIR4RH-Definition subgroup meeting on July 11, 2023	
hardware in research and RH (purpose)	Intent is not criteria for research part in hardware as there is repurposing (Julien) The purpose of hardware should included - primarily intent for research (Vladimir, Nadica, Robert, Ana)
Software/firmware	Interdependent (Moritz) Part of RH if important for functioning (Nadica)
Design files and documentation	Part of the RH (Moritz, Nadica)
Research hardware in relation to scientific hardware	Quality defined by design files and documentation will make it research hardware (Nadica, Ana, Julien) Quality defined by design files and documentation will not make it research (Alexander, Moritz)
FAIR inclusion (R)?	Yes, as in reproducible research (Robert) No (Alexander, Nadica, Ana)
Include research outside of academia, no qualifying word	Yes (Alexander, Ana, Moritz, Nadica, Vladimir) No (Robert)
Define research process	Yes (Julien, Moritz)
Move 2nd sentence from Julien's def	Yes: Moritz, Alexander, Nadica, Vladimir, Ana
Hardware is physical objects	Nadica, Ana,

Hardware is not digital design solely as already proposed for some definitions for OH [32, 35, 68], but requires atoms [18], so the physical part cannot be neglected for RH definition. RH comprises both digital design and physical embodiment. Other identified parts of OH include "(1) the source code for electronics (e.g., VHDL or Verilog source codes), (2) the source code for associated softwares (e.g. development tools, SDK, etc.), (3) the schematics, the design files and the technical drawings (what we named "hardware design"), (4) the aesthetic value, (5) the documentations, and (6) the brands." [11]. Similar lists have been reported elsewhere, for example in [9]: "the bill of materials, schematics, assembly instructions, and procedures needed to fabricate a digital replica of the original" and in [48] where OH digital form includes physical design, software, and documentation. **The proposed RH definition incorporates digital parts (firmware, gateware, and ISA) and recognizes separately design files and documentation.**

Software, firmware, and code loaded into programmable devices are excluded from the open hardware licenses such as TARP and CERN (the European Organization for Nuclear Research) OH due to the legal obstacles [7, 21], but those may enter research hardware definition as being essential for the hardware functioning. In support of this claim: (1) publicly open review process of TARP license resulted in developers seeking for a unique license for hardware and dependable software [21] which was not fulfilled due to the legal reasons in creating such license (similar statement can be found in [19] "The design files released should include all hardware design and software code)" and (2) OSHWA certification incorporates documentation, software, and physical design [ref]. Similar analogy is used for the collaborative design model that is translated from software to hardware domain [20]. **The proposed RH definition recognizes interdependences with software and other relevant interfaces (e.g., firmware, gateware, instruction set architecture) required for proper hardware operation.**

Research hardware can be described as hardware that is used and/or created as a result of research in literature. However, we were not able to identify papers focused solely on research hardware - separately from scientific hardware and from OH. RH can have multiple purposes [9], as for example for science, politics, and leisure (art) [29]; it can be exercised and developed by people with diverse backgrounds (e.g., students, researchers, consumers, hackers, hobbyists, and users) [1, 4, 20]. The actors/designers/users of open science hardware are both academic researchers and citizens (e.g., citizen scientists, artists, and enthusiasts) [1, 29, 41, 44] which may be important for research hardware definition. Practically, this means that from the point of view presented in [41], research hardware can be specifically made for research and research hardware can be hardware created for any purpose that is used for research. On the other hand, in [39] OH is indirectly defined as hardware that could be made, modified, and shared for scientific use which emphasized the hardware purpose. Common ground would be probably that research hardware is used for research purposes primarily, but does not exclude other applications as similar has been stated for educational devices that are "built primarily for educational purposes, rather than research" [39]. Also, there is a question whether research hardware is developed during research and whether for research. If we consider analogy with open-source hardware, the level of openness could be applied to both product and the process [31-32], then research hardware should be a research result of the research process. **It is important to emphasize that customization and repurposing of a hardware is a common process, and research hardware definition should not jeopardize existing customization practices. We have already stated that practices are specific for different communities and disciplines i.e., projects. Therefore, the proposed definition does not have any intent to limit current practices around RH.**

Jenny Melloy, researcher at the University of Cambridge, UK, stated that the main difference between open hardware in the makers community and in the science is the need for "quality assurance, adherence to standards, calibration and reproducibility" [39], where the repeatability and replicability claims are further confirmed as important factors in scientific methodology in [8, 22-23] together with maintenance, upgrading, repair, recycling, safety, risk-free operation, and end of life disassembly being part of the available DIN SPEC 3105-1 OH standard. This is a rather important feature of research hardware and there are repositories such as NIH 3D Print Exchange (U.S. Department of Health and Human Services — National Institutes of Health) that emphasize that 3D-printable models (open research hardware) should be both scientifically accurate and applicable in science [45]. The question of research hardware quality may be an important one for the distinction of research hardware from hardware in general. We should emphasize here that our RH definition considers that scientific hardware is a type of RH. **What makes hardware a research hardware? Is it a purpose? Is it a creator? Is it a quality standard? Could possibly research hardware definition address quality standards in a way that would not restrict what is a research hardware from the community perspective? This question is still open with the proposed RH definition. Basically, the proposed definition does not limit the purpose, creators, and standards - it is left for communities and disciplines to exercise their own or to develop new practices.**

The scales of research hardware vary tremendously from small accessories and building blocks to very complex machines being either of low or high complexity in its design, size, and dependencies presenting either standard or custom equipment [16, 20-21, 23, 25, 28, 30, 32, 37, 39, 48], or it is simply referred as a physical artefact or product [31]. This range of hardware complexity is mostly defined for OH, as available literature rarely uses and exploits research hardware per se. Without loss of generality, we can assume that the same applies to research hardware. To what extent can hardware be defined as supplementary material to research hardware (part of the research hardware) and to what extent as a unique and separate part or tool? **Is there any level of complexity in scales and building blocks that should be incorporated in the definition? Is the RH functioning and utilitarian nature important for an item to be identified as separate and independent RH? The proposed definition does not deal with the building blocks and does not limit RH component definition. Depending on the purpose and discipline, building blocks can be either RH or RH components.**

The OSHWA certification considers four elements: a) the **hardware**, b) **software**, c) **documentation** and d) **branding**. Depending on the type of project and scope one or two elements might not be relevant but for the most part having a plan for all four is a good idea.

Overview of existing definitions related to the research hardware

Table 1, includes an overview of definitions found in literature and on the Internet. All definitions are inspected for four parts that are identified as relevant for RH definition. Three parts: (1) physical component, (2) design files, and (3) documentation are directly relevant for the RH definition, while the fourth part (openness) is not required for RH definition, but it is recognized as important in makers communities and in scientific research that follows open science practices.

Table 1, Comparison of the proposed RH definition with existing definitions.

Definition	Physical components	Design files	Documentation	Openness
Proposed RH definition	Yes	Yes	Yes	Not required
[57]	Not applicable	Not applicable	Yes	Not required
[58]	Yes	Yes	Not mentioned	Required
[60]	Yes	Yes	Not mentioned	Required
[41]	Yes	Not mentioned	Not mentioned	Required
[35]	No	Yes	Not mentioned	Required
[29]	Yes	Not mentioned	Not mentioned	Required
[32]	No	Yes	Not mentioned	Required
[21]	Yes	Yes	Yes	Required
[16]	Yes	Not mentioned	Not mentioned	Required
[7]	Yes	Yes	Yes	Required
[1]	Not mentioned	Not mentioned	Not mentioned	Not required
[28] OH definition	Yes	Yes	Yes	Required
[28] hardware definition	Yes	Not mentioned	Note mentioned	Not mentioned
[4]	Yes	Yes	Not mentioned	Required
[10]	Yes	Yes	Yes	Required
[59]	Yes	Yes	Not mentioned	Required
[68]	Yes	Yes	Not mentioned	Required
[70]	Not mentioned	Yes	Yes	Required

The proposed research hardware definition explanation is partly inspired, created, and modified from the Summary report - Defining Research Software: A Controversial Discussion and research software definition by the FAIR4RS RDA group [57].

> *"Research Software includes source code files, algorithms, scripts, computational workflows and executables that were created during the research process or for a research purpose. Software components (e.g., operating systems, libraries,*

dependencies, packages, scripts, etc.) that are used for research but were not created during or with a clear research intent should be considered software in research and not Research Software. This differentiation may vary between disciplines. The minimal requirement for achieving computational reproducibility is that all the computational components (Research Software, software used in research, documentation and hardware) used during the research are identified, described, and made accessible to the extent that is possible."

GOSH (Gathering for Open Science Hardware) definition of open science hardware [58]:

> "*Open Science Hardware (OScH) refers to any piece of hardware used for scientific investigations that can be obtained, assembled, used, studied, modified, shared, and sold by anyone. It includes standard lab equipment as well as auxiliary materials, such as sensors, biological reagents, analog and digital electronic components. Given that proprietary "black box" instrumentation cannot be fully inspected or customized, and can be unreasonably difficult and expensive to obtain and maintain, we believe that scientific hardware design should be open to allow for the exercise of these basic freedoms.*",

Open Source Hardware Definition v1.0 [60]:

> *"Open Source Hardware (OSHW) is a term for tangible artifacts -- machines, devices, or other physical things -- whose design has been released to the public in such a way that anyone can make, modify, distribute, and use those things. This definition is intended to help provide guidelines for the development and evaluation of licenses for Open Source Hardware. Hardware is different from software in that physical resources must always be committed for the creation of physical goods. Accordingly, persons or companies producing items ("products") under an OSHW license have an obligation to make it clear that such products are not manufactured, sold, warrantied, or otherwise sanctioned by the original designer and also not to make use of any trademarks owned by the original designer."*

Science and Technology Innovation Program (Wilson Center) [41]:

> "*Open hardware is physical—typically made from functional chunks of metal and plastic—but the way it is developed, shared, and used generates a social infrastructure that has great potential to respond to societal challenges.*"

Rakitin & Markova, 2022 [35] defined OH as design files by excluding physical parts from the OH definition:

> "*"Open source hardware" or "Open hardware" specifies the physical real object's design, which specifications are licensed in a way which that object can be changed, modified and distributed by everyone. "Open hardware" is a composition of design principles and legal matters and does not refer to a certain object or type. Therefore, the "Open hardware" can point to anything - such as*

cars, tables, electronics, or even buildings."

Kera 2017 [29] used the following OH property to define OH:

> "*Open science hardware (OSH) presents an alternative to proprietary, standardized (above 109 ISO norms), and often expensive laboratory instruments.*"

Acosta 2009 [32] used the definition derived from literature and internet sources dedicated to OH in which OH is not considered physical artefact, but hardware design:

> "*The general consensus is that Open Source hardware is electronic hardware design that is "freely available under one of the legally binding recognized open source licenses". The open source hardware includes schematics, diagrams and design rules that can be used, studied and modified without restriction and can be copied and redistributed in modified or unmodified form either without restriction,or with minimal restrictions only to ensure that further recipients can do the same.*"

Ackerman 2008 [21] used the following definition for the TARP (Tucson Amateur Packet Radio) OH license where they emphasized that the documentation includes design:

> "*Open Hardware is a thing – a physical artifact, either electrical or mechanical – whose design information is available to, and usable by, the public in a way that allows anyone to make, modify, distribute, and use that thing. In this preface, design information is called "documentation" and things created from it are called "products."*"

Bonvoisin et al., 2020 [16] defined OH as:

> "*Open Source Hardware (OSH), often simply referred to as Open Hardware, is an emergent phenomenon applying to physical products the alternative approach to traditional intellectual property (IP) protection that has been developed in Open Source Software (OSS) through decades of practice.*"

Ayass & Serrano, 2012 defined OH for the purpose of introduction of CERN (The European Organization for Nuclear Research) OH license as [7]. Their definition has an extensive list of terms that can be considered documentation including designs:

> "*Documentation" means schematic diagrams, designs, circuit or circuit board layouts, mechanical drawings, flow charts and descriptive text, and other explanatory material that is explicitly stated as being made available under the conditions of this Licence. The Documentation may be in any medium, including but not limited to computer files and representations on paper, film, or any other media. "Product" means either an entire, or any part of a, device built using the Documentation or the modified Documentation.*"

Murillo & Kauttu, 2017 [1] adopted the following reference from literature which we consider rather abstract:

> “*For our purposes, OH will be described as a highly adaptable platform to integrate present and future “knowledge infrastructures,” which represent “robust networks of [scientists], artefacts, and institutions that generate, share, and maintain specific knowledge" in various professional and academic fields (Edwards, 2010).*”

Hannig & Teich, 2021 [28] used the following OH definition:

> “*Open source hardware (OSH) refers to physical components generated by a decentralized design and development model encouraging open collaboration. OSH is an analogy to open source software. OSH usually intends that information about the hardware is readily identifiable so that others can make it. OSH refers to hardware designs whose specifications, construction instructions, and documentation can be publicly accessed, modified, and used by others. Hardware generally can refer to everything that can be built.*”

Powell, 2012 [4] used the definition introduced by Open Hardware and Design Alliance:

> “*Hardware Freedom 0. The freedom to use the device for any purpose; Hardware Freedom 1. The freedom to study how the device works and change it to make it to do what you wish. Access to the complete design is precondition to this; Hardware Freedom 2. The freedom to redistribute the device and/or design (remanufacture); Freedom 3. The freedom to improve the device and/or design, and release your improvements (and modified versions in general) to the public, so that the whole community benefits. Access to the complete design is precondition to this. (Open Hardware and Design Alliance, 2009).*”

Söderberg, 2011 [10] underlines the importance of source code and the aesthetic value.

> “*The open source hardware consists of some items to protect: (1) the source code for electronics (e.g.: VHDL or Verilog source codes), (2) the source code for associated softwares (e.g.: development tools, SDK, etc.), (3) the schematics, the design files and the technical drawings (what we named “hardware design”), (4) the aesthetic value, (5) the documentations, and (6) the brands.*”

Opensource defines OH as [59]:

> “*"Open hardware," or "open source hardware," refers to the design specifications of a physical object which are licensed in such a way that said object can be studied, modified, created, and distributed by anyone. "Open hardware" is a set of design principles and legal practices, not a specific type of object. The term can therefore refer to any number of objects—like automobiles, chairs, computers, robots, or even houses. Like open source software, the "source code" for open hardware—schematics, blueprints, logic designs, Computer Aided Design (CAD) drawings or files, etc.—is available for modification or enhancement by anyone under permissive licenses.*”

Free Software Foundation defines free hardware as free-design hardware by focusing on the four essential software freedoms that can not be applied directly to the physical object [68]:

> "*Applying the same concept directly to hardware, free hardware means hardware that users are free to use and to copy and redistribute with or without changes. However, there are no copiers for hardware, aside from keys, DNA, and plastic objects' exterior shapes. Most hardware is made by fabrication from some sort of design. The design comes before the hardware… By contrast, hardware is a physical structure and its physicality is crucial. While the hardware's design might be represented as data, in some cases even as a program, the design is not the hardware.*"

DIN (Deutsches Institute fur Normung) SPEC 3105 standard defines open hardware mainly in relation to hardware openness while it does not recognize design files and documentation as separate digital assets [70]:

> *"Open source hardware (OSH) is hardware for which a free right of any use is granted to the general public and whose technical documentation is completely available and freely accessible on the internet."*

The OH definition proposed by Hannig and Teich incorporates general hardware definition [28], where by "everything" they probably refer to "physical objects":

> "*Hardware generally can refer to everything that can be built.*"

Research Hardware Use Cases

The goal of this chapter is to review collected examples/use cases that contributed to the definition of the research hardware. Specific attention is given to the boundary cases and their inclusion or suspension in the Discussion section.

Overview of Collected Use Cases

Research is conducted in several parts of our society. Dedicated hardware is reused or created for particular use cases. There are interactions or collaborations between the academic community, commercial industry, military organizations, NGOs, public services, and citizen scientists.

The Subgroup 1 on FAIR4RH-Definition reached out to different stakeholders and individuals to attract diverse contributions about research hardware use cases from around the globe including users and practitioners from low and moderate income countries. The list presented in Table 2 provides examples to illustrate the variety of research hardware.

Collected use cases:

- Biosolar project from Siemen Brinksma - TU Delft - Part of a thesis, a research project that then evolved in to a open source company, https://www.biosphere.solar/
- Plastic scanner from Jerry de Vos - TU Delft - Part of thesis, awarded the Dyson prize and then prize money used to further develop
- Mirror as an hardware: needs a lot of documentation, also in terms of calibration. E.g. 10.1107/S1600577520014563 or grating: https://opg.optica.org/oe/fulltext.cfm?uri=oe-29-9-13416&id=450206
- Citizen science sensor network: Sensor Kits (created in research for research)
- BRUVS - Baited Remote Underwater Video Systems
- Recording system in social sciences
- Electron microscopes e.g. TEM
- X-ray detector e.g. Dectris
- Data Compared to standard, (calibration?)
- Western blot machine: ladder as positive control/calibration
- CERN has use cases for scientific hardware https://ohwr.org/welcome

Table 2, Overview of selected published research hardware / use cases

Reference(s)	**Research hardware**	**License**	**Repository**	**Area of application**	**Type of hardware**
[43]	PlasPI marine camera	CERN OH v1.2	OSF	Marine Science	Mechanical, electrical, and optical parts with dedicated software required for operation
[20]	Open source Magnetic Resonance Imaging (MRI) device (COSI, Cost–effective Open-Source Imaging)	CERN OH v1.2	GitHub	Healthcare technologies	Mechanical, electrical, software, and accessories
[17]	RISC-V instruction set integrated within a processor	BSD license and CC licenses for documentation	GitHub	General-purpose electronics, Computer science	Interface between software and hardware

Reference(s)	Research hardware	License	Repository	Area of application	Type of hardware
[46]	Inline monitor/tester for ventilators	HW: CERN OH v2 SR SW: GPL v3.0 Doc: CC0	GitHub	Healthcare technologies	Mechanical, electrical, software
[47]	MPPT/PWM solar charge controllers and battery management systems	HW: CERN OH v2 WR SW: Apache v2	GitHub	Electric power generation	Electrical, Electronic Software, Mechanical
[51]	Audiomoth	HW: Creative Commons Attribution SW: MIT	GitHub	Biology	Electronic, Mechanical (case), Software
[52]	White Rabbit	HW: CERN OHL v1.x SW: GNU GPL v2 GW: No license	Open Hardware Repository	Computer science, Laboratories	Electronic, Software, Gateware, Mechanical (case)
[53]	Smart Citizen Kit	HW: CERN OHL v1.2 SW: GNU GPL v3.0	GitHub	Environmental protection, Citizen science	Electronic, Software
[54]	GORGAS tracker	GPL v3.0	GitHub	GPS tracking	Electronic, Mechanical (case), Software
[55]	un0rock/lit3rick ultrasound boards	HW: TAPR Open Hardware License v1.0 SW: GNU GPL v3.0+ Docs: CC BY-SA v3.0	GitHub	Ultrasound experiments	Electronic, Software Gateware
[61]	Spiker box	CC BY-SA, certified as open source hardware and for software commonly free MIT license	Website, Google drive, GitHub, scientific publications	Electrophysiological equipment (recording electrical potentials in humans and animals)	Electronic, Firmware, Software
[62]	RaspberryPi	For documentation various CC licenses, for software various free BSD, MIT, and GNU GPL , and hardware design is open without specific license (where design files of some parts are closed)	Website and GitHub	Single board computer with general purpose input output pins	Electronic, Firmware, Software, Documentation
[3, 13, 63]	Arduino boards	Hardware is licensed by CC-BY SA and software with GNU GPL and GNU LGPL for software libraries	Website and GitHub	Microcontroller-based boards with programming environment and	Electronic, Firmware, Software

Reference(s)	Research hardware	License	Repository	Area of application	Type of hardware
				dedicated shields (add-ons)	
[3, 13, 64]	RepRap (Replicating Rapid-prototyper)	GNU Free Documentation license for documentation, designs use different licenses (commonly GNU GPL and CC), the RepRap itself is licensed by GNU GPL	Website, GitHub, and Thingiverse	Self-replicating manufacturing machine (3D printer)	Electronic, Mechanical, Software, Documentation

Discussion

FAIR4RH IG aims to examine case studies that highlight key issues in research hardware creation, deployment, and dissemination in relation to the FAIRness of research hardware. This sub-chapter focuses on insights, challenges, and other important factors that are taken into account for research hardware definition and derived from collected use cases, as well as from discussion within IG.

In our definition we propose that hardware developed in and during the research process would result in research hardware. This may be early prototypes or even fully developed and tested pieces of equipment like dedicated sensors. Over time, such a piece of hardware may be made available to other interested parties, likely including licensing terms. It may be repurposed and/or incorporated as a building block into other (research) hardware. This could be a transitional change that may benefit from the wording “hardware in research” instead of research hardware. Such a timeline or transition is likely domain-dependent and hard to pinpoint. We suggest that communities use the different wording at their own discretion.

While the proposed definition does not require openness of research hardware and related material, the concept of open hardware design is expected to benefit society. It improves global knowledge sharing and may benefit sustainable manufacturing [71]

For including different perspectives, we can take a look at an article from Robert:
https://www.forbes.com/sites/trondarneundheim/2022/04/04/why-we-need-open-manufacturing-and-what-that-would-mean-for-you/?sh=32f12a002512
Some points that could be included:

- Open design can enable global knowledge sharing for open local distributed and sustainable manufacturing
- Accessibility to modeling and production engineering tools needed in order to realize both. An open tool chain would be ideal in the long-term which serves community interests.

In addition to existing use cases and existing research hardware solutions, a new field of services emerged. Such service is oriented towards development of open science tools and research equipment replication for commercial distribution. Currently, such service is offered by the Prometheus Science company [65] and the LabMaker GmbH [X].

In the course of discussions, the question of hardware and software relation emerged. Specifically, we discussed how different and separate firmware and hardware are. The National Institute of Standards and Technology in the USA defines firmware as a software program and data stored in hardware [66], it is a subclass of software [67]. ISO/IEC/IEEE International Standard 24765-2010 defines firmware [73] as a "combination of a hardware device and computer instructions or computer data that reside as read-only software on the hardware device". Our decision to include firmware in research hardware definition is based on the fact that firmware can be crucial for hardware operation – making hardware and software mutually dependent, not just in terms of functioning, but also in terms of energy consumption [15]. In support of the proposed RH definition is the fact that the borderline between hardware and software nowadays is less apparent than ever before [12]. Further, we would argue that firmware could be considered part of the hardware design closely related to its purpose in similar manner as design files and documentation [13]. Moreover, even though firmware is undoubtedly a piece of software, it is in such a close relation to the hardware within [74] that both hardware and firmware are only useful in conjunction. Although closely related to RH, firmware, design files, and documentation (often) do not represent a physical object that consists of atoms [18].

While firmware represents executable computer code, there is also "gateware" closely related to hardware [67]. Gateware can be used to produce a specific hardware design or to reconfigure specialized digital devices to emulate the hardware design. Some references define gateware as an entirely different entity from the firmware [67], while others define gateware as a type of firmware [68]. Programming files for FPGA (Field

Programmable Gate Arrays) and HDL (Hardware Description Languages) running in FPGA are both considered as gateware [12, 67] or firmware by sources that do not recognize gateware as a separate instance [68].

Another interesting question in regards to complex interactions of physical artifacts with other RH instances is whether or not a processor instruction set architecture represents an integral part of the research hardware and whether it should be incorporated in the RH definition. We provide here a special case of RISC-V (free instruction set architecture/design within the processor), and settle for: Such an instruction set architecture is essential for microcontroller operation and it can be defined as an interface between hardware and software within the processor [17, 69]. Whereas some sources have classified the RISC-V instruction set architecture as a software that enables microprocessor design [16], some processor core designs implementing RISC-Vs have been explored in the sense of the open source hardware example [26]. Further, Hannig and Teich referred to RISC-V as an open source hardware solution [28], probably in the sense of the building block which is commonly used for hardware components. On the other hand, OpenRISC [13] is an open core based on the RISC-V instruction set that completely complies with the definition of hardware. Note that an ISA is really an interface specification [72], and not an implementation. As such it is more an integral part of hardware documentation or specification than the actual hardware implementation which just conforms to it. On the other side, ISA is also a software specification. In conclusion, whether defined as a software or hardware-software interface, an instruction set architecture (ISA) is a building block of some research hardware. Therefore, the proposed RH definition incorporates instruction set architectures (ISAs) as integral RH parts.

Research Hardware Reported in Literature

This chapter focuses on overview of Research Hardware (RH) in literature. The aims of this overview are: (1) to find relevant quotes around RH and relevant terms (e.g., “open hardware for research/science”) and (2) to provide relevant factors that should be taken into account for suggesting research hardware definition.

This subchapter presents an integrative overview of selected references performed with the aim to detect patterns and produce new insights that could be important for RH definition. This is neither exhaustive nor systematic review, but rather an in-detail overview performed on selected literature determined by the relevant keywords and snowballing method. Based on the selected reference readings, four different aspects are identified and discussed in this subchapter in relation to the RH definition:

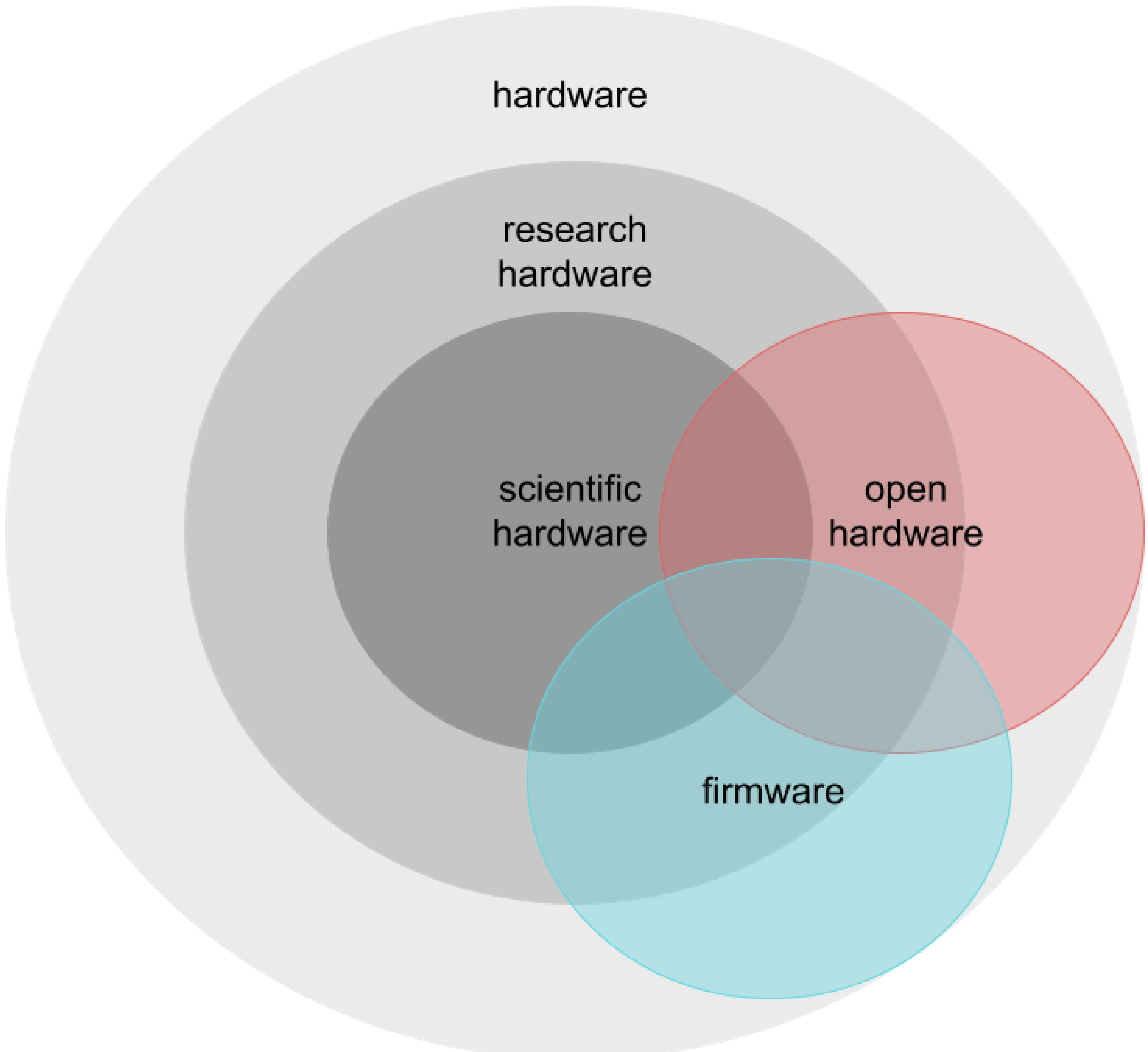
- Physical and Digital Research Hardware Components with one subchapter titled

Additionally, Identified RH Terms in Literature are given at the end of this subchapter and commented in relation to four identified relevant factors for RH definition.

Physical and Digital Research Hardware Components

Research hardware does not necessarily identify with Open Hardware (OH[2]), but the majority of reviewed literature is organized around OH for science. Although researchers and scientists may be primarily interested in OH products and its open dissemination [12, 19], this does not necessarily apply to research hardware in general. Specifically, OH in science presents only a small portion of research hardware as illustrated in Fig. 1. Expectedly, OH definitions are mainly concerned about openness and the digital assets of hardware that could be shared via the Internet. However, hardware in its core requires atoms [18] and therefore cannot be made just of digital design solely (either designs are openly available or closed). In terms of openness, different levels of design and process availability have also been discussed, such as closed hardware, open interface hardware, open design hardware, and open implementation [6], but they are all related to freedoms derived from the free software world and we will not discuss them separately from OH. As the proposed RH definition recognizes interrelations with software, especially firmware, we emphasized that in Fig. 1.

[2] The term used to describe open hardware varies in literature. Such discussion is out of scope of this report, but we do acknowledge that alternate phrases are in use such as Libre Hardware, Free and Open Source Hardware, Open-Source Hardware, Free Hardware, Free Hardware Design, Free Digital Hardware Design, and Open Hardware. For the sake of simplicity, in this report, we adopt Open Hardware (OH). Some of the ambiguities are described in the Free Software Foundation (FSF) article by Richard Stallman https://www.gnu.org/philosophy/free-hardware-designs.en.html and elsewhere.


hardware
research
hardware
scientific
hardware
open
hardware
firmware

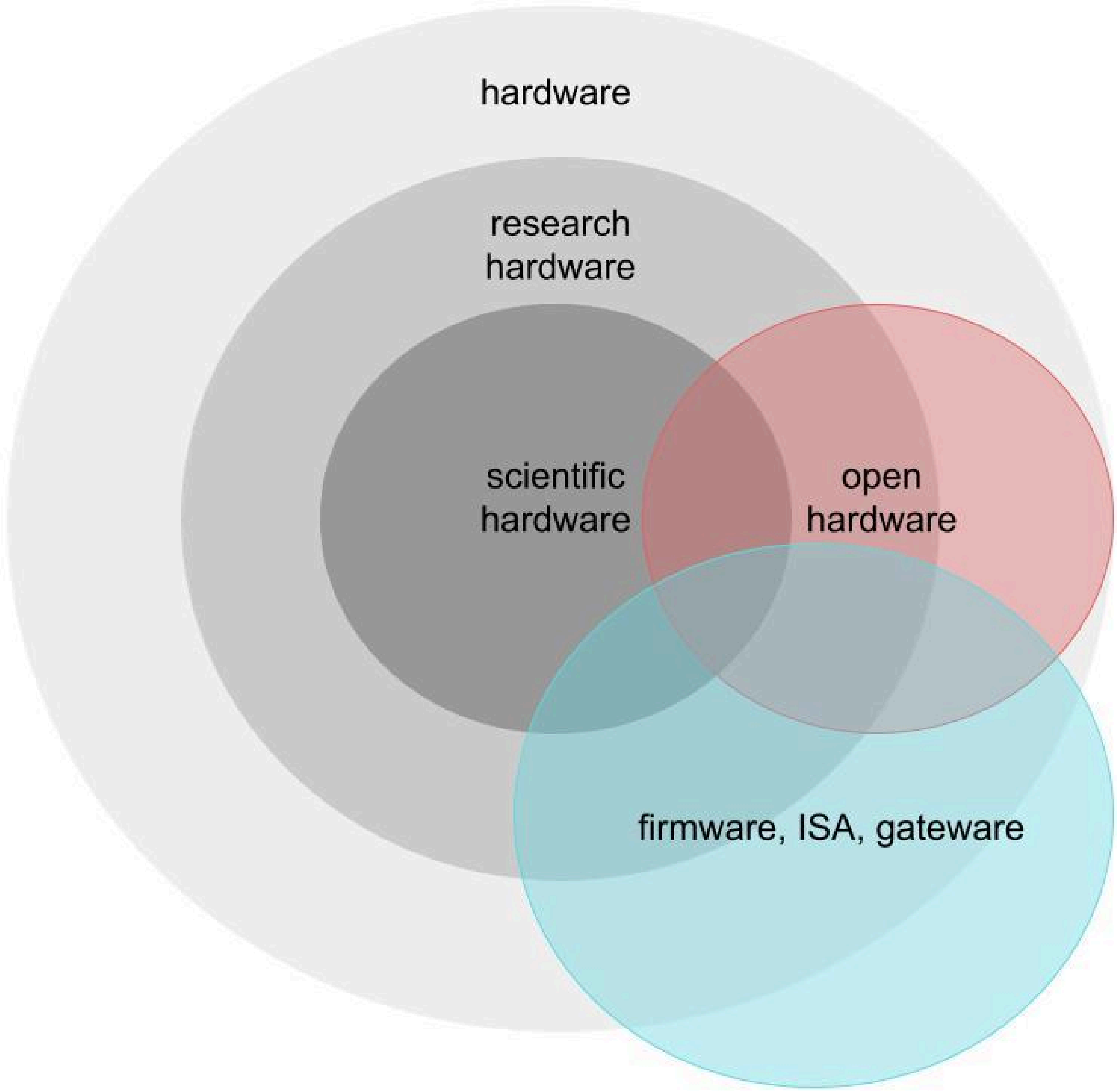


Figure 1, Graphical representation of interactions and intersections of possible levels of hardware (hardware in general, research hardware, and scientific hardware). Openness and firmware are represented in colors to emphasize different hardware features and to complement the existing levels of granularity.https://docs.google.com/drawings/d/1MVmaCH9nOBwZ2jEJ0M0-bbsEqBa9GeFGfmMX6SV5jwI/edit

https://docs.google.com/drawings/d/1ON3J4puI9uYQXbe_IJsG_x69qQapp7c8AHVoGUAg3os/edit?usp=sharing

https://docs.google.com/drawings/d/1PEdz99_1qoWXWYQeFTW_jxjdRuNiD7iiixYf8sMeRks/edit?usp=sharing

The majority of available sources uses the definition proposed by the Open Source Hardware Association (OSHWA) "The term Open Source Hardware (OSH) refers to a product "whose design has been released to the public in such a way that anyone can make, modify, distribute, and use" it" [1, 8, 10, 12, 16, 19-20, 26-27, 30-31, 48] and the definition proposed by the Global Open Science Hardware Manifesto from 2016/2018 [14, ref2-2018] as the hardware that can be used by anyone to "create, obtain, study, modify, distribute, use, and share (scientific instruments) designs" [29, 44]. Open hardware has been described in a context of "collaborative design model" where Herrera emphasized the development aspect of OH [26]. Also, depending on the context, authors tended to use very narrow oriented definitions, as in [1] where the definition of OH was extended to the innovation platform as a potential business model. Bonvoisin et al. 2020 [16] explores the previous definitions for OH and conclude that it emerged around electronics, but that today it does not exclude mechanics and textiles. Regardless whether hardware relates to electronics, mechanics, textiles, or of any combination thereof, it can comprise both digital design and physical embodiment. The digital aspects of OH are printed circuit board designs, photomask layouts, and mechanical assemblies where the complete documentation contains both text (e.g., bill of materials and source code), as well as binary files (e.g., circuit board layout) [22]. Other identified parts of OH include "(1) the source code for electronics (e.g., VHDL or Verilog source codes), (2) the source code for associated softwares (e.g. development tools, SDK, etc.), (3) the schematics, the design files and the technical drawings (what we named "hardware design"), (4) the aesthetic value, (5) the documentations, and (6) the brands." [11]. Similar lists have been reported elsewhere, for example in [9]: "the bill of materials, schematics, assembly instructions, and procedures needed to fabricate a digital replica of the original" and in [48] where OH digital form includes physical design, software, and documentation.

Hardware in Relation to Software

An interesting definition of OH has been proposed by Hannig and Teich [28] as they incorporate general hardware definition ("Hardware generally can refer to everything that can be built."). They also use an analogy from open source software to OH where such analogy is also stated in many resources as for example in [3-4, 8-14, 16, 21-22, 27, 48]. This analogy originates, among other factors, from the license definition, as OH licenses are derived directly from free and open-source software licenses raised around copyright concepts [21] and by other good practices inherited from the Free Software Foundation, as well as general software community such as version tracking (e.g., Git, Subversion, and Mercurial) [22] or those that emerged from the software community to serve the needs of the makers community (e.g., GitBuilding, Hardocs, DocuBricks, and Wikifactory) [16]. Corresponding analogy is also incorporated in the OSHWA definition. Distinctive parts of hardware in relation to software, from the copyright point of view, are utilitarian and mechanical nature [21], which are not in literature directly related to the research hardware or hardware definition, but may be used in the context of FAIR4RH subgroup for research software definition. Software, firmware, and code loaded into programmable devices are excluded from the open hardware licenses such as TARP and CERN (the European Organization for Nuclear Research) OH due to the legal obstacles [7, 21], but those may enter research hardware definition as being essential for the hardware function. In support of this claim: (1) publicly open review process of TARP license resulted in developers seeking for a unique license for hardware and dependable software [21] which was not fulfilled due to the legal reasons in creating such license (similar statement can be found in [19] “The design files released should include all hardware design and software code”) and (2) OSHWA certification incorporates documentation, software, and physical design [ref]. Similar analogy is used for the collaborative design model that is translated from software to hardware domain [20].

Therefore, one important aspect of OH, as well as of research hardware, is that it often comprises both physical part(s) and digital assets. If so, then these two are inevitably connected. The proposed extended RH definition incorporates digital parts and recognizes separately design files and documentation.

Research Hardware Purpose and Customization

Research hardware can be described as hardware that is used and/or created as a result of research in literature. However, we were not able to identify papers focused solely on research hardware - separately from scientific hardware and from OH. For example, in [35] one of the identified OH applications is “in support of research”. Further, in [34] “scientific equipment”, “open-source designed for lab. equipment”, and “scientific hardware/tools” developed by researchers are discussed, though research hardware is not mentioned *per se*. In a similar manner, Kera [33] refers to customizable laboratory equipment for experimental research. “Hardware in science” has been described as a both “research product” and “scientific result” [41]. We decided to follow the relations presented in Fig. 1, so we used existing literature on OH and hardware for science, to identify possible important topic(s) related to research hardware such as purpose and customization.

The common resources to find open hardware in science are Google search, YouTube video tutorials, reddit forums, and online maker meetups, as well as Internet blogs [42]. Although these means are viable and present typical makers’ approach to find appropriate hardware, they may not be ideal for proper dissemination of research output. GitHub is a commonly used open repository for open-source hardware as it cherishes connected and decentralized makers communities [30]. Sourceforge and Google Code are also used along with GitHub [10]. Besides GitHub, makers of free and open-source hardware for science are advised to share their designs on as many places as possible including, but not limited to, the Open Science Framework, SourceForge, NIH 3D Print exchange, Ultimaker YouMagine, or MyMiniFactory repositories of open-source companies [23], as well as at the specialized Open Hardware Repository [7]. Also, availability of research hardware to everyone in the maker community (precisely in the hobby, do-it-yourself, makerspace, hackerspace, and fab lab communities [26]) despite the scientific background, may make the definition of research hardware a bit more complex as such hardware may have multiple purposes [9], as for example for science, politics, and leisure (art) [29] exercised and developed by people with diverse backgrounds (e.g., students, researchers, consumers, hackers, hobbyists, and users) [1, 4, 20]. The actors/designers/users of open science hardware are both academic researchers and citizens (e.g., citizen scientists, artists, and enthusiasts) [1, 29, 41, 44] which may be important for research hardware definition. Kera in [29] emphasizes the role of OH beyond professional research and science communication, such as citizen science and others. For example, in a report that emphasized the role of open hardware in the open science ecosystem [41], open source microscopes could be used for both diagnostics and research. Further, such microscopes have been created in different circumstances and for a variety of purposes, but they can all impact the researchers' work [41]. Practically, this means that from the point of view presented in [41], research hardware can be specifically made for research and research hardware can be hardware created for any purpose that is used for research. On the other hand, in [39] OH is indirectly defined as hardware that could be made, modified, and shared for scientific use which emphasized the hardware purpose. Common ground would be probably that research hardware is used for research purposes primarily, but does not exclude other applications as similar has been stated for educational devices that are "built primarily for educational purposes, rather than research" [39]. Also, there is a question whether research hardware is developed during research and whether for research. If we consider analogy with open-source hardware, the level of openness could be applied to both product and the process [31-32], then research hardware should be a research result of the research process.

There is a question whether research hardware is created for research purposes or research hardware is hardware created with any purpose, but used for research. It is important to emphasize that customization and repurposing of a hardware is a common process, and research hardware definition should not jeopardize existing customization practices. We have already stated that practices are specific for different communities and disciplines. Therefore, the proposed definition does not have any intent to limit current practices around RH.

The Question of Research Hardware Quality

Jenny Melloy, researcher at the University of Cambridge, UK, stated that the main difference between open hardware in the makers community and in the science is the need for "quality assurance, adherence to standards, calibration and reproducibility" [39], where the repeatability and replicability claims are further confirmed as important factors in scientific methodology in [8, 22-23] together with maintenance, upgrading, repair, recycling, safety, risk-free operation, and end of life disassembly being part of the available DIN SPEC 3105-1 OH standard. This is a rather important feature of research hardware and there are repositories such as NIH 3D Print Exchange (U.S. Department of Health and Human Services — National Institutes of Health) that emphasizes that 3D-printable models (open research hardware) should be both scientifically accurate and applicable in science [45]. Moreover, it has been stated that product innovation is more intense for scientific equipment than for other sectors of application [44], making research hardware probably to a greater extent vulnerable to interoperability and reusability. The extended RH definition relates to quality with validation and verification reports.

Research Hardware Building Blocks

The scales of research hardware vary tremendously from small accessories and building blocks to very complex machines being either of low or high complexity in its design, size, and dependencies presenting either standard or custom equipment [16, 20-21, 23, 25, 28, 30, 32, 37, 39, 48], or it is simply referred as a physical artefact or product [31]. This range of hardware complexity is mostly defined for OH, as available literature rarely uses and exploits research hardware *per se*. Without loss of generality, we can assume that the same applies to research hardware. On the other side, GOSH definition of open science hardware addresses "any piece of hardware used for scientific investigations that can be obtained, assembled, used, studied, modified, shared, and sold by anyone" which incorporates not just specific laboratory equipment, but also supplementary materials (e.g., reagents, sensors).

To what extent can hardware be defined as supplementary material to research hardware (part of the research hardware) and to what extent as a unique and separate part or tool? **Is there any level of complexity in scales and building blocks that should be incorporated in the definition? Is the RH functioning and utilitarian nature important for an item to be identified as separate and independent RH? The proposed definition does not deal with the building blocks and does not limit RH component definition. Depending on the purpose and discipline, building blocks can be either RH or RH components.**

Identified RH Terms in Literature

Provided list of identified relevant terms in Table 2 is neither exhaustive nor complete and should serve only to give relevant insights from literature that is mostly focused on OH for science.

The terms were identified from the literature and grouped into the following groups (Table 2): (1) equipment, (2) instrument, (3) hardware, (4) tool, (5) design, (6) device, (7) physical object, (8) product, (9) parts/building blocks, (10) platform, and (11) miscellaneous (containing prototype, infrastructure, sensor project, and lab set-up). The categorization is rather appealing as it partly resembles the important topics identified in the literature and presented in previous subchapter, except for the quality topic. Namely, categories 5 (design) and 7 (physical object) specifically emphasize the question of physical and digital RH components. The purpose is emphasized in the equipment, instrument, tool, product, platform, and miscellaneous groups, whereas parts/building blocks are highlighted in a separate category. It is interesting to note that research did not appear in the following categories: (5) design, (7) physical object, (8) product, (10) platform, and (11) miscellaneous, while the majority of references used (1) equipment and (5) design.

Table 2, List of terms identified in available literature in relation to the research hardware. All reviewed references and terms are used in the context of open hardware. This is not a result of an in-detail and exhaustive text mining procedure, but a result of manual selection of relevant and common terms from literature. Therefore, the number of references could be analyzed with the grain of salt. The identified terms are either equivalent (==) or present a subset (⊆) of Research Hardware (RH).

Grouping terms	Term	Reference(s)	RH relation	Number of references
equipment	scientific equipment, science equipment	3, 8-9, 17, 23, 25, 34, 44	⊆	13
	research equipment	8-9, 44	==	
	highly specialized equipment	9	⊆	
	customized equipment	8	⊆	
	physical equipment	41	⊆	
	laboratory equipment	34	⊆	
	hardware equipment	3	⊆	
	equipment	2-3, 8, 14, 18, 22, 41	⊆	
instrument	scientific instrument, scientific instrumentation, science instrument	1, 3, 8, 22-23, 25, 29, 41	⊆	9
	research instrumentation/instrument, research-grade scientific instruments	1, 8, 25, 29, 41	==	
	laboratory instrument	29	⊆	
	instrument / instrumentation	14, 22	⊆	
hardware	scientific hardware, hardware for science, science hardware, hardware in science	2-4, 8-9, 14, 23, 34, 39, 41, 44, 48	⊆	13
	electronic hardware	4, 21	⊆	
	research hardware, hardware resulting from research, hardware for research	14, 44, 48	==	
tool	highly customized low-volume tools	9	⊆	12
	laboratory tool	22	⊆	
	scientific tool, tool for science, science tool, scientific tool	3, 8, 23, 25, 29, 34, 41	⊆	
	research tool	2, 8	==	
	common tool	1	⊆	
	tool	1, 8-9, 14	⊆	
design	manufacturing designs	25	⊆	17

Grouping terms	Term	Reference(s)	RH relation	Number of references
	scientific design	9, 25	⊆	
	scientific hardware design	9	⊆	
	electronic design / design schematics / design scheme	4, 7, 10, 48	⊆	
	hardware design	4-5, 9, 11-12, 22	⊆	
	physical design	18	⊆	
	open (source) design	8, 10, 16	⊆	
	instrumentation design	14	⊆	
	electronic hardware design	21	⊆	
	design files for hardware	10, 17	⊆	
	hardware design and implementations	21	⊆	
	digital design of physical object / design of material object	3-4	⊆	
device	scientific device	9, 25	⊆	11
	mechanical and electronic devices	4. 18	⊆	
	research device	41	⊆	
	machine	8, 10, 22	⊆	
	device	1, 3-4, 7, 9-10, 22	⊆	
physical object	physical embodiment of a circuit board	21	⊆	5
	physical artefact and technologies	20	⊆	
	physical artifact / artifact	4, 8, 48	⊆	
	physical sample	48	⊆	
	physical implementation of the board	21	⊆	
	functional object	21	⊆	
product	physical product	18, 20-21	⊆	8
	tangible product	7, 19	⊆	

Grouping terms	Term	Reference(s)	RH relation	Number of references
	electronic product	21	⊆	
	product manufactured from the documentation	21	⊆	
	product	4, 7, 16, 48	⊆	
parts/building blocks	physical component	18	⊆	6
	custom component	8	⊆	
	component	8, 21	⊆	
	part	16	⊆	
	item	21	⊆	
	Research equipment, spare parts, and consumables	44	==	
	reagent	14	⊆	
platform	scientific platform	23	⊆	3
	platform	1, 3	⊆	
miscellaneous	prototype	18	⊆	3
	infrastructure	1	⊆	
	sensor project	22	⊆	
	lab set-up	22	⊆	

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