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Collaborative capacity of open source hardware communities: A cross-sectional study

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***Abstract*—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 (DIN SPEC 3105). While OSH has the potential of facilitating participation in product development on a broadly distributed scale, the need for physical production adds a layer of complexity compared to the development of free and open source software (FOSS). More evidence is needed on the transferability of open source development processes from software to physical products. This cross-sectional study therefore takes a closer look at the transition of open source practices from bits to atoms on the activity level. It investigates the issue of how practitioners work together to design OSH products as well as associated limitations in practice.**

***Keywords*—open innovation, open design, open source hardware, open source product development**

I. Introduction

With the advent of the millennium, the open source agenda has extended from software to electronic hardware to mechanical products. This transition has created the field of open source hardware (OSH). Due to its emphasis on values of freedom and openness, the free and open source movement is seen as a mediator to democratise innovation and production [1]. Moritz et al. [2] posit that OSH has the potential to morph into an effective participation mechanism and reconfigure future value chains. For example, OSH has been promoted as a tool to cut costs of scientific equipment and increase the control of scientists over their experimental setups [3]. In light of the COVID-19 pandemic, OSH has been enthusiastically viewed as a vector of rapid and citizen-driven technical innovation [4], while also pushing forward, in future, with critical hardware solutions such as ventilators for passing clinical trials [5]. While there is still some way to go for OSH to establish itself as an economically viable alternative to closed source innovation practices and to compete with today's industrial product development standards [6], achievements reached by OSH development communities such as RISC-V [7] and White Rabbit [8] demonstrate a non-negligible momentum putting OSH on the path once taken by free open source software (FOSS). In OSH projects, success characteristics can be categorised in terms of the process, the product and value creation to different stakeholders [9]. Uptake of OSH is expected to depend on the quality of produced products, the motivations of users to engage with OSH, access to local manufacturing means and materials, and OSH community resources [10]. In the first place, the potential of OSH to scale and generate vibrant innovation ecosystems depends, among other factors, on the capacity of this movement to develop best practices facilitating the collaboration of loosely-coupled communities around the development of physical products. Such practices may be inherited from FOSS while some others need to be reinvented in order to fit with the constraints of building physical products in contrast to compile software products.

Against this background, this study investigates the following research questions: To what degree is the open source development logic from software being implemented in the development of mechanical and mechatronic OSH products (Q1)? What gaps hinder the collaborative development of mechanical and mechatronic OSH products (Q2)? In order to investigate the two questions above, a survey was conducted which examined collaborative development practices in the field of OSH and in turn observed empirically the collaborative capacity of OSH communities.

II. Collaborative Development Activities as a Frame of Reference

This study investigates collaborative development of complex mechanical and mechatronic OSH products on an activity level. Borrowing from Boujut et al. [11], this study adopts the characterisation of CBPP as activity systems that are generally oriented towards specific products and evolve over time. In accordance with Briggs et al. [12], collaboration means that individuals integrate their efforts according to joint or convergent goals. This requires first of all strategic activities of reaching a collective understanding. Wider streams of activities have been observed in FOSS development such as "new member integration" and "collective innovation" [13] which are summarised in this contribution as capacity building for community mobilisation. Ye & Kishida [14] further characterise open source practices around problem-solving activities which emerge as fostered immersion "toward the center of the community through continual contributions". Ordinary task coordination contributes to the key characteristics in open source practices of transparency and accessibility [15]. Hence, collaborative development encompasses activity sets ranging from establishing a participative context to collective engagement as follows:

- Reaching a collective understanding (strategic activities)
- Building of mobilisation capacity (middle layer activities)
- Task coordination (operational activities)

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Since the strength of OSH lies in the spirit of openness and community, this study takes a special focus on the subject of task coordination. The open source version control system "Git" has strongly influenced task coordination in open source development. Linus Torvalds created Git for the development of the Linux Kernel to serve the need for an open source toolchain for software development. The collaboration platform GitHub™ further advanced the Git workflow by offering it as a service and is also widely used in open source product development (OSPD) [16].

Fig. 1 depicts a descriptive process model of task coordination in OSH communities previously derived by the authors [17] which defines the basic logic of the open source development approach as per the following main elements: (1) Task definition and assignment based on an issue management system; (2) contributing and reviewing of tasks as per the "pull and push" model from the version control system Git; (3) integrating of tasks according to automated merging functions from version control system Git or as a manual process, and (4) continuous technical documentation as well as transparent processes that allow for any person interested to join according to the idea of "openness". The model reflects the layer structure of an OSH community [14]: a stable core team and contributors around it which form an amalgamation with the environment. Through its fluid nature which places stakeholder groups across different layers, the process model provides a flexible structure that allows for guided and freely evolving contributions. This study investigates the wider adoption of this model in OSH.

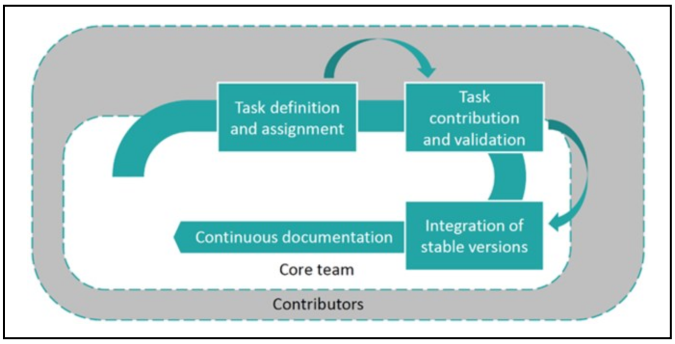

Fig. 1: Open source product development process model according to Mies et al. [17]

III. SURVEY DETAILS

Quantitative data acquisition through a survey was chosen to address the above research questions. The survey design builds on a basic statistical approach (see Fig. 2) of inputs (independent items), outputs (dependent items), and other assumed influences of the dependent items which are not the direct focus of the study (controlling items). The items resulted from iterative brainstorming and iterations of internal reviewing. The survey was implemented in the open source web tool LimeSurvey for statistical surveys and lasted circa 15 to 20 minutes. A pretest with five volunteers from OSH projects provided the needed feedback to refine it.

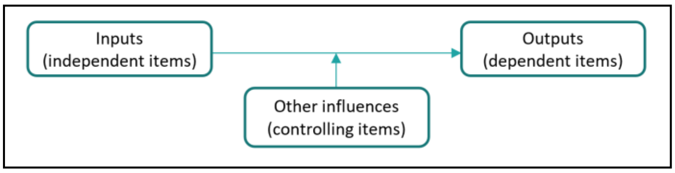

Fig. 2: Survey Design

A. *Conditional questions and inputs (independent items)*

OSH comprises different strategies to facilitate participation and design reuse: It is not by default based on collaboration, but also on broadcasting and mere generative design / remixing (which means to download a design in order to edit and then submit it back or share it). The survey therefore asked conditional questions to check for general concepts and prerequisites which allowed to filter out items that were not deemed applicable to the concrete scenario or answerable by respondents.

As per Section 2, the survey comprises the following six categories of inputs (independent items):

TABLE I. SIX CATEGORIES OF INPUTS (INDEPENDENT ITEMS)

Types of inputs	Categories of inputs
I Context-related items on the establishing of a participative context of collaboration	1. Reaching a collective understanding 2. Building of mobilisation capacity
II Process-related items on the open source development logic	3. Definition and assignment of tasks 4. Self-assignment of tasks 5. Validation of tasks Openness in OSH

The associated item statements are listed in Tab. 5 in Appendix A. The items of the category "reaching a collective understanding" relate to the above-mentioned definition of collaboration (see Section 2) and have been associated with advanced stages of collaborative development [18].

The category of building capacity for community mobilisation encompasses tactical aspects such as "attracting new members", "joint conceptualisation of ideas", or occasional "face-to-face meetings" [13]. Recurring occasions of physical co-working have been shown to create favourable conditions for collaboration. As per Olson & Olson [19] collocated work outperforms remote work by establishing a common ground and trust. Generally, virtual design and communication technologies of the foreseeable future can be expected to rather narrow and complement this physical-virtual gap.

The next two categories of items focus on how tasks are distributed. A salient aspect tested here is the concept of "super-positioning" of tasks [20] observed in FOSS development meaning that tasks which are dependent on previous tasks are deferred/postponed until those previous tasks are fulfilled. In more structured and advanced open source development projects, the practice of "self-selection of tasks" by contributors is commonplace [21]. The survey concretises this concept and distinguishes two different forms of self-selection: self-initiating of new tasks and self-assigning of predefined tasks.

The last two categories of inputs (independent items) look at the reviewing of tasks and openness in OSH. The former is critical to collective problem-solving [22]. The latter concentrates on the points of public sharing of technical drawings and 3D models in editable format (for means of transparency) and feedback for contributed tasks, and the use of versioning systems (for means of accessibility). Further items on equally important practices such as the sharing of bills of materials or information under which licences files are shared were not included to be economical with respondents' time. With regard to licences, on a partially overlapping sample of projects it was shown previously that 93% of projects sharing CAD files used licences that allow for free redistribution [23]. So, despite its normative relevance, this aspect was not included in the survey.

B. Other influences (controlling items)

Three items control for relevance of the collected data: First, the "year of project foundation" is expected to influence the outputs (dependent items) because newly founded projects are unlikely to have deployed properly yet to reach the same outcome as more mature projects. Second, the shares of the "development scope" in terms of nonelectronic hardware (e.g. mechanics), electronic hardware, and software are expected to influence the outputs. Since the development of physical products involves significantly more degrees of freedoms, it is expected to be more complex than the development of software. As a consequence, the varying levels of scopes are controlled for. Third, the "stage of development" in terms of concept, design, or production stage has an effect on outcomes, e.g. as the availability of a functional prototype can facilitate for contributors to propose and develop additional functions and features. From production onwards, it becomes possible for independent contributors to obtain physical products as a collective reference for co-development.

C. Outputs (dependent items)

With regard to key indicators of distributed collaboration, actors in the open source domain understand success more holistically than conventional actors of innovation and product design. They define outcomes on the three levels of: technology, people, and processes [24].

Looking first of all into technology output requires for example a better understanding of the notion of "release early, release often" and how it is practiced in open source development [25]. This policy was used in the development project of the Linux operating system to push and ease rapid debugging (detecting and eliminating errors) by developers and testers. The need for physical production of OSH limits this approach as it is associated with additional expenditure of time and marginal fabrication costs. The idea of going into production with a merely adequate product design has for example become a central element of the lean start-up approach to better gauge customer requirements and reduce the time to market [26]. Crowston et al. [20] propose in this regard the key indicator: number of product releases.

Concerning the subject of people, OSH communities have been characterised by a high turnover of contributors[1] and a strong immersion of core team members balancing their efforts on product development activities and community building [27]. On the subject of people, Crowston et al. [20] propose the key indicator: number of contributors.

With regard to processes, Lee & Cole [22] found in their seminal work that learning through critical feedback is associated with successful development outcomes in the Linux project. Similar to a zero defects mentality, they argue that rejections of contributions are in fact positive as they give constructive feedback and highlight concrete development potential for future improvements. In order to achieve learning and personal development in open source communities, Ye & Kishida [14] likewise encourage responding to questions, reviewing contributions, and recognizing the relevance of learning. So, the establishment of peer-reviews offers a useful proxy variable to measure successful dynamics of OSH communities. This leads in sum to the following four outputs (dependent items) which serve as proxy variables for successful collaboration outcomes:

TABLE II. SUCCESSFUL COLLABORATION OUTCOMES

ID	Item description
O1	Number of releases - released product generations by a project
O2	Number of contributors - people who submitted contributions within 1 year
O3	Share of distributed validations - out of all reviewed contributions
O4	Share of rejected contributions - out of all reviewed contributions

D. Item scales

Six-point Likert scales were applied across all inputs (independent items) in order to get reasonably detailed responses and avoid respondents choosing the most neutral category as per the so-called "tendency to the middle". Relative quantitative controlling and dependent items (shares) were constrained to 5% steps. Absolute quantitative controlling and dependent items (durations, amounts, etc.) were constrained to discrete numbers.

E. Sample

As target group the survey defined a list of 169 active projects from the Project Directory of the Open Hardware Observatory (219 projects in total)[2]. This curated list of rated mechanical and mechatronic OSH products according to the knowledge of the authors was the most extensive list of this kind at the time and therefore served as a representative population of projects in the field of OSH. The following table shows the sampling and contact method:

TABLE III. SAMPLING AND CONTACT METHOD

Sampling method	No. of projects	Contact method
Desktop research of contact details	81	E-mail
Desktop research of contact details	22	Online enquiry form
Available to the authors from a previous interview campaign	20	E-mail

The remaining projects used social media accounts as means of contact or it was not possible to find the contact details, e.g. because of dead links or insufficient information. Since e-mail and contact forms are more containable and the former is a widely accepted medium in open source contexts, they were deemed sufficient. Subsequently, an inquiry to participate and share the survey was sent in December 2017 to 123 project contacts with a second notice one month later. The leading German online magazine on internet culture Heise promoted the survey by means of a news bulletin[3]. The P2P Foundation Greece also kindly wrote a posting about the survey on their web blog[4]. Additionally, one of the authors of this study was given the opportunity to write a post about the survey on the Hardware News blog of the discontinued collaboration platform by the British startup Wevolver LTD.

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[1] In the survey a contributor was defined as "anyone who is making contributions towards this project" and a contribution as "a task which is performed for this project".

[2] See URL: https://en.oho.wiki/wiki/The_OHO_Project_Directory.

[3] See URL: https://www.heise.de/make/meldung/TU-Berlin-Umfrage-zu-Offener-Hardware-3876744.html.

[4] See URL https://blog.p2pfoundation.net/open-source-hardware-collaboration-survey-people-work-together-design-open-source-products/2017/11/10.

The communication campaign achieved a total of 73 responses from 51 different OSH projects. Since the unit of analysis is projects, this translates in a response rate of 41% which is still very high. 70 responses from 48 projects fulfilled the essential criterion that the development scope includes nonelectronic or electronic hardware and thus made up the surveyed sample. For responses from the same project, mean values were calculated.

IV. RESULTS

This section presents and discusses the processed results of the survey, starting in the first subsection with the conditional questions and inputs (independent items), following up in the subsequent sections on the other influences (controlling items), and the outputs (dependent items).

A. Conditional questions and inputs (independent items)

The responses to the conditional questions (see Fig. 3) reveal that 61% of the projects established task separation and generated distributed contributions as the main currency of collaborative OSH development. The conditional question on the subject of task separation was to check for a division of efforts into reasonable contributions as a prerequisite for task organisation and issue tracking (hence some areas in the diagram are marked as inapplicable). Offering a contribution guide is followed by 46% of the projects, which could be an indication that it may not be critical for collaboration. Only 4% of the projects follow none of these practices.

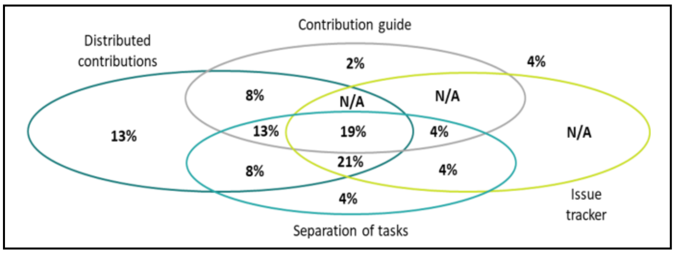

Fig. 3: Euler diagram of responses to the conditional questions (n=48)

The responses to the six categories of inputs (independent items) can be found in Appendix B. The responses for the three items of the first category "Reaching a collective understanding" were relatively promising: 96% of projects in the sample (n=48) responded at least with slight agreement across this category. This strongly indicates a common purpose in the overwhelming majority of projects.

The responses for the four items of the category "Building of mobilisation capacity" are not as pronounced as for the items in the previous category. Out of the projects for which responses are available to the four items of this category (n=30), 33% responded to these items at least Ye & Kishida with occasionally. Considering the two items on face to face interactions (I6 and I7), the cumulative percentage value appears less discernible, as the physical-virtual gap in open source development unarguably presents one of the major challenges of OSH. However, the fact that 48% of projects in the sample (n=48) engage at most rarely in active recruitment of new contributors highlights a striking gap.

Each of the process-related items I8-23 was responded at least with occasionally or slightly agree for 17% of projects (eight projects in total) in the sample (n=48). This indicates a moderate process continuity within these projects (as per the simplified OSPD process model in Fig. 1) and can be partly explained by the number of items and the stringent conditional questions which rigidly decrease the sample of n=48 to 19 projects. On the one hand, the low number of projects for which these practices can be confirmed raises questions about the overall feasibility to implement the open source development logic for hardware. On the other hand, some of the less prevalent practices may also be supplementary or less critical for hardware development.

On a granular level, the responses to the conditional questions and inputs (independent items) make it clearly visible that several open source development practices are widely established as they are very prevalent amongst most projects (agreement/frequent occurrence in at least 70% of the subset of responses). Yet, other surveyed practices are not so widely spread (agreement/frequent occurrence in 50 to 69% of responses) and may be characterised as related to the emergence of more advanced projects. Moreover, a number of gaps prevail which appear as essential practices but are nonetheless not widely implemented (agreement/frequent occurrence in less than 50% of the subset of responses). The following table distinguishes widely and less widely established practices, prevailing gaps and potential benefits of establishing associated best practices:

TABLE IV. OVERVIEW OF ESTABLISHED PRACTICES, PREVAILING GAPS AND BENEFITS OF CLOSING GAPS

Widely established practices (at least 70%*)	**More advanced practices (50 to 69%*)**	**Prevailing gaps (less than 50%*)**	**Benefits of advancing / closing gaps**
i. Prerequisites			
• Distributed contributions • Separation of tasks	• Using an issue tracker • Offering a contribution guide		• Push-starting collaborative development
ii. Strategic and middle layer			
a) Reaching a collective understanding			
• Mutual trust amongst contributors • New/different perspectives are reflected • Contributors follow shared goals/purposes			
b) Mobilisation capacity			
	• Conducting of core team meetings	• Active recruitment • Physical meetings • Physical co-working	• Reaching a dynamic and consolidated community
iii. Operational layer (process-related items)			
a) Task definition / assignment			
• Appropriate modular structure • "Super-positio-ning" of tasks • Defining task requirements	• Exclusive task responsibility • Contributors share on which tasks they are working	• Task assign-ment to contributors	• Relieving the core team • Avoiding duplication of works
b) Self-selection of tasks			
	• Self-initiating of new tasks	• Regular updates of goings-on • Self-assigning of defined task	• Pro-active task organisation
c) Validation of tasks			
	• Reviewing of contributions		• Enabling learning and

	• Providing feed-back for rejected contributions • Reviewing tasks according to requirements		individual progress
d) Openness in OSH			
• The public sharing of CAD files • … in editable format	• Public sharing of feedback for contributions • Use of versio-ning systems		• Making OSPD processes more seamless

* Responses: yes; at least agree; or at least frequently (see Annex B).

B. *Other influences (controlling items)*

With regard to the development scope, Fig. 4 shows the profiles of each project in the ascending order of the shares of the nonelectronic scopes of development. Each of the shares of the three scopes: software, electronic hardware and nonelectronic hardware were requested from respondents in 5% steps, making up 100% overall. Out of the overall scope, nonelectronic hardware development makes up a share of at least 50% for 44% of the project (in comparison electronic hardware development makes up a share of at least 50% for 23% of the projects; and software development makes up a share of at least 50% for 25% of the projects). So, overall, the sample is well-balanced and reflects a sample where the open source approach has transitioned from software to mechatronic and mechanical products.

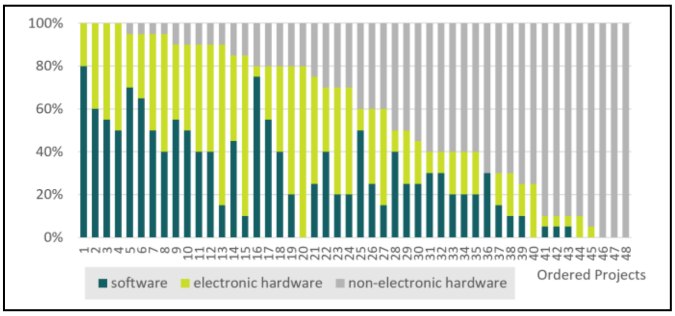

Fig. 4: Development scope (n=48)

On the foundations of projects, Fig. 5 shows that 60% of the projects were founded in the last five years; and 40% of the projects in the period 2002 - 2012. The dotted exponential regression curve in the figure points towards an upward trend over the 16-year period. Due to the limited number of projects, the deviations from the trend around the year 2012 do not allow for any conclusion on statistical effects.

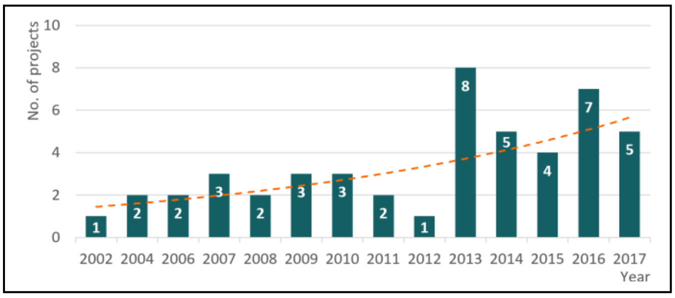

Fig. 5: Year of project foundation (n=48)

Not as much is known about the capacity of OSH projects to generate designs of complex products that are ready for production / replication. As per Fig. 6, 4% of the projects are at the concept stage which hardly allows for distributed development; 31% of the projects confirmed to have reached the prototype stage; and 65% of the projects reached the production stage. These results indicate a general viability of the field of OSH to create replicable products.

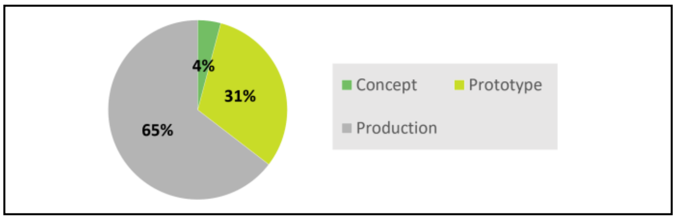

Fig. 6: Reached stage of development (n=48)

C. *Outputs (dependent items)*

Once a project has reached the production stage, the results in Fig. 7 strongly indicate the emergence of a continuous process of multi-generational product creation.

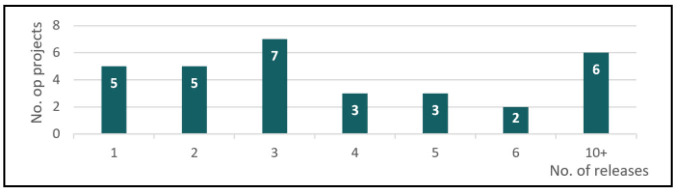

Fig. 7: No. of released product generations (n=31)

As per Fig. 8, 39% of the above-mentioned projects that have reached production stage (see Fig. 6), needed an average time to release a new product generation since project foundation of less than one year. This indicates a general capability of projects for OSH to develop replicable product designs. The overall distribution of the project durations is in line with results from cross-sectional studies of conventional product development in industry [28]. However, closer investigation on impacts of OSPD practices on time-to-market and readiness for production is needed to derive more conclusive results.

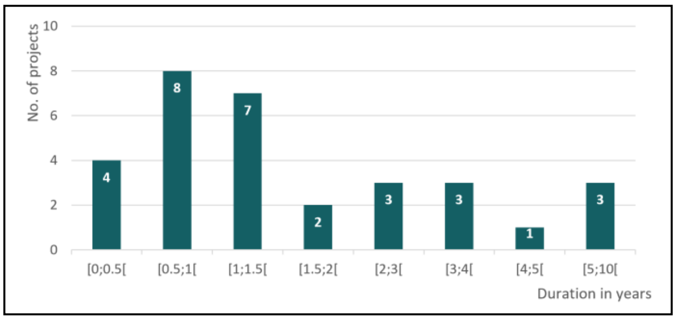

Fig. 8: Average time to release of a new product generation since project foundation (n=31)

Fig. 9 reveals that 54% of the projects have up to ten people contributing and 16% of the projects have formed large OSH communities of more than 50 people. This provides an interesting snapshot, in view of the ongoing expansion of the field of OSH (see Fig. 5), as the formation of further large communities can be expected in the coming years. The number of projects would generally be expected to decrease along with the number of contributors per project. The figure resembles this more or less apart from the fact that 8% of the projects (four projects) had no activity of contributors in the last twelve months; and 21% of the projects only one to two contributors. This is however in line with the fact that the survey asked “how people work together to design open source products" which called for more collaborative projects to participate.

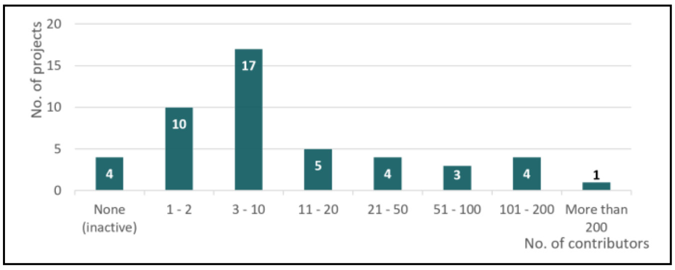

Fig. 9: Number of contributors in the last 12 months (n=48)

As mentioned in Section III-D, in FOSS rejected contributions commonly serve the purpose of providing suggestions for improvements. Moreover, distributed validations are needed to broadly realise learning and personal progress of newcomers. Fig. 10 reveals that out of the projects that had distributed contributions (see Fig. 3), 25% have a share of distributed validations of more than 10%; 44% have a share of rejected validations of more than 10%; and 9% have a share of both ratios (distributed validations and rejected contributions) of more than 10%. The heatmap illustrates that there is a great potential in OSH to increase leverage on both ratios. In fact, it appears from the data that there is a cutting edge to achieve both ratios beyond the orange demarcation line in the heatmap. On the positive side, the results could be viewed as promising as the majority of projects engage at least partially in one of the two practices of peer-to-peer validation or learning through critical feedback.

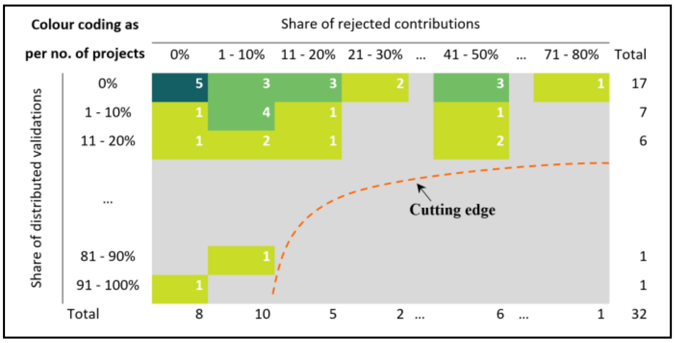

Fig. 10: Share of distributed validations *versus* share of rejected contributions incl. heatmap (n=32)

V. SUMMARY

The results of this study illustrate the diffusion of best practices and prevailing gaps of collaborative development in OSH on activity sets ranging from strategic activities to middle-layer activities to operational activities. The responses on the strategic level indicate that a conducive climate of collaboration is relatively widespread. Yet, only one third of projects engage in occasional mobilisation activities according to the cumulative responses to the items in this category. These results reflect the seldom discussed characteristic in OSH of: occasional face to face interaction. Indeed, it does appear to matter in OSH to complement computer-mediated work. This points towards OSH also being rooted locally while providing a source for global sharing of knowledge. Moreover, improved task organisation of assignment and self-assignment of tasks is identified as a prevailing gap which may however also come at the expense of creativity and require consideration of incentive structures and roles and relations.

The responses on the subject of task coordination illustrate that a number of best practices from the domain of FOSS have been adopted successfully in the field of OSH. The study in particular identifies a small minority of projects which prove the feasibility of closely transferring the open source development logic from bits to atoms. At the same time, the large majority of projects that do not implement comprehensive process continuity attests to the richness of the concept of OSH beyond open and participative processes of collaborative product creation.

With regard to the research questions of this study, the results on the inputs (independent items) allow to distinguish widely and less widely adopted practices (Q1), prevailing gaps (Q2) and potential benefits of establishing associated best practices. A great potential exists to implement best practices which are associated with the identified gaps so that projects improve towards even greater stability and maturity.

The results on the other influences (controlling items) additionally illustrate that the field of OSH nowadays includes a balanced mix of products with varying shares of mechanical and mechatronic scopes. It shows that it has been expanding and continues to do so, and that a general capability exists to create replicable products. The results on the outputs (dependent items) illustrate that the field of OSH has also clearly advanced in recent years to build large-scale communities. It continuously releases new product generations and it supports learning and personal progress.

It should be noted that this study is based on cross-sectional data and therefore only gives a snapshot of a momentary state of the field of OSH. The collecting of longitudinal data would be of great importance to derive more robust findings in the future, in particular on relative contributions of the identified practices to balanced outcomes. Finally, no statistical relationships were analysed due to the sample being of a small size.

VI. CONCLUSION AND OUTLOOK

This contribution adds to existing literature on the still relatively young and growing field of OSH by providing empirical evidence on the diffusion of best practices for collaborative development within a sample of 48 OSH projects for mechatronic and mechanical products. It confirms a moderate collaborative capacity for a small subset of OSH communities. However, the larger subset of projects in the sample faces shortcomings of transferring the open source logic from bits to atoms within a continuous process. This study makes them visible by exploring prevailing gaps and less widely diffused practices in the field. Narrowing these gaps is expected to have a positive impact on projects' convergence as well as people and technological outputs. Herein, learning and personal growth would be expected to be amongst the most crucial ones to facilitate progress in the future. Yet, further research is needed to explore the relative importance of different practices.

The findings of this study are also hoped to provide a deeper understanding of collaborative development in the field of OSH in research and for practitioners, as the identified categories and activity sets can serve as a benchmark for OSH communities to (self-)assess where they stand. Some issues raised on best practices and improvement potentials could indeed be viewed as good practices for project management which may also be applicable in more traditional domains. Additionally, the survey design provides a statistical model with metrics which can be used in further research.

A larger sample would allow for analysing and testing of statistical relationships as well as distinguishing between different categories. Since the time the survey was conducted, the responding projects were not followed specifically and it would be interesting to get a snapshot on them today as part of follow-up research. The authors explicitly encourage further research on developing hardware according to OSH principles from industry and academia as well as for technology transfer to unlock the potential of OSH as a promising participation mechanism in future product creation. It should be noted that OSH is typically developed in highly diverse environments which heavily rely on computer-mediated work. As mentioned above, different design rationales are at play in OSH, from broadcasting to evolutionary design to collaboration. Of the ones mentioned, this study only focuses on the latter. Further research is needed to grasp the broad spectrum of strategies and potential impacts of OSH such as design reuse, eco-design, or the internet of product creation.

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APPENDIX A

TABLE V. STATEMENTS OF INPUTS (INDEPENDENT ITEMS)

ID	Item statement
Category - Reaching a collective understanding	
I1	Contributors mutually trust each other within this project.
I2	New/different perspectives within this project are accommodated and reflected.
I3	Contributors are following shared goals and purposes.
Category - Building of mobilisation capacity	
I4	New contributors are actively recruited, for example through the project's online presence, publications or at fairs.
I5	The core team holds regular meetings (online or offline).
I6	Periodic physical meetings are held where contributors come together.
I7	Contributors physically work together in co-working places.
Category - Definition & assignment of tasks	
I8	Within this project an appropriate modular product structure has been defined according to which tasks are organised.
I9	Tasks that are dependent on previous tasks are deferred/postponed until those previous tasks are fulfilled.
I10	When tasks are defined, product requirements are included (or linked) in the task description as well. Requirements are needs or expectations that are stated, generally implied or obligatory.
I11	Tasks are supervised by a task owner, who has exclusive task responsibility to ensure it is performed successfully, whether by supervising it or performing it themselves.
I12	Individual contributors are being assigned tasks to work on.
I13	Contributors publicly share which tasks they are working on before submitting their results.
Category - Self-assignment of tasks	
I14	Contributors get updated on general happenings within this project (e.g. through newsletters or mailing lists).
I15	Contributors make use of the issue tracking system to define tasks they work on.

I16	Contributors make use of the issue tracking system to assign themselves to tasks they want to work on.
	Category - Validation of tasks
I17	Distributed contributions are reviewed where necessary.
I18	Feedback for rejected contributions provides appropriate guidance for future improvements.
I19	Distributed contributions are reviewed according to previously specified product requirements. Requirements are needs or expectations that are stated, generally implied or obligatory.
	Category - Openness in OSH
I20	Within this project design files (e.g. 2D drawings or 3D models, circuit board layouts, schematics or additional technical drawings) are shared publicly for anyone to access them.
I21	Design files are shared publicly in editable formats. This means that export formats are avoided (e.g. ODT/DOC instead of PDF).
I22	Contributions are submitted via versioning tools such as GitHub, GitLab, Wikis, etc.
I23	Feedback is provided publicly for each distributed contribution where necessary.

APPENDIX B

See legends at the end of the appendix.

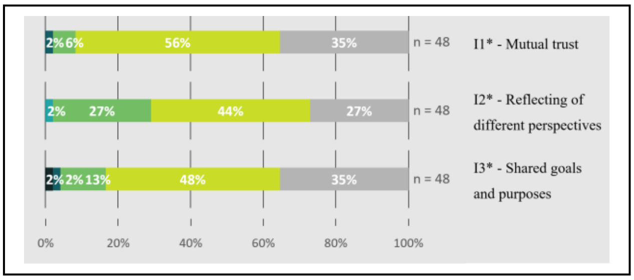

Fig. 11: Reaching a collective understanding

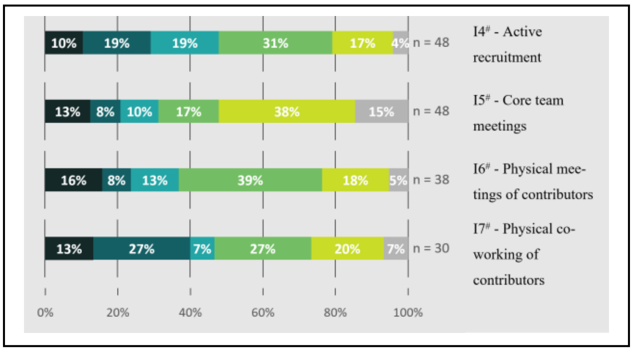

Fig. 12: Building mobilisation capacity

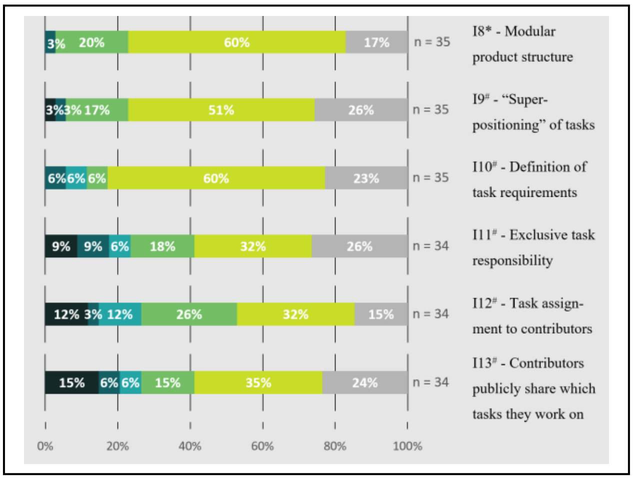

Fig. 13: Definition and assignment of tasks

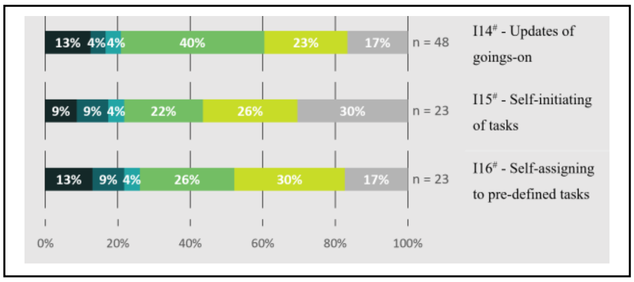

Fig. 14: Self-selection of tasks

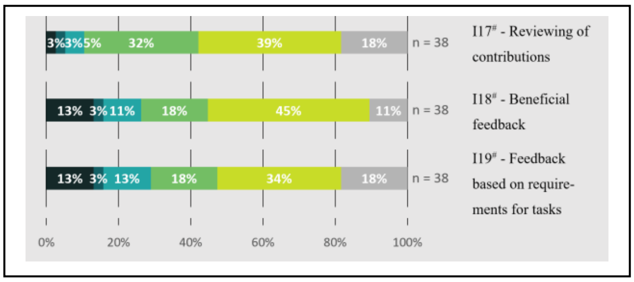

Fig. 15: Validation of tasks

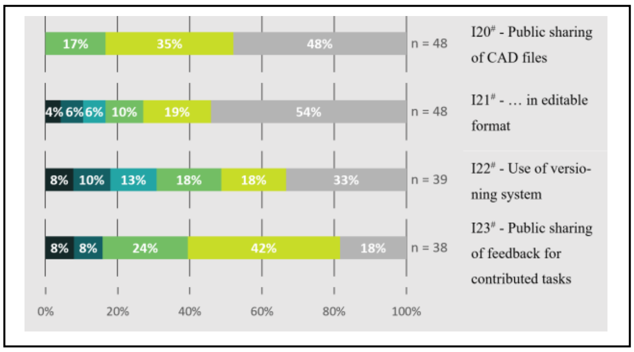

Fig. 16: Openness in OSH

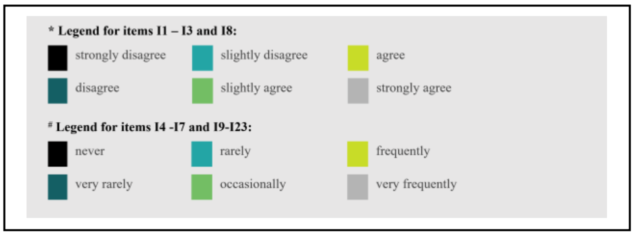

Fig. 17: Legends