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Makerspaces in Low-, Middle-, and High-Income Countries to Support Student Development of Engineering Design Skills*

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Design spaces are important for the development of engineering design solutions in low-, middle-, and high-income countries. Only recently has literature begun to comprehensively document and compare makerspaces; however, this comparison is frequently only based on measurable properties such as size and number of machines. Instead, we argue that the defining characteristics of a makerspace are facilitation of prototyping, curricular outcomes, and management philosophy. This study compares three makerspaces in countries with different economic backgrounds: the Oshman Engineering Design Kitchen (OEDK) at Rice University in Houston, TX, USA; the Laboratório de Fabricação (LABFAB) at the Pontifical Catholic University of Rio Grande Do Sul in Porto Alegre, RS, Brazil; and the Polytechnic Design Studio (PDS) at Malawi Polytechnic in Blantyre, Malawi. We provide insight into how these economic differences present themselves in the governance of the makerspaces including space access, partnerships, policies, procedures, and staffing models. Additionally, we highlight how economic differences impact the level and quality of prototypes achievable by students. Despite these differences, all three institutions have experienced rapid growth in the number of users, supported projects, and staff within their makerspaces. Support for this growth came from investments made into curricular resources like dedicated classes, workshops, and one-on-one mentoring. We conclude with some suggestions for future makerspace development incorporating these same principles.

Keywords: makerspace; engineering design; student development; prototyping; engineering education

1. Literature Review

In the last ten years, there has been a global increase in the interest in design, fabrication, and creation of physical objects. Local responses to this interest have resulted in the creation of centralized hubs called makerspaces. These functioning guilds have formed within cities, higher education institutions, and libraries, and are collectively part of what is referred to as the "maker movement." Generally, makerspaces are facilities with traditional and digital fabrication capabilities that support collaboration, design, and problem-solving. People using makerspaces celebrate learning by solving problems with the development of tangible devices or art projects [1]. The makerspace movement extends beyond the US, with over 1000 makerspaces and Fab Labs having opened internationally in the previous ten years [2].

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College campuses have always had the components of makerspaces such as machine shops, wet labs, and tool centers; however, combining them all under one roof and unifying the name (makerspace) has helped to stimulate creativity and serendipity alongside knowledge sharing. This effort has been bolstered by government and NGO reports such as the Engineer of 2020 by the National Academy of Engineering and the UN's Sustainable Development Goals, which lend themselves to the application of project-based learning [3, 4]. Many academic makerspaces have stated goals to build capacity for engineering and technical skills as well as entrepreneurship within students and community-members alike. Generally, makerspaces impose a process and locale for the creation and iteration of products and solutions [3]; academic makerspaces localize talent regardless of department, which cultivates a community that celebrates and contributes to the production of creative physical artifacts [4]. Specifically in engineering, advantages include the opportunity to do hands-on and project-based work, a beneficial departure from traditional engineering education which favored theoretical and model-based work [5, 6].

1.1 The potential Impact of Makerspaces

Besides the educational benefits that have resulted in increased numbers of makerspaces in academia, the general public is also interested in growing makerspaces. The popular press has latched onto the potential impact of makerspaces to usher in a new manufacturing revolution [7]. One reason to celebrate more makerspaces is that in an increasingly globalized economy, every participant (workers, students, manufacturers) need to understand the complex interplay between technical skills and professional skills. Makerspaces are uniquely tailored to grow users' abilities in both areas.

Studies have already shown the impact of academic makerspaces on a student's capacity for technical skills such as: entrepreneurship [8], problem solving [9, 10], physical prototyping [11, 12], increased 3D printing capabilities [13], and creative problem solving [14]. Students also learn professional skills like communication [15] and teamwork [16]. Finally, makerspaces improve student self-perception through increased self-efficacy and self-confidence [17], as well as drive economic development [18]. Institutionally, these professional and technical skills fit existing curricular goals for authentic engineering design and makerspaces are also the ideal site for exploring new learning models.

1.2 Learning Models Applicable to Makerspaces

Several educational models have already been used to describe how learning happens within a makerspace. The Community of Practice model describes learning that happens in a space as a function of the members all participating in a space and sharing their knowledge. In an attempt to apply this model to makerspaces, Sheridan et al. found some overlap with the concept that users have shared practices but were unable to describe formal methods of knowledge and skill sharing [10]. The constructivist model developed by Piaget is considered to be one of the most important theories describing learning in makerspaces. Constructivism is effective at describing individual learning accomplishment; however, it does not properly account for learning when aided by an instructor or guide [3]. The Situated Learning Model can describe how students acquire skill proficiency in much the same way that apprentices learn when surrounded by skilled professionals [20].

Active learning is a type of education that prioritizes learner-centered instruction through hands-on activities, group work, and mentoring rather than lecturing. The application of active learning most commonly breaks down between formal methods, like curriculum integration [4, 22], and informal methods, like trainings or workshops. This model fits much of a makerspace as the space itself is designed for maximum engagement [21]. Curricular integration is where courses voluntarily use the facilities at a makerspace, leveraging tools and skill proficiency that can be acquired through the availability of such a space. An example of curricular integration that happens most frequently in the US is when an engineering design course interfaces with a makerspace, such as with cornerstone [17, 9] or capstone courses [23]. This method has been shown to have many benefits to students, including providing context of, relevancy for, and persistence in engineering [24–27].

1.3 Cataloging Characteristics of Academic Makerspaces

It is difficult to generalize the description and characteristics of all educational makerspaces because the educational models vary just as wildly as the structure, shape, and inventory of each space. Recent literature has only begun to compare the different types of academic makerspaces as a nascent taxonomy. In a recent study, Barrett et al. completed a comprehensive survey of academic makerspaces taken from US News and World Report's list of Top 100 universities. Their characterization of 40 spaces included location, home department, membership, prototyping tools, and management [28, 27]. A follow-up paper by one of the group's authors, Craig Forest, used a small subset of four large research-based US institutions and one international space: MIT, Stanford, ASU, Georgia Tech, and TU Berlin. This study compared staff, users versus space, average supervision per user, and a variety of other metrics that characterize the physical makeup of a space [29]. Each space was recorded having a difference in their *total users* and *total staff*, as expected. What was unexpected was the different ratios of technical assistance per user, which ranged from 0.28 to 0.56 hours per user per week. This suggests that each makerspace applies a different management and operating style. None of these papers looked at the characterization of makerspaces by comparing their operational philosophy.

1.4 Philosophy of Makerspace Management

Literature has just started to explore the impact of makerspaces' operational philosophy and mission (programming) beyond simply benchmarking the quantifiable aspects (machines). Wong elaborates: "While makerspaces are being opened around the world, little has been written about the experiences of conceiving of and establishing a space." [30]. Krummeck and Rouse advocate for the intentional design and support for a maker culture to ensure a successful space. They outline three elements of their philosophy: (a) encouraging student ownership, (b) encouraging a maker mindset, and (c) showcasing achievements [31]. Dousay reflects on the evolution of a makerspace designed for teacher education and cites that more time should have been allocated to the installation of an innovative culture with planned activities and programming [32]. From another paper by Wilczynski discussing makerspace features, the most effective methods to run a makerspace include: setting the makerspace mission from the beginning (first in the list); aligning access times with students, not staff; and, paying attention to the development of a maker community on campus [33]. In this paper, we attempt to unpack how one philosophy evolved and shaped the growth in three different makerspaces in Brazil, Malawi, and the USA.

1.5 Economic Differences of Makerspace Usage and Management

Even when makerspaces align on mission and philosophy, the management will be heavily dependent upon context, community, and geography. Nowhere is this more relevant than in a resource-constrained area. Few studies have detailed the challenges of running a makerspace in such a setting. Okapala discusses the management and philosophy of a new "mobile" makerspace inside the library at University of Nigeria, Nsukka (UNN). Challenges include inconsistent power, difficulty of training users, and security. In addition, all users of the space need to supply their own materials, which is not always possible in these settings [34]. In another paper detailing the history of a makerspace in India over several years of growth, Kulkarni lists many challenges that are specific to low income settings: acquiring donated equipment that never worked, finding workers who had necessary technical training, and repeated staff departure after successful skills training [18]. On the other hand, the author states that, "It is often said that the Fab Lab is not about the machine. It is about the makers and them making things!" [sic]. The authors of this paper agree with Kulkarni and argue that the underlying philosophy governing a makerspace determines its success, not the tools it houses.

This paper details how a student- and course-driven philosophy has been actualized, over ten years, in three distinct makerspaces: low-, middle-, and high-income situations. We attempt to explore how the shared philosophy affected the growth of the makerspaces regardless of their context while highlighting how economic settings shaped the differences in the physical space, its management, and its resulting community. Finally, we discuss how makerspaces in high-income settings can champion the creation and self-management of partner spaces in low- and middle-income countries.

2. Methods

The three makerspaces in this paper were chosen based on their student- and course-driven philosophies developed through collaboration and partnership with Rice University. Information about the spaces was collected via a survey completed by the directors of each of the spaces. The survey included questions about the physical space including square footage and availability of materials; number of users and faculty within the space; disciplines that utilize the space; courses and workshops offered within the space, and management of the space including funding and program development. Follow-up interviews were conducted to highlight specific features of each makerspace. Additional information was provided in the form of material and tool inventories and photographs of the spaces.

3. Comparison of Spaces

Descriptions of the history and characteristics of the OEDK, PDS, and LABFAB are found below with a reference table of comparisons in Table 1.

3.1 Oshman Engineering Design Kitchen, Rice University (OEDK)

The OEDK opened in spring 2009 with a footprint of 1114 m^2 (12,000 sq. ft.) in the building that originally housed the central kitchen where all

Table 1. Characteristics of makerspaces in three global universities

Category	**Oshman Engineering Design Kitchen (OEDK)**	**Laboratório de Fabricação (LABFAB) + Laboratório de Projetos em Engenharia (LPE)**	**Polytechnic Design Studio (PDS)**
Opened	2009	2014 and 2017	2016
Square Footage	1,860 m^2	93 m^2 and 310 m^2	90 m^2
Host Unit	School of Engineering	School of Engineering (now School of Technology)	School of Engineering
Hours of Operation	24 hours/day (7 days per week)	8:00–22:00 (weekdays)	8:00–17:00 (weekdays)
Users of Space	Undergraduate students only (free usage)	Any student (free usage)	Any student, community member (membership fee)
Professional Staff	2 Facility directors, 4 full-time support staff, 2 full-time technicians, one part-time support staff	2 Facility directors, 4 full-time technicians	1 Studio manager, 2 full-time technicians
Student Staff	~30 Paid lab assistants / semester ~30 Paid teaching assistants / semester	Informal student volunteers, 2 paid student lab assistants	Informal student volunteers
Dedicated Faculty	2 Teaching faculty	0	0
Disciplines Represented	All disciplines in engineering: BIOE, CHMBE, CEVE, CAAM, COMP, ELEC, MSNE, MECH, STAT*	All disciplines in engineering: Automation Control, Electrical, Chemical, Civil, Computer, and Mechanical	Technical Education, ICT department; All disciplines in engineering: (BCEW/T/S; BEEE, BETE, BECE, BBME; BAEN, BIEN, BME, BEE; BMEN, BGEN, BMMP)*
Academic Courses Supported	Y	Y	Y
Academic Courses	Nine (9) courses taught in the space and thirty (30) courses supported that use the space	Two (2) courses taught in the space and five (5) courses supported that use the space	Three (3) courses with final year projects use the space
Extracurricular Workshops	Workshops taught by student lab technicians on prototyping topics	Workshops taught by lab technicians on prototyping topics and Open Short Courses on CAD taught by staff	Workshops taught by Design studio manager or lab technicians on prototyping topics
Access: People	Based on course enrollment, extracurricular club, or project-based	Free access	Based on course-related labs and project-based
Access: Time	24/7 except for machine shop (M-F 8:00 – 19:00)	8:00-22:00 (weekdays) all spaces	8:00 – 17:00 (weekdays) all spaces
Approved Use	course, club, research and approved design projects	course, teams, research projects	coursework, personal design projects, extracurricular design projects
Users/Year	~1,000	~250	~200
Finances	Partially university funded; subsidized by industry sponsors	Fully university funded	No university funding; Funded by Lemelson Foundation and Rice 360°; membership fee

* Materials available as a result of the collaboration between the PDS and the Rice 360° Institute for Global Health with funding provided by the Lemelson Foundation.

campus food was prepared (Fig. 1), thus the name the Kitchen. The space was developed with a mission to enrich the design experience in existing engineering programs without adding more course requirements to an already packed curriculum. Early users came from two courses: the senior capstone design requirement in five of the ten engineering programs and two years later a freshman introduction to engineering design. At its core, the OEDK's development represents a broader shift in the culture of engineering design at Rice University to equip students with the skills needed to succeed after college. Hands-on experiences, when tied to real-world design challenges, foster enthusiasm for problem-solving and keep students engaged throughout their academic careers. Following two major expansions of the space, the now 1860 m^2 (20,000 sq. ft.) OEDK is more than a place where design happens – it has become a hub of activity and a social center that emphasizes creativ-

Fig. 1. Oshman Engineering Design Kitchen at Rice University. At left, the view shows the two floors of the 20,000 sq. ft. facility. Visible in the top left of the photo is the Maker Bar which includes many of the desktop digital fabrication machines like 3D printer. In the basement, the table structure is replicated for teams to work on their projects. At right, the view shows the machine shop which is the only room of the facility that is not open 24 hours a day. In this room are industrial level machines including mills, lathes, and CNC machines [35].

ity and experimentation. In addition to centralized prototyping and work areas, the space includes over 75 work tables, multiple conference rooms, two classrooms, and a wet lab.

The OEDK is a 24-hour locked facility with card entry access required at all times All projects and activities done in the OEDK must be approved by the staff and faculty but usually fall into three categories: coursework, club activities, and organized design competitions. Priorities for granting access to the OEDK also follow that order. No student may work on commercial ventures at the OEDK: they may work in the facility until the project finishes the prototyping phase. No faculty, staff, or community members may use the space. Exceptions exist for some graduate students to use the space. To gain access, users must watch a safety video and review written safety guidelines before taking (and passing) a safety quiz. Once the student has access, they may register their team for other amenities like a work table, conference room reservations, or material requests. Some amenities, such as the machines, follow a color-coding system that denote the level of training and supervision required, from no training at all to only usable by technicians.

As of 2019, the OEDK has a faculty director, an executive director, two dedicated engineering faculty members, two technicians, four administrative staff, and a shared machinist on site. Managing the OEDK is also shared by paid student lab assistants that are trained using self-guided modules that instruct proper and safe use of machines. Regardless of role, each person employed by the OEDK is an active participant in the development, implementation, and enforcement of the processes and procedures necessary to run the facility smoothly. Additionally, every member of the team plays a role in the technical or logistical support of student design projects.

3.2 Laboratório de Fabricação, Pontifical Catholic University of Rio Grande Do Sul (LABFAB)

The LABFAB at PUCRS was opened in 2014, inspired by the OEDK at Rice University. The LABFAB was originally grown out of an existing machine shop, adding two new areas for prototyping and advanced manufacturing (Fig. 2). The mission for the space is to focus on undergraduate students and the application of the engineering design process. Originally, emphasis was placed on the mechanical engineering program and one project-based course: Mechanical Experimental Integration (see Table 2). In 2017, a separate area with 310 m^2 ($\sim$3000 sq. ft.) was provided in the same building and named the Engineering Design Laboratory (both are collectively referred to as LABFAB in this paper). This new space includes room for computers, six work tables, prototyping areas, and three dedicated spaces for student clubs. The space is currently utilized by two mechanical engineering courses and supports five other courses. In addition, other engineering departments, architecture, and computer science use the space for project development and capstone design.

The LABFAB is open from 8am to 10pm daily with sign-in access. Any student (undergraduate or graduate) at PUCRS may use LABFAB so long as they have both an approved project and a supervisor. Faculty, staff, and community members may not use the space. Free access to machines is achieved once a student has demonstrated knowledge of its use to a technician. Safety is mitigated with color coded signs that indicate potential

Table 2. Engineering Design Courses Taught at Makerspaces

University	Course	# of students in the course	How the course uses the makerspace
Rice	ENGI 120 / FWIS 188 – Introduction to Engineering Design	84 in Fall 2018, 36 in Spring 2019 (course offered each semester)	Students learn engineering design in teams while working on client-based projects
	ENGI 210 – Prototyping and Fabrication	12 in Fall of 2018, 12 in Spring of 2019 (course offered each semester)	Students learn best case examples of how to use prototyping tools and machines.
PUCRS	IME 4445J – Mechanical – Experimental Integration	48 as of Fall 2018, 36 as of Spring 2019 (course offered each semester)	Students learn engineering design in teams while working on client-based projects
	PP 4441F – Design of Products	25 as of Fall 2018, 19 as of Spring 2019 (course offered each semester)	Students learn engineering design in teams while working on advanced projects
Malawi Polytechnic	N/A		

hazards and precautions when working with a machine. Signage also indicates when and where to utilize safety glasses. Student use of the advanced manufacturing tools (3D printer, laser cutter) is scheduled online but not charged. Students or teams do not formally register in the LABFAB; they may use the facilities to work on products for developing companies, but a pipeline to start these companies is housed elsewhere in PUCRS.

Two faculty directors manage the LABFAB including upkeep, purchasing, and curriculum development. Two unpaid undergraduate volunteers from the MECH department each provide support in the space for 20 hours per week. The volunteers and directors meet only as necessary for space management.

3.3 Polytechnic Design Studio, Malawi Polytechnic (PDS)

The Polytechnic Design Studio (PDS) was opened in May 2016 in a 90m^2 unused classroom (Fig. 3). The makerspace was created through a collaboration between the Rice 360° Institute for Global Health and the Malawi Polytechnic (formerly the University of Malawi Polytechnic) with funding from the Lemelson Foundation. The PDS was founded with the mission to improve engineering education in Malawi by providing access to hands-on, problem-based learning opportunities where innovators could gain real-world experience. Initially, the PDS targeted biomedical and electrical engineering programs, but it is now open to all 14 Bachelors of Engineering and 11 diploma (technician) programs in civil, electrical, mechanical and mining engineering as well as departments in the Faculties of Commerce, Education & Media Studies, and Built Environment. The majority of PDS users are undergraduate engineering students from the Polytechnic but the PDS is open to students from other universities, Malawi University of

Fig. 2. Laboratório de Fabricação at the Pontifical Catholic University of Rio Grande Do Sul. At left, the view shows the classroom and team tables. Visible on the wall are low fidelity prototyping materials, basic power tools, and electronics. Also contained in this room but not visible are the 3D printers. At right, the view shows the heavy project work area which is not available to students at all times. In this area are industrial machines including mills, lathes, and presses. Not visible in the photo are the low fidelity prototyping materials and the laser cutter [36].

Fig. 3. Polytechnic Design Studio at Malawi Polytechnic. At left the view shows the entire design studio including tables for teams to work, laser cutter, 3D printers, low fidelity prototyping cart, material storage, and lockers. At right the view shows another corner of the space that houses electronics equipment including components, bread boards, and soldering supplies. [37].

Science and Technology, and non-STEM disciplines, staff, entrepreneurs, and anyone in the community with an idea.

The PDS has only recently needed to develop formal policies and procedures in the space. The space opens at 8 AM and stays open during working hours. Any project is allowed within the PDS so long as it does not present immediate danger to other users of the space. Due to recent rapid growth, users are now granted access by filling out a form that contains the rules of the space. Future plans include implementing a safety quiz, similar to the OEDK.

Membership at the PDS is available for any student, faculty, staff, or community member working on any project for a membership fee of roughly $1 USD per month. Any materials that are used exclusively inside of the PDS are free, but if a user intends to remove the materials or intends to produce final prototypes they must pay for their materials. Users are not restricted in the development of commercial ventures while using the PDS space.

The PDS employs two full-time staff that both support student projects and manage the facility. Two recent graduates from the Polytechnic serve as volunteers who provide technical support. Historically, a US-trained engineer from the Rice 360° Institute for Global Health served as the managing director. There are currently long-term plans to transition this role to a graduate from the Polytechnic.

4. Growth of Spaces Over Time

Since their inception, the OEDK, the LABFAB, and the PDS have all experienced tremendous growth. This growth has largely been facilitated by the increase in curricular integration into the makerspaces.

4.1 Growth of Courses and Workshops in Spaces

There are two formalized education models in a makerspace that utilize the space exclusively: workshops and courses. Courses provide foundational knowledge inherent in engineering while workshops develop practical skills. At the OEDK, faculty from engineering departments and the OEDK have developed nine engineering design courses that are taught exclusively in the space. At LABFAB, two courses have been developed that are taught inside the space, modeled after the core engineering design courses at the OEDK. The growth in the number of courses taught exclusively within these spaces is included in Fig. 4. At the PDS, due to curricular constraints, no courses have been taught exclusively in the space. Instead, faculty now include projects in their curriculum that require the use of the space. Growth of workshops at all these spaces is also highlighted in Fig. 4. The LABFAB continues to add more workshops every year and has recently deployed open-course tracks that teach advanced manufacturing skills. The PDS is in the process of developing formalized workshops that will debut in the fall of 2019.

4.2 Growth of Users in Spaces

As the number of courses and workshops taught within the three makerspaces has grown, so has the number of users. As shown in Fig. 5, the OEDK opened with 500 users in 2009 and has grown to almost 1400 users by 2019. This growth has been bolstered both by additional programming in the space and opportunities for users to engage with new machines. The space has also physically grown and expanded twice to meet the demand for new

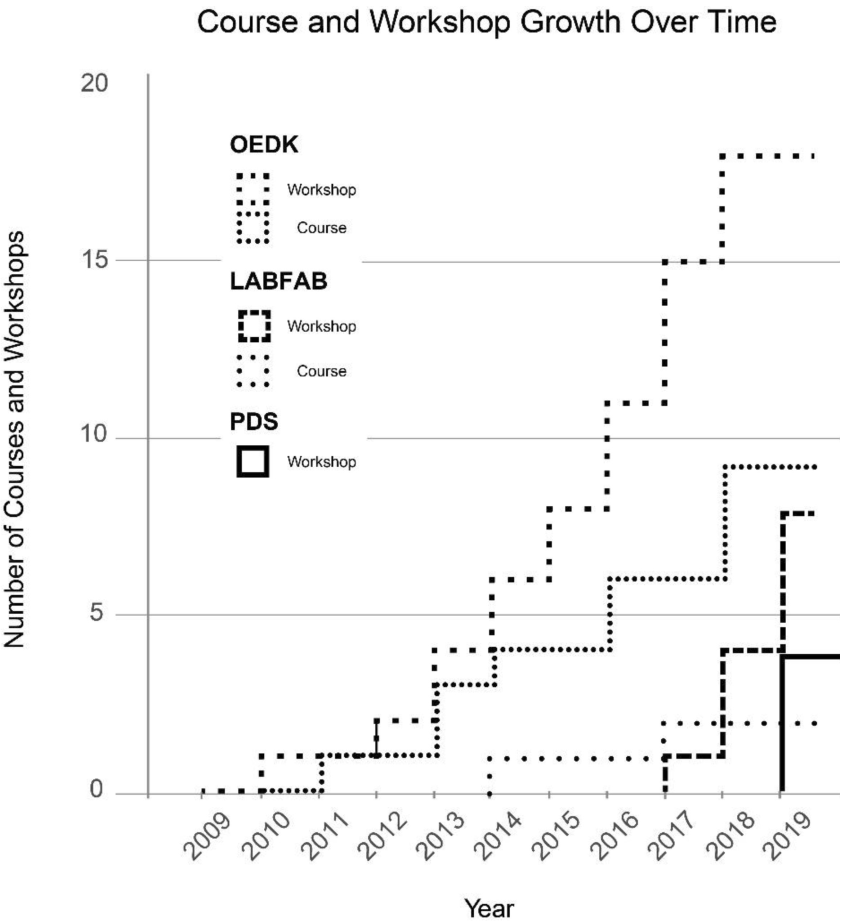

Fig. 4. The growth in the number of dedicated courses and workshops in the OEDK, the LABFAB, and the PDS for academic years starting in 2009 until 2019. Values for 2019 are projected. Note: The PDS is currently developing workshops but has no dedicated courses.

team designated spaces. LABFAB has grown to over 300 users for the 2019 academic year. The PDS has expanded from 50 to 200 users over the four years it has been open. This growth has been supported by an increase in programming alone, as the space has remained the same.

4.3 Growth of Projects in Spaces

One consequence of user growth is the rapid increase in the number of projects supported in each space, shown in Fig. 6. At the OEDK, the space opened with only 30 student projects. Over the years, new classes and clubs began to use the space, which dramatically increased the number of supported projects to over 130. At LABFAB, the number of projects supported by the space has grown to over 20 in the span of five years. Their growth is due to a new, larger space, as well as increased enrollment in their IME 4445J – Mechanical – Experimental Integration and the creation of the follow-on course. Still young, project numbers at the PDS have increased steadily, overtaking the LABFAB, due to a concerted effort at integrating more senior projects into the space, while simultaneously welcoming more users with personal projects.

4.4 Staff Growth and Design Support during User Growth

Staff growth at all three spaces is shown in Fig. 7. The OEDK began with only two full-time employees but has expanded to six full-time and one part-time employee in its 10 years of existence, with a gender breakdown of 71% female, 29% male. The LABFAB opened with two full-time technicians and one full-time staff, adding two additional full-time technicians since then, with a gender breakdown of 100% male. The PDS opened with several full-time technicians but has grown to include other part-time technicians as well, with a gender breakdown of 100% male (not including one former female director). The total working hours of the staff in all three spaces during the 2018 academic year can be found in Fig. 8. The OEDK is the only makerspace of the three with dedicated administrative staff, which is also reflected in Fig. 8.

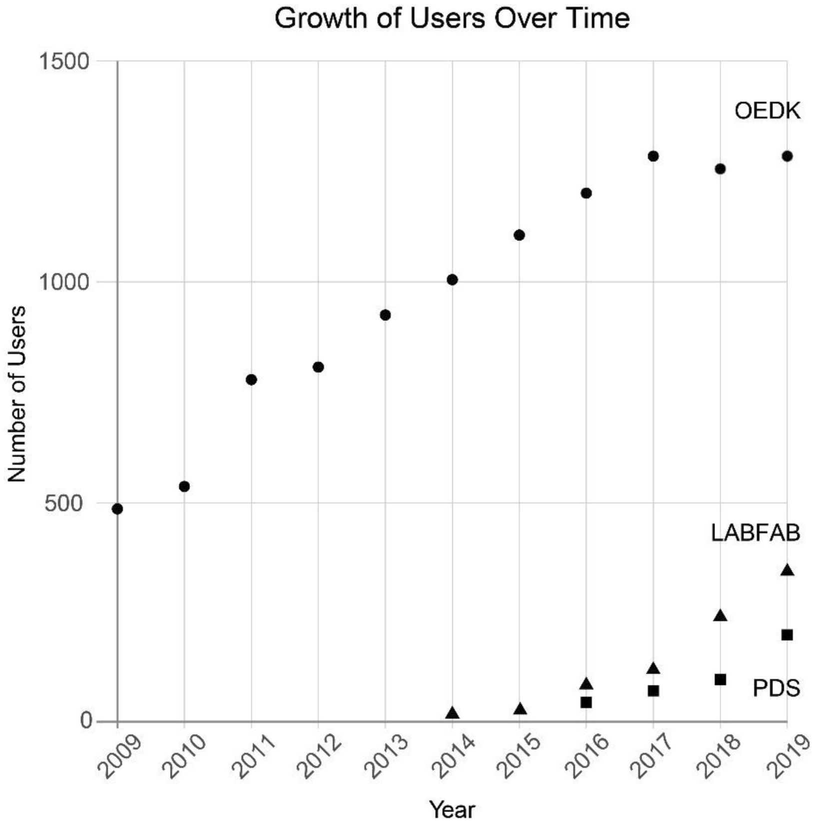

Fig. 5. User growth in the OEDK, the LABFAB, and the PDS for academic years starting in 2009 until 2019. Values for 2019 are projected.

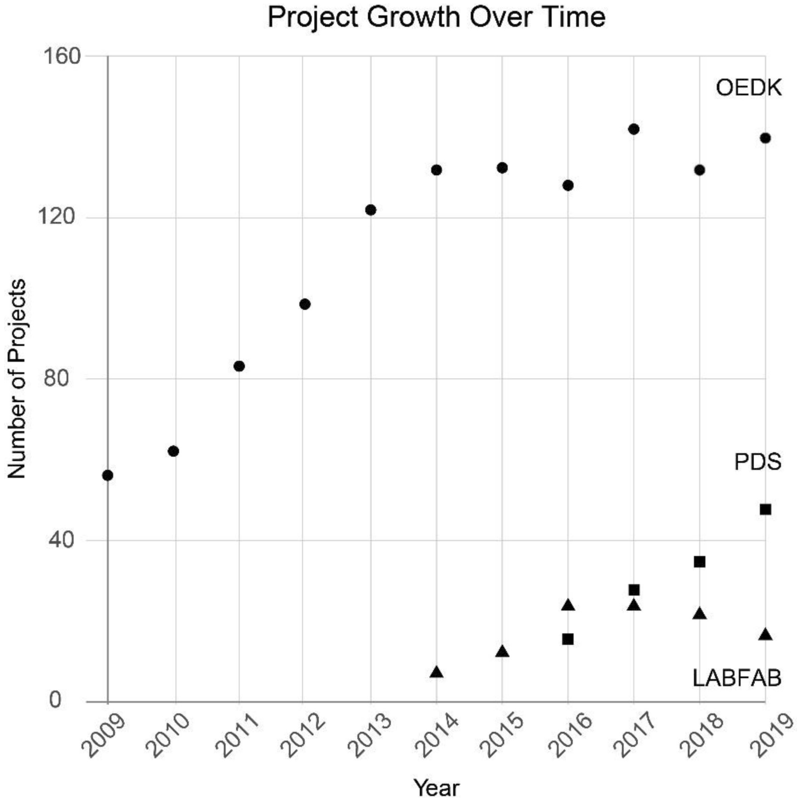

Fig. 6. Number of projects supported in the OEDK, the LABFAB, and the PDS for academic years starting in 2009 until 2019. Values for 2019 are projected.

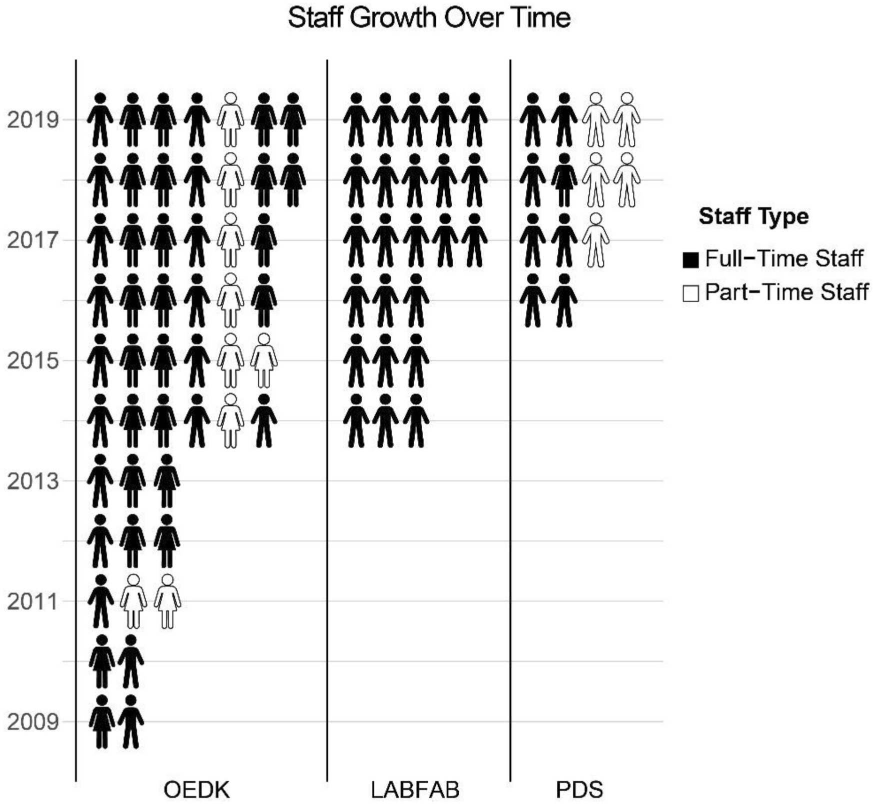

Fig. 7. Part-time and full-time staff growth in the OEDK, the LABFAB, and the PDS for the academic years from 2009 until 2019. Staff gender is also denoted for each role. Values for 2019 are actual.

The responsibility of upskilling users initially rests with the staff who manage the makerspaces. Evaluating the ratio of design support time to users can be a helpful metric for determining when to start using workshops and courses to upskill workers. A breakdown of support time per user per week is shown in Fig. 9 by dividing technical support staff hours by the number of users. The ratio of staff to users for the PDS is 0.5 meaning that each user of the facility can receive around 30 min of dedicated help from a technician per week when working on their project. At the OEDK, this ratio is 0.21 equating to less than 15 min of dedicated support time per person per week. The LABFAB has a ratio of 0.72 meaning closer to 45 min per person.

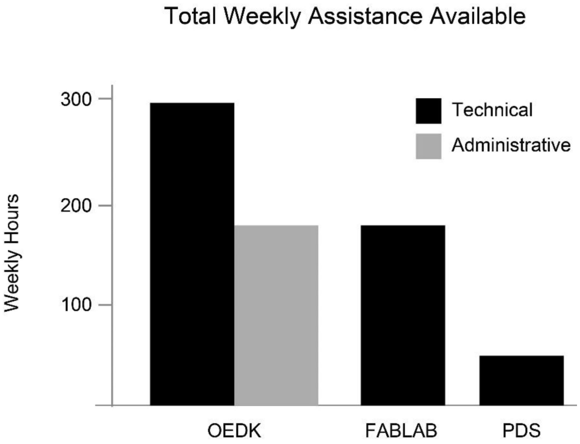

Fig. 8. Weekly assistance available for users. This is calculated from the total number of hours worked by each technician, part-time staff, administrative staff, and student technicians. Values represented in this graph are taken from staffing numbers during the 2018 academic year.

5. Discussion of Similar Makerspace Model Across Differing Contexts

The three spaces were all formed in the past ten years sharing a similar philosophy. The guiding principle is that educational objectives and student programming drive the makerspace – not the other way around. Supporting this point, Wilczynski et al. has highlighted that curricular integration is an important programming aspect for many US makerspaces [22]. This integration is reflected in the histories of each of the described spaces, which are rooted in developing engineers first and then developing engineering products. The impact of this guiding principle can be seen in many aspects of the spaces:

1. Prototyping: Spaces are set up to reduce barriers for students to accomplish their engineer-

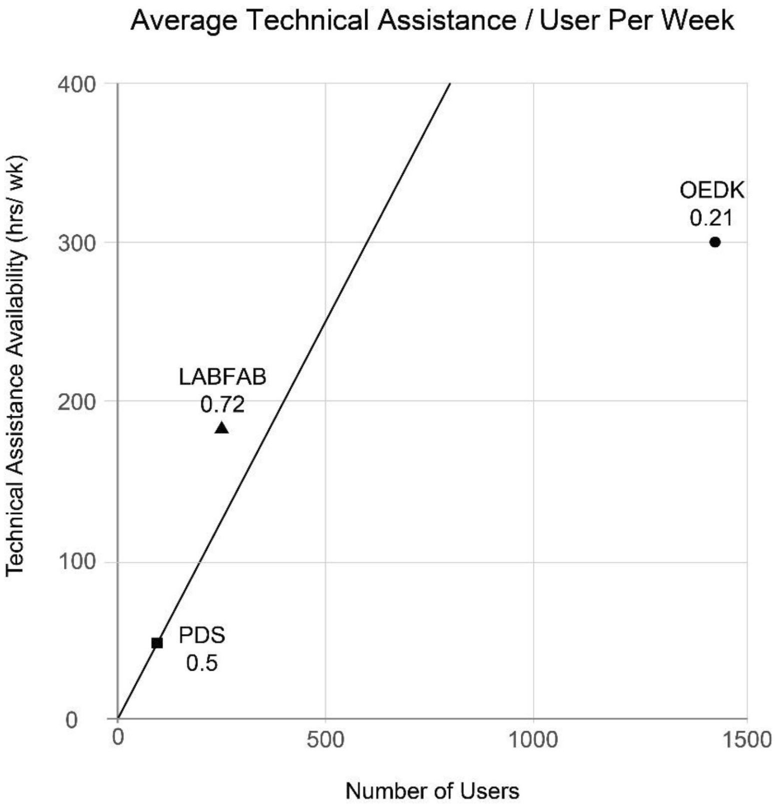

Fig. 9. Technical assistance availability is based on the number of hours a technician is available per week versus the number of users in each of the OEDK, the LABFAB, and the PDS. The straight line shows where students would receive one-half hour of dedicated support per week. Values represented in this graph are taken from current staffing numbers and 2018 user numbers.

ing design tasks by enabling rapid design, build, and test cycles for prototypes. While the barriers are culturally and logistically different, the overarching desire to lower them is paramount.

2. Learning: Courses and workshops exist to support student learning. Students are encouraged to try, expected to iterate, and permitted to fail. The primary focus is on production of engineers and the secondary focus is on the production of engineering artifacts.
3. Governance: The tools, materials, staff, and management contained in the makerspaces support users in their construction of physical and digital design prototypes.

5.1 A Planned Approach to Prototyping

The maker community agrees that makerspaces cannot function without machines and tools; however, the authors propose *how* the machines and tools are made available to the users is dominant. Because the resources available to makerspaces often depend on economic status or geography, resource distribution and tool access varies. Ultimately, this affects the level or fidelity of prototypes that users can achieve. Low fidelity prototypes rely on the simplest materials and tools available, such as cardboard, scissors, and hot glue. Medium fidelity prototypes involve the use of 3D printers and laser cutters or are made of more rigid materials like wood or ABS plastic. High fidelity prototypes exhibit the polish, precision, and functionality of devices produced by professional manufacturing processes like injection molding and metalwork. Though the final achievable fidelity of a project differs across the three spaces, the educational philosophy around prototyping education does not.

In all three spaces, students are encouraged to begin prototyping using low fidelity materials. There are several reasons for using the simplest types of materials for producing prototypes instead of those that reflect traditional manufacturing capabilities. First, no specialized training is necessary to learn how to use simple materials such as cardboard or tape; thus, everyone can participate fully. Second, construction of prototypes with these materials allows designers to minimize the importance of "how something looks" and focus more on "how it functions." Finally, this method allows designers to focus on communicating their idea using a physical artifact.

Prototyping materials are made freely available to students in all three makerspaces. The managers of the spaces stock materials in the facility that are known to be used regularly. This is one demonstration of the impact of country income on access to materials. In particular, the OEDK generally has the greatest variety and volume of materials across all three fidelities, LABFAB has some variety, and the PDS has the least. Despite this, the PDS has a wealth of electrical engineering related materials due to the focus of the space and the partnership with the Rice 360° Institute/Lemelson Foundation. This economic impact also affects ability to order materials that are not readily available. At the OEDK, the funding model supports students purchasing additional materials through the full-time purchasing staff member. At LABFAB and the PDS, students must purchase additional materials for their projects themselves, source them from local areas, or repurpose existing materials. Examples of the materials supplied by the three makerspaces are listed in Table 3.

Though makerspaces have machines and tools to produce a range of fidelities, few completed projects reach high fidelity prototypes at any of the spaces. This is due to the nature of the core users of these spaces: student users participating in educational experiences, not trained professionals. At the OEDK, students in senior design (two-semester duration) make projects that usually end at medium fidelity, while students in the one-semester freshman course primarily produce low fidelity prototypes. Some students in the OEDK produce high fidelity components in the machine shop or wet lab that are included in their lower fidelity prototypes. At LABFAB, the upper-level engineering design courses produce prototypes that are of medium fidelity after one semester of work. Students in clubs and competitions at the OEDK and the LABFAB produce high fidelity prototypes over terms longer than one academic year. At PDS, final year projects produce low to medium fidelity prototypes, but they are unable to produce high fidelity prototypes due to tool and resource limitations. Courses taught in each space have codified these prototyping expectations into their curricular materials or educational models.

5.2 *Using Curricular Coursework to Grow Engineers*

Despite the differences in prototyping fidelities achieved at each makerspace, every space saw growth in its user base since its inception. It is likely no coincidence that growth in the number of users and faculty corresponded to a growth in the number of courses, workshops, and mentorship opportunities available in each space. We believe the growth was and is at least partially facilitated by the student- and course-centered model. Krummeck and Rouse encourage the development of a space where students are "immersed in a maker culture" and walk away with a "maker mindset" [31]. By focusing on the students and their access to engineering education within the makerspace, the faculty and staff are afforded the freedom to build and shape the makerspace to fit those needs regardless of the economic context. This freedom has taken form as formal coursework, extracurricular learning (workshops), and peer-mentorship programs in all three spaces.

Coursework serves as the foundational structure for all three spaces. The OEDK, the LABFAB, and PDS all offer their space to, at most house, and at least support courses that require some component of design work (Table 2). This is consistent with Wong, who demonstrated that coursework is among the most common uses of an academic makerspace [30]. In the student- and course-centered model, the makerspace is not simply an auxiliary tool to complete a project. Instead, it is the epicenter of learning, offering courses taught exclusively within the space. The OEDK is novel among its American counterparts in that it has developed nine dedicated makerspace-exclusive courses. From this the LABFAB has developed two courses, and the PDS is currently developing its own. This commitment to dedicated coursework is a boon for the makerspace, which legitimizes it as more than a machine shop and instead an immersive learning environment.

Workshops and extracurricular learning happens alongside coursework in all three makerspaces. This is often a time where students can learn either an advanced skill or gain foundational knowledge that will help them in their problem solving. Foundational workshops and basic skills are taught in Solidworks, electronics soldering, and hand tools. Other opportunities to learn are rooted in the development of a community of practice in each space: working alongside others gives the ability to learn from their work or help theirs by sharing a best practice. The LABFAB and the PDS offers more assistant support to their users when compared to the OEDK (0.72/0.5 vs. 0.21). Forest et al. describe that differences in assistant availability per user could depend on the efficiency of assistant support, where more developed makerspaces require less interface between their users and technicians [29]. Importantly, Forest et al. did not find any correlation between the size of the makerspace and their assistant availability per user.

5.3 *Governing Based on Context*

Each space exists in its own culture, society, and university; this context shapes the governance as much as the types of machines and courses found

Table 3. Materials and Tools/ Machines Available at Makerspaces

Stock Material	**OEDK**	**LABFAB**	**PDS**
Low Fidelity Materials			
Cardboard	■	■	▨
EVA foam, Styrofoam	■	■	
Popsicle Sticks	■	▨	
Legos/K'nex	■	▨	
Rubber Bands, String	■	■	■
Velcro	■	■	■
Magnets	■		
Playdoh/Clay	■	▨	
Medium Fidelity Materials			
PVC	■	■	▨
Acrylic (sheets, cylinders)	■	■	
Wood (plywood, plank, MDF, dowel)	■	▨	▨
Fabric	▨		
High Fidelity Materials			
Electro-mechanical components (motors, sensors, pneumatics, pumps)	■	▨	▨ *
Metals (sheets, bars, cylinders, rolls, tubes)	■	■	
Mechanical components (bearings, springs, gears, cable, brackets)	■	■	▨
Miscellaneous Materials			
Electronics Prototyping Materials (PCBs/sensors/breadboards/circuit supplies)	■	▨	■
Liquid Adhesives (hot glue, PVA glue, epoxy, spray adhesive, superglue)	■	■	■
Physical Adhesives (duct tape, tape, zip-ties, staples, clips)	■	■	■
Mechanical Fasteners (bolts, nuts, screws, hinges)	■	▨	▨
Post-Processing Materials (spray paint, wood stain, sealant, paintbrushes, powder coating)	■	▨	■
Molding/Casting Materials (urethanes, silicones, acrylic casting,	■		
Metrology instruments (tape measure/ metersticks, caliper, rulers)	■	■	■
Tools and Machines			
Whiteboards	■	■	▨
Office Equipment (printer, photocopier, plotter)	■	▨	■
Computer Equipment (desktops, design software)	■	■	▨
Fume Hood	▨		
Electronics Prototyping (soldering stations, power supplies, function generators, reflux oven)	■		■
Microcontrollers: Arduino, PCB	■		▨
Welding	■	■	
Scanning and Visualization (virtual reality, laser scanning)	■		
Precision Cutting tools (scissors, utility knives, x-acto knives)	■	■	■
Hand Tools (hammers, screwdrivers, wrenches, hand saws, clamps, files, rasps, sandpaper)	■	■	■

Table 3. *Continued*

Powered Machines			
Light Duty Power Tools (jigsaw cutter, corded/uncorded drills, dremel multitool)	■	▨	▨
Medium Duty Power Tools (drill press, belt sander, grinder, sand blaster, router)	■	▨	▨
Heavy Duty Machines (mill, lathe, bandsaw, large format CNC)	■	■	□
Laser Cutters	■	▨	▨
3D Printers – desktop	■	■	▨
3D Printers – (large format, industrial, requires significant post-processing)	■	□	□
Sewing Machines	■	□	■
Advanced Manufacturing Machines (plasma cutter, water jet cutter, CNC machines, vinyl cutter, PCB mill, vacuum former)	■	□	▨

Schemas:

Table key for materials:

- Solid black: The makerspace stocks this item and/or it is frequently used.
- Grey: The makerspace does not stock this item, but it can be ordered or procured on a case-by-case basis for users.
- White: The makerspace does not stock this item, and it is difficult to obtain.

Table key for equipment:

- Solid black: The makerspace has many types of this equipment.
- Grey: The makerspace has at least one of this equipment.
- White: The makerspace does not have this equipment.

* Materials available as a result of the collaboration between the PDS and the Rice 360° Institute for Global Health with funding provided by the Lemelson Foundation.

inside each makerspace. The context of the OEDK that most shapes its governance is that the space supports >1300 users across many courses and project-based teams. Having physical space demands management of that space, which explains the number of administrative staff to support the logistics of courses and projects. Additionally, to support the high number of individuals working on projects, the lab technician program was initiated and results in a shared governance with the student workers who both improve projects through mentorship and improve the space through expertise. The context of FABLAB that drives its governance is that student paid positions are uncommon thus technical assistance has been fulfilled through full-time technical staff. In Malawi where financial support is difficult to secure, the cultural context supports growing talented staff from volunteers while also charging any user (faculty, student, community) to use the space in order to support it. Additionally, the management of the space has been held by both an American representative alongside local individuals with a plan for transition to only Malawi staff.

5.4 Working across Financial Boundaries

Access to funding underscores the economic differences between the spaces. Funding at the OEDK comes from many different sources including direct fundraising, project sponsorships, grants, support from the Dean of Engineering, as well as centrally from Rice University. These finances support the facility as a whole, including salaries, machines, supplies, and materials. The OEDK also engages with other higher education institutions, community partners, professional industry and institutions within the Texas Medical Center to solicit projects for the engineering design classes. Some projects are proposed and financially supported by industry partners (some industry partners exercise the option to collect the intellectual property developed). Regardless of the funding models achieved by the partnerships, they all facilitate professional interactions between donors and students.

At PUCRS, funding comes mostly from traditional institutional sources but LABFAB has adapted funding models from the OEDK to support the space. University funding covers the operating costs of LABFAB, but the space has also benefitted from grant funding. In one instance, a corporate sponsorship located at PUCRS Tech Park paid student technicians that work in the space. In another instance, an academic research group at PUCRS received a grant from a Brazilian petrochemical company. This funding allowed the research group to purchase machines and materials, which can be accessed freely by the LABFAB users. It is uncommon for a university to have private partnerships in Brazil. Therefore, the LABFAB does not currently work with or for companies in their engineering design work.

The PDS was founded and continues to be funded by a grant from the Lemelson Foundation, mediated by the Rice 360° Institute for Global Health. These funds have supported staffing, machines acquisition, material orders and allowed the PDS to make material/tool purchases in local markets. For materials not found in the region, the relationship with Rice 360° allows for material to be ordered from the US and transported to the PDS quarterly. Corporate partnerships at the PDS are limited and often facilitated by students. In most cases, when a student has participated in an internship or works for a company with a design need, they may take on a project for the company. These partnerships are more available with government funded institutions, such as Escom and the water management board, but recent corporate partnerships have been forged with telecom companies like Airtel and premium tobacco processing companies.

6. Conclusion

This paper describes the philosophy, management, and programing of makerspaces in high-, medium-, and low-income countries based on our collective experiences running these spaces. Unlike previous studies, this paper attempts to document aspects of a makerspace that are not easily counted, such as the managing philosophy of a space, and its approach to curricular integration wrapped with a goal of developing engineers. Because economic status differentiates the makerspaces, we were able to analyze how the number and types of machines and materials impacted the space.

Despite traditional assumptions, resource limitations have not stifled the growth and productivity of these makerspaces. Rather, growth of the spaces was most positively impacted by curricular integration, facilitation of prototyping, and governance. By developing and implementing dedicated courses, workshops, and one-on-one mentoring, all three spaces saw growth in the number of users, projects, and staff. This growth in users drove the demand for additional machines and tools. This flips the currently understood model, where the availability of machines drives the number of users and projects.

Our findings are limited by our bias of what a well-equipped makerspace looks like, which influenced both the design of the survey and the questions asked in the interview. In both cases, we utilized a high-income, western vocabulary to discuss materials and machines, governance, philosophy, and course structure. As such, it is possible that we missed materials and tools that are not common or available in the United States. Additionally, both the PDS in Malawi Polytechnic and the LABFAB at PUCRS were inspired and/or funded in part by Rice University. We feel strongly that institutions in high income areas can (and should) do much to support the inception of makerspaces in middle- and low-income settings. A strong collaboration between LABFAB, PDS and Rice University served as a catalyst, and then curricular integration ensured growth and longevity. Furthermore, we hope this paper serves as a rallying call for institutions in low- and middle-income areas to seek out partnerships with institutions in high-income areas and work together to cement vibrant maker communities that tackle real-world challenges.

Future studies could continue to catalog the growth of makerspaces in different countries and analyze the impacts of their management philosophies. Additionally, future studies could compare the creation and growth of makerspaces with and without strong partnerships with high-economic spaces. It is our observation that successful makerspaces put philosophy ahead of tools and develop coursework before buying machines.

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