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# The SmithVent Experience and a Framework for Collaborative Distributed Design and Fabrication*

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This paper addresses the collaborative journey of the SmithVent team, a 30-person distributed group of volunteers, who designed, fabricated, and tested a simplified and cost-efficient ventilator over a three-month period, and won the CoVent-19 Challenge in July 2020. The paper first presents the SmithVent experience through a co-constructed narrative that describes the team's approaches to collaborative distributed design and fabrication. The paper next reviews frameworks from five theoretical lenses and then details the process of extracting, synthesizing, and organizing relevant factors to create a new and emergent framework reflective of the SmithVent experience. Lastly, the paper discusses educational implications of the SmithVent experience and proposed framework, emphasizing that the team's strategies provide a model for educational and industry settings for future collaborative and distributed design and fabrication.

**Keywords:** distributed fabrication; collaboration; distributed design; virtual teams; remote making; remote learning; Scrum; ventilator; SmithVent; CoVent-19 Challenge; COVID-19

## 1. Introduction and Motivation

In March of 2020, the world experienced an unprecedented pandemic that caused massive disruptions and challenged the limits of the global medical infrastructure. Emergency rooms faced a critical shortage of ventilators due to a sudden increase in demand. Further complicating matters were worldwide shutdowns that limited manufacturing and hampered the supply chain of essential ventilator components. To meet these challenges and to contribute solutions to the global ventilator shortage during the COVID-19 pandemic, the CoVent-19 Challenge [1], an open-source competition to design a rapidly deployable and affordable mechanical ventilator, was launched on 1 April 2020. The competition featured two main phases: an open Round 1 for conceptual designs in April 2020 and an invitation-only Round 2 for fabrication and testing in May-June 2020. More than 200 teams from 43 countries participated in the competition.

The competition winner was the SmithVent team [2], a group of 30 Smith College alumni, faculty, staff, and friends (including all the authors on this paper). Our team formed on short notice five days after the competition had already started; we were physically dispersed by both geography and pandemic distancing restrictions. All team members were volunteers who already had full-time jobs or studies. We all had a technical foundation in engineering and/or computer science, but none of us had expertise in ventilator design or medicine. After winning the competition, our team was repeatedly asked by other designers, friends, colleagues, and the press how we had been so successful despite the many potential obstacles – a question for which we had no ready or succinct answers.

What made the SmithVent collaboration work so well, and what can others learn from the experience? The goal of this paper is to unpack the SmithVent experience and to identify the strategies that enabled our team to form a thriving collaboration and achieve a winning design in order to inform future design teams and engineering educators. To do so, we engaged in a systematic process in which we (a) collaboratively described our experience in rich detail by synthesizing team and project documentation, interviews, and personal memory, (b) conducted a robust literature review to identify potential explanatory frameworks and factors, (c) iteratively applied those frameworks and factors to our experience, modifying constructs and definitions as needed to effectively explain the experience, and (d) generated a synthesized explanatory framework for collaborative distributed fabrication.

This paper is organized in the following manner. Section 2 provides a co-constructed narrative of the SmithVent experience. Section 3 presents an analysis of that experience, beginning with representative frameworks from the literature (most of which were identified after the competition) and proceeding to propose a multifaceted framework of emergent



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factors informed by and mapped to the SmithVent team's successful collaboration. Section 4 details the educational implications of the SmithVent experience and proposed framework, addressing how engineering educators can leverage the SmithVent success factors when guiding teams on similar remote projects.

## 2. The SmithVent Experience

This section describes the processes and strategies that we used to form and grow our team, develop the conceptual ventilator design, and fabricate and test the physical prototype, all while working remotely across nine time zones. Unlike the competition submission entries that detail the ventilator design itself, the description below focuses on our individual and collective actions and interactions so as to document our internal processes along the way.

We co-constructed this narrative based on a multitude of sources: project documentation (including a detailed task backlog), internal progress reports and email communication, videos and presentation slide decks by and about our team, interviews and podcasts conducted both during and after the competition, and our individual memories of personal experience. The initial description was drafted by three members of the author group, supplemented by quotes from our extensive database of videos and interviews, and then circulated for review by the full author group.

### *2.1 Team Formation*

The SmithVent team started with an email from Susannah Howe, a Smith College engineering capstone professor, recruiting former students to join a team for the CoVent-19 Challenge. Within three days, we were a 30-person team of Smith College engineering alums, faculty, staff, and friends located across the U.S., from California to Florida to Maine, and also in Canada and Germany. We were all volunteers with different levels of availability: many of us were working as engineers or pursuing graduate degrees in engineering but without expertise in either ventilator design or medicine. The majority of our team members knew at least one other team member from overlapping years at Smith, but no one knew everyone prior to the collaboration. We launched our collaboration with two kick-off meetings to accommodate the range of time zones, a slide deck featuring photos and short bios of all team members, and an overview of the competition goals and timeline.

Our SmithVent team members came together for a variety of reasons. The growing impact of COVID-19 in April 2020 provided motivation for many to collaborate meaningfully on pandemic amelioration efforts. "During this pandemic I've felt so helpless. I jumped at the chance to work on this project because I want to support our healthcare workers and help them care for people," one team member said. "I wanted to make an impact and contribute to something bigger," said another. Additionally, many team members who were socially isolated due to the pandemic were eager to join fellow Smith alums in an experience like their capstone design course (Design Clinic), which most had taken while at Smith. According to one team member, "I absolutely enjoyed the camaraderie, the collaboration, and the dedication for a global cause. . . The bonus was the Design Clinic experience and the mini-reunion with my classmates."

Our team did not intend to build an entire ventilator initially, given that we had no previous ventilator experience and were starting from scratch (in contrast to other competitors who already had functioning devices). Moreover, as we noted in interviews during and after the competition, we did not even expect to advance to Round 2. Collectively, we wanted to design something – even a singular component – that could contribute to the larger effort: "For me this competition has never been about winning or losing," one team member reflected. "It's been about coming together, sharing our efforts, learning from each other, and contributing something to a bigger cause."

### *2.2 Round 1 – Conceptual Design*

During Round 1 of the CoVent-19 Challenge, which spanned the month of April 2020, our team focused on developing a conceptual design and system architecture for a ventilator informed by stakeholder requirements. To enable this conceptual design work in a virtual setting and with so many unknowns, SmithVent team leaders decided to use a modified Scrum approach to project management (as originated by Schwaber and Sutherland [3]), primarily for its ability to embrace change in uncertain environments. Since we were starting with so little information about COVID-19 patient and healthcare worker ventilator needs, we knew our design would benefit from iteration and continuous improvement.

To allow for quick improvement cycles, we used 5-day increments called Sprints to rapidly set goals, complete work, inspect progress, and adapt the plan as needed to meet the next goal. This established a rhythm that continued throughout the competition. Of the typical Scrum ceremonies and artifacts, our management incorporated four key components: Planning Overview, Sprint Backlog, Sprint Planning, and Sprint Review. The Sprint Planning and Sprint Review meetings allowed us structure for team communication and alignment with minimal overhead. The use of shared documents for the Planning Overview and Sprint Backlog as information radiators supported the self-organizing nature of the team: team members could volunteer asynchronously for and collaborate on meaningful work without a hierarchical power structure for assigning that work. In every sprint, team members chose which pieces of the project they wanted to work on based on their interests and available time.

Early on in the project, team leaders set expectations for both collaboration and teamwork with the intent of creating a welcoming and understanding environment within which to work; there was no expectation that anyone would work a certain number of hours per Sprint. Rather, team members worked as much as they were able, even if only an hour or two in a given Sprint, contributing to the collective completion of tasks. According to one team member, "Everybody was doing this on a volunteer basis and everybody understood that. We tried not to send each other emails constantly because we already knew everybody was busy with their regular work." Another team member noted, "The team was set up so that you could dedicate many hours during weeks when you had the time, and then step back and put in fewer hours when you had other things going on. I would routinely work my 9-to-5 job and then switch to working on our ventilator well into the evening."

At the end of each Sprint Review meeting, we built in time for team members to reflect on the ways of working, including what to continue and what to change. For example, after a few weeks some team members shared an interest in building a stronger team dynamic with each other since we had never met the majority of our team members in person. This interest led to these team members organizing events such as online games and travel photo sharing to promote further social interaction and team building. As one team member put it, "I think that we found time to enjoy each other's company. In this moment where everything has to be remote, actually having time where we're going to play games after our meeting, play Pictionary after our meeting [is] really important to us working well as a team, because then you also build that relationship." "We had all kinds of ways to celebrate each other and to have fun together," another team member added.

Team leaders strove to create a psychologically safe environment [4] for all team members where significant learning could take place. "The ability to openly ask questions and learn without judgment creates an environment that encourages contribution," said one team member. "I've learned so much in such a short time and really enjoyed digging into such a challenge with a group of people who are so committed to learning together," said another. Reflecting upon their experience, a third team member said, "I had a serious case of imposter syndrome before this project – that imposter syndrome is now completely gone. . . A team with no previous experience with ventilators and very limited medical knowledge, working all remote – and the makeup of the team being quite the opposite of other finalists – won the worldwide challenge." Another commented, "Everyone was treated as capable and everyone was empowered by the belief that, together, the SmithVent team could make a relevant and meaningful contribution."

For internal communication and collaboration, the SmithVent team made extensive use of the Google Suite of tools. We detailed tasks on a Sprint Backlog Google Sheets spreadsheet shared with the entire team; we organized tasks and team members by sub-teams that each focused on different aspects of the project. We housed all documentation in a shared Google Drive folder; and we conducted our communication via group email with links to our Google Docs, Sheets, and Slides. We scheduled meetings on a shared Google calendar, held them all in a dedicated Zoom room, and invited the full team to attend. Throughout the project, however, we never once had all team members in attendance at the same time because our members had busy schedules with their full-time jobs, graduate school, or other commitments, not to mention the challenges of time zone differences. While we completed most tasks asynchronously, most sub-teams scheduled at least one synchronous meeting per Sprint to facilitate interactive collaboration.

Our design process started primarily with researching mechanical designs for air delivery and meeting with medical professionals virtually to gather user requirements. We learned about existing ventilator designs, the challenges facing health care workers in the beginning of the pandemic, and what improved ventilators would look like for both COVID-19 patients and their caretakers. We then moved into developing our own ideas for designs and developing criteria for selecting the one that would best fit the needs of the pandemic. Based on our research, we decided to focus on a design that was cost-effective, easy-to-build, and catered to the needs of COVID-19 patients and health care workers. After selecting our overall design, we divided into subsystem teams to develop the specific components of the conceptual design, such as airflow, circuits, user interface, and enclosure. We specifically solicited input from external experts, such as respiratory therapists and clinicians, to inform the subsystem development.

Finally, we integrated the subsystems and refined the design of the overall system concept.

In addition to the technical work, we came together as a team to celebrate our progress and milestones. At the end of Round 1 of the CoVent-19 Challenge, more than a dozen team members gathered via Zoom for a live watch party of our submission materials. This proved especially useful when we realized we needed a short description of our design for the submission website and were able to co-write it together in real time. Once the submission materials were officially submitted, we celebrated with a virtual toast and captured our excitement with Zoom screenshots. The next day (long before we knew the results of the Round 1 submission), we held an all-team Gratitude meeting to recognize everyone's individual contributions. The team leaders created a shared slide deck with a slide for each team member and the team as a whole; we synchronously added notes of gratitude for all the team members with whom we had worked during that Round. An excerpt from one of the notes directed at the whole team is included below:

> "Thank you for being a part of this amazing, crazy adventure. I signed up not knowing what I was getting myself into, and I am so thankful to have been a part of this experience. I learned so much from each and every one of you. I loved having the chance to learn from Smithies of various class years & connect with the Picker Engineering Program in a new way. I am thankful and grateful for each and every one of you, and we should be proud of our product regardless of whether we make it through to the next round."

### *2.3 Round 2 – Fabrication and Testing*

The SmithVent team was one of seven finalists invited to continue on to Round 2 of the CoVent-19 Challenge to fabricate and test its ventilator design. Creating a purely conceptual design remotely in the midst of a pandemic had been complicated enough, but turning the concept into a physical prototype added further layers of complexity.

The stringent limitations on co-locating during the COVID-19 pandemic plus the dramatic shortages of components and materials presented steep challenges to remote making. Fortunately, we received special approval to work in a fabrication facility at Smith College even while the institution was technically closed; however, access was granted only for four members, who were required to maintain social distancing measures while working. Simultaneously, there was a sharp increase in maker projects for PPE (personal protective equipment) and ventilator components due to global disruptions in supply chains and manufacturing [5]. To work around the shortages, we sourced parts from non-medical suppliers where possible, paid for expedited shipping when needed, and also 3D-printed several custom components in-house.

For software-dependent work, we relied on cloud-based modeling and programming to enable multiple distributed team members to work in parallel. We selected Fusion360 for CAD models, the Arduino integrated development environment for programming, and GitHub for a shared code repository. For some hardware aspects, including the pressure sensors and the user interface screen, we ordered duplicate parts so that multiple team members with relevant expertise had access to physical materials at their home locations in addition to those in the Smith fabrication facility.

During the assembly phase, we leveraged the expertise of geographically distributed members to support work in the fabrication space. Multiple times we had a knowledgeable but remote team member provide directions over Zoom to one of the four local team members with access to the fabrication space. This approach enabled the local team members to complete complex tasks where they lacked expert knowledge, such as how to electrically connect the sensors, valves, and power supply. These remote Zoom sessions were open to all team members, who, if not providing technical expertise, contributed to supporting tasks such as note-taking and video documentation. Below are quotes from two different team members describing their experiences: one was giving instructions remotely and the other was in the fabrication space following remote guidance:

> "I remember one time that we [had] a problem on a circuit. Susannah and I were trying to troubleshoot on a Zoom call. I was telling her that we could use a multimeter to measure connectivity at some voltage points on a circuit that could be either high or low. She was actually balancing an iPad with the camera on her knees so that I could see the circuit, putting a multimeter on the desktop, and then using two hands to poke the two leads that we want[ed] to measure."

> "I ended up fabricating a shield for an Arduino. I didn't really know what I was doing on that, I'd never done it before, but another person on our team who was in Pennsylvania had it down – like totally – so they could have just walked in and done it. But they couldn't walk in and do it, so they had to tell me how to do it [from 250 miles away]. So we did this via Zoom on a Saturday and I spent, that poor person spent six hours staring at my hands, talking to me, walking me through the whole thing, and we got it done. It worked perfect[ly]."

Each local team member contributed to the effort in different ways, an approach facilitated by the modular nature of the work. One local team member, who managed the fabrication space for his primary job, served as the point person for 3D-printing custom fittings, assembling the airflow system, and building the test bench enclosure. Another local team member focused on testing and troubleshooting the system as the assembly progressed and the code was developed. A third local team member led the effort to implement and calibrate a data acquisition system that could verify prototype functionality. In keeping with social distancing protocols, the local team members staggered their in-person work in the fabrication space to avoid overlap when possible. Despite the physical restrictions of social distancing, the local team members did not need to work alone, as they were often joined virtually on Zoom by other team members who provided support for both technical issues and ongoing documentation. During the final testing day, for example, a local team member conducted numerous tests in person while a dozen remote team members advised and supported via Zoom.

We also engaged external experts from diverse fields – clinicians, respiratory therapists, electrical engineers, software developers, and legal professionals – throughout the entire project. Informed by the expert advice, we made changes to our prototype at critical stages in the development process. We invited the external experts to some of our Sprint Reviews and sub-team meetings and to our full-team Design Review in Round 2, which was also open to the greater Smith engineering alumni community, to gain input and feedback from a broader audience.

The progression through Round 2 brought with it some strain on team members' schedules and availability. Our team members had joined together for the first Round of the competition; we had never expected to be selected for Round 2. We were all honored to be chosen to fabricate and test our design, but the team leaders in particular were mindful of burnout on the part of the volunteer team. As such, we continued to hold social events for team bonding, initiated a social media campaign to promote our successes, and adjusted schedules to accommodate team members who had to step back temporarily due to work or school demands or illness – even as the rest of the team was driving forward at full speed to finish fabrication and testing. When the CoVent-19 Challenge organizers decided to extend the competition by three weeks, we made the internal collective decision to extend for only two of those weeks in recognition of everyone's schedules and other obligations.

### 2.4 Submission and Celebration

At the end of the competition, we gathered several times remotely to celebrate collectively what we had accomplished together. We organized a Zoom presentation for friends and family to share our process and achievements with them, and to recognize their support and interest. It also served in part as a dress-rehearsal for the virtual presentation to the competition judges. The following week, before the results of the competition were announced, we held a remote closing Gratitude session (as we had done at the end of Round 1), celebrating each team member in turn as well as the project/team as a whole. Fig. 1 shows a collage of some of the gratitude notes directed to both the SmithVent

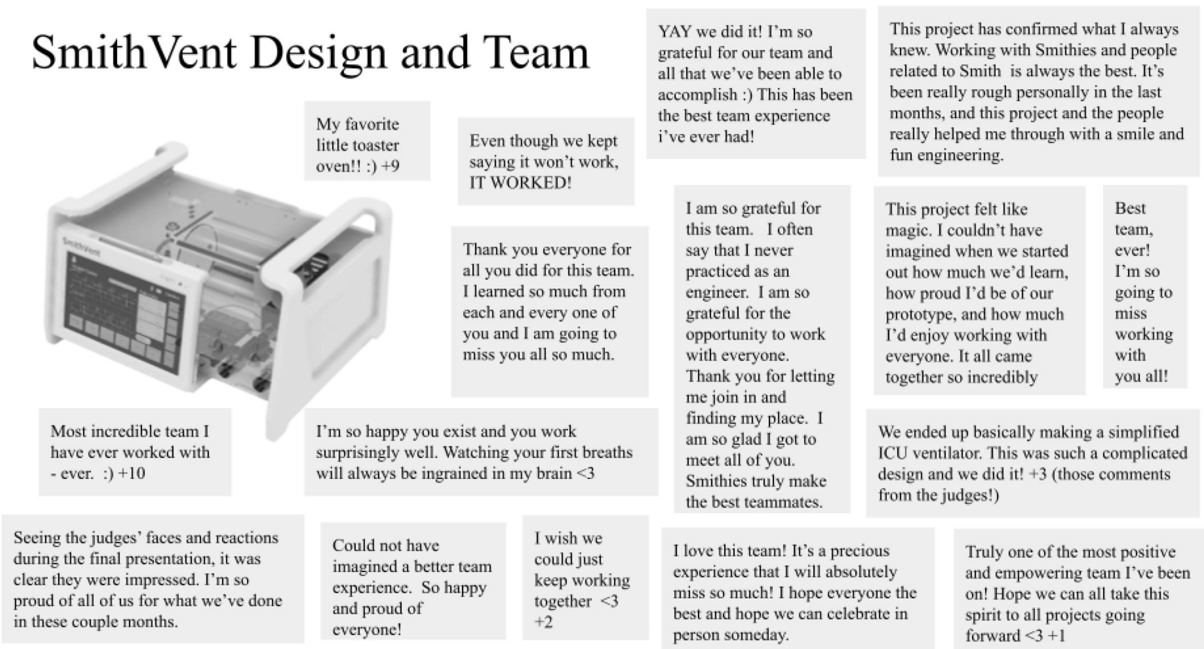


**Fig. 1.** Gratitude Collage for the SmithVent Design and the Team.

design and the team overall. Our two team leaders also prepared a retrospective slideshow of the team experience and a poem in honor of the team.

Our winning SmithVent design is documented extensively and is available as open-source content. The full competition submission is available on Google Drive [6]. The CAD files are also accessible on GrabCAD [7] and the code can be found on GitHub [8].

## 3. Analysis and Proposed Framework

The SmithVent team developed its working style organically and incrementally as informed by the experience and emergent suggestions of its members. The set of factors that enabled the SmithVent team to succeed was not something that any of us were fully aware of during the competition or even in our initial reflections afterwards. This paper's motivation stems from our team's desire to better understand the experience and what elements made the team work so effectively. To conduct this analysis, we followed a modified explanation building approach [9] by drawing on existing theoretical work, proposing an emergent framework, and demonstrating how the framework was operationalized in the SmithVent experience. The framework proposed herein offers guidance for understanding and undertaking similar collaborative distributed fabrication projects in the future.

### *3.1 Identifying Theoretical Lenses and Representative Frameworks*

We started our analysis by reviewing the literature on collaborative and distributed teams, hoping to find an overarching theoretical framework that would explain the factors that enabled our success. After consideration of various frameworks, we realized that none captured the multiple dimensions of our collective experience. We therefore expanded our literature review to focus on five main theoretical lenses that we felt collectively defined and framed our experience: collaborative work, distributed teams, iterative development, open innovation, and feminist pedagogies.

We selected each of these five lenses for specific reasons. Collaborative work and distributed teams reflected the pivotal roles that teamwork and remote interaction played in our experience. We selected iterative development because our team leaders had intentionally implemented a Scrum approach for project management from the beginning of the project. Open innovation referenced the fact that the CoVent-19 Challenge itself was framed as an open-source design challenge, and we had committed to sharing our design work publicly. We selected feminist pedagogies on the recommendation of a faculty colleague at Smith who was familiar with our experience and the teaching methods used in the capstone Design Clinic course.

An overview of each of these lenses and associated literature is provided below, along with additional explanation of the connection between the dimension and the SmithVent experience.

- Collaborative Work is based on the principle of people and organizations collaborating for a common goal. Since formal definitions of collaboration abound, Wood and Gray [10, p. 146] proposed a composite definition that "collaboration occurs when a group of autonomous stakeholders of a problem domain engage in an interactive process, using shared rules, norms, and structures, to act or decide on issues related to that domain." In an effort to understand what makes collaborations work, especially given the prevalence of collaboration across many sectors of work and education, numerous researchers have proposed frameworks of key factors for successful collaboration. Some of the frameworks center on interdisciplinary and interagency collaboration, and build on the literature of organizational collaboration [11], social work theory and practice [12], and case studies and interviews in public administration [13]. Others focus on collaboration in project-based industries [14, 15] or scientific collaboration [16, 17]. The proposed frameworks vary in their details, but similarities include shared purpose and commitment, collective processes, interdependent structure, and clear communication. Additionally, collaboration can be considered both a process and an outcome, complex and evolving over time [18]. The heart of the SmithVent initiative was a collaboration between 30 people pursuing a common goal. This collaboration formed and grew over time, eventually extending to include external subject-matter experts, CoVent-19 Challenge contacts, and even manufacturing suppliers.
- Distributed Teams collaborating virtually have been an integral part of the workplace since the late 1990s [19] and are commonplace today. According to a 2016 survey by Culture Wizard [20], 85% of global business professionals spend at least some of their time working on virtual teams. The switch to work-from-home protocols and social distancing brought about by the COVID-19 pandemic only increased the prevalence of distributed teams across the world and in different industries. The ability to work effectively together across large geographical distances allows for broader disciplinary expertise on a given team [21], but often presents special

challenges [22–24]. A substantial body of literature documents effective strategies for virtual teams, from comprehensive models [22, 25] to specific examples identifying anywhere from three main themes [26, 27] to thirteen success factors [28]. Commonly identified elements include team formation [29], trust [30], and adequate technology [29, 31, 32]. Olson et al. succinctly and comprehensively attributed successful remote scientific collaboration to five key factors: the nature of the work, common ground, collaboration readiness, management, and technical readiness [33]. Spread across nine time zones and locked down at home as a result of the pandemic, the SmithVent team operated primarily as a distributed team throughout the competition.

- Iterative Development practices, as promoted through Agile methodologies, have been widely used by software teams for decades to deliver customer-centered value via cross-functional teams [34]. Scrum is one Agile management methodology that "helps teams and organizations generate value through adaptive solutions for complex problems" [3]. Unlike the traditional, plan-driven hierarchical approach, a self-managing Scrum Team coordinates their own work by dividing a project into multiple, time-boxed sprints, each with specific goals set by the team itself [35]. The absence of a power structure [36] also fosters initiative-taking and shared leadership [37] where the entire team is accountable [3] and focused on one common goal [24]. In a "zero-information state" where previous knowledge is not applicable, teams find their own order [37]. Co-location was a key assumption for the original Agile framework [38], but Paasivaara et al. [24] reported that software development teams could innovate successfully even when working remotely. Moreover, Agile values have been successfully adopted beyond the software industry: Cooper and Sommer [34] found that incorporating Agile with a traditional Stage-Gate model could significantly benefit manufacturers of physical products ranging from industrial equipment to food to toys. Similarly, the Wikispeed team of 44 volunteers in four countries successfully leveraged Scrum methodologies to develop an ultra-efficient car for the Progressive Insurance XPrize competition, and beat out many long-established teams [39]. Several SmithVent team members had previous experience managing projects using Scrum at work on self-organizing and iterative projects, and they suggested that the SmithVent team follow a similar approach. The Scrum framework [3], which is lightweight and empirical, was the one existing approach that the SmithVent team knowingly implemented during its fast-paced collaboration, albeit with some modifications to suit the circumstances.
- Open Innovation, as popularized by Chesbrough [40], is the concept that companies can leverage ideas generated outside their organization to increase their value. Making the boundaries between a company and its surrounding environment more porous [40] in essence opens up the innovation process [41]. Although the concept of open innovation started with a focus on corporate commercialization, it has evolved over time to be applicable to non-profits and organizations whose mission is social change. For example, in a subsequent work on open social innovation, Chesbrough noted, "The ideas of in-bound and out-bound open innovation, and the integrating role of the business model, are relevant well beyond the business world. . . A comprehensive view of open innovation strategies can be very relevant for social entrepreneurs." [42, p. 187] A related but distinctly separate concept is that of user innovation, as pioneered by von Hippel [43], which highlights innovation by users rather than by companies. User innovators frequently extend the openness of innovation by free-revealing their innovations for others to use, learn from, and improve [44]. At the intersection of open innovation and user innovation is the space where individual user innovations benefit firms [45]. Contest crowd-sourcing is one approach to recruiting ideas from individuals and communities of innovators more broadly, and can be especially effective when organizers interact with participants and develop approaches to integrate proposed concepts [46]. Aiming to understand what factors are important to successful open innovation, both Durst [47] and Subtil de Oliveira et al. [48] separately reviewed the open innovation literature to extract the key success factors. Their proposed frameworks have many similarities, including relationships, management structure, and culture. The open innovation dimension is relevant to the SmithVent case given the open-source premise of the CoVent-19 Challenge and the creation of the SmithVent team itself as an open innovation community.
- Feminist Pedagogy is an approach to teaching and learning that values individual differences, non-hierarchical interactions, and the development of an empowered community. The methodology has grown beyond its historical origins and may be applied in any educational or collaborative setting. Feminist pedagogy reflects an ethos of care and democratization applicable to any learning environment striving for inclusivity

[49]. It also opens up discourse and challenges hierarchical power structures [50]. While feminist pedagogy shares some similarities with collaborative learning (social context of learning, interdependent knowledge construction, and a safe learning space), it is built on a foundation of social action and critique of traditional power structures [51]. Shrewsbury [49] emphasizes three main themes within feminist pedagogy: community, empowerment, and leadership. Webb [52] expands this definition to include reforming power relationships, privileging individual voices, respecting diversity of personal experience, and challenging traditional views. The capstone design course at Smith College that most of the SmithVent team members participated in as undergraduates incorporates elements of feminist pedagogy; Smith College is itself steeped in feminist history and much of its curriculum is informed by feminist praxis. While the SmithVent team did not consciously set out to apply feminist pedagogy, its commitments permeated the team's interactions. The fact that the SmithVent team successfully included demographics traditionally underrepresented in STEM is in itself a demonstration of the methodology's influence.

Having identified these five lenses, we also selected a representative framework for each one by choosing a key publication that offered a comprehensive framework for that lens and which was also widely cited in the associated literature. Each framework in the list of publications below includes a set of 3–6 primary categories, and each category has 2–14 factors. The tables in Appendix A list these frameworks in more detail. Although the frameworks have some overlap, each framework offers something the others do not, thus confirming our initial decision to pursue frameworks from multiple theoretical lenses.

- Collaborative Work [CW]: *Collaboration: What Makes It Work?* [11]
- Distributed Teams [DT]: *A Theory of Remote Scientific Collaboration* [33]
- Iterative Development [ID]: *The Scrum Guide: The Definitive Guide to Scrum* [3]
- Open Innovation [OI]: *Critical Success Factors for Open Innovation Implementation* [48]
- Feminist Pedagogy [FP]: *What Is Feminist Pedagogy?* [49]

### 3.2 Extracting Factors from Selected Frameworks

We next analyzed each of the five selected frameworks, extracting those factors from each framework that were reflected (either intentionally or emergently) in the SmithVent experience described in Section 2. We conducted this work initially in pairs, with each pair investigating one of the five selected frameworks in depth and extracting the relevant factors that mapped to the SmithVent experience. We discussed and refined our lists of extracted factors with the full author group, continually revisiting our collective SmithVent experience and articulating connections between the theory and our lived experience. The bold items in the tables in Appendix A indicate the final set of extracted factors from each framework.

From this extraction process, we recognized that the frameworks themselves do not map equally to the SmithVent experience. For example, only the Feminist Pedagogy [FP] framework has a 100% mapping (meaning that 100% of the factors in the [FP] framework mapped to the SmithVent experience). The Collaborative Work [CW], Distributed Teams [DT], Iterative Development [ID] frameworks have about a 75% mapping. The Open Innovation [OI] framework has a 50% mapping. The incomplete mapping is not surprising given the context of the reference frameworks: the Collaborative Work [CW] and Distributed Teams [DT] frameworks were based on collaboration by individuals between organizations, and the Open Innovation [OI] framework was focused on companies commercializing technology. Furthermore, our team intentionally implemented a modified Scrum (Iterative Development [ID]) framework.

### 3.3 Constructing a New Framework

Continuing our explanation building approach, we synthesized the extracted factors into a new consolidated and emergent framework. First, we compiled all the extracted factors into one single list of 83 total items, color-coded to represent the published frameworks from which they had been extracted. Working collaboratively and iteratively in a shared document over Zoom (as we had done often during the SmithVent experience), a sub-team of half the authors then combined the 83 factors into a new set of 21 emergent themes by identifying synergies and grouping similar items. Once we agreed on the groupings, we also developed names for each of the themes so as to have a common language and definitions. We then divided into five small groups to determine different ways to organize the 21 themes; each group organized the themes into 4–6 broader categories. We then met as a single online group to review the proposed organizational schemes, to discuss similarities and differences, and to agree collectively on a single scheme. During that recursive process, we also reduced the number of themes down to 20 to eliminate overlap. Our final organizational scheme thus includes 20 themes (which we call SmithVent

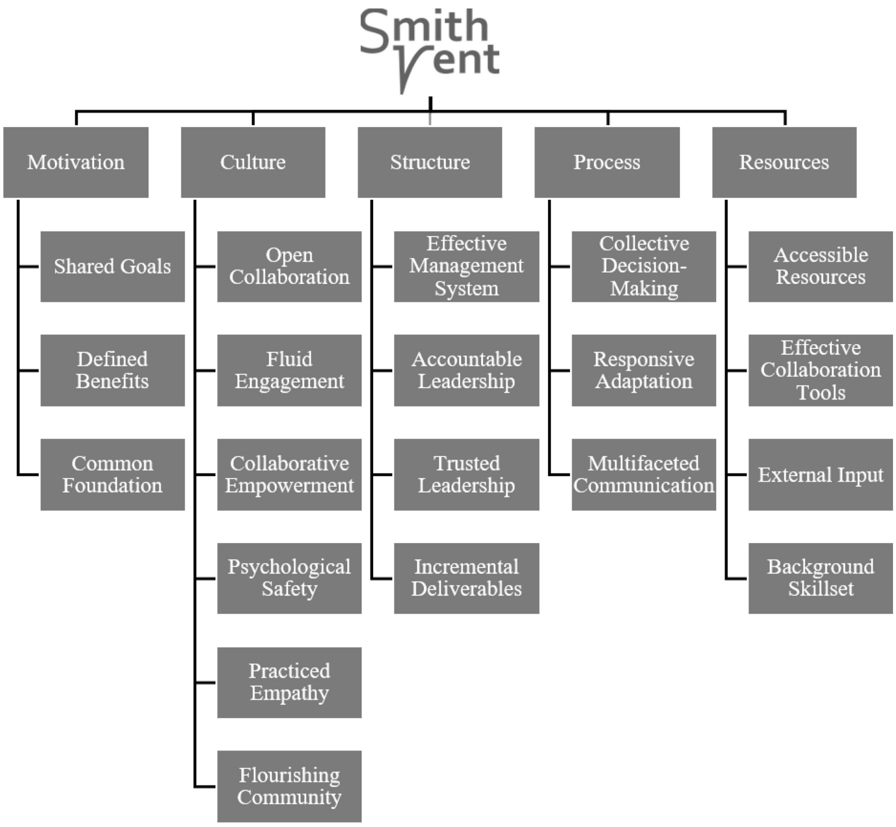


**Fig. 2.** Proposed SmithVent Framework: Categories and Factors.

factors) organized into five main categories: Motivation, Culture, Structure, Process, and Resources. Our resulting proposed SmithVent framework, with its categories and factors, is depicted in Fig. 2. Appendix B shows how these SmithVent factors are connected to the extracted factors from the previously published frameworks.

Together, the five categories and 20 SmithVent factors represent a new and emergent framework for collaborative distributed fabrication. Many of the SmithVent factors reflect factors from multiple frameworks. For example, all five published frameworks include their own factor related to Collective Decision-Making (see Appendix B). There also are SmithVent factors, such as Background Skillset, that correlate to a single factor within just one framework (Open Innovation, in this case). Conversely, the Feminist Pedagogy framework maps to all of the SmithVent factors under the Culture category and is the only framework to contribute to all factors in one category. In finalizing the organizational structure, we decided there was an important distinction between Motivation and Culture: the factors under Motivation reflect what spurred our team members to join SmithVent and kept us going, but the factors under Culture created the inclusive environment that we wanted to foster and sustain.

### *3.4 Mapping to the SmithVent Experience*

As the final step in our modified explanation building process, we mapped the new framework to our SmithVent experience, by treating the 20 SmithVent factors as *a priori codes* to analyze the experience. For each factor, we drafted an evidence-based narrative either individually or in pairs, and then reviewed the narratives with the full author group. The sections below detail the completed mapping, demonstrating how the proposed framework was operationalized:

**Motivation**

- Shared Goals: The SmithVent team was unified in working towards a common goal due to the shared desire to help with COVID-19 amelioration efforts. The team collectively committed to interim goals in Sprint Planning sessions to keep focused, and defined success not by the final ranking within the competition, but by the contributions made to the open-source community.
- Defined Benefits: The open-source nature of the CoVent-19 Challenge enabled a climate of contribution, and the all-volunteer team's united commitment to public benefit was a crucial motivator.
- Common Foundation: Most of the team members shared a common foundation as engineering

graduates of Smith College and as past students of the capstone engineering design course; some team members also had a history of successful prior collaboration with each other. The team made a conscious effort to maintain a common vocabulary and to follow an agreed-upon project management style.

**Culture**

- Open Collaboration: Team members shared information and ideas freely, so that all teammates could learn together and contribute collectively with shared ownership of the process and outcomes. The team utilized open and transparent means to collaborate through structured asynchronous and synchronous methods via Google Docs/shared drive, GitHub, and shared software.
- Fluid Engagement: A flexible work structure, supported by an environment where team members could freely articulate their needs, allowed members to adjust their engagement as necessary. The tasks were defined such that team members could work independently during Sprints. As a community of learners with both autonomy and mutuality, team members knew how to find the knowledge needed to complete tasks independently, but could always reach out to one another as well.
- Collaborative Empowerment: The urgency of the pandemic and the complexity of the challenge created value in collaboration, and team members approached the project, which had no value asymmetries, with a collaborative mindset. Every team member was seen as capable; as a collective, the group had even more capacity for creativity, energy, potential, and power. Individual members were empowered by the belief that, together, the SmithVent team could make a relevant and meaningful contribution.
- Psychological Safety: Mutual trust and respect for each other encouraged open discussions where every team member's opinion or input was valued. In an environment that fostered significant learning, team members acknowledged without hesitation if there was something they did not know.
- Practiced Empathy: SmithVent team members treated each other with compassion and care. Team members supported each other during challenging personal and professional situations, and took the time to celebrate individual and group moments. Mindfulness practices, including meditation and breathing exercises, were also incorporated into meetings to help everyone de-stress and re-center.
- Flourishing Community: Individual authenticity and differences were recognized and appreciated for the value they brought to the team. Team members understood the responsibility each person had as a community member and acted accordingly. The team held socializing events for further bonding and relationship building, which included playing games and celebrating individual and team achievements and milestones.

**Structure**

- Effective Management System: Thorough documentation by all team members kept track of project details. Regular Sprint Reviews provided opportunities for sub-teams to update the full team on progress made and to reflect on what was working well and what needed improvement.
- Accountable Leadership: Leadership was seen as a collective responsibility that required courage and taking ownership. Leadership and followership were dynamic when necessary as the team leaders were able to step back and follow just as well. The team leadership was well-versed and experienced in implementing the outlined management methods effectively; they would also meet explicitly to ensure everything was proceeding as expected and to proactively address challenges.
- Trusted Leadership: SmithVent team leaders were experienced, skilled, and had a history of demonstrated leadership competence prior to this collaboration; as a result, they were respected and trusted. Leaders leveraged their professional experience during the collaboration and contributed substantial hours to the team and project.
- Incremental Deliverables: Team members worked together to subdivide the tasks so that the expected work was unambiguous. Implementing a cadence of short Sprints, which helped maintain focus, the team collectively established reasonable and clear goals each Sprint to develop the working product incrementally.

**Process**

- Collective Decision-Making: SmithVent's goal to contribute to the open-source community for COVID-19 amelioration efforts was collectively determined and stated clearly from the start of the project. Through open and frequent communication, team members were encouraged to express individual views and ideas when team decisions had to be made. The Sprint backlog, which also was crucial for inspection, was a constant source of readily accessible information.
- Responsive Adaptation: The team was flexible and ready to adapt so that the appropriate forward momentum of the project could be maintained. The team's resiliency also enabled

it to respond nimbly to the necessary design changes.

- Multifaceted Communication: The team had an overall communication plan in place, but remained flexible regarding which modes of communication were used. Generally, interactions took place via Zoom meetings or over email. Formal meetings were set involving the entire team and individual sub-teams. As needed, team members would also reach out to each other via email to set informal synchronous work sessions or to discuss and provide answers to questions.

**Resources**

- Accessible Resources: Access to sufficient and strategic resources enabled the team to work effectively and efficiently. The team used agreed-upon collaboration platforms that everyone could use to ensure everyone had access to all team information. The team had sufficient funding through Smith to purchase necessary materials, as well as access to a fabrication space for hands-on prototyping.
- Effective Collaboration Tools: Having the right collaboration tools, which were functional, user-centered, and reliable, was key. The SmithVent team committed fully to the Google Suite of tools for documentation and task sharing, Fusion360 for collaborative CAD modeling, GitHub for shared code development, and Zoom for video conferencing.
- External Input: SmithVent team members met with clinicians and respiratory therapists to gain a better understanding of COVID-19 patients' requirements, what ventilator features would enable health professionals to provide better care for their patients, and what resources were available when using these devices, among other factors. The team also consulted experts in related fields such as electrical engineering, human-computer interaction analytics, and software development.
- Background Skillset: SmithVent team members brought a strong engineering foundation and diverse technical skills from their experiences in industry and graduate studies.

## 4. Education Implications

The strategies that the SmithVent team used for successful collaborative distributed fabrication can transfer readily to an educational setting. Given the shift to remote learning as a result of COVID-19 protocols, many educational institutions and faculty members have already had to grapple with how to provide hands-on and physical making experiences for their geographically dispersed students, and remote learning will undoubtedly continue in the future [53, 54]. The 2021 American Society for Engineering Education (virtual) conference, for example, included many papers describing the approaches educators used to shift to remote fabrication in a range of courses, from first-year design projects [55, 56], to labs and technical depth courses [57–59], to capstone courses in the senior year [60–62]. Some authors also reported on adjustments at the full program level [63, 64] and at academic makerspaces [65, 66]. Similarly, in their study of eight courses that taught digital fabrication online during the pandemic, Benabdallah et al. [67] identified strategies such as collaborative CAD tools, distributed labor, and local expertise during remote collaboration for physical making.

The proposed SmithVent framework includes 20 *factors* organized into five categories: Motivation (M), Culture (C), Structure (S), Process (P), and Resources (R). As discussed in Section 3, this framework provides guidance on how to achieve success in team-based, remote making projects. For example, in order to create an adaptive Structure that allowed for rapid changes in a distributed environment, the SmithVent team used a modified Scrum approach as an *effective management system* (S) for realizing *incremental deliverables* (S). The team leveraged *accessible resources* (R) and *effective collaboration tools* (R) for video-conferencing, sharing models and code, and incorporating remote expertise. Moreover, the SmithVent team implemented Processes such as *collective decision-making* (P) and *multifaceted communication* (P) to ensure that the entire project was convenient for all team members to contribute, regardless of the team member's level of engagement with the project. Perhaps as important as these methodological tools (whose significance is also noted elsewhere [66]) were the Cultural and Motivational practices adopted by the team that allowed it to thrive under difficult circumstances. Building on a strong *common foundation* (M), the SmithVent team regularly reflected on the team's *shared goals* (M) and intentionally hosted team activities and celebrations to build *psychological safety* (C) and *practiced empathy* (C). This reflects a feminist approach to prioritize the skills of respecting and working with others, alongside critical thinking [48], to support the creation of a *flourishing community* (C). Given that distributed collaboration and fabrication are likely to become increasingly common in the continued pandemic and post-pandemic world, students will benefit from learning how to leverage these factors effectively. Providing students with a holistic experience of beneficial structures, resources, processes, as well as team motivation and culture, is especially important in the classroom: a place to support the development of critical skills.

Looking ahead, the strategies demonstrated by the SmithVent project may prove crucial in solving other difficult and complex problems. The future may see new pandemics as deforestation and rising demand for meat create new opportunities for virus crossover [68–70]. Accelerating climate change may lead to more destructive natural disasters and mass migration events [71] that could disrupt infrastructure [72], exacerbate geopolitical frictions [73], and lead to other societal stresses and breakdowns. The next generation of engineers will need to know how to implement effective processes that support rapid innovation in response to urgent global needs. The SmithVent ventilator design itself, which has been profiled in several studies on open-source ventilator development [74, 75], is a prime example of successful rapid innovation that was enabled by an adaptive distributed collaboration.

Educators, in turn, have a responsibility to prepare their students for the increasingly complex and globally interconnected world. For those educators specifically working with students in resource-poor communities, the SmithVent framework for distributed collaboration may be beneficial in improving education access and democratizing science education [33]. Through experiences that foster collaborative skills, students can learn how to engage constructively within teams, whether composed of fellow classmates or citizens of a broader community, to work together. With guidance, students will learn to recognize and appreciate the interdependence within their communities throughout their lives [76]. Indeed, these students and their skills – both technical and interrelational – will soon enough spread to the world beyond the classroom and serve to benefit the global community [49]. The SmithVent framework for collaborative distributed fabrication can serve as a guide in these endeavors.

## 5. Conclusions

The SmithVent team of alumni, faculty, staff, and friends from Smith College formed with the intent to contribute to COVID-19 response efforts through the CoVent-19 Challenge. Three months later, the team won the competition for their ventilator design. After reflecting on this journey and analyzing the literature, the authors (who represent about half the SmithVent team) recognized that no single existing teamwork or innovation framework adequately captured what enabled our team to be so successful in collaborative distributed design and fabrication. We therefore developed a new framework that combines relevant elements from published frameworks in Collaborative Work, Distributed Teams, Iterative Development, Open Innovation, and Feminist Pedagogy. The proposed SmithVent framework includes 20 distinct factors organized into five main categories (Motivation, Culture, Structure, Process, and Resources); it is a comprehensive reflection of the environment and ways of working that contributed to the SmithVent team's success.

As the world continues to grapple with devastating pandemics, climate change, and other disasters, there will be an increased need for distributed collaboration efforts. Implementing distributed collaboration effectively requires the use of existing technology as well as comprehensive, supportive frameworks. The SmithVent team's experience winning a ventilator design competition with a distributed team and with no previous ventilator design experience demonstrates the success that is possible for remote collaboration and fabrication projects. The SmithVent framework provides a guide for future distributed teams within and across academia, industry, and government for years to come.

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## Appendix A – Published Theoretical Frameworks

**Tables A1–A5** detail the categories and factors of the selected published frameworks (one per relevant dimension). The **factors in bold** reflect those that map to the SmithVent experience.

**Table A1.** Collaborative Work Framework [11]

| Category | Factors |
|---|---|
| **Environment** | History of collaboration or cooperation in the community<br>Collaborative group seen as a legitimate leader in the community<br>**Favorable political and social climate** |
| **Membership** | **Mutual respect, understanding, and trust**<br>Appropriate cross section of members<br>**Members see collaboration as in their self-interest**<br>**Ability to compromise** |
| **Process/ Structure** | **Members share a stake in both process and outcome**<br>Multiple layers of participation<br>**Flexibility**<br>**Development of clear roles and policy guidelines**<br>**Adaptability**<br>**Appropriate pace of development** |
| **Communication** | **Open and frequent communication**<br>**Established informal relationships and communication links** |
| **Purpose** | **Concrete, attainable goals and objectives**<br>**Shared vision**<br>Unique purpose |
| **Resources** | **Sufficient funds, staff, materials, and time**<br>**Skilled leadership** |

**Table A2.** Distributed Teams Framework [33]

| Category | Factors |
|---|---|
| **The Nature of the Work** | **Participants can work somewhat independently from one another**<br>**The work is unambiguous** |
| **Common Ground** | **Previous collaboration with these people was successful**<br>**Participants share a common vocabulary; if not, there is a dictionary**<br>**Participants share a common management or working style** |
| **Collaboration Readiness** | **The culture is naturally collaborative**<br>**The goals are aligned in each subcommunity**<br>**Participants have a motivation to work together**<br>**Participants trust each other**<br>**Participants have a sense of collective efficacy** |
| **Management, Planning, and Decision Making** | **The principals have time to do this work**<br>The distributed players can communicate with each other in real time more than 4 hours a day<br>There is critical mass at each location<br>There is a point person at each location<br>**A management plan is in place**<br>**The project manager is respected, has real project management experience, exhibits strong leadership qualities**<br>**A communication plan is in place with room for reflection and redirection**<br>No legal issues remain (e.g., IP)<br>No financial issues remain (e.g., money is distributed to fit the work, not politics)<br>**A knowledge management system is in place**<br>**Decision making is free of favoritism**<br>**Decisions are based on fair and open criteria**<br>**Everyone has an opportunity to influence or challenge decisions**<br>**Leadership sets culture, management plan, and makes the collaboratory visible** |
| **Technology Readiness** | **Collaboration technologies provide the right functionality and are easy to use**<br>**If technologies need to be built, user-centered practices are in place**<br>**Participants are comfortable with the collaboration technologies**<br>**Technologies give benefit to the participants**<br>**Technologies are reliable**<br>**Agreement exists among participants as to what platform to use**<br>Networking supports the work that needs to be done<br>Technical support resides at each location<br>An overall technical coordinator is in place |

**Table A3.** Iterative Development Framework [3]

| Category | Factors |
|---|---|
| **Agile Values** | **Individuals and interactions over processes and tools**<br>**Working software [or product] over comprehensive documentation**<br>**Customer collaboration over contract negotiation**<br>**Responding to change over following a plan** |
| **Scrum Pillars** | **Transparency**<br>**Inspection**<br>**Adaptation** |
| **Scrum Values** | **Commitment**<br>**Focus**<br>**Openness**<br>**Respect**<br>**Courage** |
| **Scrum Team** | Developers<br>Product Owner<br>Scrum Master |
| **Scrum Events** | **The Sprint**<br>**Sprint Planning**<br>Daily Scrum<br>**Sprint Review**<br>Sprint Retrospective |
| **Scrum Artifacts** | Product Backlog<br>**Sprint Backlog**<br>**Increment** |

**Table A4.** Open Innovation Framework [48]

| Category | Factors |
|---|---|
| **Leadership** | **Management Competence**<br>**Leadership Competence**<br>Employee Commitment<br>External Partners Commitment |
| **Internal Innovation Capability** | **Dynamic Capabilities and Governance**<br>**Technical Competence**<br>**External Knowledge Inflow** |
| **Network and Relationships** | Intellectual Property Management<br>Relationship Management<br>Trusting Relationships<br>**Public Benefits** |
| **Strategy** | Absorptive Capacity<br>**Implementation Competence**<br>**Innovation Strategy**<br>**Strategic Resources** |
| Technology Management | Technology Maturity<br>Cost Evaluation<br>Technology Networks |
| **Culture** | **Open Innovation Culture**<br>Culture Change<br>**Organizational Learning**<br>**Objective Alignment** |

**Table A5.** Feminist Pedagogy Framework [49]

| Category | Factors* |
|---|---|
| **Empowerment** | **Power as capability: increase power of all actors, not limit power of some**<br>**Power as creative community energy rather than domination**<br>**Ability to engage in significant learning**<br>**Shared ownership of process and outcome**<br>**Authenticity and celebration of difference** |
| **Community** | **Relationship building and connectedness**<br>**Compassion and care**<br>**Community of learners with both autonomy of self and mutuality with others**<br>**Collective self-confidence in a people's capacity to act and effect their fate** |

**Table A5** (*continues*). Feminist Pedagogy Framework [49]

| Category | Factors* |
|---|---|
| **Leadership** | **Liberation: ability and willingness to act on individual beliefs**<br>**Analysis of and solutions for organizational challenges**<br>**Articulation of needs of self and others**<br>**Interplay between leadership and followership**<br>**Evaluation of actions and connections between objectives and achievement**<br>**Morality of responsibility**<br>**Leadership as collective responsibility: necessity for agency by community members** |

* Note: Shrewsbury [49] presents solely the three main categories, supported with extensive narrative. As part of our analysis of this framework, we identified these factors within each category. Interestingly, none of the feminist pedagogy frameworks we reviewed deconstructed their categories into discrete factors, unlike the frameworks for other dimensions.

## Appendix B – Proposed SmithVent Framework Factors

**Table B1** lists how the SmithVent factors are connected to the factors within the selected published frameworks.

**Table B1.** Mapping of SmithVent Factors to Published Framework Factors

| SmithVent Category | SmithVent Factors | Supporting Factors from Published Frameworks* |
|---|---|---|
| **Motivation** | **Shared Goals** | [CW] Shared vision<br>[DT] The goals are aligned in each subcommunity<br>[ID] Sprint Planning<br>[OI] Objective Alignment |
| | **Defined Benefits** | [CW] Favorable political and social climate<br>[OI] Public Benefits |
| | **Common Foundation** | [DT] Previous collaboration with these people was successful; Participants share a common vocabulary; Participants share a common management or working style |
| **Culture** | **Open Collaboration** | [DT] The culture is naturally collaborative; Leadership sets culture, management plan, and makes the collaboratory visible<br>[ID] Openness<br>[OI] Organizational Learning<br>[FP] Shared ownership of process and outcome |
| | **Fluid Engagement** | [CW] Flexibility<br>[DT] Participants can work somewhat independently from one another<br>[FP] Community of learners with both autonomy of self and mutuality with others; Articulation of needs of self and others |
| | **Collaborative Empowerment** | [CW] Members see collaboration as in their self-interest<br>[DT] Participants have a motivation to work together; Participants have a sense of collective efficacy<br>[ID] Commitment<br>[FP] Collective self-confidence in a people's capacity to act and effect their fate; Power as capability: increase power of all actors, not limit power of some; Power as creative community energy rather than domination |
| | **Psychological Safety** | [CW] Mutual respect, understanding, and trust<br>[DT] Participants trust each other<br>[ID] Respect<br>[FP] Ability to engage in significant learning |
| | **Practiced Empathy** | [FP] Compassion and care |
| | **Flourishing Community** | [FP] Authenticity and celebration of difference; Relationship building and connectedness; Morality of responsibility |
| **Structure** | **Effective Management System** | [DT] A knowledge management system is in place<br>[ID] Sprint Review<br>[OI] Implementation Competence<br>[FP] Analysis of and solutions for organizational challenges; Evaluation of actions and connections between objectives and achievement |
| | **Accountable Leadership** | [CW] Members share a stake in both process and outcome; Development of clear roles and policy guidelines<br>[DT] A management plan is in place<br>[ID] Courage<br>[OI] Managerial Competence<br>[FP] Leadership as collective responsibility: necessity for agency by community members; Interplay between leadership and followership |

**Table B1** (*continues*). Mapping of SmithVent Factors to Published Framework Factors

| SmithVent Category | SmithVent Factors | Supporting Factors from Published Frameworks* |
|---|---|---|
| **Structure** (*continued*) | **Trusted Leadership** | [CW] Skilled leadership<br>[DT] The project manager is respected, has real project management experience, exhibits strong leadership qualities; The principals have time to do this work<br>[OI] Leadership Competence |
| | **Incremental Deliverables** | [CW] Concrete, attainable goals and objectives<br>[DT] The work is unambiguous<br>[ID] Working product over comprehensive documentation; Focus; Sprint; Increment |
| **Process** | **Collective Decision-Making** | [CW] Open and frequent communication<br>[DT] Decisions are based on fair and open criteria; Decision making is free of favoritism; Everyone has an opportunity to influence or challenge decisions<br>[ID] Inspection; Transparency; Sprint Backlog<br>[OI] Innovation Strategy; Open Innovation Culture<br>[FP] Liberation: ability and willingness to act on individual beliefs |
| | **Responsive Adaptation** | [CW] Adaptability, Ability to compromise, Appropriate pace of development<br>[ID] Adaptation; Responding to change over following a plan<br>[OI] Dynamic Capabilities and Governance |
| | **Multifaceted Communication** | [CW] Established informal relationships and communication links<br>[DT] A communication plan is in place with room for reflection and redirection<br>[ID] Individuals and interactions over processes and tools |
| **Resources** | **Accessible Resources** | [CW] Sufficient funds, staff, materials, and time<br>[DT] Agreement exists among participants as to what platform to use<br>[OI] Strategic Resources |
| | **Effective Collaboration Tools** | [DT] Collaboration technologies provide the right functionality and are easy to use; If technologies need to be built, user-centered practices are in place; Participants are comfortable with the collaboration technologies; Technologies give benefit to the participants; Technologies are reliable |
| | **External Input** | [ID] Customer collaboration over contract negotiation<br>[OI] External Knowledge Inflow |
| | **Background Skillset** | [OI] Technical Competence |

*CW = Collaborative Work [11], DT = Distributed Teams [33], ID = Iterative Development [3], OI = Open Innovation [48], FP = Feminist Pedagogies [49].

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