Transforming Traditional Teaching Laboratories for Effective Remote Delivery

– A Review

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Abstract

Teaching laboratories form an essential component of any engineering education. They enable students to participate in various stages of experiential learning including conceptualization and experimentation followed by reflection, analysis and interpretation of data. However, operating teaching laboratories with social distancing measures poses significant logistical and safety challenges, and alternative modes of delivery may be a realistic way forward in adapting engineering curricula to the post COVID-19 world. Best practices from spaces such as distance learning and virtual / remote laboratories can be leveraged to facilitate educators' responses. This review is aimed at identifying evidence-based approaches for transforming hands-on labs into virtual or remote operation to achieve desired learning outcomes without compromising on soft skills and student self-efficacy. A critical review of the recent literature on delivering STEMM education laboratories in either a virtual or remote setting or a combination of both is presented here. Commonly emerging approaches

are identified and strategies to implement remote or mixed-mode (a combination of remote and traditional lab components) delivery are highlighted. The value of these approaches to the educator is assessed based on claimed learning outcomes, availability of resources, technology, scheduling, and cost factors.

Keywords

Experiential Learning, Hybrid Labs, Hands-on Learning, Pedagogy Transformation, Teaching Laboratory

1. Introduction

The experiential learning component of any Science, Technology, Engineering, Math and Medicine (STEMM) course is broadly accepted as being an integral part of the education journey (Abdulwahed and Nagy, 2009; Feisel and Rosa, 2005). These experiences come in diverse forms such as laboratory sessions and projects (Abdulwahed and Nagy, 2009; Chen et al., 2019), field trips (Vollaro, 2002), design projects (Pekdemir et al., 2006), internships, co-ops and work placements (Inguva et al., 2018; Rompelman and Vries, 2002) as well as service learning (Dukhan et al., 2008; Ropers-Huilman et al., 2005). The various types of experiential learning activities are represented in the engineering curriculum in different ways across disciplines and institutions. This includes providing them as an activity to complement a lecture-based course, an elective or capstone project during term time, a summer activity or a voluntary / mandatory placement.

The desired learning outcomes are diverse and include intellectually straightforward goals such as demonstrating concepts and principles from the classroom (Augusto et al., 2019; Chen et al., 2016) while providing the opportunity to learn necessary practical skills such as performing medical procedures (Tabas et al., 2005) or working in a lab and performing data analysis (Feisel and Rosa, 2005; Xie et al., 2020). Higher level learning objectives include developing professional competencies such as teamwork, proficiency in research or various cognitive and meta-cognitive skills needed for independent learning (Cukurova, 2014; Shah et al., 2020).

The recent COVID-19 pandemic and resultant social distancing measures have caused significant disruption to many aspects of our lives, including education. Many traditional modes of instruction which require in-person presence such as lectures and

laboratories are no longer possible and educators are adapting their teaching methods while still meeting students' needs (Almarzooq et al., 2020; Crawford et al., 2020). This may take various forms such as reducing the coursework load, substituting conventional content delivery, interaction and assessment modes with online modes (Foster and Layman, 2013) and transforming practical teaching into virtual, remote or hybrid experiences (Glassey and Magalhães, 2020).

Pedagogical trends and tools from spaces such as Massive Open Online Courses (MOOCs) (Zhang et al., 2020), educational technology (EdTech) (David et al., 2020) and distance learning can provide the resources and know-how needed to adapt courses for online / remote delivery. Within the experiential learning space, specific trends such as the increasing prominence and adoption of virtual / remote labs (Darrah et al., 2014) and experiences (Fung et al., 2019) offer much insight that can guide an educators' strategy. Developments from industry such as the Internet of Things (IoT) (Bagheri and Movahed, 2016) and digital twins (David et al., 2018) can also be explored in the transformation process.

The process for transforming currently in-person experiential learning activities to ones suitable for remote delivery depends on several factors such as the nature of the experiment (simulation heavy vs hands-on heavy) as well as the available time and resources. Some educators may choose to adapt hands-on experiments for remote delivery (forward design), while others may restructure the activity altogether by concentrating on learning objectives (backward design).

This review aims to serve as a handy reference for instructors engaged in re-designing teaching labs, one of the most common experiential learning activities. Examples and best practices are drawn from a wide variety of STEMM subjects such as medicine,

basic sciences and the different engineering specialisations. The medical community in particular offers valuable insight in how to provide simulated learning experiences as they have extensive experience developing methods and resources (Bradley, 2006; Kelay et al., 2019) and integrating them with state-of-the-art technology to bring them into the classroom (McGaghie et al., 2010; Sadideen et al., 2017). There is a significant driver for such innovation and development in the medical education space as fresh graduates are expected to be competent practitioners almost immediately. Medical educators operate in a more constrained environment than other STEMM educators due to domain specific issues such as patient safety (Weldon et al., 2019), access and ethics (Datta et al., 2012) together with commonly faced problems such as resource limitations.

We highlight the various considerations and know-how needed to formulate a transformation strategy. Laboratory activities are divided into three categories based on the nature of the experiment and the features of that type of activity which impact the transformation process. The various modes of module delivery along with enabling tools are explored within the context of each category.

2. Nature of Experiments in Teaching Laboratories

The types of experiments and projects in teaching laboratories vary extensively across disciplines. Some require extensive use of equipment and are therefore, highly hands-on. Others can be performed using computers to achieving desired outcomes or are a combination of hands-on and simulations. One of the major factors which influences the transformation strategy is the role of equipment in the experiment. Keeping this in mind, we have categorized the nature of experiments into three broad categories:

A) Experiential learning activities where the hands-on skill is the objective: Hands-on skills are an important aspect of professional STEMM practice. These experiments allow students to familiarize themselves with the equipment or environment and provide tactile information which influences their cognitive and psychomotor domains (Balamuralithara and Woods, 2009; Heradio et al., 2016). These experiments also require infrastructure and resources which may be a challenge, especially in current circumstances. Surgical procedures and equipment handling require hands-on experiences and skills. These activities form a significant component of medicine education especially when these skills are essential for maintaining safety and comfort of patients in the future (Weldon et al., 2020). In addition to medical trainees, experienced doctors also require training of specific procedures to gain expertise. Traditional methods include in-person training by professionals on real patients. Another class of activities which also fall in this category are field trips. These provide opportunities for students to engage with the environment and are frequently used in school education (refer elsewhere (Behrendt and Franklin, 2014) for a detailed review). These new learning experiences foster motivation and can have lasting cognitive and socio-cultural effects (Forest and Rayne, 2009).

B) Experiential learning activities where equipment is used but not the main objective of the experiment: Most of the experiential learning activities involve students applying their theoretical knowledge in real life experiments. These activities do not necessarily require students to become experts at operating specific equipment, but instead, use it as a tool to gather data or accomplish a task. The focus shifts from manual operation to data collection, analysis, and interpretation. The process of designing the experiment focuses on applying a scientific approach with less

time and effort spent on equipment training. Typical examples include titrations, membrane processes, distillation, spectroscopy, etc.

C) Experiential learning activities that use simulations as the primary mode of experimentation: There are many experiments which do not require physical equipment to achieve learning objectives. These typically employ simulations or other digital experiences to provide students with a learning activity. These experiments can span a diverse range of topics: visualising molecular mechanisms (e.g., molecular simulations (Kinnaman et al., 2018), protein dynamics (Bennie et al., 2019), etc.), studying phenomena at different length and time scales which may not be accessible for study with equipment in teaching labs (e.g., fluid motions at small and large scales (Zhou and Wang, 2018), heat transfer, plastic deformation, etc.) or rapidly testing and optimising different designs using powerful computational resources (e.g., ASPEN (Ruiz-Ramos et al., 2017), CAD, FLUENT or COMSOL modelling, etc. (Inguva et al., 2020)).

Although an experiment or project may include aspects from more than one category, they can easily be divided into sub-parts with different learning outcomes which fall into one of them (Table 1). The Accreditation Board for Engineering and Technology (ABET) has proposed several learning objectives for laboratories in engineering education (Most and Deisenroth, 2003). These cover knowledge in the cognitive domain, psychomotor domain, and affective domain (Balamuralithara and Woods, 2009) which we aligned with the three categories shown in Table 1. Guidance from other accreditation boards such as the IChemE (IChemE, 2020) can also be understood through the lens of Table 1 as there is significant commonality and overlap in the desired attributes and learning outcomes of graduate engineers.

Table 1: Description of different types of experiments and corresponding learning outcomes overlapping with those outlined by ABET (Most and Deisenroth, 2003). CD: Cognitive domain, AD: Affective domain, PD: Psychomotor domain,

Nature of experiment	Examples	Example/Possible Learning outcomes	Overarching Learning Outcomes
A: Experiential learning activities where the hands-on skill is the objective	Assembling an equipment; Operating	(CD, PD) Design, build, or assemble a part, product, or system, including using specific methodologies, equipment, or materials	(CD) Devise an experimental approach, specify appropriate equipment and procedures, implement these procedures, and interpret the resulting data to characterize an engineering material, component, or system
		(CD) Develop system specifications from requirements	(CD, PD) Demonstrate the ability to collect, analyse, and interpret data, and to form and support conclusions.
B: Experiential learning activities where equipment are used for experiment, but not the main objective of the experiments	Titrations HPLC Controls	(CD, PD) Test and debug a prototype, system, or process using appropriate tools to satisfy requirements	(CD) Make order of magnitude judgments and use measurement unit systems and conversions.
		(CD, PD) Apply appropriate sensors, instrumentation, and/or software tools to make measurements of physical quantities	(CD, AD, PD) Identify unsuccessful outcomes due to faulty equipment, parts, code, construction, process, or design, and then reengineer effective solutions
C: Experiential learning activities that use simulations as the primary mode of experimentation	Visualizing molecular interactions Techno-economic analyses Process Optimization	(PD) Use the human senses to gather information and to make sound engineering judgments in formulating conclusions about real-world problems	(CD, AD) Demonstrate appropriate levels of independent thought, creativity, and capability in real-world problem solving
		(CD) Identify the strengths and limitations of theoretical models as predictors of real-world behaviours	(CD, AD) Identify health, safety, and environmental issues related to technological processes and activities, and deal with them responsibly
			(CD) Communicate effectively about laboratory work with a specific audience, both orally and in writing, at levels ranging from executive summaries to comprehensive technical reports.
			(AD) Work effectively in teams, including structure individual and joint accountability; assign roles, responsibilities, and tasks; monitor progress; meet deadlines; and integrate individual contributions into a final deliverable
			(AD) Behave with highest ethical standards, including reporting information objectively and interacting with integrity

	(PD) Demonstrate competence in selection, modification, and operation of appropriate engineering tools and resources.
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3. Mode of Delivery of Experiential Learning Activities

Traditional delivery of experiential learning activities in categories A and B is primarily done in-person in a laboratory or medical facility. The training resources and handouts can be delivered in various ways including online videos, reading material, etc. With the need for alternative methods to enable experiential learning in a remote setting, we identified several examples from the literature for remote labs:

- a) Virtual: Virtual labs refer to the delivery method where all the content and experiment is delivered in a virtual environment with the help of videos and simulations. Category C experiments can be delivered using virtual labs, provided all the software and resources necessary for performing simulations are available to students from anywhere across the world. Category A and B experiments face challenges for their virtual delivery due to their reliance on equipment. Nevertheless, several studies have shown evidence for transformation of experiments from these categories including surgical training and field trips to virtual labs which received favourable responses from students. Surgical training is an important component of medical training (Kneebone et al., 2006). A survey of medical students by (Greene et al., 2006) showed a clear preference for simulations to learn invasive methods. Since then, several approaches including training videos (Maloney et al., 2013) and computer-based simulations (Tsai et al., 2008), virtual reality (VR) based simulations of procedures (Luursema et al., 2010)

have been applied in medicine (refer elsewhere (Cook and Triola, 2009) for a detailed review).

In engineering and science disciplines, virtual experiments have been used for teaching concepts related to physics (Darrah et al., 2014; Olympiou and Zacharia, 2012), protein structures (Doak et al., 2020), reaction kinetics (Bennie et al., 2019), plastic deformation (Brophy et al., 2013), metal forming processes (Sharma, 2016), machining (Li et al., 2018) and heat transfer visualization (Ayatollahi et al., 2008). Virtual field trips using VR can mimic a real environment and reduce the significant costs associated with planning, travel, and execution necessary for a real field trip (Fung et al., 2019). Several studies have received positive responses from students with regards to these virtual field trips in various disciplines including environmental sciences (Çalışkan, 2011a; Fung et al., 2019), and chemistry (Forest and Rayne, 2009; Malbrecht et al., 2016; Pullen and Brinkert, 2014). Recently, (Fung et al., 2019) used a VR platform to provide a virtual experience of exploring specific areas of Ungaran, a town in Indonesia, using VR goggles and lenses.

With recent advances in various emerging technologies including augmented reality (AR), the virtual experiences are bound to get more engaging and useful for students to achieve the desired learning objectives. We will discuss the required tools for developing virtual environments in the next section.

- b) Remote: In this mode of delivery the students can perform the experiments from anywhere in the world by directly controlling the equipment in the lab. Category B experiments can be delivered remotely if appropriate infrastructure and controls are available. The essentials include a live video and audio feed so that students can view experiments and controls in real time without the need for in-person

handling (Nickerson et al., 2007). Pedagogically, several studies have observed negligible difference in conducting experiments via Internet versus in an actual laboratory (Lang et al., 2007). Control engineering experiments (Fabregas et al., 2011; Sáenz et al., 2015; Santana et al., 2013; Soares et al., 2014) and telecommunications (Sicker et al., 2005) are especially amenable to transformation to remote labs with the aid of various software tools. The basic requirements to implement remote labs for highly hands-on unit operations in chemical engineering was discussed by (Shin et al., 2002) and essentially include an experimental component, a system to track users and keep records, a repository of relevant information for students and teaching staff and an interface for use. A study by (Dolgoff et al., 2003) found little difference between performing membrane experiments hands-on or in a remote environment. (Lee, 2004) used a remote control integrated system for a pneumatic excavator mechanism in design and mechatronics courses. (Klein and Wozny, 2006) developed a fully automated distillation column integrated with real-time video streaming which could be accessed and operated remotely. Recently, (Tan et al., 2020) developed a fully automated remote titration experiment by combining expertise from chemistry and computer science. (Grodzki et al., 2018) outlined the advances made at three universities in Germany engaged in the Excellent Teaching and Learning in Engineering Science (ELLI) for implementing remote and virtual labs in manufacturing and materials testing. The authors employed a variety of techniques such as robotics and sophisticated control systems to digitalise manual handling and control tasks. This mode of delivery also opens the potential for sharing expensive equipment between different departments and institutions (see (Cooper and Ferreira, 2009) for a detailed review on remote labs).

c) Hybrid: A hybrid mode of delivery involves combining some hands-on activities with remote delivery. While remote delivery requires the equipment to be ready for remote operation, there are many set-ups which may not be ready to perform their function in an autonomous manner without any manual intervention. In such experiments, usually a student or member of staff performs limited tasks to operate the equipment manually based on instructions provided by the students who are not in the actual laboratory. The implementation of hybrid labs requires a high-quality real-time live feed and communication with the person operating/handling the equipment. Mixed reality technologies can prove beneficial in implementing such labs, e.g. (Dunnagan et al., 2020) used immersive technology to operate infrared spectroscopy equipment and analyse spectra. (Bailey and Dean, 2020) used an immersive environment with real-time live feed to mimic the experience one might have of being present in the operation theatre to observe a surgical procedure and communicate with the training surgeon. This technology is also being used by doctors at St. Thomas hospital in London during the coronavirus pandemic (“Mixed-reality headsets in hospitals help protect doctors and reduce need for PPE | Imperial News | Imperial College London,” 2020) as well as industry to provide training to new recruits and professionals (“Using VR for Employee Training | Here are real-world examples!,” 2019).

A summary of different experiential activities which have been delivered either via virtual, remote or hybrid mode is provided in Table 2.

Table 2: A summary of different studies that have used alternative mode of delivery. (Category A: Hands-on skills central, B: Some equipment used, C: Mostly simulations)

Discipline	Mode of delivery	Category	Experiment/Activity	Reference(s)
Medicine	Remote/ Virtual	A	Physiotherapy training	(Maloney et al., 2013)

	Virtual		Port A catheter injection training	(Tsai et al., 2008)
			Colonoscopy training	(Luursema et al., 2010)
Physics	Virtual	B	Multiple	(Darrah et al., 2014)
			Light and Colour Concepts	(Olympiou and Zacharia, 2012)
Biochemistry	Virtual	C	Protein structures	(Doak et al., 2020)
		C	Reaction kinetics	(Bennie et al., 2019)
Chemistry	Virtual	A	Field trip	(Malbrecht et al., 2016)
			Field trip	(Pullen and Brinkert, 2014)
			Field trip	(Forest and Rayne, 2009)
	Hybrid	A	Infrared spectroscopy	(Dunnagan et al., 2020)
Chemical Engineering	Virtual	C	Heat transfer	(Ayatollahi et al., 2008)
	Remote/Virtual	B	Level control rig	(Abdulwahed and Nagy, 2013)
	Remote		Distillation Column	(Klein and Wozny, 2006)
			Membrane experiments	(Dolgoff et al., 2003)
			Titration	(Tan et al., 2020)
Environmental Engineering	Virtual	A	Field trip	(Fung et al., 2019)
			Field trip	(Çalışkan, 2011b)
Metallurgy	Virtual	B	Plastic deformation	(Brophy et al., 2013)
			Metal forming processes	(Sharma, 2016)
Mechanical Engineering	Virtual	A	Machining	(Li et al., 2018)
	Remote/Virtual	B	ELLI project	(Grodzki et al., 2018)
	Remote		Conservation of Angular momentum	(Lee, 2004)
	Remote	B	Machine dynamics	(Nickerson et al., 2007)
Electrical and Control Engineering	Remote/Virtual	B	Multiple	(Sáenz et al., 2015)
	Remote		Ball and Hoop apparatus	(Fabregas et al., 2011)
			Robotic Systems	(Santana et al., 2013)
			eMERGE project	(Lang et al., 2007)
			Mobile robot control program	(Mejías Borrero and Andújar Márquez, 2012)
			Switch and router management	(Sicker et al., 2005)
			Multiple	(Soares et al., 2014)

4. Tools and Resources

In this section, we will briefly discuss the important tools and resources which enable the transformation of teaching labs to one of the three modes of delivery.

4.1. Virtual Labs

The creation of a virtual lab requires the development of a virtual environment. This can be done using commercially available platforms (Bric et al., 2016; Jang et al., 2017; Viitaharju et al., 2021), custom built platforms (Darrah et al., 2014) and even using the popular online video game Minecraft (Nebel et al., 2016). The suitable integration of the physical models and scientific content relevant to a lab in the virtual environment is also important. This can be achieved by providing a virtual environment where students can interactively view different animations of a physical simulation that has been carried out (Zhou et al., 2017) or where the components capture the relevant physics and combine to form the desired virtual experiment (Garcia et al., 2019). These can be highly specific to the experiment and can include various features such as easy measurement, data recording and automatic report generation (Darrah et al., 2014). The VR set-up also requires multiple hardware components such as stereoscopic displays, e.g. Oculus, and motion tracking devices to enable users to interact with the virtual environment in an authentic manner (Veleev and Zlateva, 2017). The interested reader can refer to the excellent review by Potkonjak et al. (2016) for further details.

Another aspect to consider is how the virtual lab is hosted and accessed by students. The virtual lab files and executables can be provided to students in multiple manners such as in an offline media in the form of a CD, downloadable (Kyaw et al., 2019), web-based applications (Abriata et al., 2018; Bánsági and Rodgers, 2018; Moreno-Ger et al., 2010), a dedicated server system held locally (Gercek and Saleem, 2008) or remotely on the cloud (Alvarez et al., 2019).

4.2 Remote and Hybrid Labs

Both remote and hybrid engineering labs typically consist of the following components: 1) actual laboratory equipment, 2) the equipment control software and hardware such as a computer, the data acquisition and control system (DAQC) and relevant software (both of these are also used in the traditional in-person labs), 3) video cameras and other sensors that enable remote users to observe the remote experiment and 4) a remote access system (Abdulwahed and Nagy, 2013; Barrios et al., 2013; Tak et al., 2020). There are different types of video cameras with functionality to pan/tilt/zoom (PTZ) which may prove beneficial in providing a real-time view from a remote location. These cameras can be connected to a network and access to them can be regulated. The relevance of the type of camera (zoom only vs. pan and tilt vs. pan, tilt, and zoom) remains to be studied in detail. Remote access to the system can be provided using different software including remote desktop connection, MS Teams, Zoom, and TeamViewer. These platforms are developing new tools and services for the education sector at an accelerated pace during the current COVID-19 pandemic.

Additional benefit of emerging technologies such as AR can be embedded even for remote/hybrid delivery (Mejías Borrero and Andújar Márquez, 2012). AR allows to interact with the physical environment and connect various resources including links, files, images, etc. which can aid in creating a stimulating and engaging environment for students (An et al., 2020).

5. Collaboration and Assessment for Remote Delivery

In addition to physical changes required for conversion of experiments to remote delivery, there are various other aspects of teaching labs including collaborative teamwork and assessment which require additional consideration. We will briefly

discuss the key technologies which can be leveraged to enable efficient online collaboration and assessment.

5.1. Online Collaboration

Collaboration in a lab setting takes place in multiple modes such as group conversations and meetings (formal and informal interactions) or collaborative work which can occur inside and outside the lab. This includes carrying out different aspects of the experiment simultaneously and writing a report together. The technological advancements of the last few decades have resulted in the emergence of a variety of platforms and tools which can be adopted by educators and used by students to interact for course-related work.

Many institutes of higher education have an integrated dedicated online learning management systems (LMS) (Almarashdeh, 2016) such as Blackboard Learn™. These platforms usually have dedicated communication channels such as forums that can be moderated by teaching staff and offer educators flexibility and control in terms of setting deadlines and providing feedback (Wood and Bhute, 2019) It is also possible to adapt widely used social media platforms (Wang et al., 2012) for this purpose. Online collaborative software (OCS) such as Slack or Microsoft Teams can be similarly used (Lee et al., 2020) as they have well developed chat and communication functionalities. Face-to-face interactions can be achieved using video conferencing software such as Zoom, Skype or the previously mentioned OCS suites. Informally, students may communicate with each other using their personal social media accounts and this is also an important mode of communication for effective group work (Contreras-Castillo et al., 2004).

A variety of software suites and cloud platforms such as Microsoft Office 365, Overleaf and Google Docs / G-Suite are commonly used platforms that students can use to write lab reports and prepare presentation slide decks in a collaborative and secure manner. Educators may want to consider the potential impact of using software and platforms not specifically designed for educational use as often, many new tools with the desired ease-of-use and functionality may be designed for corporate use or not be fully verified for security limitations. Some of these platforms also have a learning curve associated with becoming an effective user e.g. using LaTeX in Overleaf. Adequate support should be provided to ensure students are well-equipped to use these tools.

5.2. Assessment

Both formative and summative assessment play an important and distinct role in practical teaching: while formative assessment aims to achieve improvement during the learning process, summative assessment measures student understanding at the end of it (Dixson and Worrell, 2016). Many of the conventional assessment modes used in teaching labs e.g. lab reports, lab notebooks, presentations and group meetings can be readily carried out remotely. The learning management systems previously described typically enable teaching staff to set-up an online submission system where students can upload their reports and lab notebooks. Educators could also consider the use of electronic lab notebooks (ELN) through dedicated platforms (Dood et al., 2018) or adapting more accessible tools such as blogs or Google Docs (Bromfield Lee, 2018). Adopting ELNs also offer opportunities beyond digital transformation such as exposing students to authentic industrial practices and enabling educators to structure the laboratory exercise more effectively (Piccione,

2020). The various OCS and videoconferencing tools previously mentioned can be used to carry out group meetings and presentations which can be assessed normally.

The remote assessment of competency in specific hands-on skills like performing medical procedures is more nuanced. A common approach for VR based modules is to record and save the video stream from the platform. The material can then be reviewed to ensure that students have completed the required tasks in a satisfactory manner and to provide feedback (Vaughan et al., 2016). More recent advances in assessing VR-based activities have incorporated Machine Learning (ML) to review the large dataset generated from VR simulators and assess competency (Winkler-Schwartz et al., 2019).

6. Transformation Process

6.1. Transformation strategy

At a curriculum planning level, educators can consider ideas of forward, central and backwards design (Richards, 2013) to guide the transformation process. There are three main components to the curriculum (overall plan for the course): 1. Content which refers to the topics that are to be taught in the course, 2. Process which refers to how the teaching is carried out and 3. Outcomes which refers to the learning outcomes of the module by achieving a certain level of competency. Forward design employs a “linear” approach to the transformation where the order is content → process → outcome. Central design first considers the process (activities and procedures used) and then structures the content and outcomes to generate a coherent plan. Backwards design considers the outcomes first and then structures the content and processes to best meet the desired outcomes.

The choice of the design approach can impact the transformation process and we advocate that educators should adopt a backwards design strategy considering the circumstances related to the COVID-19 pandemic, evaluating first the desired learning outcomes of the laboratory activity. This information is essential in navigating the variety of options available for the transformation and can aid the decision-making process by focusing on meeting learning outcomes (McTighe and Wiggins, 2005; Ritter et al., 2018). If an educator decides that the desired learning objective can be met through non-laboratory activities or through another taught module, it may be more expedient to substitute the lab course and/or provide a non-experiential learning activity to the students. A forward or central design approach may result in the emphasis being placed on the transformation process itself and educators striving to provide students with an experiential learning activity regardless of whether it is necessary or appropriate.

From a more operational perspective, educators can consider the “Iron Triangle” of project management: time, cost and scope, in formulating their transformation strategy. Arguably, in the current circumstances, time constraints are the hardest constraint as universities hope to be able to resume classes at the earliest opportunity. Therefore, educators have to navigate between the other two factors: cost and scope. For example, if educators have the budget, professional developers and companies could be brought in to develop the virtual and/or remote environments. However, this solution can be prohibitively costly and runs the risk of not being completed and adequately tested in time. Hybrid delivery modes have smaller scopes as educators are not creating completely new environments or significantly modifying experiments with costly equipment but have the risk of not being viable if laboratories are closed due to public health advice. If there are significant costs constraints, various

substitutions such as providing low-cost simulations and virtual experiments in platforms such as MATLAB or ASPEN can be considered.

6.2. Development Stage

Once the educator has decided that the provision of an experiential laboratory activity is necessary, a review of the resources and constraints such as manpower (staff and teaching assistants), the available materials, and technical know-how, is needed to guide how the transformation will proceed. In this section we have divided the transformation process into the development and delivery stages. Most of the transformation including design and testing of infrastructure will be carried out in the development stage. The provision of support when students interact with the experiment/activity can be considered as the ‘delivery’ stage. Depending on the category of the experiment and its intended mode of delivery, the requirement of technical expertise, manpower, resources vary widely in the ‘development’ and ‘delivery’ stages. A summary of these requirements is shown in table 3.

Table 3: Summary of resource requirements for various transformation strategies at the development and delivery stages. (Category A: Hands-on skills central, B: Some equipment used, C: Mostly simulations)

Category	Mode of delivery	Development			Delivery	
		Technical expertise	Manpower	Resources	Manpower	Resources
A/B	Virtual	High	Medium	High	Low	Low
	Remote	High	High	High	Low	Medium
	Hybrid	Medium	High	Medium	High	High
C	Virtual	Low	Low	Low	Low	Low

During the development stage, the technical expertise and know-how required for transformation varies with the category of experiment and the mode of delivery. Transformation of category A/B to virtual will require developing a platform for carrying

out virtual experiments. This will require significant resources and can only be accomplished with specialist IT skills. Remote modes require significant expertise and resources to fully automate existing physical systems due to trialling and testing demands. In contrast, category C experiments can be most readily transformed for a virtual mode of delivery as outlined earlier with minimal effort and are also much easier to beta-test. Hybrid modes of delivery, although comparatively less technically challenging and resource intensive to develop, still require significant testing (and therefore, manpower) and onsite resources.

From our experience in the teaching labs both before and during the pandemic, involving students in the entire module design (transformation in this context) process in a participatory design framework has several benefits and can address many limitations that educators may encounter. Students often have specialist skills and know-how that can meet certain technical demands or if they lack such skills, they are able to become competent contributors in a short period of time with adequate support (Inguva et al., 2018). As many internships and placements have been cancelled, educators can help students obtain a meaningful work experience through such an arrangement. Furthermore, students' insights and feedback during the development process can help solve many problems at an early stage which reduces stress on educators and ultimately provides a higher quality experience for students (Inguva et al., 2018; Ramírez et al., 2020).

6.3. Delivery Stage

During the delivery stage, virtual modes have the advantage of being available anywhere in the world and their delivery requires few additional resources. Remote modes also have relatively lower manpower requirements due to automation but since

there is physical equipment involved, it does draw on additional resources such as consumables or maintenance. During the delivery stage, there is the need for physical presence. There might be additional technical expertise needed during the delivery stage to provide support to students and this will be highly dependent on the type of experiment, level of complexity, as well as student ability and experience.

Another dimension that educators need to consider during course delivery is the use of physical teaching spaces. Whilst pure virtual and remote modes of delivery significantly reduce demand for space, the diversity of experiments in a single space may require additional attention in scheduling and access control. Many labs therefore will likely have combinations of experiments that are run in the various modes. Therefore, social distancing measures both at the student and staff levels need to be considered. Basic policies such as limits on the number of personnel in the lab space at any time and the mandatory wearing of face masks / shields can be implemented as a default. At the staff level, educators could coordinate segregated teams of staff and teaching assistants to ensure continuity in operations. At the student level, approaches such as creating segregated and self-sufficient spaces within the lab can help minimise the need to students to move around the whole lab. In addition, spreading out time in the lab through scheduling should be considered. Even if only a portion of experiments can be transformed into virtual / remote / hybrid experiences, this significantly reduces the demand for in-person access to the lab which enables better laboratory management.

7. Future Dividends of Transformation

The current COVID-19 pandemic and the required adaptation of courses including teaching laboratories may initially seem onerous and temporary, i.e. once the

pandemic is over, course operations will revert to the previous normal. For the most part, a reversion to pre-pandemic times is desired, however, the transformation process does yield certain benefits that educators could retain going forward. Some of these benefits include:

- Integration of various technological features and support material that enhance the overall learning experience. During the transformation process, additional material developed such as more comprehensive equipment descriptions and explanatory videos can be retained and provided to students. The various technologies adopted such as IoT sensors, cameras and AR tools can also be retained during in-person course operation.
- Ease of scheduling and more flexible course operations. If the experiment has been successfully reconfigured for remote delivery, students and educators will have more flexibility when to run the experiment. Furthermore, not all students would need to be in the lab at the same time which enables students to achieve a better work-life-balance.
- Possible addition of experiential learning components to MOOCs. Educators can adapt the experiments developed in teaching labs and integrate them into future online courses and MOOCs to augment the course experience (Grodotski et al., 2018).

8. Conclusions

In adverse circumstances, there are often many opportunities. Responding to the COVID-19 pandemic by adapting teaching practices for remote delivery presents an unprecedented opportunity to take stock and conceptualise how learning experiences can be delivered going forward. Whilst the immediate priority is to ensure students'

safety and to provide the best possible learning experience which may involve temporary measures and stopgap solutions, many aspects of the response can be retained following the pandemic. For example, the integration of various technologies such as IoT sensors and AR/VR capabilities can help rejuvenate traditional teaching labs, augment student experience and enable educators to conceive of new experiments and modes of delivery. The onus is now on us as educators to take this opportunity to reflect on our current practice and to use it for positive change in our response to the current crisis.

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