Remote Laboratories: Uncovering the True Costs

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***Abstract*—Remote laboratories have been the subject of both technical development and pedagogic analysis. Much of the associated literature uses arguments regarding the relative value of these laboratories to justify the work in this area. Whilst many of these arguments are focused on pedagogic opportunity or logistical flexibility, they often also argue for the financial benefits that accrue from the ability to share laboratory resources. In this paper we consider the prevalence of these arguments and the extent to which they are (or are not) underpinned by research-based evidence. We do attempt to draw any conclusions on the cost benefit of RLs but rather argue for the need for better and more rigorous remote laboratory cost models on which future cost benefit analysis could rest. We provide preliminary work on a framework for collecting significant robust data on the costs associated with developing and maintaining remote laboratories, and provide initial suggestions regarding elements that need to be included in this framework.**

***Index Terms*—Remote laboratories; development costs; development process; financial viability.**

I. INTRODUCTION

Over the last decade there has been a growing interest in remote laboratories as an education tool. Research in this area has been spread between technical designs (including both general architectures and specific implementations) and pedagogic considerations [1]. Despite numerous (almost ubiquitous) claims regarding the financial benefits of remote laboratories, there has been very limited research into the cost effectiveness of this mode of laboratory access.

We recognise that there is a body of carefully considered research that acknowledges that remote laboratories provide a unique set of benefits and are appropriate to be used in their own right, rather than being seen as a replacement or supplement for existing „hands-on‟ labs [1–3]. Given this observation, we argue that any discussion of the cost-effectiveness of remote laboratories should consider this benefit in the context of the remote laboratories themselves, rather than as part of a comparison to hands-on laboratories [4]. Indeed, given the substantial lack of any systematic study of the costs of conventional teaching laboratories, a comparison becomes even more problematic.

There are significant challenges in reliably determining the costs associated with remote labs. A key difficulty is that most existing laboratories have been developed either as research projects or as pilots to assess the approach. Consequently, the costs are typically drawn from diverse sources, and often there are considerable in-kind contributions made to the development – typical sources include the time of the researchers who are involved, „unspecified‟ workshop support, student involvement in the design and development, etc. Interpreting the reported costs of development is further complicated given that many projects are „one-off‟ pilots, meaning that there is considerable time committed to developing supporting infrastructure (both hardware and software) that might be amortised across numerous remote laboratory experiments in those cases where multiple developments are carried out. Conversely, in environments involving numerous remote laboratories as part of one facility, it may be very difficult to accurately attribute costs to specific projects or items of apparatus.

Essentially, the cost of remote laboratory development and operations depends on numerous factors: the complexity of the labs; the experience of the developers; the nature and number of users; amongst many other factors. If we are to interpret data on the costs of remote laboratories then we need to understand not just the base costs, but the effect of these factors.

In the next section we will analyse the current dependence of the remote laboratories literature on arguments associated with cost benefits, and the extent to which these arguments are (and are not) supported in the literature. In section III we then consider how we can improve this situation by investigating what information can and should be collected, and how this might be structured to allow valid comparisons to be made. Section IV gives an illustrative example, and in Section V we provide a general discussion and conclusions, with a specific call to the broader community to support work in this area.

II. LITERATURE ANALYSIS

As discussed above, there has been a growing body of literature related to remote laboratories. The justifications and/or impacts described in much of this literature regularly includes statements around the cost benefits provided by remote laboratories. To illustrate this we randomly selected a sample of 50 papers published on remote laboratories across a diverse range of forums. We excluded from this list any publications by the authors of this paper. The list of papers analysed included:

- 28 journal papers, including 5 in IEEE transactions, 6 in iJOE, and 4 in the Journal of Eng. Education
- 22 conference papers, including: 7 in REV conferences and 6 in FiE conferences.
- Topics covered: architectures, systems and algorithms (15 papers); description of specific items of apparatus (11 papers); and theory/pedagogy (24 papers).

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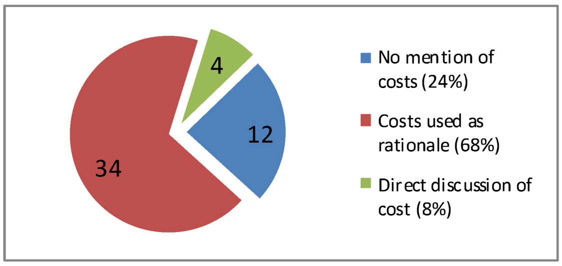

Figure 1: Consideration of costs in representative sample of remote laboratories papers.

We then analysed these 50 publications to assess the extent to which they considered issues related to cost, particularly in terms of understanding the extent to which the literature is making assumptions regarding the cost of remote laboratories as a motivation for their development and use (and potentially how this compares to the cost of „hands-on" laboratories). A summary of the analysis is given in Figure 1. This highlighted a number of significant issues, as follows.

No mention of cost:

Twelve of the papers (24%) made no significant mention of issues associated with the cost of remote laboratories. Of these, 10 papers explicitly discussed the rationale for choosing to use remote laboratories, typically focusing on a range of non-cost-related issues. For example:

"The shift to remote access addresses many of the difficulties involved in undergraduate laboratory work. It allows flexibility in time and place of access ... it can eliminate safety risks ... it can also allow access to hardware that would otherwise be unavailable". [5]

Cost used as rationale for Remote Labs:

A total of 34 papers (68%) referred to the costs of remote labs as part of justifying their development and use. Typical comments include:

"Sharing experiments locally and remotely allows unique laboratory equipment to be utilized more fully, brings down the experiment cost per student, and makes more experiments available to students." [6]

"While remotely controlled physical laboratories would be fairly expensive to implement online, cost savings could ultimately be appreciable if high-cost instrumentation could be shared among institutions." [7]

"Experimental laboratories, however, represent a great investment, both in term of required money and space, that may become unbearable to the schools, especially when the number of students and the number of subjects that require lab classes in- crease. Remote laboratories are a very cost-effective solution to this problem". [8]

An interesting observation was made by Salzmann and Gillet [9], who argued that for remote laboratories to be cost-effective may require them to be shared across institutions: "*An effective remote laboratory facility is costly to develop and to maintain for a single academic institution. Commercial trials have also shown that the economical value of such a settings is not high enough for establishing a viable business model.*" They don"t however provide references regarding the „commercial trials" that are referred to.

In other words, there is an almost universal referral in over two-thirds of the papers we reviewed, of cost savings being at least one of the drivers that justify the use of remote laboratories. Despite this, only 1 of these 34 papers gave a citation supporting this argument. Cao and Zhu [10] argue that "*hands-on labs are severely constrained by their limited scheduling and high cost of space, equipments and maintenance*", and then cite [11] in support of this. The cited paper however only discusses concerns around the high costs of traditional laboratories and does not discuss at all the concept, or cost, of remote laboratories.

Direct discussion of cost:

Four of the 50 papers (8%) provided direct discussion regarding the costs of remote labs. Otoakhia et al [12] gave a specific example of the costs for developing a remote laboratory (focused on measuring the electrical characteristics of a diode). The cost details are, however, limited to the experimental hardware and the authors do not attempt to quantify the labour costs or ongoing maintenance costs that might be required.

In a 10-year retrospective analysis, Trevelyan [13] gives a more comprehensive estimate of development costs, though unfortunately with little granularity or explanation. It is particularly unclear what proportion of the costs related to initial development of the supporting infrastructure and hence what the incremental cost might be for the development of additional laboratories or research into new techniques.

Cooper [14] provides an interesting discussion on the cost benefits of remote laboratories. Whilst he does not provide a direct cost analysis, he does make a number of salient points that relate to the interpretation of remote laboratory costs: "*A cost benefit analysis is very specific to the details of a particular case and many of the benefits are difficult to quantify*". He goes on to identify a number of factors that can affect whether the costs of a remote laboratory are justified by the benefits: numbers of students to be supported; whether or not tutor or instructor support is required; the opportunity costs of provide the remote laboratory [14].

Possibly the paper that comes closest to truly acknowledging the current situation is by Jona et al [15]. They discuss the significance of the cost of remote laboratories – posing the specific question as to whether they are worth their cost. The authors comment that "*scaling up remote labs may require significant costs in purchasing and maintaining expensive equipment*" but argue that in some cases the costs are justified. They do, however, acknowledge that "*little empirical data exists on the actual costs of providing online laboratory access at scale*". They also make the salient point that "*While we await more conclusive data on financial costs, we can be- gin to consider the educational affordances that remote labs provide and factor this into the value proposition for remote labs.*"

III. COST MODELLING

The above discussions indicate that whilst there are often pedagogic or logistical arguments for remote laboratories, their cost-effectiveness is also a significant factor in their use. For this argument to have substance, however, we need to have a much better understanding of the costs of remote laboratories (and indeed also hands-on laboratories and simulations). Further, this understanding should be based on rigorous data across multiple projects.

To achieve this level of rigor, we argue that we need to establish a repository of information on development costs that enables an understanding of where costs are incurred and comparisons between different projects. Such a repository should include both information on development and maintenance costs, and where and how these were incurred, as well as contextual information about the development that ensures that valid comparisons can be drawn between development projects (in effect ensuring that cost analyses are valid – and not „comparing apples with oranges"). Let us begin by considering the latter of these two elements.

A. Remote Laboratories: Contextual Information

Understanding the context in which a particular remote laboratory development project was undertaken can be crucial to interpreting information on the costs of that development. For example, a greenfield project being carried out by a team with no prior experience may be likely to be more costly than a project being carried out by a well-established team with existing infrastructure and experience. Similarly, a project being carried out with involvement of students, who can provide significant input and expertise, may have various costs hidden by this involvement.

A useful starting point in identifying relevant contextual information is the work of Cooper [14]. Whilst this work focuses on determining the issues that affect adoption rather than costs, it nevertheless points towards factors that may relate to whether the costs of a lab are considered to be justified. There is also considerable literature on the factors that affect lifecycle costs more generally in IT projects. A useful starting point in this area is the considerable body of work on cost/size/effort estimation techniques, and the factors that are used to adjust estimates. For example, Intermediate Cocomo [16] is used to estimate the development effort for software projects based on determination of a likely project scale. It includes a number of „cost drivers" which are used to adjust the estimates based on project attributes.

Based on an analysis of these sources, Table 1 outlines a preliminary set of proposed contextual descriptors that we argue should be specified when collecting information on the lifecycle costs (i.e. both development and maintenance) for remote laboratory projects. This list is not intended to be definitive nor complete, but rather to be a starting point for discussions around a more complete list of factors that potentially influence costs. For each descriptor we will also need information on the form that a response ought to take. Ultimately this table will be used to guide the collection of contextual information that assists in interpreting remote laboratory costs.

B. Remote Laboratories: Development Process

In order to understand, manage and compare the life cycle costs for remote laboratory development and operations we ought to be able to understand where these costs were incurred.

To provide a simplistic illustration of this, consider an example that involved the initial development and evaluation of a preliminary prototype and the subsequent development and operational deployment of a revised version of the remote laboratory. The total cost for this project was $40k. Our subsequent estimates for what it might cost to deploy an additional 5 copies of the remote laboratory will vary enormously on where we incurred the $40k costs in the initial development. If the prototype was $20k and the final deployed version was $20k, then another 5 copies may cost $100k. Conversely, if the prototype was $38k and the deployed version was $2k, then the 5 copies may only add another $10k in costs.

In order to support provision of cost information and comparison of these costs across projects, we therefore need to understand the development processes. We argue that the best way to achieve this is to establish a generalized reference model, and associated controlled vocabulary, for the development process of remote laboratories.

TABLE 1: RAL LIFE CYCLE CONTEXTUAL DESCRIPTORS

Name	Description
Usage Context	
StudentNum	Intended numbers of students that each individual RAL should be able to support.
StudentCollab	Will the lab support multiple-student groups?
SupportTutor	Whether it is intended that lab tutor support generally be available whilst the RAL is in use.
SupportTechnical	Whether it is intended that technical systems support generally be available whilst the RAL is in use.
PedagogicRelevance	The extent to which the experiment needs to capture complex conceptual elements from the underlying theory.
Prior Context	
LabExist	Is there an existing hands-on laboratory that the RAL is replacing/supporting?
LabDuplic	Is an existing lab (if it exists) functionally equivalent to the RAL under development?
LabMode	Will the lab be dual model (remote + hands-on, teaching + research, ...)
Lab Characteristics	
LabReliability	The required reliability of the RAL
LabRepeatability	An estimate of the extent to which the system must behave in a repeatable and predictable way.
LabComplexity	An estimate of the technical/functional complexity of the RAL
IFComplexity	An estimate of the complexity of the RAL user interface
SharedInfra	The extent to which the project makes use of shared infrastructure
Team Charact's	
TeamTechExpert	The level of technical expertise of the team undertaking the development
TeamDiscExpert	The level of disciplinary expertise of the team undertaking the development
TeamExperience	The level of experience with RAL systems of the team undertaking the development
TeamStudents	The extent to which students have been involved in the project
Project Charact's	
ProjSchedule	The urgency of the development
ProjSupport	The level of institutional support provided for, and commitment to, the RAL project
ProjOthers	The extent to which other development projects are underway concurrently

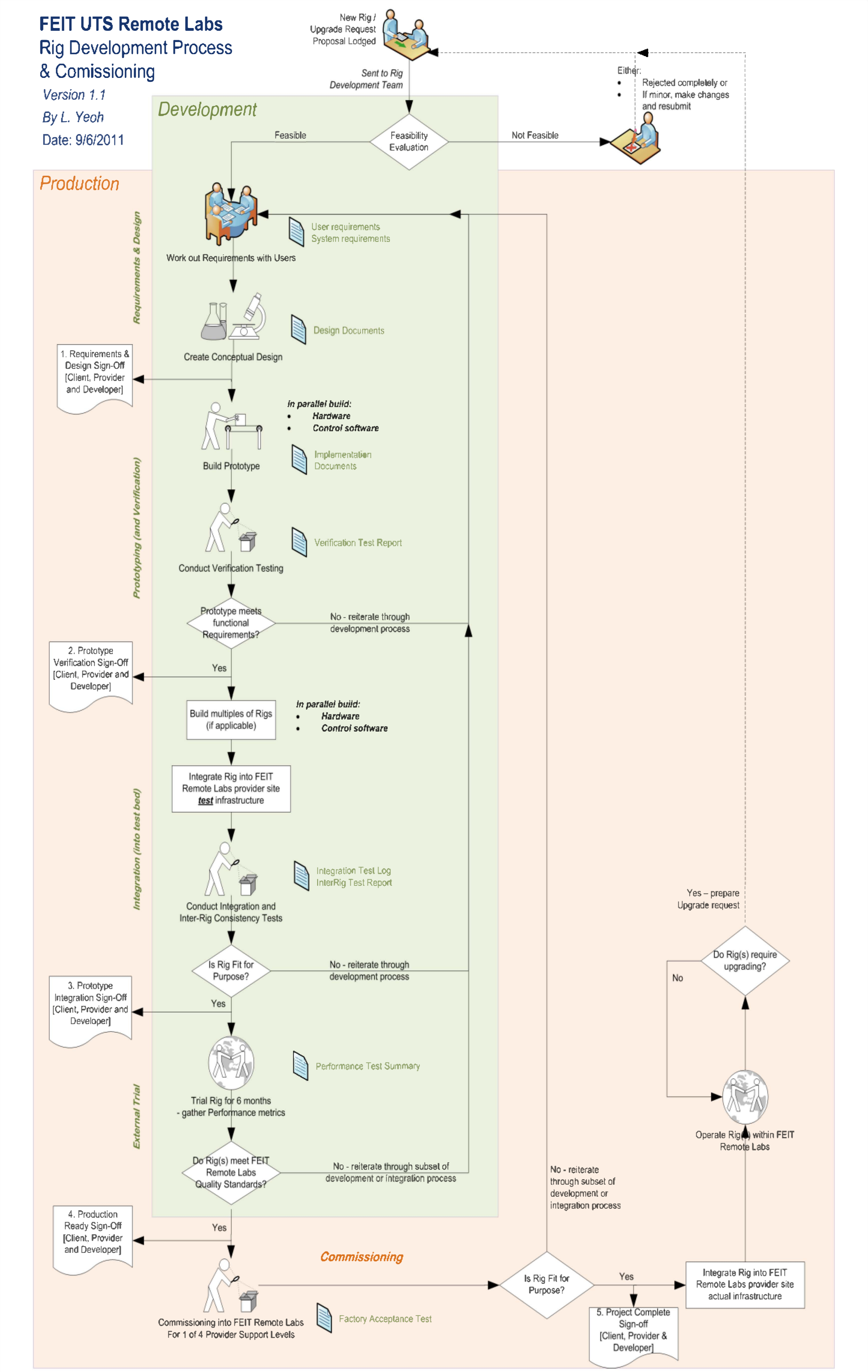

Figure 2: Illustrative process for Remote Laboratory Development at the University of Technology Sydney

The creation of such a reference model is beyond the scope of this paper – and indeed we believe that it should be carried out as a broader exercise of the research community in this field (possibly under the auspices of the Global Online Laboratory Consortium[1]). We can, nevertheless provide both an illustrative development process (which may inform the creation of a reference model) and a case study that illustrates where costs can be incurred. This is presented in the following section.

IV. EXAMPLE PROCESS AND COSTS

Whilst providing a single example of costs associated with a remote lab development will be of only limited use given the reliance of costs on specific contextual factors, a concrete example will nevertheless help to anchor discussions and provide a starting point for further work. It will also inform decisions about how a reference model might be constructed.

A. *Illustrative Development Process*

Firstly, to provide an example of a development process we will discuss the approach used at the University of Technology, Sydney. Figure 2 therefore shows a representation of the development cycle used by the UTS remote laboratories team. This development lifecycle is a fairly standard waterfall model with iterative elements. The model consists of the following stages:

- *Feasibility evaluation*: A proposal for a new RAL is evaluated for practicality, ability to be built, and fit with the general remote lab design philosophy
- *Requirements and Design*: User requirements are documented, deconstructed, refined and used as a basis for the high level and then low level design of the new remote lab.
- *Prototyping*: Each revision of the design is implemented and verified against the functional requirements isolated in the requirements phase.
- *Integration*: The new remote lab is integrated into a specific „test" instance of UTS"s provider site infrastructure for more detailed „fitness for purpose" testing.

    Note: In practice several iterations through the prototyping and integration phases may be required to achieve the desired functionality and quality. Each iteration tends to have a different focus as noted in Section IV-B.

- *Trialling*: The new remote lab is tested by „friendly" users tasked with providing feedback on the performance of the new remote lab.
- *Commissioning*: The new remote lab undergoes final acceptance testing and is moved into the provider site"s production infrastructure.

Note that this process only covers the remote lab development and not the ongoing operations and maintenance. A full life cycle model would also need to consider these aspects.

B. *Project Costs Case Study*

The application of this process to a development project can be illustrated by considering the Coupled Tanks (Revision 2) project. UTS first implemented a Coupled Tanks remote laboratory in 2004. This apparatus was used to explore the open-loop modeling of a dynamic system, and the subsequent close-loop control of the apparatus using a standard PID control algorithm. Over the 7 years of use of the apparatus there were increasing concerns about both increased maintenance issues and the pedagogic relevance of the current design (the physical system had a number of inadequacies that made using it to explain theory somewhat problematic). This led to a decision to replace the existing system with a new design.

The following information relates to the development of the Coupled Tanks (Revision 2) project to the point of operational delivery of three new remote laboratory rigs. This example does not yet extend to include a full life cycle, ie one that includes ongoing operations and maintenance as well as development. It is, however, worth noting that during the development we placed a premium on designing the system to maximise reliability such that maintenance costs later in the life cycle would be minimized.

The broad information on the development project includes (all costs are in Australian Dollars):

- Project duration: approximately 15 months
- Total project cost: $112k (for 3 rigs)
- Development costs: $65k
    - Labour: 915 hours, $45k
    - Materials: $20k
- Marginal cost per rig: $15.7k
    - Labour: 130 hours, $6.7k
    - Materials: $9k

In other words, the effective cost of the first rig was $80.7k, and the 2nd and 3rd rigs were $15.7k each.

Detailed costings can be obtained by breaking the development into phases. Essentially these covered: feasibility, requirements, prototyping, integration, trialing and commissioning. Each phase was then broken into separate activities, and the materials and labour figures for each activity determined.

A number of the phases were iterated multiple times as a consequence of iterative refinement of the remote laboratory design. Specifically, the following iterations occurred:

- *Proof of Concept*: to evaluate rig feasibility (approximately $28k);
- *First prototype*: to assess rig functionality without considering the ability to replicate the rig (approximately $36k);
- *Production prototype*: consideration of minimization of multiple rig cost and ease of construction (approximately $48k for 3 rigs).

In interpreting the above data it is worthwhile noting that there were a number of factors that had a significant impact on the project costs. Table 2 list these against the relevant contextual descriptors from Table 1.

[1] See http://online-lab.org/ for information on GOLC.

TABLE 2: CONTEXTUAL INFORMATION FOR THE UTS COUPLED TANKS REVISION 2 (CT2) PROJECT

Name	Description
Usage Context	
StudentNum	The CT2 rigs are intended to be able to support a minimum of 1000 students per 10 week semester.
PedagogicRelevance	The CT2 labs must strongly demonstrate behaviours predicted by theory (such as non-linearity) and changes in measured variables must be large enough for the behaviours to be clearly evident. For the CT2 rig these behaviours were particularly challenging to meet.
Prior Context	
LabExist	Yes, there was an existing laboratory being replaced, and the limitations of the existing lab were well understood.
Lab Characteristics	
LabReliability	The design of the CT2 rigs must ensure very high reliability and low maintenance costs.
SharedInfra	The CT2 rigs can make use of the existing UTS RemoteLabs infrastructure.
Team Charact's	
TeamTechExpert	The development team has a high level of both hardware and software capability.
TeamExperience	The development team has a high level of existing remote labs expertise and familiarity with the Sahara system.

V. DISCUSSION AND CONCLUSIONS

In this paper we have demonstrated that the research literature on remote laboratories has a significant reliance on arguments associated with the cost benefits of remote laboratories. Despite this there is very little research studying the costs associated with remote laboratories – with the community generally relaying on anecdotal information and supposition that the ability to share equipment will lead to higher utilization and hence lower per-usage costs.

We argue that for remote laboratories to be more widely accepted as a valuable learning tool, we need to have a much improved understanding of the lifecycle costs associated with their development and operations. This understanding should be based on robust data that can be reliably compared across projects. To this end, this paper is ostensibly a call to the broader community to support the provision of such information. We provide some preliminary analysis and suggestions regarding framework which can support this data collection, and look forward to further work in this area.

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