In this article we described a framework that we developed to help us implement ready4 - a MOSCEM in youth mental health. We outlined framework standards for an accountable, reusable and updatable MOSCEM and described the modelling toolkit we created for applying those standards to the development and use of the ready4 MOSCEM. We also provided an overview of an initial set of MOSCEM modules developed with the framework to implement a utility mapping study. We reviewed the modules, datasets and analyses generated by that study against framework standards. The work we have described has potential implications for the development of the ready4 MOSCEM and for health economic modelling in mental health. A number of issues have more general relevance to health economic modellers and funders of health economic research.

Consistent use of meaningful naming conventions when authoring code is recommended [39,40]. Code can be made easier to follow by using the practices of abstraction [41], where only simple, high level commands are routinely exposed to reviewers, and polymorphism [42], where the same command (e.g. “simulate”) can be reused to implement different algorithms of the same type. Programs to implement model analyses can be made comprehensible to even non-technical users through the use of literate programming techniques and tools like RMarkdown [43] that integrate computer code with plain English descriptions.

Transcription errors - mistakes introduced when transferring data between sources, models and reports - are very common in health economic models [8]. The risk of these errors might be lower if there was full transparency across all steps in a study workflow. Scientific computing tools now make it relatively straightforward to author programs that reproducibly execute all steps in data ingest, processing and reporting [39].

Code and data should be distributed with tools that make it easy for potential users to appropriately cite each model artefact.

To make model code and data widely re-usable by others, it is important to provide users with appropriate and explicit permissions. For code, it may be appropriate to adopt the prevailing open source licensing practice within the programming language being used. For data, it may not be sufficient to simply choose between a permissive license like the Public Domain Dedication (CC0) [47] or a copyleft option such as the Attribution-Share Alike (CC-BY-SA) [48]. In addition to ensuring that data is ethically appropriate for disseminate in open access repositories, responsible custodianship of some de-identified or aggregated data may involve using or adapting template terms of use [49] which have a number of ethical clauses (for example, prohibiting efforts to re-identify research participants).

Clear distinctions should be made between model modules (code that defines abstract data structures and the algorithms that can be applied to data described by these structures), model datasets (digital information such as parameter values, unit records, etc) and model analyses (code that links model datasets to model modules and specifies the algorithms to apply to data associated with each module).

The software development practice of encapsulation [41] can be used to help ensure that model modules continue to work as intended when they are combined [50]. In some cases, combining modules may mean new versions of modules have to be created to better account for interaction effects. The concept of inheritance [41] can be used to write code that efficiently achieves this objective as well as to facilitate selective editing of modules when transferring models to different decision contexts [50]. Model modules of a similar type or purpose can be efficiently distributed and documented by bundling them as code libraries. It is good practice to make available test or toy data to demonstrate the use of model algorithms [39].

Statistical models are a common output of health economic evaluations, but they are often not reported in a format that enables others to confidently and reliably re-use them for out of sample prediction [51]. Open source approaches can help address this by disseminating code artefacts that enable easy and appropriate use of a statistical model to make predictions with new data. However, great care must be exercised when publicly releasing model artefacts derived from data on human subjects as they may by default embed a copy of the source dataset. Sensitive dataset copies must therefore be replaced (for example, with synthetic data) and the amended artefact’s predictive performance then retested before any public release. Another way to make MOSCEMs easier to use is to develop simple user-interfaces for non-technical users.

Issues such as privacy and confidentiality can limit public release of some sensitive health economic model artefacts [15].

selectively restrict access to data that are confidential, while disseminating all other model artefacts. Separating code and data will also make it easier

Model authors may wish to facilitate reuse in both contexts to which their model can be

Such flexibility is useful when transferring a health economic model developed for one jurisdiction for application in another, as this task typically involves retaining some model features and updating others [16].

When used in conjunction with toolkit repositories, the six R libraries provide support for implementing 17 out of 20 framework standards (Table **[1](#timelygls)**). Standards relating to safe dissemination of statistical models (R8), user-interface development (R9) and deprecation conventions (U4) are better met through using existing third party R libraries. Preparing statistical models for dissemination can be accomplished with standard R data management tools like the dplyr [71] and purrr [71] libraries. User-interfaces are typically developed with the shiny [72] library, for which a tutorial aimed at health economists is available [73]. The library lifecycle [74] provides tools for R developers to consistently deprecate their code.

## Paradigm

Barriers to health economists adopting open source approaches include concerns about intellectual property, confidentiality, model misuse and the resources required to support open source implementations [15,27].

Our interest in modular and open source approaches developed when we began seeking an appropriate framework for undertaking and validly synthesising diverse types of economic research in mental health. Mental disorders impose high health, social and economic burdens worldwide [29,30]. Much of this burden is potentially avertable [31], but poorly financed and organised mental health systems are ill-equipped for this challenge [32,33]. A substantial economic literature already exists to assess the affordability and value for money of mental health interventions [34]. This economic evaluation work is an essential prerequisite for improving allocative efficiency in mental health, but could be of greater value to systems planners if integrated with a broader program of economic research.

However, there now appears to be strong in principle support from many health economists for greater use of open-source CHEMs [15]. However, open-source CHEMS remain relatively rare [13,25,26] and better guidance for how to implement CHEMs as open-source projects is needed [28].

Funding for health economic modelling projects rarely extend to provision of medium term support for model updates and improvements. The career trajectories of health economists can also mitigate against adequate maintenance of a model. For example, it is relatively common for model authors to have moved on from the team that owns the model and / or from working on the health condition for which the model was developed.

Computational health economic models (CHEMs) are widely used, influential, increasingly complex and subject to potentially under-appreciated limitations.

There is significant scope for the acceptability, adequacy for purpose and social benefit of CHEMs to be enhanced.

## 2.2 Desireable CHEM attribues

These issues have the potential to compound as CHEMs become more complex – with concomitant accountability obligations for model authors [12,13].

An existing ethical framework for public health modelling [<https://doi.org/10.3389/fpubh.2017.00068>] suggests four criteria for considering the suitability of models to inform policymaking – independence, transparency, beneficence and justice.

The growth in the volume and breadth of published health economic analysis [REF] suggests that substantial public funds are now invested in developing CHEMs. The social returns from this investment could be enhanced if CHEMs could be more readily and appropriately used by all who could benefit from them and if the lifetime for their valid application could be extended.

Not in – representativeness & engagement [Conceptual model development, partially addressed under TRU]

Adherence to good practice guidance is an essential requirement for healthcare modelling [2]. Peer reviewed articles on health economic modelling practice typically consider issues specific to computational implementation in conjunction with other issues such as development of the conceptual model, the identification and selection of input data and study reporting.

Individual guidelines from this literature that are specific to the computational implementation of models address issues of both development and use. Guidelines for the development of CHEMs include recommendations on code organisation, data file management, version control [[10.1186/s12967-020-02540-4](https://doi.org/10.1186/s12967-020-02540-4)], verification [[10.1186/s12967-020-02540-4](https://doi.org/10.1186/s12967-020-02540-4), <https://doi.org/10.1093/epirev/mxab006>],XXXXXXXXXXX) and validation [[10.1186/s12967-020-02540-4](https://doi.org/10.1186/s12967-020-02540-4), <https://doi.org/10.1007/s40273-021-01110-w])>]. Guidelines on how model authors can support appropriate use of CHEMs address issues such as availability [[10.1186/s12967-020-02540-4](https://doi.org/10.1186/s12967-020-02540-4), <https://doi.org/10.1093/epirev/mxab006>, https://doi.org/10.1007/s40273-021-01110-w], developer documentation [[10.1186/s12967-020-02540-4](https://doi.org/10.1186/s12967-020-02540-4)], fitness for purpose [[10.1186/s12967-020-02540-4](https://doi.org/10.1186/s12967-020-02540-4), https://doi.org/10.1007/s40273-021-01110-w], reproducibility [[10.1186/s12967-020-02540-4](https://doi.org/10.1186/s12967-020-02540-4), <https://doi.org/10.1371/journal.pcbi.1010856>, <https://doi.org/10.1093/epirev/mxab006>], re-use [https://doi.org/10.1007/s40273-021-01110-w], terminology [**<https://doi.org/10.1002/jrsm.1333>**], user-documentation [[10.1186/s12967-020-02540-4](https://doi.org/10.1186/s12967-020-02540-4), <https://doi.org/10.1007/s40273-021-01110-w>] and user-interfaces [https://doi.org/10.1007/s40273-021-01110-w].

We are developing a computational model to explore multiple economic topics relating to the mental health of young people aged 12 to 25 called ready4 ([www.ready4-dev.com](http://www.ready4-dev.com)).

We have developed a framework that:

* specifies a set of guidelines for implementing a transparent, reusable and updatable CHEM;
* provides a toolkit of online services and novel software for implementing a youth mental health model that meet these standards.

## Modelling toolkit

We developed a toolkit to help us develop ready4 as a CHEM that meets all six TRU standards. The toolkit is comprised of accounts that we have established and configured using existing online services and novel software that we have written as R libraries (for details, see Availability of Data and Materials).

Advantages of modular models include feasibility (large projects are broken into smaller tasks, with each component independently developed and tested) and flexibility (making it easier to selectively replace or update specific parts of a model and to scale up or down the level of granularity) [19]. Modular approaches are currently being used to facilitate the development of complex computational models in disciplines such as biology [19], ecology [20] and neuroscience [21]. In health economics the related and enabling concept of reference models has been recommended [22], but peer reviewed studies describing modular health economic models remain relatively rare, though examples exist in infectious disease [23] and cardiology [24].

Modular models also provide an opportunity for multiple modelling teams to contribute to, test and reuse models. To enhance this capacity, modular models may be implemented as open source projects that give others liberal permissions to access and use model source code and data [19–21].

####

Commiting to a software framework, particularly a project with modular implementation, many contributors and multi-annual planning horizon, is a major decision.

We believe that projects to develop and promote adoption of such software frameworks, both in R and other open source languages such as python, would be a significant step forward.

We began developing an unreleased prior version of our software framework in December 2018 to try to automate and standardize a number of tasks we were repeadedly performing when authoring code to help implement our youth mental health models. However as the amount of code we wrote grew, our initial framework proved too cumbersome to scale. In August 2020 we publicly released the source code of a major overhaul of our software framework, and since then have iteratively extended and refined the framework to solve issues arising from its use in authoring ready4 model modules.

reproducibility [4–6], and uncertain validity [7,8], limited reusability [13,25,26] of health economic models

Addressing this issue will require technical innovation, skills development and changes to the way research proposals and research careers are assessed.

Currently,

The use of shared software frameworks may help reduce the burden associated with implementing some aspects of ethical modelling practice. Collaboration between teams of health economists can also make some complex modelling projects more feasible [14]. Developing networks of modellers working on common health conditions has been recommended as a strategy for improving model validity [28] and some of us are part of a nascent initiate of this type in mental health [94].

Ideally health economists would explore these complex topics in partnership with modellers from other disciplines (in particular epidemiology and health services research) and a wide range of stakeholders such as other researchers, policymakers, service planners and community members. Modular and open source approaches would facilitate such investigations by breaking down ambitious and long term goals into manageable time-bound discrete projects, each progressed by different teams. To facilitate such an approach, a common framework of standards and tools would be needed. To be suitable for such a task our framework would need additional development, with its overall architecture reviewed for scalability and suitability and to provide better integration with and use of other open source languages (particularly python) and repositories. Whatever MOSCEM infrastructure is developed, its resilience would depend on a community of open source contributors sufficiently large and active to ensure that all core modules are maintained even after their original authors cease their involvement.

However, having features that facilitate accountability, reuse and updating is not the same as being accountable, reused and updated. If diverse groups of stakeholders do not review model components, suggest improvements and develop alternatives, then little progress is made towards enhancing model legitimacy. Similarly, making code and data publicly available does not guarantee that others will know of the existence of these tools, trust their validity and find them easy to use. Without reuse, errors in model artefacts are more likely to remain undetected. Even when errors are detected, they still need to be fixed, but maintaining code and data requires ongoing resourcing through a combination of centralised infrastructure and an active open source community.

To progress from a technical capability to behavioural outcomes, both our framework and MOSCEM need further work. Currently all the framework and model module libraries we have developed are available only as “development” releases. An early priority for us is to undertake the additional development, testing and documenting of these libraries so that we can submit production versions of each library to CRAN [56]. Making an R library available on CRAN is normally a prerequisite for a high level of use.

Some of the issues we have discussed in the context of the development of our model or health economic modelling in mental health are potentially relevant to health economists and funders of health economic research more generally.

Proactive measures by funders to encourage more accountable, reusable and updatable health economic models is not a need confined to mental health.

However, funders also need credible proposals to support and this is an area for health economists interested in MOSCEMs to prioritize. Health economists could use existing and new special interest groups to identify opportunities and enablers of more collaborative approaches to model development, potentially as the basis for future funding proposals.

Adopting MOSCEMs will expand the type of skillset typically engaged in health economic modelling projects, with a much greater role for data-scientists, software engineers and online community builders. The requirement for these roles should be incorporated into project proposals. Not all efforts by health economists to promote MOSCEMs need to depend on the decisions of research funders. Releasing selected subsets of unmaintained model artefacts in open source repositories is still better than not providing access to any code and data and can typically be accomplished within existing project budgets. Developing knowledge and skills of MOSCEMS can be advanced by making small contributions (e.g. improvements to documentation, code contributions) to open source projects. Our project website [58] includes details of multiple ways to contribute to ready4.

and the significant deficits in our understanding of the systems in which mental disorders emerge and are treated [95] suggest that there are a number of candidate topics in mental health that might benefit from pooling of efforts. The weak theoretical underpinnings for understanding complex mental health systems [96] may be a place to start. It remains unclear why increased investments in mental health care have yet to discernibly reduce the prevalence and burden of mental disorders[97]. The literature, and evidence base, regarding how the requirements, characteristics and performance of mental health services are shaped by spatiotemporal context needs to be further developed [98]. There is also a need for better evidence to identify the social determinants of mental disorders most amenable to preventative interventions, and for which population sub-groups such interventions would be most effective [99].

## Implications for implementing ready4

The most direct implication of the development of the ready4 framework is that it makes it feasible for us to implement a MOSCEM in youth mental health. The standards specified by the framework have enabled us to partially automate workflows for developing and applying ready4 through use of the framework’s modelling toolkit. We have demonstrated the practical utility of the modelling toolkit by applying it to authoring, documenting and disseminating ready4 module libraries [76–79], datasets [81,82]; analyses [83–85], reporting templates [86,87] and prediction tools [80]] used in a utility mapping study [75]. The standardised and partially automated workflows used in creating and sharing these artefacts has the potential to generate significant efficiencies as we apply the ready4 framework to undertaking new economic studies.

We have also been able to demonstrate the interoperability of the initial ready4 modules developed with the modelling toolkit. The program used to implement the utility mapping analysis [83] combines modules from four module libraries ([76–79]) and two framework libraries [69,70]. Example literate programs published on the ready4 documentation website [58] use toy data [81] to illustrate the potential for ready4 modules to facilitate study replication and transferability. As demonstrated by the checklist we developed (Table 3), our framework’s standards also provide a mechanism for to assess the extent to which the ready4 MOSCEM meets explicit objectives.

The transferability claims we make for our existing modules are to date supported only by example programs using toy data. Our future work aims to address this with real world studies that apply modules to different concepts and contexts. Our current work program also aims to create new ready4 modules for modelling help-seeking choice, spatial epidemiology, household populations and primary mental health services that we hope will provide others with more reasons to use ready4 and contribute to its development. To facilitate code contributions by third parties, our libraries for authoring modules [67] require some additional development to make them easier to use by third parties without knowledge of the naming and directory structure conventions we use in authoring code.

## Implications for economic modelling in mental health

Open source approaches have been recommended to help develop the mental health modelling field [88] but only one mental health related model (in Alcohol Use Disorder [89]) is currently indexed in the Open Source Models Clearinghouse [25,90]. We are aware of just one other open source mental health model - a reference model in Major Depressive Disorder - that is currently in development [91].

Approximately 4,000 mental health focused economic evaluation reports were produced between 2000 to 2019 [34]. The intellectual asset represented by this literature could be enhanced if many of the models described in these reports could be brought and kept up to date and made available in formats that maximised transferability to diverse decision contexts. We believe that modular and open source approaches would be well suited to accomplishing this goal and that the framework we have developed could act as an early prototype for solving some of the technical challenges of this task. Ideally such a program of research would be resourced to be sustained over the medium to long term and to engage a diverse network of investigators, contributors and advisers from high, middle and low income countries.

In addition to extracting more value from the existing health economic knowledge base in mental health, there is an opportunity for research funders to shape how future health economic models in mental health are undertaken. Mental health topics accounted for 268 of the 2829 (10%) peer reviewed economic evaluations undertaken during 26 month period in 2012-2014 identified by a review [93]. The ongoing annual output of economic research in mental health that focuses on the other 11 domains identified by Wagstaff and Culyer [35] is probably also substantial. Funders should provide support for the projects and infrastructure to promote greater collaboration, interoperability, transferability and maintenance of future mental health modelling projects.

## General issues for health economists and health research funders

Of the known barriers to adoption of open source models by health economists (including issues like intellectual property and confidentiality [15,27]), our experience suggests that the biggest challenges may be the enormous effort required to first prepare model code and data for public release in formats that facilitate appropriate reuse by third parties and to then maintain and continually improve potentially large numbers of digital artefacts.