A software framework for implementing a transparent, reusable and updatable economic model of youth mental health

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**Summary:**  Economists who use modeling techniques to help inform health policy make limited use of the modular and open source approaches that other disciplines use for collaborative development of complex models. We propose a framework for developing a modular open source economic model (MOSCEM) in youth mental health called ready4. The framework includes of set of seven standards for implementing a MOSCEM that is accountable (three standards), reusable (two standards) and updatable (two standards). We provide a rationale for each standard. The framework also includes a modelling toolkit of open access repositories and six R libraries for authoring MOSCEM modules, supplying those modules with data and implementing reproducible modelling analyses. We describe an early application of the framework to implementing a utility mapping study and detail how the MOSCEM components produced by that study meet 18 framework standards. We discuss how the framework will enable us to undertake and synthesise diverse economic modelling studies in youth mental health and highlight some broader implications for undertaking MOSCEMs to explore mental health and other topics.

**Code:**  Visit <https://www.ready4-dev.com> for more information about how to find, install and apply ready4.

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# Introduction

Health economics is a discipline concerned with problems that arise due to scarce resources, such as how to value health and healthcare, allocate healthcare budgets and configure health services [REF]. In seeking to solve these problems, health economists typically use models which are simplified and selective representations of systems that are believed to influence human health. These representations can be described in words and pictures (a *conceptual* model), in equations (a *mathematical* model) or in computer code (a *computational* model). The predictions reported in health economic studies are typically generated by the execution of a computer program which applies a computational model to compatible data inputs (e.g., parameter values) and performs a sequence of numeric calculations.

Computational models are now widely used to inform health policy and system design [1,2]. This level of influence has concomitant ethical responsibilities for model developers that are often poorly understood and inadequately fulfilled [<https://doi.org/10.3389/fpubh.2017.00068>, 10.1001/amajethics.2021.599., thompson2022escape, thompson2019escape].

We are developing a model to explore multiple economic questions relating to the mental health of young people aged 12 to 25. When making choices about how to implement this model computationally, we wished to facilitate ethical development and use. However, we are not aware of any software framework for implementing CHEMs that adhere to explicitly stated ethical requirements.

In this paper, we describe:

1. a set of ethical responsibilities for CHEM developers and criteria for assessing responsible CHEM implementation;
2. a software framework for ethical implementation of CHEMs; and
3. use of the software framework to develop a computational economic model with an initial focus on valuing outcomes of clients of primary youth mental health services.

# Ethical requirements and assessment criteria

We considered prior literature on modelling practice, our own professional experience and the needs of our project, to identify three core ethical responsibilities of CHEM developers and six criteria (two for each of three model attributes) for assessing ethical CHEM implementations.

## Ethical responsibilities of CHEM developers

We believe that health economists have ethical responsibilities relating to the social acceptability, adequacy for purpose and public benefit of how their computational models are developed and used.

The value judgments of model developers influence the assumptions, selection of model features and standards for evidence that shape the CHEM development process [[https://doi.org/10.1016/j.socscimed.2020.112975](https://doi.org/10.1016/j.socscimed.2020.112975" \t "_blank" \o "Persistent link using digital object identifier)]. These value judgments are rarely made explicit, omissions that may lead to socially unacceptable policy recommendations [9]. For example, to reduce the risk of inequitable policy implementation, it may be important for of a model to predict the benefits of harms of an intervention for different subpopulations [<https://doi.org/10.3389/fpubh.2017.00068>], but model developers may prefer to allocate a project budget to other priorities [thompson2022escape, thompson2019escape].

Health economists have a duty to take sufficient care that a CHEM is adequate for the explicit purpose for which it was developed and to provide potential third party users with the means of assessing its adequacy for their proposed purposes [[10.1186/s12967-020-02540-4](https://doi.org/10.1186/s12967-020-02540-4), https://doi.org/10.1007/s40273-021-01110-w, <https://doi.org/10.3389/fpubh.2017.00068>, thompson2019escape]. Currently, it is common for CHEMs to have poor reproducibility [4–6], insufficient validation [7] and undeclared errors [8], which make achieving these goals more difficult.

Even an acceptable and adequate CHEM will have limited public benefit if it not much used or when its acceptability and adequacy rapidly decay. Model reuse relates to the concepts of generalisability (application without adaptation) and transferability (selective reuse and/or modification of model components) [https://link.springer.com/article/10.2165/11313670-000000000-00000]. Model re-use can also make model implementations more efficient [14]. Common barriers to model re-use include commercial and legal considerations [13], as well as challenges related to model transferability across jurisdictions [GARCIA-MOCHON – Check still valid for rephrase]. To remain valid for longer, models should be continually updated and refined as new evidence emerges and healthcare systems evolve [17]. The temporal window for valid application of CHEMs is often limited by implementation choices that rarely facilitate routine updates [18]. Without appropriate maintenance, a model may become less reliable without that deterioration being apparent to model users and is at greater risk of being deployed for purposes for which it is poorly suited [[10.1098/rsos.172096](https://doi.org/10.1098%2Frsos.172096" \t "_blank)].

## Criteria for assessing ethical CHEM implementation

The acceptability, adequacy and public benefit responsibilities for CHEM developers are easier to state than to measure. It may therefor be pragmatic for assessments of the ethical implementation of CHEMs to instead measure model attributes that promote fulfilment of model developer responsibilities. As described in Table 1 [AUTOMATE\_REF], we believe that implementing CHEMs that are transparent, reusable and updatable (TRU) can help health economists meet their ethical obligations.

**Table 1: How transparent, reusable and updatable models can promote ethical modelling practice.**

|  |  |  |  |
| --- | --- | --- | --- |
| **Model attribute** | **Promotes:** | | |
|  | **Acceptability** | **Adequacy for purpose** | **Public benefit** |
| **Transparent** | Enables assessment. | | Reduces risk of inappropriate use. |
| **Reusable** | Allows adaptation by users with different value judgments. | Facilitates testing by third parties. | Applied to more decision contexts, reduces duplication. |
| **Updatable** | Facilitates adaptations required for application to multiple purposes / contexts. | Extends valid lifetime. |

Transparency has been recommended as a core criterion for assessing ethical public health modelling practice [<https://doi.org/10.3389/fpubh.2017.00068>]. Guidance on transparency in health economic modelling recommended that model code and data should be clearly documented, potentially with different versions for technical and non-technical users [12]. Notably, the same guidelines, published over ten years ago, did not include recommendations on sharing model code and data. However, more recent guidance recommends publicly dissemination of healthcare model artefacts using online repository services [2]. Repositories such as Zenodo [37] and Dataverse [38] provide persistent storage solutions that generate a Digital Object Identifier (DOI) for each code and data collection. An essential component of quality assuring health economic models is verification - ensuring that calculations are correct and consistent with model specifications [44]. The extensiveness of verification checks can be reported using the concept of code coverage [45] - the proportion of model code that has been explicitly tested. The nature and extent of individual model authorship contributions can become unclear when models are implemented over longer time-frames with a large and changing group of collaborators [10]. This issue can be addressed by use of online repository services such as GitHub [36], that provide citation tools and can transparently record all individual code contributions to a modelling project over its lifecycle.

Guidelines for a transparent CHEM:

* T1: All model code, non-confidential data and testing procedures and outcomes are available in open access repositories.
* T2: It is easy to see who developed and tested each part of the model and to identify the modelling team’s assumptions, judgments and theories about model development and use.

Making a CHEM’s code, data and documentation publicly available is helpful but insufficient for promoting model re-use. The choices that CHEM developers make about model implementation and licensing will also shape who can use a model and for what purposes. Using open-source development platforms and licenses can aid both generalizability and transferability. Compared to using commercial modelling software, authoring CHEMs in an open-source language like R [@RCORE2022] makes it easier to store model algorithms and data in distinct files and locations (as opposed to hard coding - embedding data such as parameter values into source code) which facilitates selective modification of model components. This benefit can be further enhanced if model developers adopt a modular approach, in which a model is constructed from multiple reusable and replaceable sub-models (modules) [19]. To grant permissions to others to use and adapt models and their components, health economists can avail of two broad categories of open source licensing options. Some guidance strongly recommends the use of permissive licensing [39] that provides users with great flexibility as to the purposes (including commercial) for which content can be re-used. An alternative approach is to use copyleft licenses [46] that can require content users to distribute any derivative works they create under similar open-source arrangements.

Guidelines for a reusable CHEM:

* R1: Model code and data are implemented to facilitate both generalizability and transferability.
* R2: Anyone can reuse model code and non-confidential data, in whole or in part, without charge under terms of use permitting derivative works.

Ensuring that a model is regular reviewed to identify and implement required improvements is a receommended defence against model validity decay [[10.1098/rsos.172096](https://doi.org/10.1098%2Frsos.172096" \t "_blank)].Key enablers of sustainable maintenance of open source research software are committed, adequately resourced core development team and active user community [REF]. Currently, the core development team for a CHEM will be typically be funded to produce a project end-point deliverable whose specifications are well defined early in the project. For more complex and multi-purpose CHEMs, particularly those designed to be incorporated into decision support systems, it may be better for development teams to adopt Agile Software Development, an approach that has been recommended for complex public health software projects. An Agile model will be less clearly specified in the initial project plan, but will instead continually develop in response to the requirements and feedback of users, who are provided with an initial, simplified working version of the model at the earliest feasible opportunity. Online communities can be an efficient means of engaging model users in testing each version of a model, identifying issues and suggesting improvements. Services such as GitHub [REF] provide tools to help elicit, integrate and reconcile contributions from multiple contributors and to ensure each update is uniquely identifiable and retrievable. It is important that verification checks are rerun with each model update, a task that can be automated using the software development practice of Continuous Integration [54]. The risk of model revisions having unintended consequences for third party users can be mitigated through the use of deprecation conventions that take an informative and staged approach to retiring outdated model code and data.

Guidelines for an updatable CHEM:

* U1: Resources and infrastructure are in place to support sustained development, testing, maintenance and version control of a model in collaboration with model users.
* U2: Each new release of a model is retested, with changes implemented to minimize potential negative impacts for existing model users.

# Software framework

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).

## Online services

We created a GitHub organisation (a collection of code repositories) where all our development code is stored and version controlled. We configured the repositories in our GitHub organisation to use GitHub actions to support continuous integration. Some of the continuous integration checks we have defined assess each R library’s compliance with policies specified by the Comprehensive R Archive Network (CRAN) [56]. To track our code coverage, we linked our GitHub organisation to an account we established at codecov [57].

To facilitate the creation and hosting of R library documentation websites, we enabled GitHub Pages in each repository we used for code library development. We also developed a consolidated and versioned project documentation website that provides guidance on how to contribute to the project. The project documentation website was developed using the Hugo framework [59], Docsy theme [60] and Algolia search [REF] and is hosted using the Netlify [61] service. We linked our Netlify account to our GitHub organisation so that the project website would automatically update whenever the source code in its GitHub repository was edited.

We also created a Zenodo community - a collection of permanent, uniquely identified repositories. We then linked our Zenodo community and GitHub organisation so that every time we specify a version of code in one of our GitHub repositories as a “release”, a copy of that code is automatically created on Zenodo with a DOI. Finally, to manage model datasets, we created a dedicated collection within the Harvard Dataverse installation.

## R libraries

We created six development version R libraries to help us author models, supply those models with data and implement reproducible modelling analyses. The six libraries, their primary focus, the standards they support and the third-party packages they depend on are summarised in Table [**2**](#cpkgs).

A key goal of the ready4 framework packages is to facilitate the standardization and interoperability that will enable the ready4 model adopt a modular approach. Model modules need to be able to share inputs and outputs with each other and to be run as independent models [20]. To achieve this goal, we adopt an object oriented approach in which each ready4 module includes both a data structure (specifying the required properties of data that can validly be supplied to a module) and a set of algorithms (specifying the operations that can be performed on data contained in a module instance).

The foundational framework,,data structure data structures be created and that enable module to be consistently namedThe ready4 library also contains tools for retrieving web based information on ready4 model modules, datasets and analysis programs and for partially automating updates to the project documentation website.

Three R libraries are designed to help standardize workflows for authoring, documenting, testing and disseminating new model modules. The ready4pack library is designed to integrate with our GitHub organisation and provides tools for authoring model modules and desseminating them as themed bundles in R libraries libraries that are:

* documented (with a website, a manual itemising selected contents and a manual itemising all contents);
* licensed (using the copyleft GNU GPL-3 [66] by default);
* easily citable (citation information can be retrieved within an R session or from hosting repositories); and
* quality assured (each update triggers continuous integration workflows, including any unit tests created by module library authors).

The ready4pack library depends on two other module authoring libraries. Writing model algorithms as collections of functions (short, self-contained and reusable software routines that each perform a discrete task), has been recommended as good practice for scientific computing [39]. The ready4fun library contains tools for authoring functions in a consistent house style that automatically generates basic documentation for each function. Functions to implement model algorithms can be associated with a module via a special type of function called a method. Tools from the ready4class [68] library can help streamline and standardise the authoring of module data structures and their associated methods and to automatically generate basic documentation for each module.

The ready4use library [69] contains tools for supplying model modules with data stored in online repositories (hosted on a Dataverse installation or on GitHub), labelling these datasets and then sharing them via online repositories. The ready4show library [70] contains tools to help author R Markdown programs that combine model modules and datasets to undertake analyses. These programs are either self-documenting (code is easy to understand and integrated with plain English explanations of what it does) or trigger the creation of separate documents (e.g. a scientific manuscript).

# Application

Currently, w

We applied the framework to develop an initial set of ready4 modules, supply those modules with data and implement modelling analyses. These outputs were created as part of a previously described study [75] to develop utility mapping models appropriate for use in samples of young people presenting to primary mental health services. The ready4 framework’s modelling toolkit created the following artefacts:

* development version module libraries for describing and validating youth mental health human record datasets [76], scoring health utility [77], specifying utility mapping models [78] and implementing reproducible utility mapping studies [79];
* a development version library of functions for finding and using utility mapping models developed with these tools [80];
* data collections of synthetic populations for testing model modules [81] and study input and results data [82];
* programs for replicating all steps from data ingest to manuscript reporting [83], applying utility mapping models to new data [84] and generating a synthetic representation of the study dataset [85];
* subroutines for creating a catalogue of utility mapping models [86] and generating a draft scientific manuscript [87] for studies implemented with these modules.

We created a checklist (Table 3) that we used to assess the extent to which study outputs met framework standards. We assessed these outputs as wholly or mostly meeting 18 out of 20 standards. The two standards where the study outputs currently fall short are in reporting code coverage and including a user-interface. Both these items are scheduled to be addressed when we release production versions of the code libraries.

# Discussion

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.

## 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.

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.

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]. 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.

Automated tools such as those we developed in our modelling toolkit can help reduce the burden associated with some of these tasks. However, we think the current low rates of adoption by health economists of open source approaches [13,25,26] (which in turn facilitate the collaboration that make modular models more attractive) will only change slowly unless there is significant and strategic investments made by research funders. Currently, incentive structures for health economists do not promote the dedication of large quantities of time to enable peers to reuse their work.

Reducing waste in research is a responsibility of research funders [92] and the poor reproducibility [4–6], limited reusability [13,25,26] and uncertain validity [7,8] of health economic models is wasteful. 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.

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]. Collaboration between teams of health economists can make some complex modelling projects more feasible [14] 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].

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.

## General issues for health economists and health research funders

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. For example, funders have been encouraged to support methodological innovation to improve model transferability [100]. 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.

# Conclusion

We have developed a framework for undertaking a MOSCEM in youth mental health and demonstrated its use by applying it to undertake a utility mapping study. We intend using this framework to undertake and synthesise multiple types of economic research. With further development the framework could be applied to extracting greater value from existing economic models in mental health and to facilitate collaborations between health economists and other stakeholders to address complex mental health modelling challenges. Although MOSCEMs provide a promising opportunity to advance the health economcis field, action from funders is required to realise this potential.

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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

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]. 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 computational health economic models (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].

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## Availability of data and materials

The most up to date and comprehensive source of documentation on our framework and model is available at <https://www.ready4-dev.com> . Development versions of all code repositories referenced in this article are available in <https://github.com/ready4-dev/> . Archived code releases are available in <https://zenodo.org/communities/ready4> . All data repositories referenced in this article are available in <https://dataverse.harvard.edu/dataverse/ready4> .

## Ethics approval

Framework development did not involve human subject research and was not ethically reviewed. The utility mapping worked example is a previously reported study that was reviewed and granted approval by the University of Melbourne’s Human Research Ethics Committee, and the local Human Ethics and Advisory Group (1645367.1).

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## Conflict of Interest

None declared.

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