

The ready4 framework for implementing a modular open source health economic model (MOSHEM) in youth mental health that is accountable, reusable and updatable

Matthew P Hamilton^{1,2,*} Caroline X Gao^{1,3,2} Glen Wiesner⁴ Kate M Filia^{1,3}
Jana M Menssink^{1,3} Petra Plencnerova⁵ David Baker^{1,3}
Patrick D McGorry^{1,3} Alexandra Parker⁶ Jonathan Karnon⁷ Sue M Cotton^{1,3}
Cathrine Mihalopoulos²

Abstract

Summary: Health economists make limited use of the modular and open source approaches to model building that other disciplines use to make large modelling projects more transparent, efficient and sustainable. We propose a framework for developing a modular open source health economic model (MOSHEM) in youth mental health called ready4. The framework includes a set of 20 standards for implementing a MOSHEM that is accountable (seven standards), reusable (nine standards) and updatable (four 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 ready4 modules (data structures and algorithms), supplying those modules with data and using the modules to implement reproducible modelling analyses. We describe an early application of the framework to developing utility mapping models that currently meet 18 framework standards. We discuss the potential benefits and challenges of extending ready4 in order to undertake and synthesise diverse economic modelling studies in youth mental health and highlight some broader implications for health economists and research funders.

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

¹ Orygen, Parkville, Australia

² School of Public Health and Preventive Medicine, Monash University, Clayton, Australia

³ Centre for Youth Mental Health; The University of Melbourne, Parkville, Australia

⁴ Heart Foundation, Melbourne, Australia

⁵ headspace National Youth Mental Health Foundation, Melbourne, Australia

⁶ Victoria University, Footscray, Australia

⁷ Flinders University, Adelaide, Australia

* Correspondence: Matthew P Hamilton <matthew.hamilton@orygen.org.au>

1 Introduction

Computational models, particularly those addressing economic topics, have become essential tools for health policy development [1,2]. Although influential and widely used, health economic models typically have a number of limitations that at best restrict their usefulness and which in some cases may facilitate harmful misuse.

There is a strong case for making health economists more accountable for the appropriate use and social acceptability of their models. Users of models should be able to assess their adequacy for a particular purpose [3]. This goal is difficult to achieve in the current context of the poor reproducibility [4–6] and

frequently insufficient validation [7] of health economic models. Many health economic models are released with undeclared errors [8]. The value judgments that strongly shape health economic analyses are rarely made explicit, omissions that may lead to socially unacceptable policy recommendations [9]. A modelling team's value judgments about what questions to address, the most important features of a system to represent and the weighting of different types of evidence may be poorly aligned with those of the people impacted by decisions informed by model analyses [10]. As health economic models adopt more sophisticated techniques, the need for accountability grows. More complex models may be more prone to propagation errors [11] and models designed to address multiple questions should be expected to meet more onerous verification and validation obligations [12,13]. The nature and extent of individual model authorship contributions may be less clear in models implemented over longer time-frames with a large and changing group of collaborators [10].

The resource and skills intensive undertaking of modelling could be made more tractable if it was easier for health economists to re-use each other's models [14]. However, as many health economic models are owned by pharmaceutical companies and consultancies, commercial considerations can limit the reuse of models and their constituent code and data [13]. Legal and ethical issues such as privacy and confidentiality requirements further limit public release of some model artefacts [15]. Transferring a health economic model developed for one jurisdiction for application in another typically involves retaining some features and updating others [16]. However, models do not always make implementation choices (for example, use of concepts with standardised meanings across jurisdictions, supplying context specific data as replaceable data-packs and distributing source code under licenses that allow derivative works) that facilitate model transferability.

Health economic models should be updated and refined as new evidence emerges and decision contexts change [17], but this occurs infrequently [18]. 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, it being 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.

A potential strategy for improving model accountability, reusability and updatability is to make models both modular and open-source.

A modular model is constructed from multiple reusable and replaceable sub-models (modules) [19]. Modules can share inputs and outputs with other modules or can be run as independent models [20]. 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 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]. Although there appears to be in principle support from many health economists for greater use of open source health economic models (OSHEMs) [15], actual implementations are rare [13,25,26]. Barriers to adoption of OSHEMs include concerns about intellectual property, confidentiality, model misuse and the resources required to support open source implementations [15,27]. Adherence to good practice guidance is an essential requirement for healthcare modelling [2], but guidelines for implementing OSHEMs remain scarce, piecemeal and need improving [28].

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.

We are developing ready4 (<https://www.ready4-dev.com>), a modular OSHEM (MOSHEM) on the mental health of young people aged 12 to 25. We are initially applying ready4 to four of the twelve domains of health economics identified by Wagstaff and Culyer [35]:

- *health and its value* (our projects: utility mapping models);
- *determinants of health and ill-health* (our projects: models for creating synthetic household populations with key risk and protective factors for mental disorders);
- *demand for health and health care* (our projects: spatial epidemiology and help-seeking choice models); and
- *supply of health services* (our projects: a model of primary mental health care services).

Once these projects are completed, our aim is to flexibly combine these models to answer questions in two additional Wagstaff and Culyer domains:

- *efficiency and equity* (our goal: assess the distributional impacts and identify the optimal targeting of care provision); and
- *economic evaluation* (our goal: assess the cost-utility of competing policy options for improving the mental health of young people).

Standardisation is an essential enabler of automation, collaboration, interoperability and transferability in modular and open source approaches. An early requirement to implement ready4 is therefore to identify an appropriate set of standards. However, we are not aware of any consolidated source of guidance about recommended standards for MOSHEMs. Once identified, the standards specified for ready4 will need to be implemented by software, some of which will require custom development.

In this paper, we describe:

- (i) the ready4 framework, that is comprised of:
 - a set of standards for implementing an accountable, reusable and updatable MOSHEM; and
 - a modelling toolkit (online repositories and software) for applying those standards to the authoring of MOSHEM modules, datasets and analyses; and
- (ii) how we used the ready4 framework to develop and apply modules for utility mapping.

2 The ready4 framework

To enable us to implement ready4, we have developed a framework that:

- specifies a set of standards for MOSHEM development and use; and
- provides a modelling toolkit (repositories and software) for authoring model modules, managing data and implementing reproducible analyses consistent with those standards.

2.1 Standards

Based on published guidance on computational modelling in health economics and other disciplines as well as our own experience, we have identified 20 standards that we believe are important for implementing a MOSHEM that is accountable (seven standards), reusable (nine standards) and updatable (four standards). The standards are specified in Table 1 and are discussed below.

Table 1: Framework standards

Objective	Standard	Meaning
Accountable - it is easy to see who developed, tested and applied a model and how they did it.		
	A1	Open online repositories are used to permanently archive, uniquely identify and transparently record authorship and development history of model code and data.
	A2	Model code and data are documented.
	A3	Model code uses consistent and abstracted syntax.
	A4	Literate programming is used to implement model analyses.
	A5	Model code coverage is reported.
	A6	All parts of a study analysis and reporting workflow can be reproduced and/or replicated.
	A7	Model code and data are distributed with tools to support appropriate citation.
Reusable - a model and its components can be used in other models and by other modellers.		
	R1	Model code is made available for re-use under copyleft or permissive licenses.
	R2	Non-confidential model data is licensed for liberal re-use (potentially subject to ethical use terms).
	R3	Model code and data are stored and managed separately.
	R4	Model code uses encapsulation and inheritance for data structures.
	R5	Model code uses functions to implement algorithms.
	R6	Model code is distributed as code libraries.
	R7	Test data is available to demonstrate the transferability of model code.
	R8	Statistical models are distributed with tools for making out of sample predictions.
	R9	User-interfaces allow non-technical users to configure and use models.
Updatable - a model and its components are maintained and continuously improved.		
	U1	Model code and data are version controlled.
	U2	The significance and status of code and data updates are indicated with semantic versioning and release types.
	U3	Continuous integration is used to verify model code updates.
	U4	Deprecation conventions are used to retire model code and data.

2.1.1 Standards for an accountable MOSHEM

Guidance on transparency in health economic modelling published over ten years ago [12] made recommendations on documenting models but notably did not include recommendations on sharing model code and data. However, more recent and multidisciplinary healthcare modelling guidance [2] recommends using existing digital repository services to these types of digital model artefacts. Some types of repository such as GitHub [36] provide tools for disseminating work in progress code and providing highly transparent records of the complete development history and individual authorship contributions of a software project, while others such as Zenodo [37] and Dataverse [38] provide persistent storage solutions that generate a Digital Object Identifier (DOI) for each code and data collection.

Model code and data should be clearly documented, potentially with different versions for technical and non-technical users [12]. 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.

An essential component of quality assuring health economic models is verification - ensuring that calculations are correct and consistent with model specifications [44]. One useful concept for informing model users about the extensiveness of verification checks is code coverage [45] - the proportion of model code that has been explicitly tested. 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.

2.1.2 Standards for a reusable MOSHEM

To make model code and data widely re-usable by others, it is important to provide users with appropriate and explicit permissions. In the context of open source models, there are two broad categories of 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 the content could 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. 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).

Storing model code and data in separate files and locations (as opposed to hard coding - embedding data into source code) can make it easier to apply models to different decision contexts and to selectively restrict access to data that are confidential, while disseminating all other model artefacts. 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]. Writing algorithms as collections of functions (short, self-contained and reusable software routines that each perform a discrete task) is recommended as good practice for scientific computing [39]. Functions to implement model algorithms can be associated with data structures (also known as a class) via a special type of function called a method. 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 doing so if models are derived from data on human subjects as some software artefacts by default contain a copy of the source dataset. Such 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 MOSHEMs easier to use is to develop simple user-interfaces for non-technical users.

2.1.3 Standards for an updatable MOSHEM

To avoid MOSHEMs going stale - losing validity and usefulness with time - they should be routinely updated. Each update of code and data should be uniquely identifiable and retrievable, a goal that can be facilitated by use of version control tools [2] such as [52].

Potential users of model code and data should be able to easily identify which version is most appropriate to their needs. Using semantic versioning [53] conventions can signal the potential importance of an update to users of model code and data. Also informative is to clearly label the type of code hosted in a repository as either:

- “development” (typically the most comprehensive and up to date source code, but potentially not yet sufficiently well documented and tested for potential users to apply to purposes other than testing);
- “production” (code that has been released with a view to it being applied to its stated purposes and therefore typically required to meet defined documentation and testing standards); or
- “archive” (permanent copies of code at key milestones in its development - potentially useful if seeking to use older versions of code to reproduce analyses).

Continuous integration [54] tools can help verify that each code update passes multiple quality tests. Finally, using deprecation conventions that take an informative and staged approach to retiring old code and data reduces the risk that model revisions have unintended consequences on third party users.

2.2 Modelling toolkit

We developed a toolkit to help us develop and use MOSHEM modules, datasets and analyses that meet the standards listed in Table 1. The toolkit is comprised of online repositories and software.

2.3 Repositories

We created a GitHub organisation (a collection of code repositories) where all our development code is stored and version controlled [55]. We linked our GitHub organisation to an account we established at codecov [56] to track our code coverage. 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 library’s compliance with policies specified by the Comprehensive R Archive Network (CRAN) [57], to which we plan submitting future production releases.

For hosting documentation websites for the code libraries we create, we enabled GitHub Pages in each library’s repository. We also developed a consolidated and versioned project documentation website [58], using the Hugo framework [59] and Docsy theme [60]. To host that website we established an account with Netlify [61] and linked that service to our GitHub organisation so that the website would automatically update whenever the source code in its GitHub repository was edited.

We also created a Zenodo community [62] - a collection of permanent, uniquely identified repositories. We then linked our Zenodo community and GitHub organisation so that every time we create a new “release” in a GitHub repository, 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 [63].

2.4 Software

We created six development version R libraries to help us author model modules, supply them 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.

A library called `ready4` [64] defines a template module (using R’s S4 type class) from which all model module data structures will inherit features and a novel syntax for implementing the algorithms attached to model modules. The `ready4` library also contains tools for retrieving web based information on model modules, datasets and analysis programs and for partially automating updates to the project website.

Three R libraries are designed to standardise and partially automate workflows for authoring new model modules. The `ready4pack` library [65] is designed to integrate with our GitHub organisation and provides tools for authoring module libraries that are:

- documented (with a website, a manual itemising selected contents and a manual itemising all contents);
- licensed (using 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. Methods from the `ready4fun` library [67] are used to verify that functions for implementing module algorithms are written in a consistent house style. That standardised format is then used by `ready4fun` methods to automatically generate basic documentation for each function. Methods from the `ready4class` [68] library are used to streamline and standardise the authoring of module data structures and the linking of methods to these data structures. Like `ready4fun`, the `ready4class` library uses standardised code implementation to automatically generate basic documentation for each module data structure.

The `ready4use` library [69] contains modules for ingesting model datasets from online repositories (hosted on a Dataverse installation or on GitHub), labelling model datasets and sharing model datasets via online repositories. The `ready4show` library [70] contains tools to help author analyses programs that are either self-documenting or which trigger the creation of a scientific summary.

When used in conjunction with repositories, the six R libraries provide strong support for implementing 17 out of 20 framework standards. 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.

Table 2: Modelling toolkit R libraries for developing and using MOSHEMs that meet framework standards




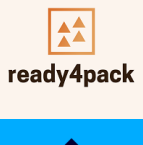


Package	Focus	Standard	Depends on these R libraries
	Foundation	A3 R4	assertthat bib2df dataverse dplyr fs Hmisc kableExtra knitr lifecycle magrittr methods natmanager piggyback purrr readr readxl rlang rmarkdown rvest stats stringi stringr testit testthat tibble tidyRSS tools utils zen4R
	Module algorithms	A2-3 R5	desc devtools dplyr generics gert Hmisc knitr lifecycle lubridate magrittr methods piggyback pkgdown purrr readxl ready4 ready4show ready4use rlang sinew stats stringi stringr testit testthat tibble tidyr tools usethis utils xfun
	Module structures	A2 R4-5	devtools dplyr fs gtools Hmisc knitr lifecycle magrittr methods purrr ready4 ready4fun ready4show rlang stats stringi stringr testit testthat tibble tidyr usethis utils
	Module libraries	A1-2,5,7 R1,3,6 U1-3	dataverse dplyr knitr lifecycle magrittr methods purrr ready4 ready4class ready4fun rlang stringr testthat tibble tidyr utils
	Datasets	A1-2,7 R3,7 U1	data.table dataverse dplyr fs Hmisc knitr lifecycle magrittr methods piggyback purrr readxl ready4 ready4show rlang stats stringi stringr testit testthat tibble tidyr utils
	Analyses	A4,6	dataverse DescTools dplyr flextable grDevices here Hmisc kableExtra knitr knitrBootstrap lifecycle magrittr methods officer purrr ready4 rlang rmarkdown stringi stringr testthat tibble tidyr utils xtable

Table 3: Framework checklist applied to utility mapping study

	Standard	Met?	Description
A1	Public	Yes	Datasets are available at https://doi.org/10.7910/DVN/DKDIB0 and https://doi.org/10.7910/DVN/HJXYKQ . For details of where to find Development and Archive code see: https://www.ready4-dev.com/docs/getting-started/software/libraries/types/module/ https://www.ready4-dev.com/docs/getting-started/software/executables/programs/ https://www.ready4-dev.com/docs/getting-started/software/executables/subroutines/
A2	Documentation	Yes	All code libraries have documenting websites with URLs that concatenate ‘ https://ready4-dev.github.io/ ’ and the library name (e.g. https://ready4-dev.github.io/youthvars). All three Markdown programs are self-documenting, with one [75] including additional instructions in a README file. Only one sub-routine [76] is documented with a meaningful README file. All datasets have meaningful metadata descriptors.
A3	Syntax	Yes	All libraries are authored with ready4pack [65] to ensure a consistent house style. All libraries except [77] use framework syntax, as does one program [75].
A4	Literate programming	Yes	All programs use literate programming.
A5	Code coverage	No	No current reporting of code coverage.
A6	Reproducibility	Yes	All parts of the study workflow from raw data ingest through to data processing, analysis, reporting and dissemination of study outputs can be reproduced (if granted access to source data) or replicated (using supplied synthetic data) with one program [75].
A7	Citation tools	Yes	All libraries can return citation details when running R’s ‘citation’ function. All code and data repositories have tools to generate citation details.
R1	Code licenses	Yes	All code libraries, programs and sub-routines use GPL-3 licenses.
R2	Data terms	Yes	Datasets use amended version of template provided by Harvard Dataverse [49].
R3	Separation	Yes	All development code is stored on repos in a GitHub organisation [55] and all archived code releases are available in a Zenodo community [62]. All non-confidential data are stored in repositories within a Harvard Dataverse collection [63].
R4	Encapsulated, inheriting	Yes	Four [78–81] out of five libraries include encapsulating and inheriting modules. See: https://www.ready4-dev.com/docs/model/finding-modules/
R5	Functions	Yes	All code libraries include functions. The most complete list of functions for each library is available by clicking the ‘Manual - Developer (PDF)’ link on each package’s documentation homepage (see item A2 above). The relationship between functions can be illustrated using an app: https://www.ready4-dev.com/docs/getting-started/software/libraries/dependencies/
R6	Libraries	Yes	All module data-structures and algorithms are distributed as five code libraries [77–81].

	Standard	Met?	Description
R7	Test data	Yes	Two synthetic datasets and their data dictionaries are publicly available in a data repository [82]. One (ymh_clinical_tb.RDS) closely resembles the study dataset and was released so that the main study algorithm [75] can be rerun by those without access to the confidential study dataset. The other (eq5d_ds_tb.Rds) is deliberately different to the source dataset in both variable naming convention and the concepts used for predictors and outcome measures. It was created to demonstrate the transferability of study algorithms.
R8	Prediction tools	Yes	Model catalogues (PDF files beginning with ‘AAA_TTU_MDL_CTG’) are available in the study results dataset [83] and describe the predictive performance of all models under a variety of usage regimes (including when the source dataset in the R model object is replaced with fake data). The youthu library [77] includes tools for searching for and applying models compatible with different types of input data. An example program to demonstrate this functionality is available in both RMarkdown [84] and rendered PDF formats (the ‘Application.pdf’ file in the study results dataset [83]).
R9	User interface	No	No user interface has yet been developed.
U1	Version controlled	Yes	All code is version controlled using git [52] and GitHub [36]. All source code is available in a GitHub organisation [55].
U2	Semantic versioning	Yes	Semantic versioning is used in all code. As no code library has yet been submitted to CRAN [57], only the development version extensions of each version number have been incremented to date.
U3	Continuously integrated	Yes	All five libraries use continuous integration (CI). CI results for each library can be viewed at a URL that concatenates ‘https://github.com/ready4-dev/’, the library name and ‘/actions’ (e.g. https://github.com/ready4-dev/youthvars/actions)
U4	Deprecation	Yes	Retired code is deprecated using tools from the lifecycle R library [74] (e.g. everything after “## DEPRECATED FNS” in https://github.com/ready4-dev/youthvars/blob/main/data-raw/fns/add.R). Package vignettes and datasets are also deprecated e.g. https://ready4-dev.github.io/youthvars/articles/Replication_DS.html)

3 Application

We applied the ready4 framework to develop an initial set of MOSHEM modules, supplying those modules with data and implementing analyses. These tools were created as part of a previously described study [85] 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 [78], scoring health utility [79], specifying utility mapping models [80] and implementing reproducible utility mapping studies [81];
- a development version library of functions for finding and using utility mapping models developed with these tools [77];
- data collections of synthetic populations for testing model modules [82] and study input and results data [83];
- programs for replicating all steps from data ingest to manuscript reporting [75], applying utility mapping models to new data [84] and generating a synthetic representation of the study dataset [86];
- subroutines for creating a catalogue of utility mapping models [87] and generating a draft scientific manuscript [76] for studies implemented with these modules.

We assess that these study outputs either wholly or mostly meet 18 out of 20 framework standards (see Table 3). 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.

4 Discussion

In this article we described a framework that we developed to help us implement ready4 - a MOSHEM in youth mental health. We outlined framework standards for an accountable, reusable and updatable MOSHEM and described the modelling toolkit we created for applying those standards to the development and use of the ready4 MOSHEM. We also provided an overview of an initial set of MOSHEM 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 MOSHEM and for health economic modelling in mental health and highlights more general issues for health economic modellers and funders of health economic research.

4.1 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 MOSHEM 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 [78–81], datasets [82,83]; analyses [75,84,86], reporting templates [76,87] and prediction tools [77] used in a utility mapping study [85]. 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 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 [75] combines modules from four module libraries ([78–81]) and two framework libraries [69,70]. Example literate programs published on the ready4 documentation website [58] use toy data [82] to illustrate the potential for ready4 modules to facilitate study replication and transferability. The framework’s standards also provide a mechanism for to assess the extent to which the ready4 MOSHEM meets explicit accountability, reusability and updatability goals.

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.

Currently all the framework and 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 [57]. Making these libraries available on CRAN is a likely prerequisite of high levels of reuse. Similarly, completing our current work program will create new tools for modelling help-seeking choice, spatial epidemiology, household populations and primary mental health services that may enhance the potential usefulness of the ready4 MOSHEM to health economists working in youth mental health.

4.2 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 enormous effort that is required to prepare model code and data for public release in formats that facilitate appropriate reuse by third parties and to maintain and improve these artefacts may be the biggest challenge.

Automated tools such as those we developed in our modelling toolkit can help reduce the burden of 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) is unlikely to change soon without significant and strategic changes by research funders. The incentive structures that health economists work within do not promote the investment of significantly more time on each study 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 very substantial 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 programme 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 about 268 of 2829 (10%) peer reviewed economic evaluations undertaken during 26 month period in 2012-2014 identified in a previous review [93]. There is also likely to a substantial annual output of economic research in mental health that focuses on the other 11 domains identified by Wagstaff and Culyer [35].

Providing adequate levels of funding to support MOSHEMs, fostering skills, supplying infrastructure (t)

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].

Estimating the potential uptake of these tools is difficult.

Similarly, developing partnerships between modellers and decision-makers across the life-cycle of a modelling project can help ensure models are appropriately conceptualised, implemented and have practical utility as decision aids [100,101].

- Community building (feasibility)
- Funding contingent directions - replications / transfers

4.3 Implications for health economists

Output by health economists [35,93,102]

4.4 Implications for research funders

- unreasonable to expect more accountability without more resources

Major mental health reform programs, can involve the identification, prioritisation, sequencing, targeting and monitoring of multiple interdependent initiatives.

The development, validation and updating of more complex mental health economic models implemented over longer time frames may be too onerous a burden for a single modelling team.

5 Conclusion

Acknowledgement

The authors would like to acknowledge the contribution of John Gillam who provided advisory input to this research.

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).

Funding

Framework development was funded by Orygen, VicHealth and Victoria University. The utility mapping study used as a worked example was funded by the National Health and Medical Research Council (NHMRC, APP1076940), Orygen and headspace.

Conflict of Interest

None declared.

References

1. Dakin H, Devlin N, Feng Y, Rice N, O'Neill P, Parkin D. The influence of cost-effectiveness and other factors on nice decisions. *Health economics*. Wiley Online Library; 2015;24: 1256–1271.
2. Erdemir A, Mulugeta L, Ku JP, Drach A, Horner M, Morrison TM, et al. Credible practice of modeling and simulation in healthcare: Ten rules from a multidisciplinary perspective. *Journal of translational medicine*. 2020;18: 369. doi:10.1186/s12967-020-02540-4
3. Thompson EL, Smith LA. Escape from model-land. *Economics*. De Gruyter Open Access; 2019;13.
4. Jalali MS, DiGennaro C, Guitart A, Lew K, Rahmandad H. Evolution and reproducibility of simulation modeling in epidemiology and health policy over half a century. *Epidemiologic Reviews*. 2021;43: 166–175. doi:10.1093/epirev/mxab006
5. McManus E, Turner D, Sach T. Can you repeat that? Exploring the definition of a successful model replication in health economics. *Pharmacoeconomics*. 2019;37: 1371–1381. doi:10.1007/s40273-019-00836-y
6. Bermejo I, Tappenden P, Youn J-H. Replicating health economic models: Firm foundations or a house of cards? *PharmacoEconomics*. 2017;35: 1113–1121. doi:10.1007/s40273-017-0553-x
7. Ghabri S, Stevenson M, Möller J, Caro JJ. Trusting the results of model-based economic analyses: Is there a pragmatic validation solution? *Pharmacoeconomics*. 2019;37: 1–6. doi:10.1007/s40273-018-0711-9
8. Radeva D, Hopkin G, Mossialos E, Borrill J, Osipenko L, Naci H. Assessment of technical errors and validation processes in economic models submitted by the company for NICE technology appraisals. *International Journal of Technology Assessment in Health Care*. 2020;36: 311–316. doi:10.1017/S0266462320000422
9. Duckett S. A journey towards a theology of health economics and healthcare funding. *Theology*. SAGE Publications Sage UK: London, England; 2022;125: 326–334.
10. Thompson E. Escape from model land: How mathematical models can lead us astray and what we can do about it. New Yourk: Basic Books; 2022.
11. Saltelli A. A short comment on statistical versus mathematical modelling. *Nature Communications*. 2019;10: 3870. doi:10.1038/s41467-019-11865-8
12. Eddy DM, Hollingworth W, Caro JJ, Tsevat J, McDonald KM, Wong JB. Model transparency and validation: A report of the ISPOR-SMDM modeling good research practices task force-7. *Med Decis Making*. 2012;32: 733–43. doi:10.1177/0272989x12454579
13. Feenstra T, Corro-Ramos I, Hamerlijnck D, Voorn G van, Ghabri S. Four aspects affecting health economic decision models and their validation. *PharmacoEconomics*. 2022;40: 241–248. doi:10.1007/s40273-021-01110-w
14. Arnold RJG, Ekins S. Time for cooperation in health economics among the modelling community. *PharmacoEconomics*. 2010;28: 609–613. doi:10.2165/11537580-000000000-00000
15. Pouwels X, Sampson CJ, Arnold RJG. Opportunities and barriers to the development and use of open source health economic models: A survey. *Value Health*. 2022;25: 473–479. doi:10.1016/j.jval.2021.10.001
16. Barbieri M, Drummond M, Rutten F, Cook J, Glick HA, Lis J, et al. What do international pharmacoeconomic guidelines say about economic data transferability? *Value in Health*. Elsevier; 2010;13: 1028–1037.
17. Jenkins DA, Martin GP, Sperrin M, Riley RD, Debray TPA, Collins GS, et al. Continual updating and monitoring of clinical prediction models: Time for dynamic prediction systems? *Diagnostic and Prognostic Research*. 2021;5: 1. doi:10.1186/s41512-020-00090-3
18. Sampson CJ, Wrightson T. Model registration: A call to action. *PharmacoEconomics - Open*. 2017;1: 73–77. doi:10.1007/s41669-017-0019-2

19. Pan M, Gawthrop PJ, Cursons J, Crampin EJ. Modular assembly of dynamic models in systems biology. *PLoS computational biology*. Public Library of Science San Francisco, CA USA; 2021;17: e1009513.
20. Barros C, Luo Y, Chubaty AM, Eddy IM, Micheletti T, Boisvenue C, et al. Empowering ecological modellers with a PERFICT workflow: Seamlessly linking data, parameterisation, prediction, validation and visualisation. *Methods in Ecology and Evolution*. Wiley Online Library; 2023;
21. Frazier-Logue N, Wang J, Wang Z, Sodums D, Khosla A, Samson AD, et al. A robust modular automated neuroimaging pipeline for model inputs to TheVirtualBrain. *Frontiers in Neuroinformatics*. Frontiers Media SA; 2022;16: 883223.
22. Afzali HH, Karnon J, Merlin T. Improving the accuracy and comparability of model-based economic evaluations of health technologies for reimbursement decisions: A methodological framework for the development of reference models. *Med Decis Making*. 2013;33: 325–32. doi:10.1177/0272989x12458160
23. Trauer JM, Ragonnet R, Doan TN, McBryde ES. Modular programming for tuberculosis control, the “AuTuMN” platform. *BMC Infectious Diseases*. 2017;17: 546. doi:10.1186/s12879-017-2648-6
24. Urach C, Zauner G, Endel G, Wilbacher I, Breitenecker F. A modular simulation model for assessing interventions for abdominal aortic aneurysms. 2013 winter simulations conference (WSC). 2013. pp. 66–76. doi:10.1109/WSC.2013.6721408
25. Emerson J, Bacon R, Kent A, Neumann PJ, Cohen JT. Publication of decision model source code: Attitudes of health economics authors. *PharmacoEconomics*. 2019;37: 1409–1410. doi:10.1007/s40273-019-00796-3
26. Michalczyk J, Clay E, Pochopien M, Aballea S. PRM123 - AN OVERVIEW OF OPEN-SOURCE MODELS IN HEALTH ECONOMICS. *Value in Health*. 2018;21: S377. doi:10.1016/j.jval.2018.09.2243
27. Wu EQ, Zhou Z-Y, Xie J, Metallo C, Thokala P. Transparency in health economic modeling: Options, issues and potential solutions. *PharmacoEconomics*. 2019;37: 1349–1354. doi:10.1007/s40273-019-00842-0
28. Sampson CJ, Arnold R, Bryan S, Clarke P, Ekins S, Hatswell A, et al. Transparency in decision modelling: What, why, who and how? *PharmacoEconomics*. 2019;37: 1355–1369. doi:10.1007/s40273-019-00819-z
29. Bloom DE, Cafiero ET, Jané-Llopis E, Abrahams-Gessel S, Bloom LR, Fathima S, et al. The global economic burden of noncommunicable diseases. 91-93 route de la Capite, CH-1223 Cologny/Geneva, Switzerland: World Economic Forum.; 2011.
30. Global, regional, and national burden of 12 mental disorders in 204 countries and territories, 1990–2019: A systematic analysis for the global burden of disease study 2019. *The Lancet Psychiatry*. 2022;9: 137–150. doi:10.1016/S2215-0366(21)00395-3
31. Chisholm D, Sweeny K, Sheehan P, Rasmussen B, Smit F, Cuijpers P, et al. Scaling-up treatment of depression and anxiety: A global return on investment analysis. *The Lancet Psychiatry*. 2016; doi:10.1016/s2215-0366(16)30024-4
32. Saxena S, Thornicroft G, Knapp M, Whiteford H. Resources for mental health: Scarcity, inequity, and inefficiency. *The Lancet*. 370: 878–889. doi:10.1016/S0140-6736(07)61239-2
33. Whiteford H, Ferrari A, Degenhardt L. Global burden of disease studies: Implications for mental and substance use disorders. *Health Affairs*. 2016;35: 1114–1120. doi:10.1377/hlthaff.2016.0082
34. Knapp M, Wong G. Economics and mental health: The current scenario. *World Psychiatry*. 2020;19: 3–14. doi:10.1002/wps.20692
35. Wagstaff A, Culyer AJ. Four decades of health economics through a bibliometric lens. *Journal of health economics*. Elsevier; 2012;31: 406–439.
36. github. GitHub [Internet]. 2007. Available: <https://github.com/>
37. European Organization For Nuclear Research, OpenAIRE. Zenodo [Internet]. CERN; 2013. doi:10.25495/7GXK-RD71

38. Quantitative Social Science I for. Dataverse [Internet]. Harvard University; 2007. Available: <https://dataverse.org>
39. Wilson JAC Greg AND Bryan. Good enough practices in scientific computing. PLOS Computational Biology. Public Library of Science; 2017;13: 1–20. doi:10.1371/journal.pcbi.1005510
40. Alarid-Escudero F, Krijkamp EM, Pechlivanoglou P, Jalal H, Kao S-YZ, Yang A, et al. A need for change! A coding framework for improving transparency in decision modeling. Pharmacoeconomics. 2019;37: 1329–1339. doi:10.1007/s40273-019-00837-x
41. Hourani H, Wasmi H, Alrawashdeh T. A code complexity model of object oriented programming (OOP). 2019 IEEE jordan international joint conference on electrical engineering and information technology (JEEIT). 2019. pp. 560–564. doi:10.1109/JEEIT.2019.8717448
42. Milojkovic N, Caracciolo A, Lungu MF, Nierstrasz O, Röthlisberger D, Robbes R. Polymorphism in the spotlight: Studying its prevalence in java and smalltalk. 2015 IEEE 23rd international conference on program comprehension. 2015. pp. 186–195. doi:10.1109/ICPC.2015.29
43. Xie Y, Allaire JJ, Grolemond G. R markdown: The definitive guide. Chapman; Hall/CRC; 2018.
44. Büyükkaramikli NC, Rutten-van Mölken MPMH, Severens JL, Al M. TECH-VER: A verification checklist to reduce errors in models and improve their credibility. Pharmacoeconomics. 2019;37: 1391–1408. doi:10.1007/s40273-019-00844-y
45. Eric Wong W, Debroy V, Choi B. A family of code coverage-based heuristics for effective fault localization. Journal of Systems and Software. 2010;83: 188–208. doi:https://doi.org/10.1016/j.jss.2009.09.037
46. Foundation TFS. What is copyleft? [Internet]. Available: <https://www.gnu.org/copyleft/>
47. Commons C. CC0 1.0 universal [Internet]. 2022. Available: <https://creativecommons.org/publicdomain/zero/1.0/legalcode>
48. Commons C. Attribution-ShareAlike 4.0 international [Internet]. 2022. Available: <https://creativecommons.org/licenses/by-sa/4.0/legalcode>
49. Quantitative Social Science I for. Sample data usage agreement [Internet]. 2022. Available: <https://support.dataverse.harvard.edu/sample-data-usage-agreement>
50. Hamilton M. Apply an object-oriented paradigm to computational models of mental health systems [Internet]. 2022. Available: https://ready4-dev.github.io/ready4/articles/V_03.html
51. Kearns B, Ara R, Wailoo A, Manca A, Alava MH, Abrams K, et al. Good practice guidelines for the use of statistical regression models in economic evaluations. Pharmacoeconomics. 2013;31: 643–652. doi:10.1007/s40273-013-0069-y
52. git. Git [Internet]. Available: <https://git-scm.com/>
53. Preston-Werner T. Semantic versioning 2.0.0 [Internet]. 2022. Available: <https://semver.org>
54. Shahin M, Ali Babar M, Zhu L. Continuous integration, delivery and deployment: A systematic review on approaches, tools, challenges and practices. IEEE Access. 2017;5: 3909–3943. doi:10.1109/ACCESS.2017.2685629
55. Orygen. ready4: A suite of authoring, modelling and prediction tools for exploring topics in young people’s mental health [Internet]. 2022. Available: <https://github.com/ready4-dev/>
56. Codecov [Internet]. Available: <https://about.codecov.io/>
57. Statistical Computing RF for. The comprehensive r archive network [Internet]. 2022. Available: <https://cran.r-project.org>
58. Orygen. ready4 - a modular computational model in youth mental health [Internet]. Available: <https://ready4-dev.com/>

59. Hugo: The world's fastest framework for building websites [Internet]. Available: <https://gohugo.io>
60. Docsy [Internet]. Available: <https://www.docsy.dev>
61. Netlify [Internet]. Available: <https://www.netlify.com>
62. Orygen. ready4: Open and modular mental health systems models [Internet]. 2022. Available: <https://zenodo.org/communities/ready4>
63. Orygen. ready4: Open and modular mental health systems models [Internet]. 2022. Available: <https://dataverse.harvard.edu/dataverse/ready4>
64. Hamilton MP. ready4: Implement open science computational models of mental health systems [Internet]. 2021. doi:10.5281/zenodo.5606250
65. Hamilton M. ready4pack: Author r packages that extend the Ready4 framework [Internet]. 2022. doi:10.5281/zenodo.5644322
66. Foundation TFS. Licenses [Internet]. 2022. Available: <https://www.gnu.org/licenses>
67. Hamilton M, Wiesner G. ready4fun: Author and document functions that extend the Ready4 framework [Internet]. 2022. doi:10.5281/zenodo.5611779
68. Hamilton M, Wiesner G. ready4class: Author Ready4 framework modules [Internet]. 2022. doi:10.5281/zenodo.5640313
69. Hamilton M, Wiesner G. ready4use: Author, label and share Ready4 framework datasets [Internet]. 2022. doi:10.5281/zenodo.5644336
70. Hamilton M, Wiesner G. ready4show: Author literate programs to share insights from applying the Ready4 framework [Internet]. 2022. doi:10.5281/zenodo.5644568
71. Wickham H, François R, Henry L, Müller K. Dplyr: A grammar of data manipulation [Internet]. 2022. Available: <https://CRAN.R-project.org/package=dplyr>
72. Chang W, Cheng J, Allaire J, Sievert C, Schloerke B, Xie Y, et al. Shiny: Web application framework for r [Internet]. 2022. Available: <https://CRAN.R-project.org/package=shiny>
73. Smith R, Schneider P. Making health economic models shiny: A tutorial. Wellcome Open Res. 2020;5:69. doi:10.12688/wellcomeopenres.15807.2
74. Henry L, Wickham H. Lifecycle: Manage the life cycle of your package functions [Internet]. 2021. Available: <https://CRAN.R-project.org/package=lifecycle>
75. Hamilton M, Gao C. Complete study program to reproduce all steps from data ingest through to results dissemination for a study to map mental health measures to AQoL-6D health utility [Internet]. Zenodo; 2022. doi:10.5281/zenodo.6212704
76. Hamilton MP. ready4-dev/ttu_lng_ss: Create a Draft Scientific Manuscript For A Utility Mapping Study [Internet]. Zenodo; 2022. doi:10.5281/zenodo.5976988
77. Hamilton MP, Gao CX. Youthu: Transform youth outcomes to health utility predictions [Internet]. Zenodo; 2022. doi:10.5281/zenodo.6210978
78. Hamilton M, Gao C. youthvars: Describe and Validate Youth Mental Health Datasets [Internet]. Zenodo; 2022. doi:10.5281/zenodo.6084467
79. Hamilton M, Gao C. Scorz: Score questionnaire item responses [Internet]. Zenodo; 2022. doi:10.5281/zenodo.6084824
80. Hamilton M, Gao C. specific: Specify Candidate Models for Representing Mental Health Systems [Internet]. Zenodo; 2022. doi:10.5281/zenodo.6116701
81. Gao C, Hamilton M. TTU: Implement Transfer to Utility Mapping Algorithms [Internet]. Zenodo; 2022. doi:10.5281/zenodo.6130155
82. Hamilton MP. Synthetic (fake) youth mental health datasets and data dictionaries [Internet]. Harvard Dataverse; 2021. doi:10.7910/DVN/HJXYKQ

83. Hamilton MP, Gao CX, Filia KM, Menssink JM, Sharmin S, Telford N, et al. Transfer to AQoL-6D Utility Mapping Algorithms [Internet]. Harvard Dataverse; 2021. doi:10.7910/DVN/DKDIB0
84. Hamilton M, Gao C. aqol6dmap_use: Apply AQoL-6D Utility Mapping Models To New Data [Internet]. Zenodo; 2022. doi:10.5281/zenodo.6416330
85. Hamilton MP, Gao CX, Filia KM, Menssink JM, Sharmin S, Telford N, et al. Mapping psychological distress, depression and anxiety measures to AQoL-6D utility using data from a sample of young people presenting to primary mental health services. medRxiv. Cold Spring Harbor Laboratory Press; 2022; doi:10.1101/2021.07.07.21260129
86. Hamilton MP. aqol6dmap_fakes: Generate fake input data for an AQoL-6D mapping study [Internet]. Zenodo; 2022. doi:10.5281/zenodo.6321821
87. Hamilton M. ttu_md_l_ctlg: Generate a template utility mapping (transfer to utility) model catalogue [Internet]. Zenodo; 2022. doi:10.5281/zenodo.6116385
88. Long KM, Meadows GN. Simulation modelling in mental health: A systematic review. *Journal of Simulation*. 2017; doi:10.1057/s41273-017-0062-0
89. Clearinghouse C. Basu, kim: Alcohol use disorder [Internet]. OSF; 2018. Available: osf.io/jvayu
90. Evaluation of Value C for the, Health R in. Open-source model clearinghouse [Internet]. Tufts Medical Center; Available: <http://ghcearegistry.org/orchard/open-source-model-clearinghouse>
91. Innovation T, Initiative V. IVI-MDD value model [Internet]. 2022. Available: <https://www.thevalueinitiative.org/ivi-mdd-value-model/>
92. Chalmers I, Bracken MB, Djulbegovic B, Garattini S, Grant J, Gülmezoglu AM, et al. How to increase value and reduce waste when research priorities are set. *The Lancet*. Elsevier; 2014;383: 156–165.
93. Pitt C, Goodman C, Hanson K. Economic evaluation in global perspective: A bibliometric analysis of the recent literature. *Health Economics*. Wiley Online Library; 2016;25: 9–28.
94. Whiteford H, Bagheri N, Diminic S, Enticott J, Gao CX, Hamilton M, et al. Mental health systems modelling for evidence-informed service reform in australia [Internet]. PsyArXiv; 2022. doi:10.31234/osf.io/uqsgy
95. Fried EI, Robinaugh DJ. Systems all the way down: Embracing complexity in mental health research. *BMC Medicine*. 2020;18: 205. doi:10.1186/s12916-020-01668-w
96. Langellier BA, Yang Y, Purtle J, Nelson KL, Stankov I, Diez Roux AV. Complex systems approaches to understand drivers of mental health and inform mental health policy: A systematic review. *Administration And Policy In Mental Health*. 2018; doi:10.1007/s10488-018-0887-5
97. Jorm AF, Patten SB, Brughra TS, Mojtabai R. Has increased provision of treatment reduced the prevalence of common mental disorders? Review of the evidence from four countries. *World psychiatry : official journal of the World Psychiatric Association (WPA)*. 2017;16: 90–99. doi:10.1002/wps.20388
98. Furst MA, Gandré C, Romero López-Alberca C, Salvador-Carulla L. Healthcare ecosystems research in mental health: A scoping review of methods to describe the context of local care delivery. *BMC Health Services Research*. 2019;19: 173. doi:10.1186/s12913-019-4005-5
99. Alegría M, NeMoyer A, Falgàs Bagué I, Wang Y, Alvarez K. Social determinants of mental health: Where we are and where we need to go. *Current Psychiatry Reports*. 2018;20: 95–95. doi:10.1007/s11920-018-0969-9
100. Zabell T, Long KM, Scott D, Hope J, McLoughlin I, Enticott J. Engaging healthcare staff and stakeholders in healthcare simulation modeling to better translate research into health impact: A systematic review. *Frontiers in Health Services*. 2021;1. doi:10.3389/frhs.2021.644831
101. Squires H, Chilcott J, Akehurst R, Burr J, Kelly MP. A framework for developing the structure of public health economic models. *Value in Health*. 2016;19: 588–601. doi:<https://doi.org/10.1016/j.jval.2016.02.011>

102. Muñoz JAM, Munoz CMM, Serrano AIP, Antón DML, Espejo ALS. Health economics: Identifying leading producers, countries relative specialization and themes. *Revista de Estudios Empresariales Segunda época*. Facultad de Ciencias Sociales y Jurídicas; 2020; 7–19.