

# A framework for implementing an open source and modular economic model of youth mental health that is accountable, reusable and updatable

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## Abstract

**Summary:** Compared to other disciplines, health economics rarely uses modular approaches to model development that facilitate re-use of model components. Although interest in open source health economic models (OSHEMs) is growing, uptake remains limited. We propose a framework for a modular OSHEM in youth mental health. The framework includes of set of X1 good practice standards for implementing a model that is accountable (X2 standards), reusable (X3 standards) and updatable (X4 standards). We provide a rationale for each standard. The framework also includes software toolkit of six R packages for authoring model 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 meet X5 standards. We discuss the potential benefits and challenges of extending this initial work to develop a more extensive model for undertaking economic analyses in youth mental health.

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

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## 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 in accountability, reusability and updatability that at best restrict their usefulness and which in some cases may facilitate harmful misuse.

Accountability limitations of health economic models include inadequate validation [3], routinely containing errors [4] and, as with health policy computational models more generally, being difficult to reproduce [5–7]. Furthermore, models reflect the value judgments of their authors [potentially: <https://doi.org/10.1177/0040571X221119276>] relating to what questions to address, what features of a system to include, the

weighting of different types of evidence and the type of stakeholders who are engaged in model design and validation [ESCAPE FROM MODEL LAND reference]. These values may at times be poorly aligned with those of the people whose lives are most impacted by decisions informed by model analyses [ESCAPE FROM MODEL LAND reference]. Some health economists have argued that more complex and sophisticated modelling methods are required to adequately explore some public health topics [8]. However, undertaking more ambitious models may accentuate accountability issues. More complex models may be more prone to propagation errors [9]. The importance of accountability grows as models evolve from relatively simple implementations that address a single question to multipurpose tools [10,11]. Transparency about the nature and extent of individual model authorship contributions can be harder to provide in models implemented over longer timeframes with a large team of collaborators [ESCAPE FROM MODEL LAND reference].

The resource and skills intensive task of model development can be made more tractable when modellers have the opportunity to re-use, test and refine the work of their peers [12]. 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 [11]. Many types of health data are highly sensitive with strict confidentiality requirements. For this reason, not all data included in some health economic models can be ethically made publicly available. Barriers to generalising and transferring health economic studies are often discussed in terms of study conclusions but also relate to model algorithms (can the same model logic be applied in different contexts?) and data (do shared taxonomies exist so that concepts have similar meanings in different jurisdictions?, which model parameters have values / sources that are context specific?) [Expand and add ref: <https://link.springer.com/article/10.1186/s12962-021-00294-4>, <https://doi.org/10.1017/S026646232200321X>].

Health economic models should be updated and refined as new evidence emerges and decision contexts change [13], but this occurs infrequently [14]. Decision makers are frequently left to rely on economic analyses that become less valid and relevant each year. A model can grow stale when changes in the real world, whether sudden (e.g. new pandemics) or gradual (e.g. demographic), is not represented by corresponding updates to relevant model features. Even when the system being modelled remains relatively stable, new research findings may potentially invalidate aspects of a model's original conceptualisation and implementation. Funding for health economic modelling projects rarely extends 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 IP 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 modular and open-source. A modular approach that ensures that model code and data are decoupled (stored in different files) can help model developers to restrict access to confidential model data, while providing open access to all other model components. Modular approaches have been used in a small number of health economic models to link multiple self-contained components that can be independently reused and extended by other projects [15,16]. Developing well validated reference models for re-used in multiple health economic modelling projects has been advocated for [17].

There appears to be in principle support from many health economists for greater use of open source health economic models (OSHEMs) that grant liberal permissions to access and re-use model source code and data [18]. Despite the potential benefits of OSHEMs, actual implementations are rare [11,19,20]. Barriers to adoption of OSHEMs include concerns about intellectual property, confidentiality, model misuse and the resources required to support open source implementations [18,21]. Adherence to good practice guidance is an essential requirement for healthcare modelling [2], but guidelines for implementing OSHEMs remain scarce, piecemeal and need improving [22]. Open source is more than open access (limited discussion).

We plan to develop a modular OSHEM of youth mental health. Open source approaches have been recommended to help develop the mental health modelling field [23] but only one mental health related model (in Alcohol Use Disorder [24]) is currently indexed [RECHECK] in the Open Source Models Clearinghouse [19,25]. Other than our own work, we are aware of just one open source mental health reference model - in Major Depressive Disorder - that is currently in development [26].

In this paper, we introduce a framework for developing youth mental health OSHEMs. Specifically we

Table 1: TIMELY Guidelines for OSHEMs

Characteristic	Guideline	Meaning
<b>Transparent - people can easily see how a model has been implemented and tested</b>		
	T1	Uniquely identified copies of model code and data are permanently archived in open online repositories
	T2	Model code and data are documented
	T3	Model code uses a simple and consistent syntax
	T4	Model analyses and reporting are implemented using literate programming
	T5	Code coverage is reported
	T6	All parts of a study analysis and reporting workflow can be reproduced and/or replicated
<b>Iterative - a model is routinely updated to maintain and improve validity</b>		
	I1	Model code and data are version controlled
	I2	Model code and data use semantic versioning
	I3	Continuous integration is used to verify model code updates
	I4	Deprecation conventions are used to retire model code and data
<b>Modular - models and their components can be combined to extend their scope</b>		
	M1	Model code and data are stored and managed separately
	M2	Model code defines encapsulating data structures
<b>Epitomising - model code can be re-used in other decision contexts</b>		
	E1	Model code is distributed as libraries of classes and functions
	E2	Model code defines inheriting data-structures
	E3	Test data is available to demonstrate generalised applications of model code
<b>Licensed - a model and its components are persistently re-usable by other modellers</b>		
	L1	Model code is made available for re-use under copyleft or permissive licenses
	L2	Non-confidential model data is licensed for liberal re-use (subject to additional terms for de-identified human data)
	L3	Model code and data are distributed with tools to support appropriate citation
<b>Yielding - a model can be simply, flexibly and reliably used as a decision aid</b>		
	Y1	Models are distributed with validated tools to support their safe and appropriate re-use
	Y2	Simple user-interfaces allow non-technical users to configure and run models

describe:

- a set of guidelines for implementing OSHEMs;
- a toolkit for applying these guidelines in youth mental health; and
- a worked example of a modelling project developed with the toolkit.

## 2 Guidelines for OSHEMs

Guidelines on health economic model transparency were published ten years ago [10] and made recommendations on documenting models; however, notably missing were recommendations on the sharing of model code and data. More recent and more general modelling guidance [2] recommends the sharing of code and data through digital repository services and the use of version control systems. Based on these and other existing sources of guidance and our own experience, we propose 20 guidelines for implementing OSHEMs that are **TIMELY** (Transparent, Iterative, Modular, Epitomising, Licensed and Yielding - see Table 1).

## 2.1 Transparent models

A range of tools and practices are available to help make models more transparent. The most efficient way to widely disseminate code and data may be to use existing open science infrastructure [2] to make permanently accessible and uniquely identified digital artefacts. Model code and data also need to be clearly documented, potentially with different versions for technical and non-technical users [10]. Consistent use of meaningful naming conventions when authoring code is recommended [27,28]. Code can be made easier to follow by using the practices of abstraction [29], where only simple, high level commands are routinely exposed to reviewers, and polymorphism [30], 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 to render documents 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 [31]. One useful concept for informing model users about the extensiveness of verification checks is code coverage [32] - the proportion of model code that has been explicitly tested. Finally, transcription errors - mistakes introduced when transferring data between sources, models and reports - are very common in health economic models [4]. 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 [27].

## 2.2 Iterative models

To avoid OSHEMs 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]. Labeling each change using semantic versioning [33] conventions can signal the potential importance of an update to users of model code and data. Continuous integration [34] 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.

## 2.3 Modular models

An important consideration when combining model components (or modules) is to ensure that interactions between two modules do not compromise the validity of either. Using the coding practice of encapsulation [29] can help ensure that model modules can be safely combined [35].

## 2.4 Epitomising models

A key challenge to generalising health economic models is that they are typically developed to inform a decision problem with a highly specific jurisdictional context. However, a number of choices about how these models are implemented can significantly increase the re-usability of model code in other contexts.

Writing code as collections of functions (short, self-contained and reusable algorithms that each perform a discrete task) is recommended as good practice for scientific computing [27]. When bundled for distribution as libraries, functions have the potential to be widely re-used, often in contexts very different than those they were originally developed for. A special type of function, called a method, can only be applied to a pre-defined class of data structure. Due to the coding concept of inheritance [29], the more restricted nature of methods can be used to enhance the re-usability of model code in different decision contexts [35]. For example, when generalising a model developed for the Australian context to a UK context, one could create a class that initially inherits all of the methods defined for the Australian model and then write new or replacement methods as needed for the UK model. Whatever type of functions are written for a modelling project, it is good practice to make available test or toy data to demonstrate their use [27].

## 2.5 Licensed models

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 [27] 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 [36] that can require content users to distribute any derivative works they create under similar open source arrangements. The most suitable approach may differ for code and data.

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) [37] or a copyleft option such as the Attribution-Share Alike (CC-BY-SA) [38]. Responsible custodianship of some de-identified mental health data may involve using or adapting template terms of use [39] which have a number of ethical clauses (for example, prohibiting efforts to re-identify research participants). Licenses may or may not specify that model re-users must give appropriate acknowledgement to model authors. Citation tools can be distributed with each individual code or data item to inform re-users of the desired attribution.

## 2.6 Yielding models

OSHEMs can be time and skills intensive for modellers to develop - but they should be easy for others to use. 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 [40]. 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 OSHEMs easier to use is to develop simple user-interfaces for non-technical users.

# 3 Modelling Toolkit

We have developed a toolkit to help streamline the process of developing OSHEMs that meet the TIMELY standards. The toolkit is comprised of online repositories and software.

## 3.1 Repositories

We created a GitHub organisation where all framework software source code is stored, documented, version controlled and continuously integrated [41]. To store citable archived copies of release copies of our software, we created a Zenodo community [42]. Finally, to manage datasets for use in models developed with the framework, we created a dedicated collection within the Harvard Dataverse [43].

## 3.2 Software

A coding framework for OSHEMs developed in the language R includes standardised approaches to directory structure and naming conventions [28].

As a foundation for implementing the framework, we authored a development version R package that defines a novel syntax and a template class for model modules [44]. To enable the syntax and module template be applied to modelling projects, we then created five additional development version R packages that provide tools for authoring:

- documented model modules [45];
- documented functions (including methods), written in a consistent house style [46];

Table 2: Framework software to enable the readyforwhatsnext model to meet TIMELY guidelines

Package	Focus	Guideline	Depends on these R packages
	Syntax	T3 M3	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
	Functions	T2-3 E1	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
	Modules	T2-3 M2 E1-2	devtools dplyr fs gtools Hmisc knitr lifecycle magrittr methods purrr ready4 ready4fun ready4show rlang stats stringi stringr testit testthat tibble tidyR usethis utils
	Libraries	T1 I1-3 M1-2 E1 L1,3	dataverse dplyr knitr lifecycle magrittr methods purrr ready4 ready4class ready4fun rlang stringr testthat tibble tidyR utils
	Data	T1-2 M1 E3 L2-3	data.table dataverse dplyr fs Hmisc knitr lifecycle magrittr methods piggyback purrr readxl ready4 ready4show rlang stats stringi stringr testit testthat tibble tidyR utils
	Reporting	T2,4,6 Y1-2	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

- citable, quality assured R packages [47];
- model datasets [48];
- model analyses and reports [49].

The six R packages, their primary focus, the TIMELY standards they support and the third-party packages they depend on are summarised in Table 2. When used in conjunction with framework repositories, the six packages extend existing R packages provide strong support for implementing 16 of the TIMELY standards. However, the software only weakly supports implementing the standards relating to disseminating statistical models (Y1) and user-interface development (Y2) and does not yet provide any workflow tools to help implement the standards for code coverage (T5) and deprecation conventions (I4). Standards not supported or weakly supported by our software can be met with existing developer tools in R and we plan to progressively integrate these third-party tools with our own in future releases of our software. Another future priority is to submit production versions of each R package for review by and archiving on the Comprehensive R Archive Network (CRAN) [50].

Table 3: TIMELY Checklist applied to utility mapping study

	Standard	Met?	Description
T1	Publicly archived	Yes	5 libraries (youthvars, scorz, specific, TTU and youthu) [51–55], 3 programs [56–58], 2 sub-routines [59,60] and 2 datasets [61,62] are permanently archived with unique identifiers.
T2	Documented	Yes	All code libraries have documenting websites with URLs that concatenate ‘https://ready4-dev.github.io/’ and the package name (e.g. https://ready4-dev.github.io/youthvars). All three Markdown programs are self-documenting, with one [56] including additional instructions in a README file. Only one sub-routine [60] is documented with a meaningful README file. All datasets have meaningful metadata descriptors.
T3	Consistent syntax	Yes	All libraries, programs and sub-routines use the same house style, which allows most library documentation to be written by algorithms from the ready4fun package [46]. All libraries except [55] use framework syntax, as does one program [56].
T4	Literately programmed	Yes	All programs use literate programming.
T5	Code coverage	No	No current reporting of code coverage.
T6	Reproducible	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 [56].
I1	Version controlled	Yes	All code is version controlled using Git and GitHub. All source code is available in a GitHub organisation [41].
I2	Semantically versioned	Yes	Semantic version is used in all code. As no code library has yet been submitted to CRAN, only the development version extensions of each version number have been incremented to date.
I3	Continuously integrated	Yes	All six libraries use continuous integration (CI). CI results for each library can be viewed at a URL that concatenates ‘https://github.com/ready4-dev/’, the package name and ‘actions’ (e.g. https://github.com/ready4-dev/youthvars/actions)
I4	Deprecation	Yes	Retired code is deprecated using lifecycle package tools (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 )
M1	Separate code and data	Yes	All development code is stored on repos in a GitHub organisation [41] and all archived releases are available in a Zenodo community [42]. All non-confidential data is stored in repositories within a Harvard Dataverse collection [43].
M2	Encapsulated	Yes	Four [51–54] out of five libraries include encapsulated modules. Examples are the items beginning with Scorz, Specific and Youthvars that are listed in this table: https://ready4-dev.github.io/ready4/articles/V_01.html#current-ready4-framework-modules as well as the S4 classes from the TTU package listed here: https://ready4-dev.github.io/TTU/reference/index.html
E1	Libraries	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 T2 above).

	Standard	Met?	Description
E2	Inheriting	Yes	All modules (see item M2) inherit from the Ready4Module class and can be inherited from.
E3	Test data	Yes	Two synthetic datasets and their data dictionaries are publicly available in a data repository [62]. One (ymh_clinical_tb.RDS) closely resembles the study dataset and was released so that the main study algorithm [56] can be rerun by those without access to the confidential study dataset. The other (eq5d_ds_dict.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 generalised applications of study algorithms.
L1	Copyleft code	Yes	All code libraries, programs and sub-routines use GPL-3 licenses.
L2	Liberal, safe data terms	Yes	Datasets use amended version of template provided by Harvard Dataverse [39].
L3	Citation tools	Yes	All libraries have a CITATION file in the inst directory. All code repositories have a CITATION.cff file. All datasets have citation generating metadata.
Y1	Prediction tools	Yes	Model catalogues (PDF files beginning with 'AAA_TTU_MDL_CTG') are available in the study results dataset [61] 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 [55] 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 [57] and rendered PDF formats (the 'Application.pdf' file in the study results dataset [61]).
Y2	User interface	No	No Shiny app user interface has yet been developed.



## 4 Application

### 4.1 readyforwhatsnext

Our approach to model development is to undertake a number of discrete modelling projects of the people, places, platforms and programs that shape the mental health and wellbeing of young people and to progressively link them together by means of a common framework. To model people we are developing synthetic representations of populations of interest [62] that describe relevant individual characteristics and their relationships, algorithms that map psychological measures to health utility [63] and choice models for predicting the helpseeking behaviour of young people [64]. Our in-development model of places [65] has the aim of synthesising geometry and spatial attribute data to characterise the geographic distribution of relevant demographic, environmental, epidemiological and service infrastructure features. We are in the early stages of a multi-annual project to develop a service platform model that will represent the processes and operations of a complex primary youth mental health service. We also plan to extend and update our prior work reviewing economic evidence relating to youth mental health programs [66] so that it can be integrated with this model.

Our initial work on **readyforwhatsnext** is focused on Victoria, Australia but the framework we are using to develop it is designed to facilitate extension by ourselves and others to different jurisdictional decision contexts. Progress is reported on a project website [67].

### 4.2 Utility mapping

We used framework toolkits to develop model code and datasets for implementing a utility mapping study that has previously been described [63]. Table 3 assesses that study against each TIMELY standard, 18 of which the study was able to meet. The two current standards where the study falls short are in reporting code coverage and including a user-interface. Both these items are current development priorities for our team.

## 5 Discussion

Mental disorders impose high health, social and economic burdens worldwide [68,69]. Much of this burden is potentially avertable [70], but poorly financed and organised mental health systems are ill-equipped for this challenge [71,72]. The large and widespread additional mental health burdens recently observed during the COVID-19 pandemic [73] and predicted as a potential future consequence of climate change [74], highlight the need to improve the resilience and adaptability of these systems. To help stem growing demand for mental health services, policymakers have also been encouraged to place greater emphasis on tackling the social determinants of mental disorders [75].

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

The significant deficits in our understanding of the systems in which mental disorders emerge and are treated [76] suggest that there is ample scope for mental health systems models to progressively improve their validity over time. Prospective work could address the weak theoretical underpinnings for understanding complex mental health systems [77]. For example, it remains unclear why increased investments in mental health care have yet to discernibly reduce the prevalence and burden of mental disorders [78]. 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 [79]. 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 [80].

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.

Developing networks of modellers working on common health conditions has been recommended as a strategy for improving model validity [22] and some of us are part of a nascent initiate of this type in mental health

[81]. 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 [8,82].

## **6 Conclusion**

We have identified a number of standards that we believe are appropriate to implementing quality OSHEMs in youth mental health. Most of these standards are probably relevant to OSHEMs in other health conditions, though some such as the copyleft licensing may be less relevant to modellers using different tools. Our framework toolkits can help support standardised approaches to dynamic systems model development that are important for collaborative and interdependent projects.

### **6.1 Acknowledgement**

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### **Availability of data and materials**

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 worked example of framework application 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.

## 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. 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
4. 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
5. 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
6. 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
7. 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
8. 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
9. Saltelli A. A short comment on statistical versus mathematical modelling. *Nature Communications*. 2019;10: 3870. doi:10.1038/s41467-019-11865-8
10. 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
11. 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
12. 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
13. 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
14. Sampson CJ, Wrightson T. Model registration: A call to action. *PharmacoEconomics - Open*. 2017;1: 73–77. doi:10.1007/s41669-017-0019-2
15. 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
16. Urach C, Zauner G, Endel G, Wilbacher I, Breitenacker 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
17. 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

18. 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
19. 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
20. 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
21. 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
22. 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
23. Long KM, Meadows GN. Simulation modelling in mental health: A systematic review. *Journal of Simulation*. 2017; doi:10.1057/s41273-017-0062-0
24. Clearinghouse C. Basu, kim: Alcohol use disorder [Internet]. OSF; 2018. Available: [osf.io/jvayu](https://osf.io/jvayu)
25. 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>
26. Innovation T, Initiative V. IVI-MDD value model [Internet]. 2022. Available: <https://www.thevalueinitiative.org/ivi-mdd-value-model/>
27. 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
28. 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
29. 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
30. 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
31. 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
32. 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
33. Preston-Werner T. Semantic versioning 2.0.0 [Internet]. 2022. Available: <https://semver.org>
34. 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
35. 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](https://ready4-dev.github.io/ready4/articles/V_03.html)
36. Foundation TFS. What is copyleft? [Internet]. Available: <https://www.gnu.org/copyleft/>
37. Commons C. CC0 1.0 universal [Internet]. 2022. Available: <https://creativecommons.org/publicdomain/zero/1.0/legalcode>

38. Commons C. Attribution-ShareAlike 4.0 international [Internet]. 2022. Available: <https://creativecommons.org/licenses/by-sa/4.0/legalcode>
39. Quantitative Social Science I for. Sample data usage agreement [Internet]. 2022. Available: <https://support.dataverse.harvard.edu/sample-data-usage-agreement>
40. 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
41. 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/>
42. Orygen. ready4: Open and modular mental health systems models [Internet]. 2022. Available: <https://zenodo.org/communities/ready4>
43. Orygen. ready4: Open and modular mental health systems models [Internet]. 2022. Available: <https://dataverse.harvard.edu/dataverse/ready4>
44. Hamilton MP. ready4: Implement open science computational models of mental health systems [Internet]. 2021. doi:10.5281/zenodo.5606250
45. Hamilton M, Wiesner G. ready4class: Author Ready4 framework modules [Internet]. 2022. doi:10.5281/zenodo.5640313
46. Hamilton M, Wiesner G. ready4fun: Author and document functions that extend the Ready4 framework [Internet]. 2022. doi:10.5281/zenodo.5611779
47. Hamilton M. ready4pack: Author r packages that extend the Ready4 framework [Internet]. 2022. doi:10.5281/zenodo.5644322
48. Hamilton M, Wiesner G. ready4use: Author, label and share Ready4 framework datasets [Internet]. 2022. doi:10.5281/zenodo.5644336
49. Hamilton M, Wiesner G. ready4show: Author literate programs to share insights from applying the Ready4 framework [Internet]. 2022. doi:10.5281/zenodo.5644568
50. Statistical Computing RF for. The comprehensive r archive network [Internet]. 2022. Available: <https://cran.r-project.org>
51. Hamilton M, Gao C. youthvars: Describe and Validate Youth Mental Health Datasets [Internet]. Zenodo; 2022. doi:10.5281/zenodo.6084467
52. Hamilton M, Gao C. Scorz: Score questionnaire item responses [Internet]. Zenodo; 2022. doi:10.5281/zenodo.6084824
53. Hamilton M, Gao C. specific: Specify Candidate Models for Representing Mental Health Systems [Internet]. Zenodo; 2022. doi:10.5281/zenodo.6116701
54. Gao C, Hamilton M. TTU: Implement Transfer to Utility Mapping Algorithms [Internet]. Zenodo; 2022. doi:10.5281/zenodo.6130155
55. Hamilton MP, Gao CX. Youthu: Transform youth outcomes to health utility predictions [Internet]. Zenodo; 2022. doi:10.5281/zenodo.6210978
56. 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
57. Hamilton M, Gao C. aqol6dmap\_use: Apply AQoL-6D Utility Mapping Models To New Data [Internet]. Zenodo; 2022. doi:10.5281/zenodo.6416330
58. Hamilton MP. aqol6dmap\_fakes: Generate fake input data for an AQoL-6D mapping study [Internet]. Zenodo; 2022. doi:10.5281/zenodo.6321821
59. Hamilton M. ttu\_md1\_ctlg: Generate a template utility mapping (transfer to utility) model catalogue [Internet]. Zenodo; 2022. doi:10.5281/zenodo.6116385

60. 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
61. 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
62. Hamilton MP. Synthetic (fake) youth mental health datasets and data dictionaries [Internet]. Harvard Dataverse; 2021. doi:10.7910/DVN/HJXYKQ
63. Hamilton MP, Gao CX, Filia KM, Menssink JM, Sharmin S, Telford N, et al. Predicting quality adjusted life years in young people attending primary mental health services. medRxiv. Cold Spring Harbor Laboratory Press; 2021; doi:10.1101/2021.07.07.21260129
64. Hamilton M. dce\_sa\_design: An R Markdown program to create the experimental design for a Discrete Choice Experiment (DCE) exploring online help seeking in socially anxious young people [Internet]. Zenodo; 2022. doi:10.5281/zenodo.6627995
65. Hamilton M. Springtides reports for Local Government Areas in the North West of Melbourne [Internet]. Harvard Dataverse; 2022. doi:10.7910/DVN/V3OKZV
66. Hamilton MP, Hetrick SE, Mihalopoulos C, Baker D, Browne V, Chanen AM, et al. Identifying attributes of care that may improve cost-effectiveness in the youth mental health service system. *Med J Aust.* 2017;207: S27–S37. doi:10.5694/mja17.00972
67. Orygen. ready4-dev - documenting the development of an open source youth mental health systems model [Internet]. Available: <https://ready4-dev.com/>
68. 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.
69. Global, regional, and national burden of 12 mental disorders in 204 countries and territories, 1990&#x2013;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
70. 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
71. 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
72. 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
73. Santomauro DF, Mantilla Herrera AM, Shadid J, Zheng P, Ashbaugh C, Pigott DM, et al. Global prevalence and burden of depressive and anxiety disorders in 204 countries and territories in 2020 due to the COVID-19 pandemic. *The Lancet.* 2021;398: 1700–1712. doi:https://doi.org/10.1016/S0140-6736(21)02143-7
74. Page LA, Howard LM. The impact of climate change on mental health (but will mental health be discussed at copenhagen?). *Psychological Medicine.* Cambridge University Press; 2010;40: 177–180. doi:10.1017/S0033291709992169
75. Organization WH, Foundation CG. Social determinants of mental health. Geneva: World Health Organization; 2014.
76. 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
77. 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
78. Jorm AF, Patten SB, Brugha 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

79. 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
80. 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
81. Mental Health Research QC for. National mental health systems modelling network [Internet]. 2022. Available: <https://qcmhr.org/research/research-streams/mental-health-services-research/national-mental-health-systems-modelling-network/>
82. 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