

IMPACT: A generalisable system for simulating public health interventions

Iain Buchan^a, John Ainsworth^a, Emma Carruthers^a, Philip Couch^a, Martin O'Flaherty^b, Duncan Smith^a, Richard Williams^a, Simon Capewell^b

^aNW Institute Bio-Health Informatics, School of Community Based Medicine, University of Manchester, UK

^bDivision of Public Health, University of Liverpool, UK

Abstract

Populations are under-served by local health policies and management of resources, partly because of a lack of realistically complex models to enable a wide range of potential options to be appraised. Rising computing power coupled with advances in machine learning and healthcare information now enables such models to be constructed and executed. However, such models are not generally accessible to public health practitioners because they do not have the requisite technical knowledge or skills. This paper presents a system for creating, executing and analyzing the results of simulated public health and healthcare policy interventions, which is more accessible and usable by modellers and policy-makers alike.

Keywords:

Computer simulation, Graphical models, Epidemiology, Medical economics, Public health, Decision modelling

Introduction

Long-term conditions, such as Coronary Heart Disease (CHD), consume the largest proportion of healthcare budgets, and are a major target for public health initiatives. Moving interventions up-stream to earlier stages of the natural histories of diseases would delay or prevent subsequent events, thereby reducing the amount of suffering over the average lifetime, and saving money. Health policy-makers and those planning and managing local health services are poorly served by oversimple estimates of the potential public health impacts of making changes to the pathways of care or taking preventive public health measures. These estimates are often unreliable [1], because the models do not adequately represent the complexity of the disease, population or care over time.

Population health impact estimation is usually done by a small group of analysts synthesizing evidence and producing a report for a decision-making team. For example, how should the balance be struck between investments in statins vs. smoking cessation vs. physical activity promotion in respect of health impact for a defined population over five years? There are three problems with this approach: a) there are not enough analysts

to support current decision-making needs, yet the available data and literature to consider is increasing - it is unlikely that health systems could afford to employ more analysts, and furthermore they are in short supply; b) a static report does not enable 'what if' scenario planning, so the options that are appraised are inflexible; c) most healthcare commissioning groups do not have the skills or time to build realistically complex models which take all reasonable factors into consideration, so decisions may be biased by where a narrowly defined model focuses - this may reflect the interests of service providers more than the needs of the population served. It is possible to construct graphical models of disease and healthcare pathways, and to use the resulting probabilistic networks to simulate outcomes for populations. Such a simulation system would enable the user to compare different intervention scenarios, with the ability to modify both clinical and public health interventions, and measure both the effectiveness based on clinical outcomes and costs. Such a system could bring together public health professionals, clinicians and service commissioners in interactive scenario planning activities to inform policy decisions. The ideal system would enable users to construct and share models around 'what if scenarios' easily; to execute individual simulations quickly; and to interpret simulation results collectively. Larger simulations, in terms of the population size, provide greater accuracy but consume more computational resources. The construction of models requires collaboration between health economists, epidemiologists, biostatisticians and typical decision-makers/leaders (public health professionals, healthcare managers, and clinicians).

In this paper we report on the IMPACT system that has been designed to enable this approach, by bringing together model builders, model users and computational resources to participate in shared decision-making.

Background

CHD is one of the most extensively modelled diseases, so we chose it as the focus for designing a generic system for modelling health impacts in defined populations.

A recent systematic review [2] of cardiovascular disease policy models concluded that models vary widely in their depth, breadth, quality utility and versatility, with few models ade-

quately validated or replicated in different settings. Moreover, few were available for inspection or transparent enough to fully understand model methods and assumptions. As such, the strengths and limitations of most models could not properly be defined, therefore few were acceptable for use in policy making. Most recently, a model published by the English Department of Health to support cardiovascular screening is both over-simple and not transparent [3]. Out of 70 modelling attempts identified in this area fewer than 10% published a paper and almost none have survived for a decade or more.

The first IMPACT model [4], typical of those used in Health Economics, was based on simple Markov propagation and implemented in a spreadsheet with over 44,000 cells – it required extensive training of users and was difficult to deconstruct for validation. Here we report a new approach to IMPACT, separating the generic modelling challenge from its application to CHD. Furthermore we separate the computation of the model from interaction with users, and address the generic problem of simulating public health impact.

Research Aim & Objectives

The mathematical methods and computing technologies required to unify model building, and use are available [5]. The aim of this work was to harness the unified modelling methods for health policy making. The main objectives were: to develop a versatile, flexible, valid and credible quantitative system for executing population disease models; to provide a single framework for domain experts to collaborate on model design and validation; and to provide a decision support capability that enables health professionals to interact with the models.

Method

System Requirements and Analysis

Taylor-Robinson et al conducted a consultation exercise with policy-makers on their attitudes to modelling and simulation [6]. The findings of that research were used to inform our requirements for the system.

Versatile and flexible

Our principal objective is to provide a generic system for simulating public health interventions, enabling users to ask, find and reuse ‘what-if’ questions about options for preventive and clinical interventions in a population’s health. This can be contrasted with the prevailing use of bespoke models often implemented with spreadsheet applications. Consequently, the system must contain a generic execution engine, that can instantiate a given *model* and perform the simulation. To create models, a model design tool is required that guides the end user through model creation and ensures valid models are created. What constitutes a valid model is intrinsically linked to the design and implementation of the model execution engine. The model alone cannot be executed; it must be configured with additional parameters that define a *simulation*. Thus a simulation is the combination of the model and the data that characterises the population, the environment, and the interventions being considered. Therefore the system must provide

a tool that enables users to define simulations for a given model. We must also consider what the system will be used for. The IMPACT system is intended for answering five types of question:

- How will the burden of disease change over time?
- What will be the impact of specific treatment interventions/technologies?
- What will be the impact of population level/public health interventions?
- In terms of life expectancy is prevention more effective than treatment?
- Are interventions targeted at high-risk groups more effective than whole population level interventions?

The system must provide a tool that enables the results of a simulation to be analysed and visualised, and for comparisons to be made between simulations.

Transparent

Transparency was identified as a key requirement for users to be able to trust and subsequently act on the result of simulations. By transparency we mean that the system must be open to inspection at all levels. Consequently:

- The system software must be open source. We have chosen the Artistic Licence 2.0. The source code must have companion documentation that describes its architecture, algorithms and implementation that is accessible from the system.
- The mathematics underpinning the models and their execution must be formally documented and accessible.
- For each model, the model builders are required to supply descriptive meta-data that describes the risk factors and disease groups; data sources and main assumptions; the relative risk reductions of interventions; the uptake (availability and adherence) of interventions; the nodes of the graphical model; the edges of the graphical model, defining transition probabilities between health states; the observable outputs of the model; and terminology.
- For each simulation, the system must enable users to inspect the configuration that defines the population & environment, and the interventions.

Accessible

To achieve wide spread adoption, access to the system must be as easy as possible for the end user. Thus we are delivering the IMPACT model as a web application that requires no end user installation, configuration or maintenance.

The user interface must be simple and intuitive to use. In order to achieve this different classes of user are defined in terms of their intended use of the system, such that the functions and features available in each user class provides a different view of the system. This enables the complexity of the system to be hidden from the user interface if it is not required. Basic users can execute simulations, compare simulations, and edit simulations (restricted to modifying population demographics and

interventions). In addition, intermediate users can create new simulations. In further addition, advanced users can edit models.

Usable for collaborative model creation and decision making

The development and validation of models requires collaboration between statisticians/modellers, epidemiologists and health economists. Health policy-making is also a multi-disciplinary process. Web-based social computing technologies are widely deployed and used across many different disciplines [7] for collaborative working. This again favours a web application such that a shared workspace can be created and technologies for storage, retrieval and search of work products can be leveraged. In essence the system must bring people, data and methods together if it is to meet our objectives.

Model and Execution Engine

In the IMPACT system a population is modelled and simulated through the use of a number of graphical models. A population model is used to generate incident patients from the general population; the patients are then consumed by the patient model that models the life course in the presence of specific disease(s) and treatments. The priorities for the population and patient side models are different, so different types of model are used. As the patient side is concerned with the healthy life years gained from treatment vs. cost, and as clinical trials study treatments in isolation from one another, strong emphasis is placed on modelling the combined effects of different treatments.

The population model employs a Bayesian network [8] and is restricted to categorical variables for tractability of computation. There is a single node for the general health state, reflecting different levels of health, and one for each of the disease states considered. There is a time period associated with these states, producing a probability distribution over the health state of an individual at a given time point.

The posterior distribution over the general health and the various disease state variables in the patient model, together with the population size, are used to sample incident cases for the subsequent time period. Any variables relevant to the disease course are included in the generated cases.

Interventions are added as variables. In the simplest case they will have just two states, 'yes' and 'no', indicating compliance (or not). The associated probability mass function will describe the probability of compliance. But as they are variables like any other, they can also be made children of variables, which are believed to influence compliance. Children of interventions need to have their conditional mass functions updated to reflect the presence of the intervention. In the simple case this means retaining the existing probabilities for the 'no' state of the intervention, and specifying a corresponding set of probabilities for the 'yes' state. It is a very flexible approach, with the graph structure implying exactly what information needs to be supplied with an added intervention. More importantly, the effects of multiple interventions are handled naturally by the causal structure, with no need to resort to simplifying assumptions.

The patient model is governed by another graph where nodes represent variables. Generally, there should be a node for each variable where a change in state will influence the likelihood of a change in state of another modelled variable. Thus it will generally contain a node for general health, and a node for each possible intervention. Interventions will generally have some influence on disease progression.

It is possible to adjust the parameters of the models to reflect external factors such as changes in the population (migration) or in prescribing/availability of treatments. Migration can be modelled by adjusting the population size of a model at, say, annual intervals, and/or by adjusting ancillary variables such as ethnicity. Non-prescription/unavailability of an intervention can be accommodated by making a suitable adjustment to the relevant survival densities for a simulated case (such that a transition from 'yes' to 'no' is made immediately, or a transition from 'no' to 'yes' is scheduled for some time well beyond death). Thus the various components can be part of a larger simulation environment. New interventions can be added easily, and the structures of the models dictate what accompanying information is required.

System Architecture

The system was designed around a number of architectural principles. In the interests of transparency open source technologies were used and the IMPACT system has Service Oriented Architecture to provide a clean separation between components with a view to minimizing the impact of future development and to enable scaling through flexible deployment across a range of hardware platforms.

The system architecture is composed of four components that work together to provide the capability to create and edit models, to create, store and retrieve simulations, to execute simulations and to analyze results. The presentation layer is a web application that provides the interface for users to interact with the system. Views are provided for model editing and for configuring individual simulations through intervention editors, adherence and availability editors, region editors and cohort simulation type that specifies whether the simulation is limited by population size or epoch over which the simulation should run. Users can therefore select an existing simulation to run, modify an existing simulation by changing its parameters, modify and existing model. User accounts and role-based access control is managed through the presentation layer component. Because the user interface requires a high degree of graphical interaction, the lack of consistent support for a common standard in web browsers resulted in both VML and SVG implementations to ensure the system works across the full range of modern web browsers. The *data management* component provides storage and retrieval services for models, simulations and results. The system domain model is defined via entities, each of which provides the definition of a domain object and, where applicable, mapping attributes that specify how it will be persisted within the database; therefore providing an abstraction of the logical data model from the physical one. The Hibernate framework is used to perform the object-relational mapping. Users can therefore select an existing simulation to run or modify an existing simulation by changing

its parameters or modify an existing model by retrieving them from the data management component.

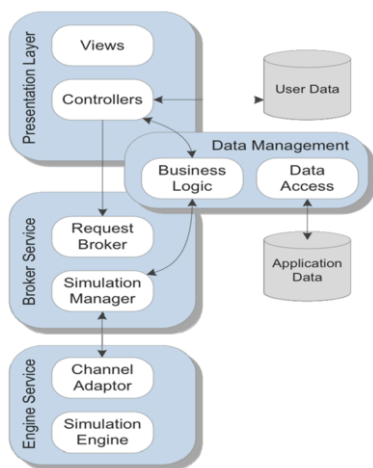


Figure 1-The IMPACT system architecture

The presentation layer interacts with the Request Broker Service (RBS) to execute a simulation. It uses the Data Management component to retrieve information required to configure simulations and to persist the results. The RBS is a client of the Engine Service, which it uses to set-up simulations, start execution and retrieve the results. The RBS is a web service and each RBS client is required to identify itself using an X509 certificate, which is validated by comparing it to existing client certificates held on the host. The use of X509 certificates enables the RBS to guarantee the integrity of the transferred data by including a digital signature in the request message. The Engine Service component is another web service that executes simulations and returns the results under the direction of the RBS. The engine service is composed of two sub-components. The Simulation Engine actually performs the simulation. Given a simulation configuration it instantiates and configures the model according to the simulation definition that it is passed. Once execution is complete, it returns the results. The simulation was developed primarily in Python with some mathematical functions written in FORTRAN. As the other components are developed in C# on Microsoft .NET technology this led to the decision to allow the Engine Service to execute on a different server from the Request Broker Service; it was therefore necessary to be able to configure a simulation and obtain results across a network. To support this, a *channel adapter* was developed for the Simulation Engine that exposes a web service interface to support both the configuration of a simulation, execution and the return of results based on the exchange of SOAP messages over HTTP. This architecture allows multiple Engine Services to be deployed to execute simulations, ensuring the future scalability of the system to many concurrent simulations and improving the tolerance of the software to problems such as hardware failures and network faults.

Results

The IMPACT simulator is deployed and available on the Internet at <http://www.impactsimulator.org.uk>.

Validation

The system has been tested by using it to implement and validate the IMPACT model of coronary heart disease.

The validation process is an integral part of model development. It helps in identifying issues with model implementation, data and assumptions. More important, it is a key element towards increasing the model value for policy makers. However, this aspect of model development has been frequently overlooked in cardiovascular disease modelling [2].

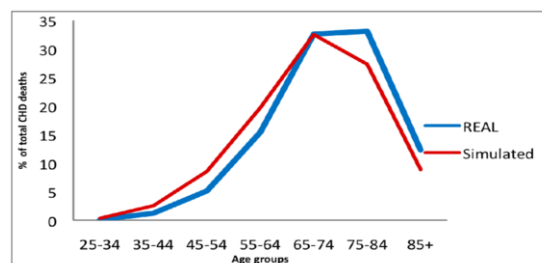


Figure 2 -Distribution of CHD deaths by age, simulated vs real

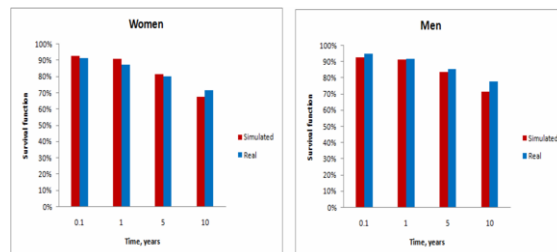


Figure 3 -Comparison of simulated and real survival functions at selected time in years, men and women.

We validated the model by simulating the SLIDE cohort, a cohort of survivors of acute coronary syndromes in Scotland [9]. Our aim was to reproduce with the model CHD mortality experience of the acute myocardial infarction sub-cohort. (n=80241). For this, we simulated a population with the same age and gender structure of the real sub-cohort, and enabling the simulation to take into account historically plausible treatments effects.

The model produces an age distribution of CHD deaths that resembles the real cohort (Figure 2), although it tends to overestimate the absolute number of events. This is probably related to the fact that the model cannot replicate the actual censoring that happened in the real cohort. Mortality calibration issues related to this particular population might be also relevant, as well as an underestimation of treatment effects, due to

lack of Scottish specific treatment uptake data for the period. The Kaplan-Meier survival functions generated by the model were similar to the observed ones (Figure 3). These preliminary results are encouraging. They demonstrate that the system is usable for model creation and execution and that the predictions of such models match observations. More validation work is needed, specifically regarding comparisons with different cohorts and populations. In addition, the validation process will offer valuable insights towards improving the model ability to produce more accurate estimates of the number of CHD deaths, data visualization and model functionality.

Figures 2 and 3 show close concordance between death rates simulated by IMPACT and those observed in a well-studied case cohort.

Discussion and Conclusion

The next phase in the evaluation will be to return to the community of planners and policy makers [6] to assess the usability, accessibility and utility of the system and the IMPACT CHD model. The usage and uptake of the system will be monitored, as this will be the key measure of success.

Future work is planned to parallelise the simulation engine to take advantage of multi-core and cluster computing. This will dramatically reduce the simulation run-time making the system more usable for complex models and large populations. The modular nature of the architecture enables the use of cloud computing infrastructure in the future.

The IMPACT simulator will be integrated into the nascent e-Lab population health information system [10]. This will leverage electronic health record data to refine, extend and localise models. The e-Lab platform provides the Work Object mechanism as a way of exchanging knowledge between federated e-Labs in different localities. The IMPACT Simulator already has the capability to export IMPACT Simulation Work Objects (ISWO) for a specific simulation, including information used to configure the simulation and the outputs from the simulation. As each simulation is configured based on evidence gathered from range of sources (including clinical trials and literary reviews) and makes use of specific statistical methods, the outcomes of each simulation can only be fully understood in the context of these methods and evidence. The ISWO provides a semantically unambiguous way to explicitly relate components of a simulation together along with statistical methods, decisions and evidence.

Unified modelling frameworks such as IMPACT may encourage epidemiologists, health economists and public health practitioners to contribute to open, accessible policy models rather than creating a blizzard of niche models.

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Address for correspondence

John Ainsworth, School of Community Based Medicine, University of Manchester, Manchester, M13 9PL, UK.

Email: john.ainsworth@manchester.ac.uk