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MOHAN, SAKSHI, Chagoma, Newton, WALKER, SIMON MARK et al. (2026) Estimating System-Wide Healthcare Costs Using a Health System Model: Application to the Thanzi La Onse Model of Malawi. Applied Health Economics and Health Policy. ISSN: 1175-5652

https://doi.org/10.1007/s40258-026-01030-w

Estimating System-Wide Healthcare Costs Using a Health System Model: Application to the Thanzi La Onse Model of Malawi

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Abstract

Objectives: Modelling approaches that consider system-wide delivery platforms rather than single diseases can be instrumental in economic evaluation and forward-looking policy formulation. This study develops a costing approach tailored to the Thanzi La Onse (TLO) model of Malawi's healthcare system, with general applicability to other health system models.

Methods: We developed a mixed-method costing approach to estimate the total cost of healthcare delivery (excluding high-level administrative costs) in Malawi using the TLO model, from a healthcare provider perspective. Through iterative adjustments of key parameters, we aligned model-based estimates as closely as possible with real-world expenditure and budget data. Costs were projected for 2023–2030 under alternative scenarios of health system capacity.

Results: A comparison with expenditure and budget data suggests our costing method is broadly reliable for the conditions captured by the model, though some mismatches remain due to data limitations and definitional inconsistencies. Under current system capacity, total healthcare delivery costs for 2023–2030 were estimated at $2.83 billion [95% uncertainty interval (CI), $2.80b - $2.87b], averaging $390.98 million [$385.92m - $396.71m] annually or $16.89 [$16.75 - $17.08] per capita. Scenario analysis highlighted strong interdependencies within the health system. Improving consumable availability alone increased consumables costs by 4.63%, while expanding human resources for health (HRH) alone increased them by 1.43%. When both HRH and consumable availability were expanded together, consumable costs rose by 5.93%, a combined effect larger than either change alone, illustrating how bottlenecks in one component constrain the impact of improvements in another.

Conclusion: Mixed-method costing using health system models is a feasible and robust method to estimate and forecast healthcare delivery costs. Clarifying assumptions and limitations can improve their utility for economic analyses and evidence-based planning in the health sector.

Keywords: Simulation Modeling, Healthcare, Health Care Financing, Public Health, Health Policy, National Government Health Expenditure

Key points for decision-makers:

- We present a mixed-method costing approach tailored to a dynamic health system model, enabling detailed estimation of healthcare delivery costs under varying system constraints.
- Our method aligns model-based cost estimates with real-world budget and expenditure data, addressing a key gap in bottom-up costing methods for health system evaluations.
- Applied to the Thanzi La Onse model in Malawi, the approach demonstrates how resource interdependencies—such as between workforce capacity and medical consumables use—can critically influence cost projections and planning.

Short title: Costing using Health System Model

Availability of Data and Materials: The data and scripts used to generate the cost estimates, calibration outputs, and scenario analyses in this study are publicly available in a GitHub repository: https://github.com/UCL/TLOmodel.

The specific scripts and data used to produce the results presented in this paper can be accessed in the scripts and resources folders, respectively.

To ensure reproducibility, the exact version of the data and scripts used for this analysis has been archived on Zenodo as *mohan-system-wide-costs-2026*, available at https://zenodo.org/records/18300209.

Facility survey data on operating costs were obtained from the Thanzi La Mawa (TLM) health facility audit and are available in a publicly accessible repository at https://zenodo.org/records/17779644.

No restrictions apply to the access or use of this material. All data used in this study are either publicly available or provided in the supplementary files.

Ethics approval: This study primarily uses secondary data sources. Ethical approval for the primary data collection informing this analysis (specifically the Thanzi La Mawa (TLM) health facility audit) was granted by the Kamuzu University of Health Sciences Research Ethics Committee (COMREC) on 15 November 2023 (Protocol number: P.09/23-0297). Kamuzu University of Health Sciences conducted the data collection and served as the study sponsor.

Consent to participate: Written informed consent was obtained from all facility in-charges participating in the health facility audit interviews. No patient-level interview or health worker observational data from the TLM Study Datasets was used as part of this study. All data were collected and stored in anonymised form, and no personally identifiable information is included in this manuscript.

Consent to publish: Consent for publication was obtained as part of the informed consent process. All data used in this study were anonymised prior to analysis, and no personally identifiable information is included in this manuscript.

Authors' contributions: SM: conceptualisation, methods, data curation, formal analysis, visualisation, and writing the original draft. NC: data curation and reviewing and editing the manuscript, SW: methods, reviewing and editing the manuscript, CAA: reviewing and editing the manuscript, MC: methods, reviewing and editing the manuscript, JC: methods, reviewing and editing the manuscript, EC: reviewing and editing the manuscript , TC: methods, reviewing and editing the manuscript, EJ: methods, reviewing and editing the manuscript, TDM: methods, reviewing and editing the manuscript, GM: reviewing and editing the manuscript, JMB: funding acquisition, MM: methods, reviewing and editing the manuscript, DN: methods, reviewing and editing the manuscript, AP: methods, reviewing and editing the manuscript, LS: reviewing and editing the manuscript, BS: data curation, methods, reviewing and editing the manuscript, WT: reviewing and editing the manuscript, PDT: reviewing and editing the manuscript, PR: supervision, funding acquisition; TBH: conceptualisation, methods, reviewing and editing the manuscript, and funding acquisition. SM and TBH have accessed and verified the data and were responsible for the decision to submit the manuscript. All the authors had access to the data in the study and they accept responsibility to submit for publication.

1 Introduction

There is a growing demand in global health research for modelling approaches which consider system-wide delivery platforms rather than single disease delivery platforms. These methods aim to capture the health system, its constraints, the dynamic connections between its components as well as interactions between multiple diseases[1, 2, 3, 4]. All-disease health system models address this need by providing a framework to evaluate the value of diverse interventions, ranging from disease-specific to system-wide interventions, while accounting for the demographic, epidemiological, and resource interdependencies within a health system.

The use of health system models in economic evaluations requires a robust and consistent costing methodology, which like the models, captures the dynamic feedback effects of changes to resource use patterns. The aim of such costing methods should be to estimate the cost of running the health system and implementing alternative policy options in a way that approximates real-world complexity.

In this paper, we develop a costing approach for the estimation of health sector costs in Malawi using the Thanzi La Onse (TLO) model, an individual-based simulation model of Malawi's health system representing the major causes of deaths and disability in Malawi [5]. Through a detailed representation of resources (i.e., healthcare workers, consumables, facilities, and equipment), the population served by the public-sector healthcare system, and policies that govern how resources for health care were arranged to meet healthcare needs, the TLO model provides a framework for implementing a bottom-up or micro costing method for a substantial proportion of health system inputs. The approach enables evaluations of healthcare delivery costs under alternative health system expansion paths, advancing the potential for economic evaluations to inform system-level decision-making, as well as planning for future health sector budget needs.

We present a method for estimating healthcare costs that aims to closely approximate actual costs incurred in Malawi by relying on local unit cost data and iterative adjustment of resource use parameters to align with (reported) national healthcare expenditure and budget data. We then apply this method to estimate total and average annual costs for the 8-year period from 2023 until 2030—the timeframe of the current national health sector strategy[6]—under four scenarios representing varying levels of health system capacity. These scenarios specifically vary in the performance of the consumables supply chain (measured by the probability of availability of medical consumables at the point of care) and the size of the healthcare workforce.

The primary aim of this paper is to describe a costing method tailored for economic evaluations using a health system model, a method of evaluation particularly suited to system-level interventions[1]. With appropriate adjustments to the calculation of capital costs, this approach can also support long-term budget planning, aid coordination[7], and investment decisions to strengthen system preparedness for future health shocks.

Box 1: Key concepts in the TLO model

Health system interaction (HSI): This is the unit of healthcare provision, through which services are provided to patients. HSIs represent the interactions between individuals and the health system (requiring available health workers, medical consumables and equipment). These HSIs may occur at an individual's home (in the case of community healthcare), in their neighbourhood (outreach services), or at a health facility.

District: One of 32 sub-national bodies (includes cities) who manage independent decentralised budgets and oversee the delivery of health within their jurisdiction [8]

Health worker cadre: The health workforce in the model is categorised into the following nine health worker cadres with different kinds of specialisation - clinical, nursing and midwifery, pharmacy, laboratory, dental, mental, nutrition, radiography, health surveillance assistants (HSAs)[8].

Facility level: Health facilities are categorised into five levels to represent their position in the referral pathway (i.e. the lowest level is that to which individuals present initially with possible onward referral to higher levels for specialised services). These levels are - health posts (level 0); health centres, maternity clinics, clinics and dispensaries (level 1a), rural or community hospitals (level 1b), District referral hospitals (level 2) and Regional referral hospitals or Central hospitals (level 3) [8].

Disease/Public health program: This represents a broad categorisation of individual health services into a disease or public health program which is usually managed/supervised by independent units within the health sector [9]. For example, HIV screening, prevention and treatment services are part of the HIV program.

2 Methods

2.1 Costing methodology

2.1.1 Estimation of resource use

The TLO model incorporates mechanistic representations of the causes of death and disability that, according to Global Burden of Disease (GBD) estimates, accounted for approximately 81% of deaths and 72% of disability-adjusted life-years

(DALYs) in Malawi during 2015–19. The scope of the model is health care provided in Malawi during 2015–19 by the public sector, which covers 66% of all facilities and more than 98% of all outreach and village clinics in 2016. The public sector in Malawi consists of a total of 734 facilities managed by the government and the government-supported faith-based organisation (Christian Health Association of Malawi); these are grouped in the model by facility level and district. A complete description of the model can be found in Hallett et al(2025)[5].

Resource use is logged in the TLO model for every *successful* health system interaction (HSI) delivered during a simulation (see Box 1 for a description of key TLO model-related terms used in this paper). The delivery of each HSI requires an appropriate quantity of medical consumables (i.e. , medicines, diagnostics, and other items needed to provide care such as gloves and syringes), patient facing time (PFT) of health workers of different cadres, functional equipment, and for the facility to be in operation. Once the patient arrives at the facility to seek care, the successful delivery of an HSI depends on the availability of sufficient PFT on a simulated day, and the availability of medical consumables and equipment, essential to its delivery. PFT is logged for every HSI which occurs before the health worker capacity for a given day at each simulated facility is exhausted.

To decide the order in which patients are seen, the 'Naive' prioritisation strategy is applied, where all non-emergency cases are assigned equal priority. This means that on a given simulated day, emergency cases are attended to first (with children prioritised over adults), following which non-emergency cases are seen in a random order[10] (see Box 2 for more detail). If the HSI occurs, the quantities of used consumables are logged when all consumables essential for its delivery are available; the availability of consumables is stochastically determined for each HSI based on empirical estimates of the average probability of availability of consumables, specific to the type of consumable, facility level, district and month of the year[11]. Similarly, the types of equipment used for each HSI are logged when available and used. In the current version of the TLO model[12], all required equipment is assumed to always be available and functional, due to data limitations.

The simulation is run from 2010 to 2030, with 2023–2030 forming the focus of our analysis. The earlier years allow the model to be calibrated with real-world data before the evaluation period begins. The initial population size adopted (in 2010) was 100,000 individuals, and we performed 10 simulations per scenario considered, each with independent random draws; both numbers were found to be large enough to give stable estimates of the mean and variance of the health burden obtained under each cause included in the simulation over independent realisations[10]. The results reported are scaled to the true population size in Malawi.

Box 2: Patient Prioritisation in the TLO model Healthcare resources are pooled in the TLO model by facility level and district, i.e. each simulated facility represents a unique combination of district and facility level (see Box 1). Within each simulated facility, constrained healthcare worker (HCW) time is allocated using a prioritisation framework that determines the order in which patients receive care. Each patient is assigned a priority level based on the urgency of their condition. Among patients with equal priority, treatment is allocated based on how long they have been waiting to be seen for that treatment, with people waiting for a longer time (earlier seekers) treated first. If multiple patients started seeking care on the same day, their order is randomised.

Healthcare service interactions (HSIs) are delivered sequentially each day under a rigid healthcare system assumption, meaning that services cannot be delivered if the health worker capacity for a given day runs out at a simulated facility. Patients who are not treated on the day they initially seek care can return to the same facility for up to seven days. Returning patients are treated before patients of equal priority who sought care more recently but after new patients with higher priority.[10]

2.1.2 Estimation of costs

We adopt a mixed-method costing approach[13, 14], combining ingredients-based micro-costing, where feasible based on data availability, with top-down costing where necessary. Specifically, we apply micro-costing to resources that are directly attributable to service delivery and apportionable by patient. For higher-level costs—such as distribution and warehousing of medical consumables, monitoring and supervision of health workers, and other system overheads—we adopt a top-down approach. The bottom-up component uses detailed estimates of the quantities of each resource used in healthcare delivery, while the top-down component draws on empirical estimates from Malawi on the share of overall resource costs attributable to such overheads (see Table 1 for more detail).

All costs are estimated from a *healthcare provider perspective*[15], as the primary aim of the analysis is to support the Ministry of Health in prioritizing investments within the health system.

Our primary focus is to cost the *health system inputs* used for *service delivery* as represented by individual HSIs in the TLO model and any administrative expenses directly associated with these. Higher-level administrative costs (such as those for *Governance* and *Financing*) are not directly associated with service delivery and are excluded because these are outside the scope of the TLO model[3].

We cost the following *health system inputs*[16], referred to as *cost categories* - i. medical consumables, ii. human resources for health (HRH), iii. medical equipment, and iv. facility operation. We present the financial costs of these resources[4], with capital costs—such as those for health workers (pre-service training) and purchase of medical equipment—annuitised over their expected useful life.

Uncertainty in our cost estimates arises from the stochastic nature of the TLO model, which simulates births, deaths, disease incidence, healthcare-seeking behaviour, and the availability of health system resources during an HSI. In line with standard practice, unit costs are treated as deterministic. All costs are reported in 2023 USD. Historical unit costs of tradable inputs (medical consumables and equipment) were inflated to 2023 values using Consumer Price Index

(CPI)-based inflation rates from the U.S. government[17], which is the recommended method for pricing internationally traded goods[18]. For non-tradeable inputs (Health worker costs and Facility operating costs), the data obtained was already in 2023 currency values, so inflation adjustments did not need to be made. Values in Malawi Kwacha (MWK) were converted to USD using exchange rates from the World Development Indicators[19].

Detailed methods for estimating each cost category are presented in the sections that follow. The analysis script and input data (including inflation and exchange rates applied) for this study are publicly available in the TLO model repository[20].

Medical consumables

The TLO model simulates a defined set of health services delivered within Malawi's public health system. The clinical workflows for these services, including diagnostic procedures, laboratory investigations, and drug prescribing practices, are parameterised using the Malawi Standard Treatment Guidelines[21]. A full description of the services modelled and their clinical pathways is provided in Hallett et al(2025) [5]. During each simulation, every consumable (along with the appropriate dosage) used during a health system interaction (HSI) is logged, including medicines, diagnostics, and laboratory tests. These logs are aggregated to estimate annual quantities of consumables dispensed. In addition to the quantity of consumables dispensed, we also assume that some quantity is wasted due to expiration, theft or mismanagement of consumable stocks[22, 23]. We derive a consumable-specific empirical estimate of the proportion of consumables *wasted* in 2018[24] in Malawi to apply this adjustment to consumable costs. We also include a top-down estimate of supply chain costs associated with the procurement, storage, and distribution of consumables from source to facility. Equations A1–A2 present the full costing formulae.[1]

For most consumables, we use local procurement prices relevant to the Government of Malawi. For donated commodities, we apply market prices relevant to international donors. Data sources for each component are described in Table 1.

$$\begin{aligned}\text{Cost of medical consumables}_t = \sum_i \Big[&\text{Cost of consumables dispensed}_{i,t} \\ &\times (1 + \text{Expected proportional loss to theft/expiry/mismanagement}_{i,t})\Big] \\ &\times (1 + \text{Expected proportional supply chain overhead}_t)\end{aligned} \tag{A1}$$

where t = year, i = type of medical consumable dispensed

$$\begin{aligned}\text{Cost of consumables dispensed}_{i,t} = &\text{Quantity of consumables dispensed}_{i,t} \\ &\times \text{Market price of consumable}_{i,t}\end{aligned} \tag{A2}$$

Human resources for Health (HRH)

Like medical consumables, the cost of employing and retaining health workers is a recurrent expense. However, unlike consumables—whose quantities scale proportionally with the volume of services delivered—the size of the health workforce cannot be easily adjusted throughout the year. Therefore, we treat HRH costs as fixed annual costs, modifiable only through explicit policy decisions related to workforce expansion[4].

Following established HRH costing guidelines[25], our estimates include: (i) remuneration, (ii) the cost of pre-service (pre-qualification) and in-service training, and (iii) the cost of routine monitoring and supervision of all health worker cadres represented in the model.

All public sector health workers are assumed to receive Malawi's standard remuneration package based on staff grade. To estimate remuneration (see Equation B2), we calculate the average annual salary and benefits (including medical and professional allowance) by cadre and facility level, weighted by the distribution of grades within each category. Ideally, remuneration would also include overtime, additional duty hours, and pension contributions. However, due to data limitations, these components are not included.

For pre-service training (Equation B3), we include the recurrent costs of tuition and faculty salaries. Following standard guidance[25], we assume tuition fees cover the cost of infrastructure and equipment used in training programmes. Faculty salaries are included to capture the opportunity cost of their time not spent in healthcare service delivery. Due to lack of data, we exclude the costs and potential benefits (service delivery) of student clinical placements.

As with the approach used for costing medical equipment with multi-year durability, we annuitize pre-service training and recruitment costs over the expected working life of each health worker, using standard annuitization methods[26]. We also adjust for the fact that only a proportion of trainees graduate, obtain licensure, and subsequently enter the public workforce. Additionally in equation B4 we demonstrate the adjustment for staff that may be recruited from abroad bypassing domestic training costs; however, current data suggests that this proportion is zero in Malawi[6]. For each new hire, a fixed recruitment cost is applied (Equation B4).

Costs for in-service training and HR monitoring and supervision are estimated using a top-down approach, expressed as a proportion of total remuneration (see Equations B5 and B6).

[1] Market prices and proportional loss due to theft, expiry, or mismanagement are assumed to remain constant over time, due to lack of data on temporal variation.

Finally, other operational overheads that support HRH functionality—such as facility management—are included under *facility operation costs*.

$$\begin{aligned}\text{Cost of human resources for health}_t = &\sum_c \text{Remuneration}_{c,t} \\ &+ \sum_c \text{In-service training}_{c,t} \\ &+ \sum_c \text{Monitoring and supervision}_{c,t} \\ &+ \sum_c \text{Pre-service training and recruitment}_{c,t}\end{aligned} \tag{B1}$$

where c = cadre, t = year

$$\begin{aligned}\text{Remuneration}_{c,t} = &\text{ Number of staff employed}_{c,t} \\ &\times \text{Annual salary and benefits}_{c,t}\end{aligned} \tag{B2}$$

$$\text{Pre-service training and recruitment}_{c,t} = \frac{\text{Cost per person recruited}_{c,t} \times \text{Number of staff employed}_{c,t}}{\text{Annuitisation factor based on expected working life}_c} \tag{B3}$$

$$\begin{aligned}\text{Cost per person recruited}_{c,t} = &\frac{\text{Cost per person trained}_{c,t}}{\text{Graduation rate}_{c,t} \times \text{Licensure rate}_{c,t}} \\ &\times \left(\frac{1}{\text{Proportion absorbed into public workforce}_{c,t}} \right. \\ &\left. + \frac{1}{\text{Proportion recruited from abroad}_{c,t}} \right) \\ &+ \text{Per-staff cost of recruitment process}_{c,t}\end{aligned} \tag{B4}$$

$$\begin{aligned}\text{In-service training}_{c,t} = &\text{ Remuneration}_{c,t} \\ &\times \text{Expected in-service training cost as a proportion of remuneration}_{c,t}\end{aligned} \tag{B5}$$

$$\begin{aligned}\text{Monitoring and supervision}_{c,t} = &\text{ Remuneration}_{c,t} \\ &\times \text{Expected monitoring and supervision cost as a proportion of remuneration}_{c,t}\end{aligned} \tag{B6}$$

Medical equipment

As with medical consumables, the model logs the equipment used to deliver each HSI, and this log can be aggregated to identify which equipment types were used at each facility level during the simulation. However, unlike consumables, the model does not estimate the quantities of equipment required per facility to deliver the simulated services. Instead, it records only whether a specific item of equipment was *ever used* or *never used* at each facility level and district. To address this limitation, we rely on local expertise to determine the quantity of equipment needed by facility level. These estimates, developed to guide prioritised equipment costing in HSSP-III [27], form the basis of our calculations. Consequently, our equipment cost estimates reflect the prioritised quantities across all facilities in the country for the list of equipment identified as *ever used* in the simulation at each facility level. We apply the standard annuitisation method[26] to spread the cost of replacing each piece of equipment over its expected lifetime.

Ensuring the functionality of medical equipment also requires recurrent expenditures for regular servicing (including spare parts) and ad-hoc corrective maintenance as needed[28, 29]. We use costing assumptions from HSSP-III to estimate these recurrent costs as a proportion of equipment replacement costs. Further details on data sources are provided in Table 1, and the cost calculations are detailed in Equations C1–C4.

$$\begin{aligned}\text{Cost of medical equipment}_t = &\sum_{e,t} \big(\text{Annuitised replacement cost}_{e,t} \\ &+\text{Major corrective maintenance}_{e,t} \\ &+\text{Service fee and spare parts}_{e,t}\big) \\ &\times \text{Quantity of equipment available}_{e,t}\end{aligned} \tag{C1}$$

where e = type of equipment,

$$\text{Annuitised replacement cost}_{e,t} = \frac{\text{Replacement cost}_{e,t}}{\text{Annuitization factor based on life span}_{e}} \tag{C2}$$

$$\begin{aligned}\text{Major corrective maintenance}_{e,t} = {} & \text{Replacement cost}_{e,t} \\ & \times \text{Proportion of equipment expected to require major corrective maintenance}_{e} \\ & \times \text{Cost of major corrective maintenance as a proportion of replacement cost}_{e}\end{aligned} \tag{C3}$$

$$\begin{aligned}\text{Service fee and spare parts}_{e,t} = {} & \text{Replacement cost}_{e,t} \\ & \times \text{Cost of service fee and spare parts as a proportion of replacement cost}_{e}\end{aligned} \tag{C4}$$

Facility operation costs

Recurrent costs associated with operating health facilities are essential components of service delivery and must be included in the costing exercise[16, 25]. Under facility operation costs, we include expenditures related to utilities (e.g., electricity and water), salaries of non-healthcare delivery staff (e.g., security, cleaning, management personnel), fuel for ambulance transport, and overheads for inpatient services (e.g., patient food).

These estimates are drawn from a bespoke facility audit conducted for the TLO model in 2024[30, 31]. Based on data from 29 health facilities, we estimate average annual facility operation costs by facility level, as reported in Table D.1.

$$\begin{aligned}\text{Running cost of operating faclities}_{t} = \sum_{l} \big(& \text{Utility bills}_{l,t} \\ & + \text{Building maintenance}_{l,t} \\ & + \text{Non-healthcare delivery staff}_{l,t} \\ & + \text{Ambulance fuel costs}_{l,t} \\ & + \text{Overhead inpatient costs}_{l,t} \big) \\ & \times \text{Number of facilities}_{l,t}\end{aligned} \tag{D1}$$

where t = year, l = Facility level

2.1.3 Other assumptions

Discounting

Although the standard application of a uniform 3% discount rate to future costs is now recognised as inappropriate due to variations in the projected growth rate of economies and in the projected marginal productivity of their health systems [32, 33], the majority of cost-effectiveness literature [32], including the latest WHO-CHOICE study [34, 35], continues to use the 3% discount rate. In order to align with the cost-effectiveness literature, our primary results apply the 3% annual discount rate. However, in Appendix section C, we additionally report undiscounted costs as well as costs discounted using country-specific variable annual projected discount rates from Lomas et al (2021)[33], with an average value of 0.39% between 2023 and 2030 for Malawi.

Temporal variation in unit cost and other assumptions

When projecting costs, it is important to consider if unit costs of health resources might change over time. For example, the cost of consumables may decline as more generics become available, health worker salaries may increase, and fuel costs may fluctuate based on global markets. In principle, the TLO model allows the application of time-specific unit costs to resource use, as all interactions are timestamped. However, for this study, we applied constant unit costs based on the most recent available data. More specifically, due to the lack of data on temporal variation, we assume the following parameters remain constant over time: *market price of consumables, expected proportional supply chain overhead, annual salary and benefits, cost per person trained, graduation rate, licensure rate, proportion absorbed into the public workforce, proportion recruited from abroad, per-staff recruitment cost, expected in-service training cost as a proportion of remuneration, expected monitoring and supervision cost as a proportion of remuneration, equipment replacement cost, and quantity of equipment available.* Again due to the lack of reliable inflation projections, we also do not adjust for annual inflation going forward from 2023 until 2030, and thus our estimates reflect real rather than nominal costs.

Note that while unit costs remain fixed due to a lack of data on temporal price trends, the epidemiological and service delivery components of the TLO model evolve dynamically over time, by design. These evolving elements drive year-to-year variation in resource use and costs, even when unit costs remain constant.

For the calibration of our cost estimates with expenditure data reported for 2018 (see Section 2.1.4), we adjusted unit prices where necessary to align with 2018 cost levels. For instance, although we apply a unit cost of $37.50 for an adult annual course of antiretroviral (ARV) treatment in the main analysis[36], we used a cost of $82[37]—reflective of 2018 prices—for validation purposes. The full set of unit costs can be accessed on the TLO model repository.

2.1.4 Calibration of estimates

To improve confidence in our cost estimates, we compared modelled costs to available data on healthcare expenditure and budgets in Malawi. Where discrepancies were identified, we adjusted our unit cost and resource use assumptions to better align our estimates with reported data. Benchmark figures were derived using the Resource Mapping (RM) data from the latest report (see Box 3).

With the goal of bringing the model-based cost estimates within the range between reported expenditure and reported budget figures in Malawi, the following steps[2] were followed -

1. Costs estimated from the model for the calendar year 2018 were compared to expenditure reported for the financial year (FY) July 2018–June 2019 and the maximum projected annual budget for FYs ending between 2020 and 2022[3].
2. If the modelled cost was outside the *target range* between reported expenditure and budget, we first revisited our unit cost assumptions and extracted data from an alternative source, if needed.
3. Next, we revisited our resource use assumptions with experts who developed the various disease modules in the TLO model. This step was only needed for medical consumables and medical equipment, because for HRH and facility operation costs, the current stock of health workers and facilities was used which was not subject to change.
    - For medical consumables, where there was a significant discrepancy between RM figures and our cost estimates, we further compared the quantity dispensed logged by the model with data on actual quantity dispensed during 2018, as recorded in Open Logistics Management Information System (OpenLMIS)[24] by health facilities. If our model assumptions were found to deviate from on-the-ground practices, the number of consumable units required for each HSI was adjusted in the model to align with practice.
    - For medical equipment, we compared the list of equipment logged by the model to the list of medical equipment costed in the HSSP-III [6], and added any missing equipment to the model.

The aim of this exercise was not to arbitrarily adjust parameters to match benchmark expenditures but to identify and address deviations in model assumptions about resource use from real-world conditions through the lens of costing. This approach was intended to improve the reliability and representativeness of the estimated costs. However, due to limitations in the granularity of the Resource Mapping (RM) data, we could only validate our cost estimates against categories for which health sector stakeholders reported disaggregated expenditure and budget figures. In some instances, despite the adjustments described, the modelled costs remained outside the *target range*. These discrepancies typically arose because the TLO model did not account for *all* indications that justify the use of certain resources[4]. To maintain transparency, we report these differences in appendix section B.

Box 3: Resource Mapping (RM) Report (Round 7) With over 60% of the health sector funding coming from external donors, and being utilised through disparate implementing partners, it can be challenging for the Ministry of Health (MOH), Malawi to keep track of resources and plan for a more efficient use of resources. To address this challenge, the MOH runs a resource mapping exercise to track expenditure and forward-looking budgets in the health sector to provide a comprehensive funding picture to help strengthen resource mobilization and resource allocation decisions for the MOH and its development partners (DPs). The RM captures data on funding for health over time, disaggregated by financing source, implementing agent, disease areas, geography, cost types and alignment to national strategic plans[38]. The round 7 data captures expenditure for the financial year(FY) ending 2019 and annual projected budgets for the FYs ending 2020, 2021, and 2022. The financial year in Malawi runs from July to June.

Although the Resource mapping report represents the best source of information on Malawi's health sector expenditure and budgets across stakeholders, because of its self-reported nature, the quality of this data depends on the response rates and fidelity to reporting guidelines of financing and implementing partners in the sector and is, therefore, not the ultimate source of truth on the health sector financing situation[7]. In fact, it has been noted that reported expenditure tends to be far lower than the budget (due to financing challenges), while the budget is better disaggregated into relevant categories than the expenditure. Therefore, we rely on the range between the two figures for the purposes of calibration, with the expenditure figure prioritised for the comparison of aggregate figures by cost category, because these are considered more representative of reality.

[2]This is different from the more detailed calibration process followed for the epidemiological aspects of the model, details of which can be found in Hallett et al (2025)[5]

[3]More recent expenditure information in the granular format provided by the Resource Mapping database is not currently available.

[4]For example, the use of Gentamicin sulphate was included for management of sepsis and pneumonia. Not all conditions which might warrant the use of this antibiotic were modelled.

2.2 Projection of costs under different health system assumptions

To demonstrate how the cost of service delivery changes interactively through changes in health system capacity/performance, we use the costing method described above to project healthcare resource use costs under four scenarios, varying the performance of consumable supply chains and size of the health workforce. We make these projections for the 8-year period covered by the HSSP-III (2023–2030).

1. **Actual:** This is the baseline scenario which aims to represent the *actual* capacity of the health system in Malawi as observed between 2017 and 2024. This includes - i. observed probability of availability for each *medical consumable* at each facility level and district[24], ii. actual stock of *human resources for health (HRH)* [8], with the historical increase in staff numbers between 2017 and 2024 incorporated into the model via a fitted growth curve (see section 2.2.1)., iii. current *performance of healthcare workers* in clinical diagnoses and probability of referrals[5], and iv. current propensity for *healthcare seeking* [39]. The *default* probability of availability of consumables of 49.2% on average (44% at level 1a and 57% at level 1b facilities). Details on the initial size of health workforce can be found in She et al (2024)[8].
2. **Expanded HRH:** Ceteris paribus, this scenario expands the number of health workers at an average annual rate of 4.87% from 2017 onward. This growth rate reflects the historical trajectory of HRH expansion between 2017 and 2024, extended forward to 2030 (described in further detail in section 2.2.1).
3. **Improved consumable availability:** Ceteris paribus, this scenario increases the probability of consumable availability in health facilities at levels 1a and 1b (see Box 1), where most of the health care is delivered, to match that of the 75th percentile of top-performing facilities. [11], at the corresponding facility level for each individual consumable[5]. This results in an 8 percentage points and 9 percentage points increase in the average probability of availability of consumables at levels 1a and 1b respectively, in comparison to the *actual* scenario. See Figures A.1 and A.2 for more detail on average consumable availability under this scenario by *program*. Note that due to lack of data on how wastage would change under the scenario of improved consumable availability, the value of Expected proportional loss to theft/expiry/mismanagement$_{i,t}$ is assumed to be the same across scenarios.
4. **Expanded HRH + Improved consumable availability:** This scenario combines the health system improvements from scenarios 2 and 3.

2.2.1 Description of HRH Expansion

Historical HRH growth was incorporated by fitting an exponential curve to Malawi Ministry of Health staffing data for 2017–2024. The fitted function generated a scale-up factor for each year.

$$Scaleup(y) = \exp(\beta(y - y_0)) \tag{E1}$$

where y represents the year, y_0 the starting year 2017, and β is the rate of growth. This was applied to the *actual* scenario.

In the *expanded HRH scenario*, this trend was extended linearly between 2025 and 2030. 4.87% represents the average compound annual growth rate (CAGR) between 2017 and 2030 in the Expanded HRH scenario, estimated as follows

$$CAGR = \left(\frac{2030\ staff\ count}{2017\ staff\ count}\right)^{\frac{1}{(2030-2017)}} - 1 \tag{E2}$$

Both the historical scale-up and the forward projection were applied uniformly across cadres.

3 Results

3.1 Performance of costing model: comparison of 2018 cost estimates to actual expenditure and budget

The total actual health sector expenditure reported in Malawi for the fiscal year ending 2019 was $624.1 million. Excluding components outside the scope of the TLO model—such as programme management and administration, newly constructed infrastructure, infrastructure upgrades, motor vehicle purchases, and medical consumables for conditions not included in Malawi's Essential Health Package (EHP)[3, 40]—the adjusted expenditure total is $404 million.

Using the TLO model, we estimate the total healthcare delivery cost in 2018 to be $362.10 million, which is 10.37% lower than the adjusted Resource Mapping (RM) expenditure figure.

Figure 1 presents a comparison of TLO model cost estimates with actual expenditure and budget allocations for each of the four cost categories. For most categories, model estimates fall within the target range—defined by the span between reported expenditure and budget figures.

A detailed breakdown of this comparison, along with a discussion of potential sources of discrepancy, is provided in Appendix section B.

[5] If the actual availability is higher, then no change is made.

3.2 Projection of costs under different health system assumptions, 2023-2030

The total cost of healthcare delivery in Malawi between 2023 and 2030 was estimated to be $2.83 billion [95% uncertainty interval (CI), $2.80b - $2.87b], under the actual scenario, and increased to $2.87 billion [$2.83b - $2.92b] under the improved consumable availability scenario, followed by $2.97 billion [$2.93b - $3.01b] under the expanded HRH scenario and finally $3.01 billion [$2.97b - $3.05b] under the expanded HRH + improved consumable availability scenario. This translates to an average annual cost of $390.98 million [$385.92m - $396.71m], under the actual scenario, $396.46 million [$391.20m - $402.50m] under the improved consumable availability scenario, followed by $410.63 million [$405.66m - $416.15m] under the expanded HRH scenario and finally $415.94 million [$410.66m - $422.09m] under the expanded HRH + improved consumable availability scenario. In per capita terms, this is $16.89 [$16.75 - $17.08], $17.29 [$17.11 - $17.50], $17.70 [$17.57 - $17.89], and $18.11 [$17.94 - $18.32] respectively under the four scenarios. Figure 2 breaks these estimates down by cost category and Figure 3 reports these by subcategory. Figure 4 reports these costs by year between 2023 and 2030. These estimates use a 3% annual discount rate. Undiscounted cost estimates and those with variable discount rates from Lomas et al (2021)[33] are reported in appendix section C.

Notably, improving consumable availability alone increased the cost of medical consumables by just 4.63% because the limited health workforce (HRH) restricts the number of feasible appointments and, consequently, the quantity of consumables dispensed. Expanding HRH alone raised consumable costs by 1.43%, without any simultaneous improvement in consumable availability. When both HRH and consumable availability are expanded together, consumable costs increased by 5.93% compared to the actual scenario, underscoring the interdependence between HRH capacity and the cost of diagnostics and treatments dispensed.

A detailed breakdown of costs by subcategory and category-specific subgroups (e.g., consumables for consumable costs, health worker cadre for HR costs) is available in Appendix section E. Figures E.1-E.4 summarize these breakdowns for the top 10 subgroups ranked by cost. Figure E.1 illustrates how the allocation towards the top 10 medical consumables shifts across different scenarios, reflecting variations in the types of health services successfully delivered under different health system capacities. First, the changes are driven by which constraint is binding. For example, the pattern of change across scenarios for the Jadelle contraceptive implant differs markedly from that of adult antiretroviral therapy (ART). Expanding HRH alone increases the cost of Jadelle implants provided by just 0.77%, whereas improved consumable availability results in a 25.11% increase, rising to 26.35% when both HRH and consumables expand. In contrast, ART costs rise more modestly across the same scenarios (0.41%, 4.00%, and 4.17%). This reflects differences in baseline availability: ART already had very high availability in level 1a/1b facilities (94.83%), and the improved supply chain scenario increased this by only around 5 percentage points. For Jadelle, availability increased from 74.78% by 13 percentage points, meaning consumable availability was a stronger binding constraint for this service. Second, cost changes do not scale linearly with changes in service coverage or system capacity. The dynamic nature of the model aggregates multiple interacting processes — such as population growth, prevention coverage, prevalence, testing rates and yields, and competition between appointments[41, 5, 10]. Consequently, while ART costs increase progressively across scenarios (0.41%, 4.00%, 4.17%), the cost of HIV testing shows a different pattern: a small increase under expanded HRH (1.30%) but reductions of 2.10% and 1.03% under the improved consumables and combined scenarios. These reductions arise because increased consumable availability intensifies competition with other services, leading to fewer HIV testing appointments being delivered. Such non-linear behaviours illustrate the complex interdependencies that determine real-world resource use.

4 Discussion

In this analysis, we used the Thanzi La Onse (TLO) model to estimate current and future costs of healthcare delivery in Malawi under different health system capacity assumptions. We demonstrated how mixed-method costing can be applied within a mechanistic health system model and the types of data sources which can be used to cost various health system inputs.

While calibration to epidemiological data is a well-established practice for individual-based models[42], there are no standardized methods for calibrating cost and resource-use estimates to real-world data[43]. Much of the previous work projecting healthcare costs has relied on top-down approaches, rather than ingredients-based methods centred on resource use[44, 45, 46, 47]. As a result, there is limited guidance on benchmark targets for calibrating cost estimates when using bottom-up costing methods. This paper makes a contribution in this space by demonstrating how an iterative process of adjusting unit costs and resource-use assumptions can help align model-based estimates with observed expenditure and practice.

We were able to align our cost estimates with Malawi's Resource Mapping data for most cost components through: i) the use of country-specific (or donor-specific) unit cost data for health resources; ii) calibration of epidemiological, demographic, and health system productivity parameters to observed data; and iii) iterative refinement of resource-use assumptions in the TLO model.

Where deviations persisted in cost estimates, we reported and discussed them transparently in order to support appropriate interpretation and application of our results. It is important to recognize that the role of a model is to approximate reality—not to replicate it exactly. The step of costing calibration followed the more standardised process of calibration of epidemiological estimates [5] and service use [8] in the TLO model. As administrative data systems continue to improve in coverage and quality, we anticipate that the process of calibrating cost estimates in health system models will become more streamlined. In the meantime, this study offers a generalisable and transparent approach to costing within health system modelling.

Using this representative costing method, we projected the cost of healthcare delivery in Malawi under alternative assumptions about health system capacity. A major strength of the TLO model is its ability to capture the feedback effects of expanding one health system component on others. Our findings underscore the importance of modelling interdependencies between health system components when forecasting future costs. This costing method provides a solid foundation for evaluating policy decisions in Malawi, particularly those involving interventions with dynamic feedback effects. At the same time, the framework can be adapted for other purposes, such as multi-year budgeting and financial planning. The key modification for budgeting applications involves treating capital costs, such as medical equipment replacement and pre-service training, on a financial or cash-flow basis, rather than using annuitised economic costs.

The TLO model is constantly evolving with greater complexity, more health conditions, health services, behavioural patterns and granularity being incorporated. In conjunction, we provide a flexible costing framework that can accommodate greater complexity over time. However, in its current application[12], several limitations should be noted. First, for certain cost components, we applied a top-down approach, assuming constant returns to scale and scope, which may not hold under non-marginal system expansion. For example, we assume supply chain costs are a fixed proportion of consumables, whereas real-world scaling may involve non-linear increases in labor, storage, and distribution needs[48, 49]. Second, consumables availability is modelled as a facility-level probability and only dispensed consumables are costed (with wastage accounted for through a proportional scaling factor). While this leads to higher consumable costs in improved system scenarios, it does not account for the fact that timely consumable availability depends not only on the total quantity purchased but also on distribution efficiency. In other words, we cost consumables from the point of view of usage rather than purchase and distribution and our method does not capture variations in availability due to differences in supply chain efficiency. Third, the TLO model currently does not simulate actual equipment availability across facilities. Instead, we adopted a normative approach based on HSSP-III targets. This ignores real-world throughput constraints (e.g., an X-ray machine's daily capacity) and potential shortfalls in functionality. Future work could estimate minimum required equipment based on utilization rates, using tools such as WHO's Essential Inputs Estimator[50], and incorporate evidence of maintenance shortfalls[29]. Fourth, in our improved system scenarios, we capture only the cost of purchasing or hiring additional resources, and exclude *implementation overheads* or complementary investments (e.g., additional facility space) that would be necessary for these resources to function effectively. Thus, our cost estimates may not reflect the full costs of system transformation. Fifth, we assume no variation in unit costs by facility ownership (government or faith-based) or geographic region, due to lack of disaggregated data. Sixth, because of limited evidence on parameter uncertainty and the large number of unit costs involved, we apply unit costs deterministically, although in reality these may vary across consumables, equipment, facility levels, districts, and years.

Finally, a limitation of our calibration process is that our costing approach estimates economic costs - through the annuitisation of capital inputs such as pre-service training for HRH and replacement costs of medical equipment —whereas the Resource Mapping (RM) exercise captures financial expenditures and budgets. Thus, the calibration required an implicit assumption that capital expenditures reported in RM are, in aggregate, spread uniformly over time. In practice, however, some components (e.g., infrastructure investments or expansion in training institution capacity) may be lumpy from year to year, whereas others (such as recurring pre-service training costs given fixed enrolment capacity) are more stable. While this mismatch in accounting perspectives limits the precision with which our model can align with RM figures, it does not undermine the overall purpose of calibration—namely, to ensure that modelled resource use assumptions are broadly consistent with observed expenditure patterns. We present these discrepancies transparently in the manuscript, as doing so helps clarify the assumptions underlying our estimates and supports appropriate interpretation of the model's outputs when they are used to inform policy decisions.

Despite these limitations, our analysis demonstrates the robustness and adaptability of the mixed-method costing approach for health system models. By integrating diverse data sources and applying a transparent, iterative method, we provide a valuable framework for evaluating the financial implications of health policy options in Malawi.In future work, we aim to extend this costing approach to additional perspectives, including patient and societal perspectives. This would allow incorporation of costs borne by patients—such as transport and other out-of-pocket expenditures associated with seeking care—as well as productivity losses and inter-sectoral costs beyond the health sector.

This approach can also be adapted to other settings—both within health system models and for broader applications such as budgeting, investment case development, and scenario planning. Its reliance on local data and alignment with country-specific health system structures ensures contextual relevance. Although our implementation uses data sources that are notably strong in Malawi, such as the Resource Mapping exercise[38] and the detailed costing inputs generated during the development of HSSP-III[6], the underlying data requirements of the framework are not unique to this setting. Many of the inputs used in our analysis are administrative datasets routinely collected in most countries, such as procurement prices, health worker salary returns, and logistics management information systems. Where domestic procurement data were not available (e.g., for donated commodities such as HIV and TB consumables), we relied on internationally negotiated price catalogues[51, 36, 52] that are widely applicable. For components where we used Malawi-specific primary data (the TLM survey for facility operating costs, Resource Mapping data for calibration), equivalent information could be obtained in other settings from routine government expenditure accounts, budget execution reports, public expenditure reviews, or national health accounts[53, 54]. Finally, in contexts where data quality is lower or data systems are less integrated, the framework can still be operationalised using broader assumptions or global benchmarks, while also highlighting priority areas for future data system strengthening. As such, implementing this approach in other countries may not only support improved costing and prioritisation but also incentivise investment in more robust, transparent health systems data. As such, this work supports evidence-based prioritization, financial planning, advocacy, and resource allocation, and marks a significant step forward in leveraging health systems modelling to inform policy and strengthen health sector planning.

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Table 1: Sources of costing data

Parameter	Data Source
Medical consumables	
Quantity of consumables dispensed$_{i,t}$	A estimate of the number of units dispensed of each medical consumable included in the TLO model is generated by a model simulation. This estimate is based on a detailed log of the quantity of consumable 'used' during each health system interaction. Note that a consumable is logged as *used* only when it is available at a health facility; any unmet *requests*, due to stock-outs for consumables are not logged.
Market price of consumable$_{i,t}$	The main reference for the price of consumables is the 2023 drug price catalogue of the Central Medical Stores Trust (CMST)[55]. Established by the Government of Malawi in 1968, CMST is the institution responsible for procuring and distributing medical consumables to health facilities. Since 2011, it has been operating as a fully autonomous not-for-profit trust[56]. When the price of a drug was not found in the CMST catalogue, we referred to the Essential Healthcare Package Tool (2021) used to guide service prioritisation for the Health Sector Strategic Plan (HSSP)-III of Malawi[57], or the One Health Tool (2016) used to guide the development of the HSSP-II. The price of consumables usually purchased by donors from international suppliers is obtained from relevant references based on the program - HIV/AIDS consumables[36], TB consumables[52], nutrition and family planning consumables[51]. Certain medical supplies have unique characteristics which do not lend themselves well to the standard cost estimation method. These *separately-managed supplies* are either produced or collected within the health system, or are delivered through a platform independent of health facilities. In this subcategory, we include the cost of oxygen, blood, and indoor residual spraying (IRS) for malaria prevention. Estimates of the per unit cost of these supplies are obtained from literature, including administration costs. The cost of oxygen is assumed to be \$0.00057 per litre based on Malawi's One Health Tool (2016)[58]. For blood, we use the estimate of \$155 per unit from Mafirakureva et al (2016)[59], which includes the cost of recruitment, collection, testing, processing, storage and distribution of blood. This estimate is from Zimbabwe and is used as a proxy for the likely costs in Malawi. For IRS, we apply a cost of \$2.58 per person protected, including the cost of personnel, equipment, fuel, logistics and planning, shipping and PPE, from a study based in Tanzania[60].
Expected proportional loss to theft/expiry/ mismanagement$_{i,t}$	Estimates of drug wastage based on literature range from 14% to 35%[61, 22]. Notably, there is considerable variation in wastage across programs [22]. To obtain granular estimates of the extent of wastage for each medical consumable, we used data from Malawi's Open Logistics Management Information Systems (OpenLMIS) records from 2018. The OpenLMIS is a monthly record maintained by all government and government-supported faith-based health facilities in Malawi of the quantity of consumables in stock, received and dispensed along with the number of days of stock-out experienced during the month. Using this data, we are able to estimate the total *inflow* of each consumables into health facilities during 2018 (excluding what remained in stock at the end of 2018 and was transferred to the stock for 2019) and the total *outflow*. The ratio of the inflow to outflow minus 1 gives us the extent of wastage of each consumable. The average wastage was estimated to be 14.3%, ranging between 2% for insecticide-treated nets to 70% for bleomycin powder. See Appendix Figure D.1 for a summary of inflow to outflow ratios by disease/public health program category of consumables. Similar to other consumables, we assume that some quantity of *separately managed supplies* may be wasted. In the absence of data on wastage specific to these consumables, we applied the average rate of wastage across all consumables (14%) to calculate the total cost of these supplies.

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Table 1: Summarized Costs by Category and Category Subgroup

Parameter	Data Source
Expected proportional supply chain overhead	Based on data on health sector expenditure from the Health Sector Resource Mapping Report Round 7 (2022)[62], we assume that the supply chain overhead costs (warehousing, storage and transportation) are 11.23% of the purchase cost of consumables. This is comparable to previous estimates from literature[63].
Human resources for Health	
Annual salary and benefits$_c$	We estimate annual salary and benefits for each of the nine health worker cadres by level of care. The salary of a staff member belonging to a specific cadre is determined by their grade. Using the detailed healthcare staff returns data from Malawi, we calculated the average annual salary by cadre and level of care, weighted by the number of staff employed at each grade for each cadre and level.
Number of staff employed$_{c,t}$	This is obtained from the HSSP-III [27]. For more detail, refer to She et al (2024)[8]. When an gradual or instantaneous increase in the size of the workforce is modelled, the number of health workers costed in each year may vary.
Expected in-service training cost as a proportion of remuneration$_c$	Based on data on health sector expenditure from the Health Sector Resource Mapping Report Round 7 (2022) [62], we assume that the cost of in-service training is 11.27% of the annual remuneration cost for every cadre.
Expected monitoring and supervision cost as a proportion of remuneration$_c$	Based on data on health sector expenditure from the Health Sector Resource Mapping Report Round 7 (2022)[62], we assume that the cost of monitoring and supervision is 48.55% of the annual remuneration cost for every cadre.
Expected working life$_c$	Based on the expected annual attrition rate of 7% assumed in the costing exercise for the HSSP-III[27], the expected working life of a health worker in the public health sector is assumed to be 14.3 years. Althuogh we would expect this to vary regionally and by cadre, due to lack of data, we assume the same expected working life across all health workers.
Cost per person trained$_{c,t}$	We estimate the cost per person trained as the cost of annual tuition (assuming these are subsidised by the government) plus the annual remuneration cost of the faculty required to run the training program times the average duration of the program. Using data from the HSSP-III HRH Costing tool[27], we estimate the former for every cadre by taking the average tuition fee across medical training institutes in Malawi, weighted by their enrollment rate. To estimate the remuneration cost of faculty, we use the ratio of students to faculty for each relevant faculty cadre from HSSP-III assumptions to estimate the faculty remuneration cost per student.
Graduation rate$_c$	Assumed to be 80% following HSSP-III costing assumptions [27].
Licensure rate$_c$	Assumed to be 90% following HSSP-III costing assumptions [27].
Proportion absorbed into public workforce$_c$	Based on HSSP-III costing assumptions[27], this varies from 61% for the pharmacist cadre to 100% for community health workers.
Proportion recruited from abroad$_c$	Assumed to be 0% following HSSP-III costing assumptions [27].
Per-staff cost of recruitment process$_c$	Assumed to be $33.75 per staff recruited following HSSP-III costing assumptions [27].
Medical Equipment	
Replacement cost$_e$	Estimates of the replacement cost of equipment were extracted directly from HSSP-III costing tools[6].
Life span$_e$	Life span of each type of equipment was extracted from the UK government's Department for International Development (DFID)-commissioned 'How to Plan and Budget for Your Healthcare Technology' report[28]
Proportion of equipment expected to require major corrective maintenance$_e$	Assumed to be 20% for all equipment over 8 years following HSSP-III costing assumptions [27].

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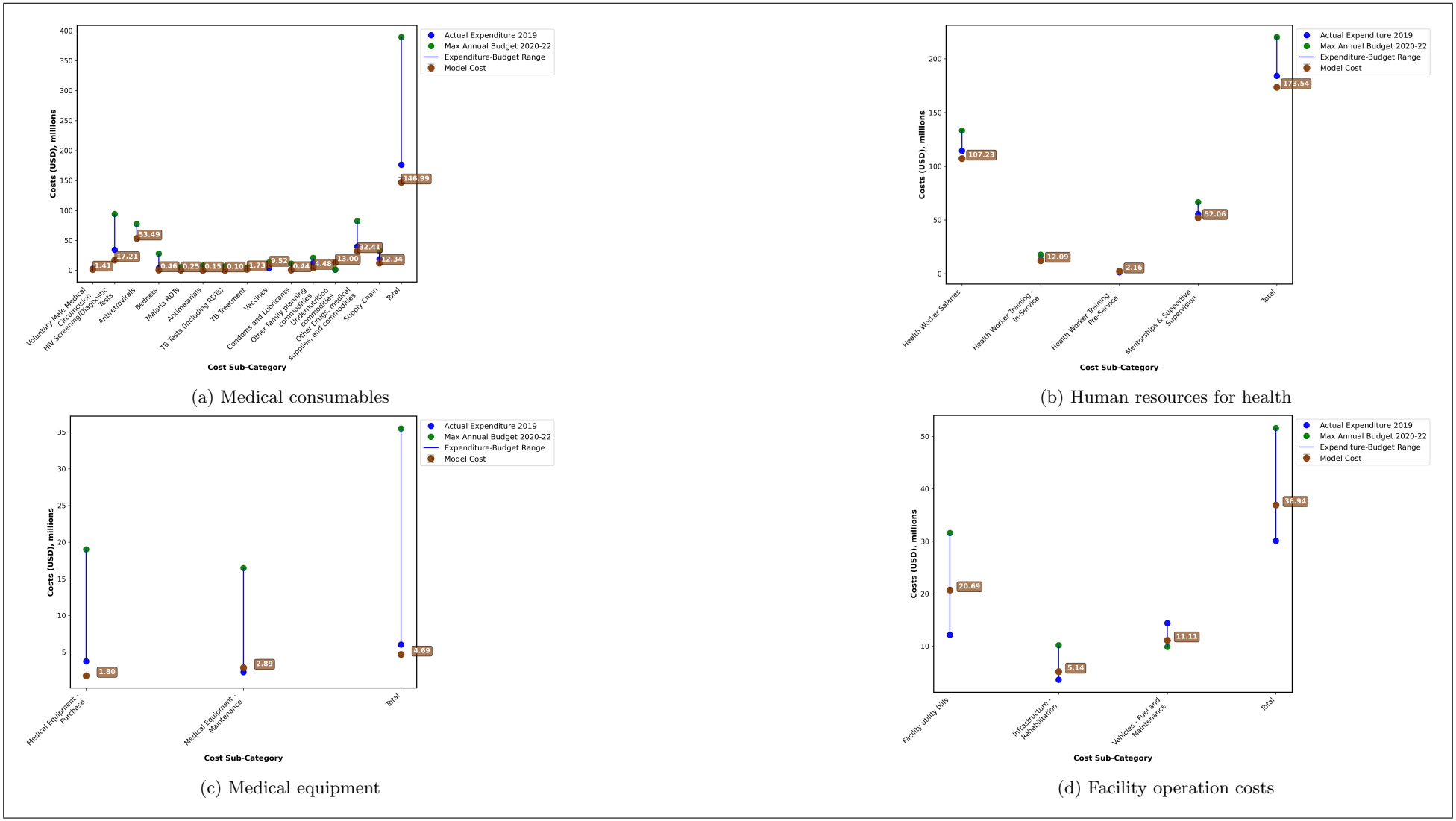
Table 1: Summarized Costs by Category and Category Subgroup

Parameter	**Data Source**
Cost of major corrective maintenance as a proportion of replacement cost$_e$	Assumed to be 20% of the cost of the equipment requiring major corrective maintenance, following HSSP-III costing assumptions [27].
Cost of service fee/spare parts as a proportion of replacement cost$_e$	Service fee assumed to be 10% of the value of the equipment annually and spare parts assumed to cost 2.5% of the value of the equipment annually, following HSSP-III costing assumptions [27].
Quantity of equipment available$_e$	The HSSP-III set out an aspirational and a prioritised quantity of each type of equipment which are required at each facility level. Due to lack of access to data on the actual equipment inventory, we used the prioritised inventory size to cost medical equipment.
Number of facilities$_l$	The TLO model represents a total of 734 government and Christian Health Association of Malawi (CHAM) facilities in Malawi grouped by facility level and district [5]. For the purpose of costing equipment we multiply the equipment cost per facility by the number of facilities at each facility level.
Facility operation costs	
Estimates of annual operation costs (monthly minimum, average, and maximum during 2024) were collected through a facility audit survey under the Thanzi La Mawa project. The estimates were aggregated by facility level. See Appendix Table D.1. In line with other deterministic unit costs used, we only used the mean value of the average monthly costs reported in our cost estimation.	



(a) Medical consumables

(b) Human resources for health

(c) Medical equipment

(d) Facility operation costs

Figure 1: **Comparison of model-based cost estimates with actual expenditure recorded for 2018/19 and budget planned for 2019/20-2021/22**: For each cost category, model-based estimates are compared with disaggregated categories from Malawi's Resource Mapping data. The objective of this comparison is to assess whether the estimated costs fall within the range bounded by actual expenditure and planned budgets, following justifiable adjustments to unit costs and resource-use assumptions to improve alignment with RM data. **Abbreviations:** RDT: Rapid Diagnostic Test, TB: Tuberculosis, HIV: Human Immunodeficiency Virus

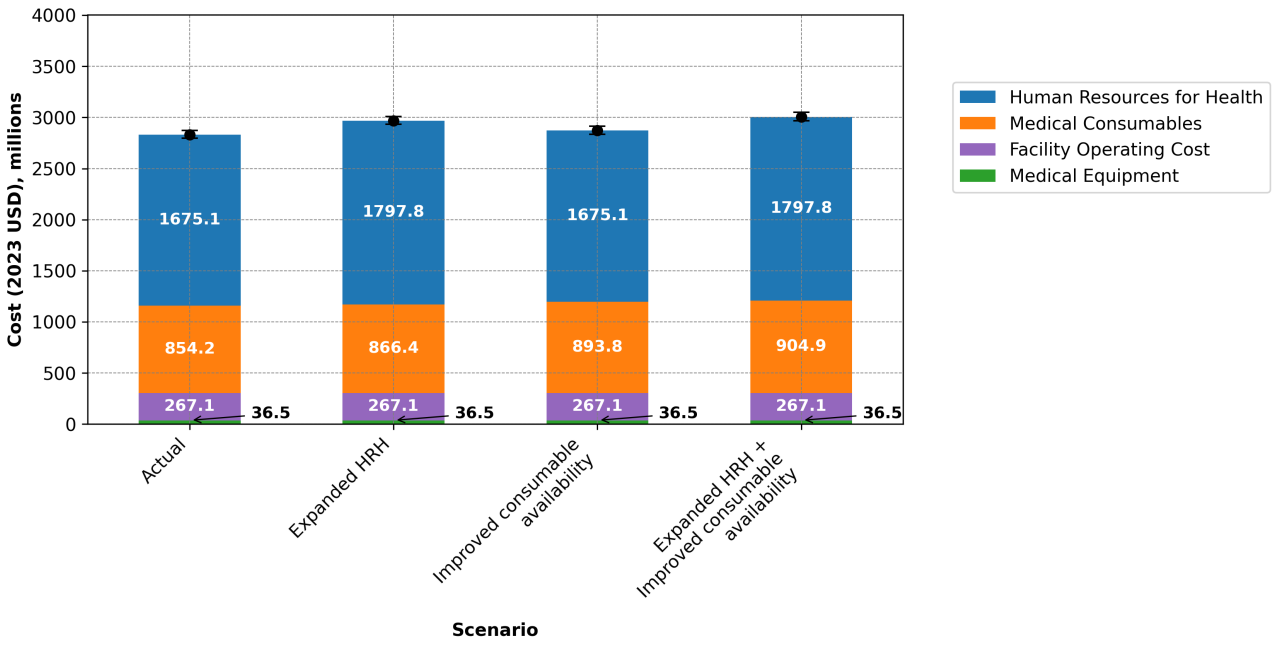
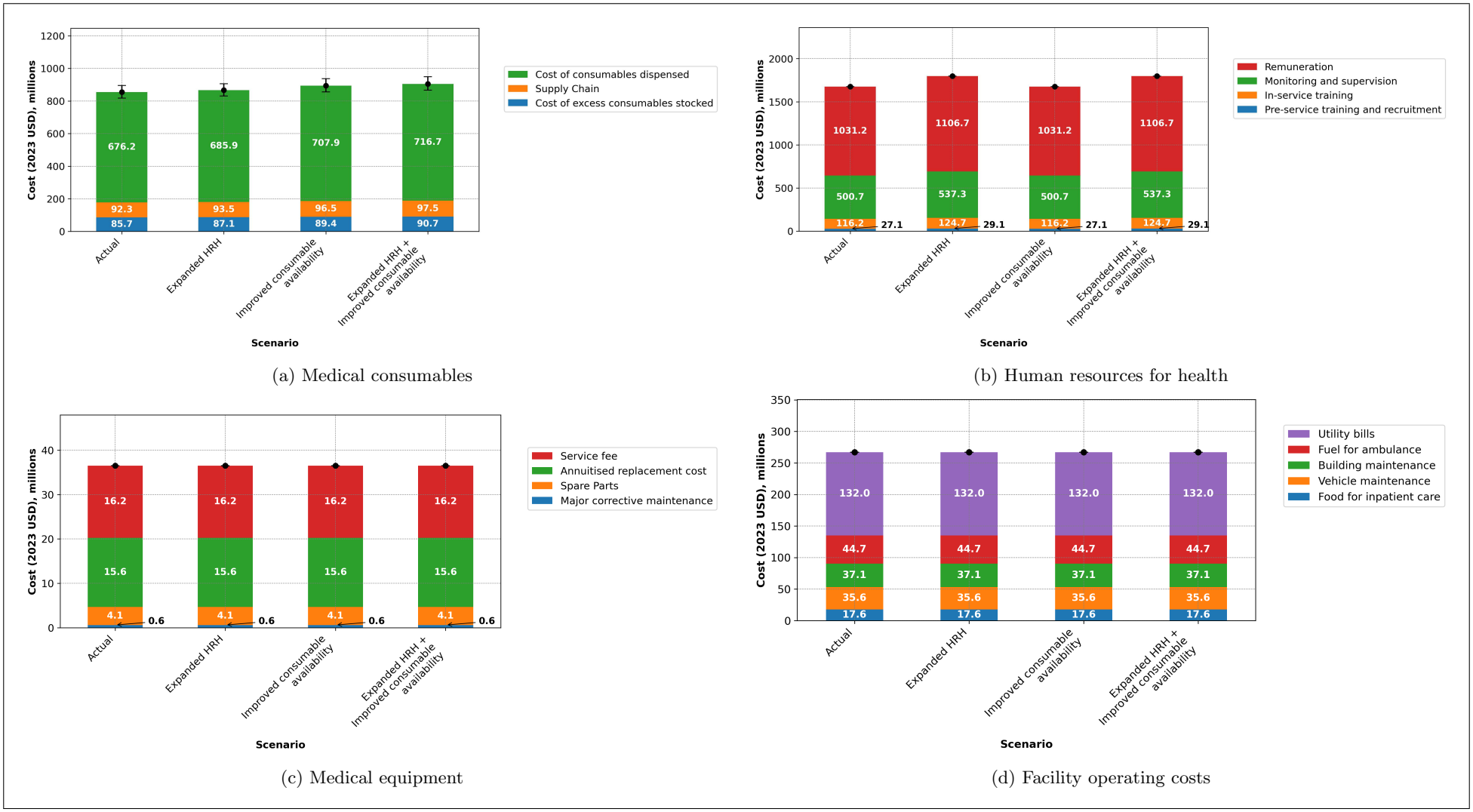


Figure 2: **Estimated costs by cost category, 2023-2030**. This figure presents total healthcare delivery costs by cost category over an 8-year period under four modelled scenarios. Black error bars indicate 95% uncertainty intervals around total cost estimates. All values are reported in 2023 USD and discounted at 3% to reflect net present value (NPV) in 2023. Uncertainty in the estimates arises from the stochastic nature of demographic, epidemiological, and resource availability parameters in the TLO model; unit costs are treated as deterministic. Note that the $36.5 million figure refers to medical equipment. **Abbreviations:** HRH: Human Resources for Health, USD: United States Dollar



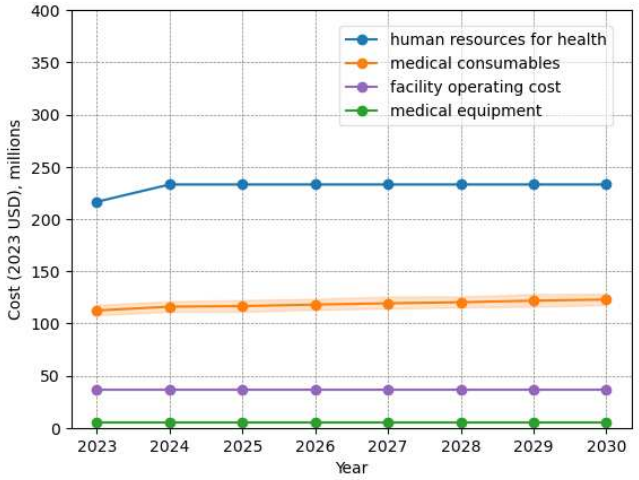
(a) Medical consumables

(b) Human resources for health

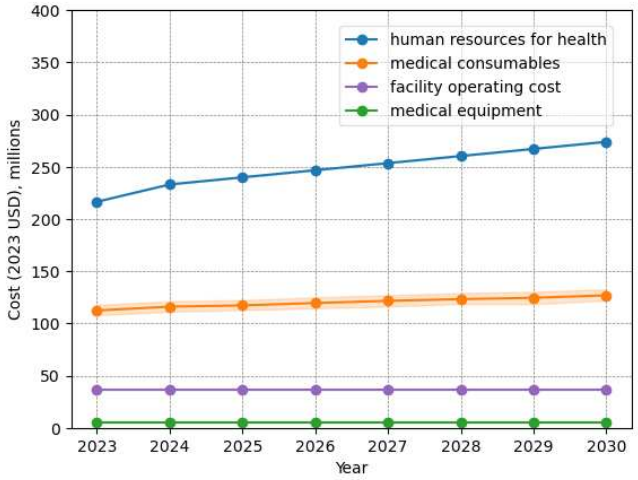
(c) Medical equipment

(d) Facility operating costs

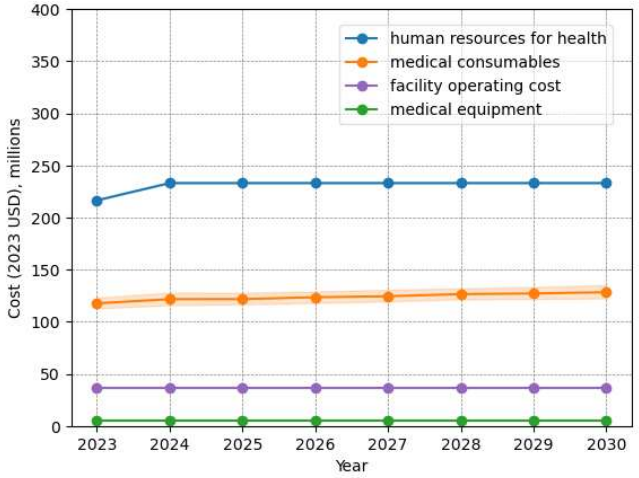
Figure 3: **Estimated cost by category and subcategory, 2023-2030.** This figure presents the total cost by category and subcategory for 8 years under four scenarios modelled. The values are measured in 2023 USD and discounted at 3%. **Abbreviations:** HRH: Human Resources for Health, USD: United States Dollar



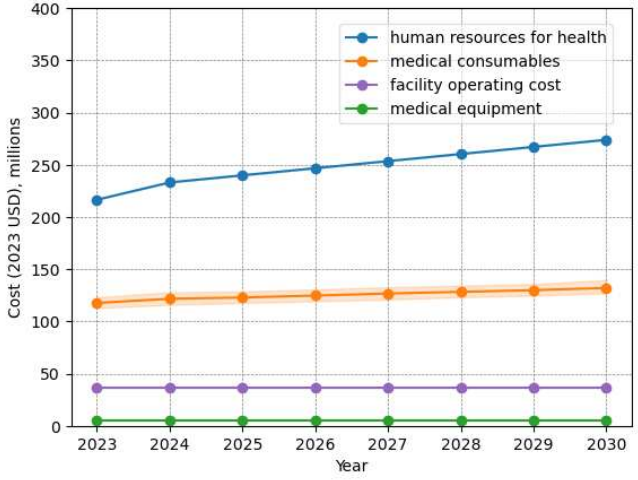
(a) Actual



(b) Expanded HRH



(c) Improved consumable availability



(d) Expanded HRH
+ Improved consumable availability

Figure 4: **Estimated cost by year, 2023-2030.** This figure presents the total cost by category for 8 years under four scenarios modelled. The values are measured in 2023 USD and undiscounted values of cost are reported for each year. **Abbreviations:** HRH: Human Resources for Health, USD United States Dollar