University of Southampton

Faculty of Social Sciences

Southampton Business School

A Simulation Modelling Study on the Contraceptive, Sexual, and Reproductive Dynamics of the Mexican Female Population

by

Nicéforo Garnelo Bibiano

ORCID ID 0000-0001-5057-1889

Thesis for the degree of Doctor of Philosophy

May 2025

University of Southampton

Abstract

Faculty of Social Sciences

Southampton Business School

Doctor of Philosophy

A Simulation Modelling Study on the Contraceptive, Sexual, and Reproductive Dynamics of the Mexican Female Population

by

Nicéforo Garnelo Bibiano

This thesis introduces a system dynamics model featuring an endogenously driven, multistate, age-structured, time-varying, and stochastic structure. The devised model allowed, for the first time, to represent the contraceptive, sexual, and reproductive behaviours that characterise different age and birth cohorts of Mexican women at their reproductive ages.

By depicting the interrelations between such behaviours, the model allowed the estimation and projection of a set of hypothetical contraceptive provision policies and programme-relevant health (i.e., unintended pregnancy, unsafe abortion, maternal deaths) and economic (i.e., cost-effectiveness) indicators. Of the compared policies, increasing adoption of modern reversible contraception, and an integrated policy that aims to increase modern reversible contraception whilst reducing method discontinuation, proved to be the two most efficient in terms of health outcomes and monetary investment.

The results obtained, and the conclusions established in this manuscript will be relevant for the Mexican context and appealing to policymakers, who are currently interested in finding innovative approaches to expanding contraceptive coverage with economically efficient strategies, as it is established in the national guidance on Sexual and Reproductive Health.

The model formulation will also be relevant in the system dynamics modelling field, as a novel, open-source, vectorised architecture will be available to study contraceptive, sexual and reproductive behaviours in different contexts. Although the data needs of the model are

substantial, most can be satisfied with regularly collected, and easy-to-access cross-sectional data or topic-specific literature.

Table of Contents

Table of Tables

Table of Figures

Research Thesis: Declaration of Authorship

Print name: Nicéforo Garnelo Bibiano

Title of thesis: A Simulation Modelling Study on the Contraceptive, Sexual, and Reproductive Dynamics of the Mexican Female Population

I declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
7. None of this work has been published before submission.

Signature: .... Date: February 29, 2024.

Para mi Leticia, para mi Nicéforo (QEPD), para mi Suzil, para mi Paul, para mi Anabel.

Su amor, comprensión y paciencia me ha llevado siempre más lejos y con más potencia de la que puedo acopiar solo.

Les agradezco y debo todo. Siempre.

Acknowledgements

This PhD has been a very challenging and emotional experience. One of victories and defeats that I am still processing from Mexico, my home country. I would not change a bit of what took place over the past years since these events built a new individual: more resilient, reflective, and capable to appreciate the little details in life.

What a pleasure has been being under Sally Brailsford's and Steffen Bayer's generous, patient, and intelligent guidance. I am a stubbornly slow learner, and it took me ages to understand many of the concepts I finally employed in my research and in this thesis. You had the nerve to endure me throughout these years, and I will be now and until the end of my days indebted to you. Thank you for your time, and for letting me attest your enormous talent as scholars.

What an enlightening experience has also been taking part in the ReGHID Project and meeting amazing scholars there as well. Pía Riggirozzi, Amos Channon: you awakened additional research interests, and generously allowed me to acquire then hone skills that are making an impact at my current responsibilities in the Mexican health system. My gratitude and admiration go to you.

David Barrera, *¿Quiubo hermano?* You were generous to Anabel and me since the first day we met you. We miss you. We hope to see you soon in the short future.

Monse, Erick, Vale, Carlos, Rose, Rafa, Josmy, Miquel. Our beloved friends. Your different perspectives on life nurtured ours. Our friendship surpasses borders.

Finally, and perhaps most importantly: I am grateful to the Mexican population, who, through the *Secretaría de Ciencia, Humanidades, Tecnología e Innovación,* allowed Anabel and I embarking in this life-changing adventure. I hope to honour your everyday struggle and return at least a small fraction of the enormous gift you have given me.

Abbreviations

ABM	Agent-based modelling
BEH	Behavioural contraception
CEA	Cost-effectiveness analysis
CEAC	Cost-effectiveness acceptability curve
CEAF	Cost-effectiveness acceptability frontier
CFR	Crude Fertility Rate
CONAPO	*Consejo Nacional de Población*
CPR	Contraceptive Prevalence Rate
C-S-R dynamics	Contraceptive, sexual, and reproductive dynamics
DALYs	Disability-Adjusted Life Years
DES	Discrete Event Simulation
DHS Program	The Demographic and Health Surveys Program
DSM	Dynamic Simulation Modelling
ENADID	Encuesta Nacional de la Dinámica Demográfica
FERMODP model	The Fertility Modeling under Family Planning model
GDP	Gross Domestic Product
Gnrl_DTH	All-cause deaths
ICD	International Classification of Diseases
ICER	Incremental cost-effectiveness ratio
IEC	Information, Education, and Communication campaign
IEEE	Institute of Electrical and Electronics Engineers
IMSS	*Instituto Mexicano del Seguro Social*
IMSS-*Bienestar*	*Instituto Mexicano del Seguro Social para el Bienestar*

INEGI	*Instituto Nacional de Estadística y Geografía*
INF_IP	Secondary infertility due to intended pregnancy
INF_UP	Secondary infertility due to UP
INSABI	*Instituto de Salud para el Bienestar*
INT	Sexually active, non-user of contraception, and intending pregnancy
IP	Intended pregnancy
ISSSTE	*Instituto de Seguridad y Servicios Sociales de los Trabajadores del Estado*
IUD	Intrauterine device
LARC	Long-acting and reversible contraception
LB	Live birth
LMIC	Low- and middle-income country
M_DTH_IP	Maternal death due to intended pregnancy
M_DTH_UP	Maternal death due to unintended pregnancy
MAPE	Mean absolute percentage error
mCPR	modern Contraceptive Prevalence Rate
MDGs	Millennium Development Goals
MMR	Maternal Mortality Ratio
M-P pseudoinverse	Moore-Penrose pseudoinverse
NMB	Net monetary benefit
NU	Non-user of contraception
ODE	Ordinary differential equation
OR/MS	Operational Research/Management Sciences
PAC	Post-abortion care
PERM	Permanent contraception

Abbreviations

POPREP model	The Population Representation model
QALYs	Quality-Adjusted Life Years
SD	System Dynamics
SDGs	Sustainable Development Goals
SI	Sexually inactive woman
SPSS	Sistema de Protección Social en Salud
SQ	Status Quo
SRH	Sexual and Reproductive Health
TRAD	Traditional contraception
U15	Under-fifteen girls
UA	Unsafe abortion
UC	Unit cost
UI	Uncertainty interval
UN	System of United Nations
UNFPA	United Nations Population Fund
UP	Unintended pregnancy
USD	United States dollars
WoRA	Women of reproductive age
WTP	Willingness-to-pay

Chapter 1 Introduction

Contraceptive provision is a major activity of family planning programmes worldwide. It is recognised as a highly effective public health intervention, benefiting individuals by helping them avoid mistimed or unwanted pregnancies. It also benefits society at large by, amongst other externalities, potentially boosting economic development (United Nations, 2019).

Modern contraceptive practice has been actively promoted since the development of the first hormonal contraceptive in the 1950s (Benagiano et al., 2007), and with renewed efforts from the outset of the 21st century through various initiatives, spearheaded by the 2000-2015 *Millennium Development Goals* (MDGs) (United Nations, 2015), and the 2015-2030 *Sustainable Development Goals* (SDGs) (United Nations, 2020a). Both MDGs and SDGs are championed by the United Nations (UN) and aim at the improvement of a broad spectrum of indicators, deemed important to the societal development within the UN member nations. In addition to the aim of universal contraceptive coverage, other Sexual and Reproductive Health (SRH) indicators, such as maternal death reduction and improved access to safe abortions, are key elements of the MDG and SDG agendas.

With the end of the SDG era in sight, progress towards the goal of universal contraceptive coverage and other SRH indicators is rather mixed. Low-and middle-income countries (LMICs), however, consistently report the smallest coverage estimates worldwide (Kantorová et al., 2020). This translates to an estimate of 218 million women experiencing unmet need for contraception, which consequently results in 111 million unintended pregnancies, 35 million unsafe abortions, and 299,000 maternal deaths in LMICs (Sully et al., 2020).

The economic burden due to unintended pregnancies in those settings is also considerable, as the cost of maternal and neonatal care arising from unintended pregnancies reaches USD30.3 billion annually (Sully et al., 2020).

1.1 Contraceptive dynamics: adoption, switching, and discontinuation

Contraceptive practices vary across the reproductive lifecycle of women. They are the result of the interplay of multiple determinants at the individual (e.g., age, number of children, schooling, reproductive goals) and societal levels (e.g., familial, peer-influence). The healthcare system tries to accommodate these by offering, ideally, a wide range of contraceptive options through a network of services (e.g., static-mobile health clinics, community health workers, private family planning clinics). Ultimately, the healthcare system tries to reduce unintended pregnancies by securing a constant availability of women's preferred contraceptives at health clinics and hospitals in the network.

The availability of contraceptive provision services, together with women's fertility intentions and their sexual behaviour, originate a dynamic process in which contraceptive methods are adopted, switched, and discontinued (Hock-Long et al., 2010). In practice, this process is directly affected by policy decisions about contraceptive provision taken at the local or national level: what contraceptives to provide to whom, through which services, and at what cost.

Contraceptive adoption, switching, and discontinuation dynamics have only been partially addressed when studying diverse sexual and reproductive health phenomena (Babigumira et al., 2012; Carvalho et al., 2013; Erim et al., 2012; Goldie et al., 2010; Hu et al., 2007; Keen et al., 2017; Kennedy et al., 2013; Zakiyah et al., 2019) and traditionally not as a jointly evolving process that affects women differently along their reproductive life years, and intergenerationally. In making policy recommendations, such previous efforts have not taken account of these two fundamental aspects, which are addressed in the present thesis.

Thus, this thesis introduces an endogenously driven, age-structured, multistate, time-varying system dynamics (SD) simulation model that explores an array of hypothetical policies (also labelled *strategies* in the document) to study their impact on unintended pregnancy and other outcomes of programmatic importance, i.e., unsafe abortion, maternal death. Lastly, the thesis establishes the cost-effectiveness of hypothetically applying the proposed policies in the Mexican context.

1.2 Study context

The study addresses the case of Mexico, an LMIC where contraceptives have been provided at no cost to the user since distribution began in 1973 (Secretaría de Salud, 2013). The Mexican health system is an intricate network of organizations, each serving different population groups according to a person's occupation or employment status.

Social security institutions, funded around the 1940s, are financed with government funds and employee-employer contributions to serve most public sector (Institute of Social Security and Services for the State Workers, ISSSTE) and private workers (Mexican Institute of Social Security, IMSS). Oil industry workers and armed forces (i.e., navy, military) are served through independent institutions, financed with the same scheme as ISSSTE and IMSS (Gómez Dantés et al., 2011). Combined, they serve approximately 48% of Mexico's 126 million individuals (Instituto Nacional de Estadística y Geografía, 2021).

The Health Secretariat (*Secretaría de Salud*) strives to serve the rest of the population via the 2022-instituted *Instituto Mexicano del Seguro Social para el Bienestar* (IMSS-Bienestar). This replaced the short-lived (2019-2022) *Instituto Nacional de Salud para el Bienestar* (INSABI) (Reyes et al., 2019), which in turn replaced the *Sistema de Protección Social en Salud* (SPSS) (Frenk et al., 2006), active from 2003 to 2019. Like its predecessors, IMSS-Bienestar is not a social security institution, but a health services provider instituted as a mechanism to expand health coverage, including individuals in the informal economy. The Health Secretariat has 32 local offices at the subnational level, one in each Mexican state, known as Health Services (*Servicios de Salud*).

1.2.1 Sexual and reproductive health indicators in Mexico

Advances in contraceptive coverage since the beginning of the programme in the 1970s have brought about the favourable evolution of some indicators, such as unmet need for contraception, which according to the latest official estimates had an overall downward trend from 1987 to 2018, with three distinctive stages (Figure 1.1). After a marked descent between 1987 and 1997, the indicator decreased further at a slower rate between 1997-2009 and increased slightly from 2009 (Consejo Nacional de Población, 2019; Secretaría de Salud, 2013).

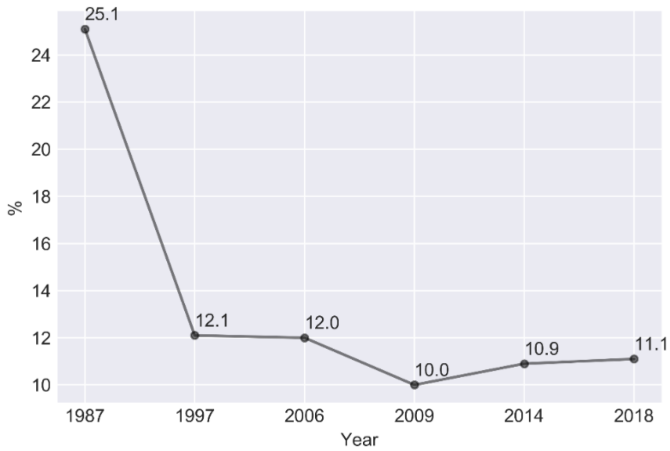


Figure 1.1. Unmet need for contraception. Mexico, 1987-2018 (Consejo Nacional de Población, 2019; Secretaría de Salud, 2013).

Note: the latest official estimate was dated in 2018.

There are no official sources to draw estimates of unintended pregnancy and unsafe abortions. Scholars place unintended pregnancies at 55% of all pregnancies (Juárez et al., 2013), and estimate a yearly total of 1.026 million unsafe abortions (B. F. Juarez & Singh, 2009). The latter figure, however, is not without controversy given its was obtained via a non-probabilistic sample of health clinics, where medical doctors gave their *best* estimate of cases of induced abortions.

While recognising the difficulty of obtaining a plausible estimate of unsafe abortions, a figure of 1.026 million seems very large for a country where an average of two million babies are born each year. Moreover, its research design has been contested by other authors (Koch et al., 2015) who call for a more robust estimation process that is less reliant on expert opinion, given its weak quality within the framework of evidence-based medicine (Burns et al., 2011).

Fifteen years of progress in containing maternal deaths were dramatically reversed by the Covid-19 pandemic (Figure 1.2). The maternal mortality ratio (maternal deaths/live births per 100k) had shown an overall downward trend from 2006 to 2019, but grew rapidly in 2020 and by 2021 had reached 59.41 (Instituto Nacional de Estadística y Geografía, 2024).

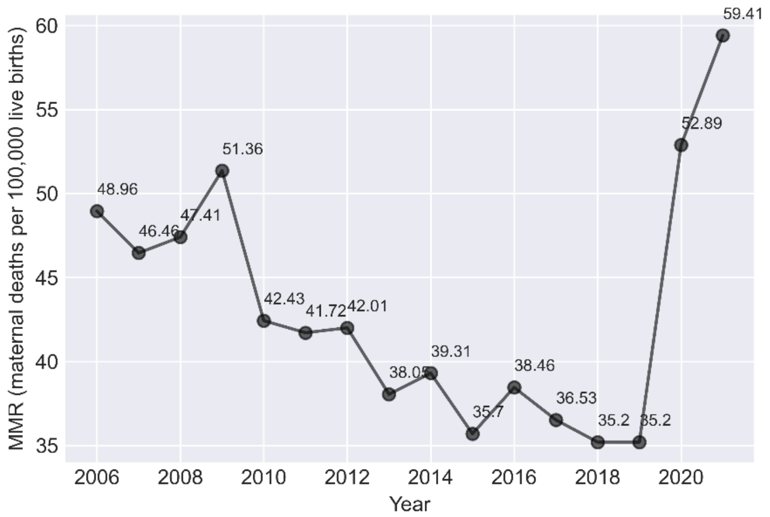


Figure 1.2. Maternal Mortality Ratio (MMR). Mexico, 2006-2021 (Instituto Nacional de Estadística y Geografía, 2024).

1.2.2 The reproductive, sexual, and health landscape of Mexico in the international context

Mexico shares some characteristics with other LMICs regarding its efforts to improve contraceptive access and address reproductive health challenges. Like Mexico, countries such as India, Bangladesh, and Ethiopia have implemented large-scale family planning programs to reduce unmet need for contraception and unintended pregnancies (Ravindran & Govender, 2020). For instance, India's National Family Planning Program provides contraceptives mostly through its public health system (Ravindran & Govender, 2020), achieving considerable declines in fertility rates (Amonker & Brinker, 2007). However, similar to Mexico, challenges remain in reaching populations in rural or underserved areas due to structural inequalities (Coleman-Minahan et al., 2022; Mitchell et al., 2023). Some LMICs, particularly in sub-Saharan Africa, still face substantial barriers, including limited contraceptive availability, sociocultural factors, and higher fertility preferences, resulting in higher unmet need compared to Mexico's relatively steady progress (Kantorová et al., 2020).

A distinguishing feature of Mexico's situation is the segmentation and fragmentation of its health system (Becerril-Montekio et al., 2024; Meneses Navarro et al., 2022), which mirrors other Latin American countries like Brazil and Colombia (Bancalari et al., 2023). Brazil's Unified Health System (SUS) aims to achieve universal health coverage, but like the Mexican health system, it struggles with resource disparities between urban and rural areas (Bancalari et al., 2023). Similarly, Colombia's dual insurance model addresses coverage gaps but faces persistent inequities in service delivery (Báscolo et al., 2018). Like in Mexico, contraceptive access in other Latin American countries has maintained a steady growth over time (Kantorová et al., 2020), underscoring the region's progress in achieving contraceptive coverage whilst still navigating the challenges posed by their health systems' design (Ponce de Leon et al., 2019).

In terms of reproductive health outcomes, Mexican trends are mixed when compared to other regions. The MMR of 59.41 per 100,000 live births in 2021 is higher than the pre-pandemic levels observed in several upper-middle-income countries but aligns with or is lower than averages seen in parts of South Asia and sub-Saharan Africa. For instance, South Asia saw MMR values of approximately 113 per 100,000 in 2020, while sub-Saharan Africa remains the most affected region globally (World Health Organization, 2023a). The reversal of Mexico's maternal health progress due to COVID-19 mirrors trends observed worldwide, as health systems struggled to maintain essential services (Kabagenyi et al., 2022). Additionally, Mexico's estimated unintended pregnancy rate is comparable to global LMIC averages (Bearak et al., 2020), although the controversy surrounding unsafe abortion figures highlights the persistent challenge of underreporting and methodological limitations, which are also common in other countries.

1.3 Research questions and study objectives

In light of this background and context, two research questions are proposed in this thesis:

1. Can a system dynamics model accurately represent the reproductive life years of women, capturing the dynamics of contraceptive adoption, switching, and discontinuation?
2. Which contraceptive coverage policies are most cost-effective in reducing unintended pregnancies and other important reproductive/maternal health and economic outcomes over the longer term, given the dynamics of contraceptive adoption, switching, and discontinuation among Mexican women?

These two research questions are broken down into three research objectives:

1. Develop a conceptual model to characterise the different stages in the reproductive life years of women aged 15 to 49, and represent their interrelations with contraceptive adoption, switching, and discontinuation.
2. Translate the conceptual model into an endogenously driven, multistate, age-structured, time-varying system dynamics simulation model which represents the evolving dynamics of contraceptive, sexual, and reproductive behaviours, to estimate its impact on the following outcomes:
    a. Unintended pregnancies due to contraception failure and non-use of contraception.
    b. Live births, unsafe abortions, and maternal deaths attributable to unintended pregnancy.
    c. Economic impact of contraceptive provision and unintended pregnancy from the perspective of the health provider.
3. Use the devised model to compare the cost-effectiveness of different contraceptive provision policies aiming to reduce unintended pregnancy.

1.4 Justification of methodology

The present study uses simulation modelling to answer the proposed research questions. Simulation modelling has been used successfully in various fields and research topics, including public health.

The simulation approach has interesting advantages compared to other possibly applicable methodologies (e.g., impact evaluation), of which two are salient: first, data generation is, overall, less expensive, and less time-consuming; second, the number of strategies to test is potentially infinite, albeit these must be plausible to make simulation modelling research relevant.

On the other hand, however, simulation modelling approaches require robust data sources to satisfy the parameter needs of models, which can be considerable. Additionally, and depending on the selected simulation technique and model size, the computing power required to generate the synthetic data might not be trivial.

Choosing SD to represent the contraceptive, sexual, and reproductive dynamics of women of reproductive ages responded to two main reasons: first, a dynamic simulation modelling (DSM) technique was needed to represent such an evolving process. Second, while it is theoretically possible to adapt discrete-event simulation or agent-based models to different aggregation levels (Roberts, 2015), SD offers a best fit among these DSM techniques to study problems at the strategic or policy level, such as is needed in this thesis.

This research is interested in depicting the impact of different policies on unintended pregnancies and other health outcomes among different age groups instead of representing individual behaviours. Thus, given the scope of the present thesis, SD was considered a pertinent choice.

1.5 Thesis structure

The remainder of the manuscript is organised into seven chapters. The second chapter presents a literature review conducted to identify modelling studies on contraceptive dynamics and give an historical account of SRH research approaches in Operational Research and Management Science (OR/MS). The chapter critically assess the gaps identified in previous approaches to the study of contraceptive dynamics and proposes possible ways of addressing them.

Chapter three explains the essential concepts used in this thesis, related to contraceptive, sexual, and reproductive behaviours, along with their possible outcomes. The chapter is complemented with a critical appraisal of simulation modelling research and a comparison of dynamic simulation modelling techniques.

Chapters four, five, and six are interrelated. This cluster introduces the simulation model devised to answer this thesis' research questions.

Chapter four gives an account of the main assumptions used throughout the modelling process, together with the presentation of the main structure of the model by means of stock-flow diagrams. The chapter also describes the methodological details of parameter estimation and specifies how the matrix structure used to numerically solve the simulation model's differential equations was developed.

Chapter five addresses the procedures implemented to verify model structure and validate simulation model results against real-world benchmarks.

Chapter six describes the use of the simulation model devised to conduct a cost-effectiveness analysis of an array of 31 contraceptive provision strategies, capable of limiting unintended pregnancies. The 31 competing strategies are introduced beforehand, their rationale explained in detail. The last section of this chapter specifies which changes in model equations had to be implemented to allow policy testing and cost-effectiveness analysis.

Chapter seven presents the unintended pregnancies, unsafe abortions, and maternal deaths estimated in each of the 31 hypothetical strategies tested. The second part of the chapter presents the cost-effectiveness analysis results.

Finally, chapter eight discusses the results presented in Chapter seven, and gives an account of the proposed simulation model's limitations. The chapter also presents the main conclusions of this research, introduces possible further research streams, and offers concluding remarks.

1.6 Chapter summary

Chapter one introduced the overarching goal of this thesis: applying a novel simulation model structure to investigate how the interrelations of contraceptive, sexual, and reproductive behaviours explain the occurrence of relevant programmatic outcomes (unintended pregnancy, unsafe abortion, maternal deaths). The chapter also presented the research questions and objectives and justified the selection of simulation modelling to address the topic of study. Finally, the chapter described the rationale of the seven remaining chapters in the manuscript.

Chapter 2 Literature Review

A scoping review was conducted to identify previous simulation studies on contraceptive dynamics and fertility. The keywords shown in Table 1 were grouped into ten categories according to their affinity. Different combinations were tried in the Web of Science, Science Direct, Cochrane Library, Pubmed, Scopus, ProQuest, EthOS, and CORE databases. Sexual and reproductive health-specific websites in the World Health Organization (WHO), United Nations Population Fund (UNFPA), UNFPA Supplies, Population Council, Guttmacher Institute, Marie Stopes International, SDG main knowledge base, Reproductive Health Supplies Coalition, Health Policy Project, and the Demographic and Health Surveys (DHS) Program were reviewed as well. Finally, the Winter Simulation Conference Archive, IEEE's Xplore, and the System Dynamics Society's websites were reviewed to retrieve additional references that might have been missed in the previous rounds.

Article abstracts (or the introduction/executive summary of reports, in the case of grey literature) were reviewed, and those considered relevant to this thesis were selected. The inclusion and exclusion criteria were as follows:

Excluded studies:

- Conducted solely in hospital settings.
- Regarding physical (i.e., educational) simulations.
- Related to the "family planning" of new commercial products.
- Whose modelling was exclusively statistical.
- Not fully accessible (i.e., older studies without an electronic version and not available through the university's library.)

Included studies:

- Conducted within countries of all income classifications (i.e., low-, middle-, and high-income.)
- In English or Spanish, not to miss potentially useful studies published in the language of Mexico and the majority of Latin American countries.
- Conducted in any year.
- Employing an Operational Research/Management Science (OR/MS) approach.

Table 2.1. Blocks of composite strings used in the literature review.

No.	Keywords category	Composite string (English)	Composite string (Spanish)
1	Sexual/Reproductive Health	sexual health OR family planning OR reproductive health OR contraception OR contraceptive OR contraceptives	salud sexual OR salud reproductiva OR planificación familiar OR anticoncepción OR anticonceptivo OR anticonceptivos
2	Contraceptive dynamics	uptake OR use OR utilisation OR utilization OR adherence OR compliance OR switching OR switch rate OR discontinuation OR discontinuation rate OR unmet need OR user OR behaviour OR behavior OR reproductive lifecycle OR coverage OR scale-up OR scale up OR scaling up OR scaling-up	uso OR utilización OR consumo OR adherencia OR cambio de método OR tasa de cambio de método OR abandono del método OR tasa de abandono de método OR necesidad insatisfecha OR usuaria OR usuario OR comportamiento OR ciclo de vida reproductiva OR cobertura OR expansión OR incremento OR aumento
3	Health Technology Assessment	cost OR cost-effectiveness OR cost-utility OR cost-benefit OR economic evaluation OR health technology assessment OR HTA	costo OR costo-efectividad OR evaluación económica OR evaluación de tecnología sanitaria OR ETS
4	Outcome-related	outcome OR mortality OR unintended pregnancy OR undesired pregnancy OR unwanted pregnancy	impacto OR mortalidad OR embarazo no intencionado OR embarazo no deseado OR embarazo no planificado
5	Healthcare levels	health clinic OR health centre OR hospital OR primary level OR first level OR secondary level OR second level OR tertiary level OR third level	clínica OR centro de salud OR casa de salud OR hospital OR nivel primario OR primer nivel OR nivel secundario OR segundo nivel OR nivel terciario OR tercer nivel
6	Micro-economics	demand OR supply	demanda OR oferta

7	Modelling/simulation	dynamic OR modelling OR modeling OR simulation OR stochastic	dinámico OR modelo OR modelación OR simulación OR estocástico
8	Operational Research	Markov OR Markov chain OR Markov model OR Markov process OR management science OR operational management OR operations management OR operational research OR operations research OR system dynamics OR SD OR hybrid OR discrete event OR discrete-event OR DES OR microsimulation OR agent-based OR ABM OR ABS OR mathematical OR mathematical programming OR optimisation OR optimization OR queue OR queueing OR queuing OR linear programming OR integer programming OR Monte Carlo	Markov OR cadena de Markov OR modelo de Markov OR proceso de Markov OR ciencia de la administración OR investigación operacional OR dinámica de sistemas OR híbrido OR eventos discretos OR microsimulación OR basado en agentes OR matemático OR matemática OR programación matemática OR optimización OR cola OR colas OR filas OR fila OR programación lineal OR programación entera OR Monte Carlo
9	Modelling/simulation in public health	compartmental OR decision tree OR decision-tree OR Markov	compartamental OR árbol de decisión OR árbol de decisiones OR Markov
10	Public Health	public health OR health care OR healthcare	salud pública

After removing duplicates and discarding irrelevant references, an initial list of more than 800 references was primarily composed. An in-depth review of such references produced the final sample of documents summarised in Table 2.2, from which the present narrative draws. A number of these documents allowed the description of the landscape of OR/MS simulation techniques applied to the study of contraception between the 1970s and 2000s (see Section 2.1).

It was generally found that the study of the joint development of contraceptive, sexual, and reproductive dynamics over time is practically absent. Thus, it follows that research is needed to analyse the implications of such interactions on a variety of important outcomes.

It was also found that whilst more recent models have attempted to analyse the different components of contraceptive dynamics partially, its full range is yet to be studied (see Section 2.2).

Table 2.2. Articles included in the scoping review narrated in this chapter.

Author(s) / Year	Title	Study objective(s)	Simulation model approach	Setting	Main modelling assumptions	Simulated scenarios	Measured outcomes	Key finding(s)	Strengths (S) / Limitations (L)
Sarma (1970)	Alternative Family Planning Strategies for India: A simulation experiment	To measure the impact of different family planning programme configurations on ten-year fertility trends.	Demographic microsimulation modelling of a human population.	India	1) only female population was considered; 2) only married women are eligible for any contraceptive method; 3)birth, death and marriage probabilities are kept constant during simulation period (ten years).	1) eligibility for permanent contraception; 2) high-low levels of adoption of family planning methods; 3) switching to permanent and IUD contraceptive methods.	Five indices of fertility: crude birth rate, general fertility rate, intrinsic rate of growth, intrinsic birth rate, net reproduction rate.	All tested strategies have significant reductions in fertility indices	S: the model explicitly introduces women's eligibility criteria into simulation architecture. L: 1) contraceptive choice independent from previous use cases; 2) model parameterised partially with data from other settings (Taiwan); 3) model replications restricted to six; 4) males not included.
Vertinsky (1972)	Family planning computer simulation: the Costa Rica population control model	To model reproductive outcomes within a reproductive decision-making and demographic framework.	Difference equation modelling	Costa Rica	1) reproductive decisions are entirely attributable to women; 2) women in their reproductive years are divided in those who seek health assitance within health care instances, and those who do receive assistance via informal channels of communication.	1) verify effects of travelling and waiting times in health seeking behaviour, 2) evaluating the effect of education and information campaigns in reducing pregnancy intentions.	1) total populationm, acceptors of intrauterine devices, oral, and traditional contraceptives; 2) averted births due to programme activities.	1) incremental trends in contraceptive use were predicted in both scenarios; 2) livebirths projected to increase linearly during the 10-year simulation window; 3) number of contraceptive adopters increases over time. Perceived susceptibility to pregnancy drives contraceptive adoption.	S: 1) explicitly includes demographic dynamics and behavioural aspects of reproduction; 2) model devised nearly after the initiation of the family planning programme in Costa Rica, and momentum to gather data and use information derived from the model was considerable. L: incomplete data to calibrate the model; 2) a list of used parameters is not available in the document.

Rao (1973)	The evaluation of four alternative family planning programs for POPLAND, a less developed country	Comparative evaluation of the impact of four alternative family planning strategies in the fictional setting.	Demographic microsimulation modelling of a human population.	Fictional setting (model parameterised with real data from an undisclosed country)	1) highest rate of increase is assumed to occur during the first three years of each strategy; 2) permanent contraception provides perfect protection against unintended pregnancy.	1) present programme as planned; 2) present programme as currently operates; 3) post-partum contraception increased; 4) strategy 3 applied in urban settings, whilst rural settings are served with strategy 2.	Birth rates, percentage of contraceptive users among currently married women, number of new -or repeat acceptors- of contraceptives for each year, age and parity distributions of women using contraceptives during the 13th year of simulation for each method of contraception and each strategy.	Differences were found in adoption rates between four strategies. However, there is no evidence of differences between strategies one to three. Strategy two implies higher birth rate in urban settings.	S: transitions and adoptions of methods are tied to age and parity. L: 1) only accounts for married women; 2) assumes resources are not limited in the context of the family planning programme.
Feinberg (1973)	Contraceptive protection provided individual couples and achievement of program goals: A computer simulation study of a marriage cohort under varying conditions associated with national family planning programs	To depict the effect of variations of family planning programmes on the fertility behaviour of a marriage cohort.	Microsimulation of fertility behaviours along the reproductive lifecycle.	Taiwan	1) only married couples are simulated, without the option of remarriage; 2) all couples in the starting cohort are in the fecund state; 3) contraceptive adoption varies with age and parity.	Two different durations of the family planning programme: 13 and 52 months.	Effect of contraception in spacing/limiting fertility behaviours.	1) the maximum level of fertility reduction is accomplished in the second scenario, and adopting a contraceptive at age 3; 2) adoption of a contraceptive after a pregnancy ends would also bring about fertility reductions.	S: the model fares well when its results are compared against other studies. L: Only centered in intrauterine devices as contraceptive methods; small timeframes for evaluating programme effectiveness.
Lachenbruch (1974)	Applications of POPREP, a modification of POPSIM	To describe whether adaptations to an already-existing model (POPSIM) to simulate live births via biological events, e.g., conception, sterility.	Microsimulation modelling	N/A	1) Age at menarche follows a normal distribution; 2) fecundability probability follows a Beta distribution; 3) Fecundability declines linearly to 0 at age of sterility, 4) switching between three contraceptives might be possible via a user-defined matrix.	Not specified	Fertility rates	The adapted model follows well the reference modes.	S: refinement of an already existent model to strenghten its applicability to other reprodcutive phenomena. L: no clear scenario testing was conducted.

Subbayyan (1982)	Modeling of a rural health system	To explain population structure in India, and how it is influenced by levels of family planning, food and crowding, and availability of health services.	System dynamics	India	1) birth and death rates are influenced by multiplicative effects of family planning, health services, food availability, and crowding; 2) 1971-72 conditions represent "normal" baseline values; 3) linear and non-linear relationships between variables based on partial empirical data and theoretical assumptions; 4) food availability per capita remains constant in future projections.	1) increasing family planning service spending (2.5-25% annual cumulative); 2) increasing health service spending (2.5-25% annual cumulative); 3) combined increases in both services.	Birth rates and death rates.	10% cumulative annual increase in both family planning and health services provides optimal control of birth rates (17.7) and death rates (9.73) by year 2000. Higher spending increases (>10%) showed diminishing returns. Health service effectiveness eventually diminishes due to crowding effects.	S: 1) comprehensive integration of multiple health system factors; 2) validation against 8 years of empirical data (1971-79); 3) flexible framework allowing for program modification. L: 1) some relationship curves partially assumed rather than empirically derived; 2) food availability held constant in projections; 3) limited geographic scope; 4) no consideration of migration effects; 5) economic factors beyond direct program costs not included.
Patil (1983)	Mathematical simulation of impact of birth control policies on Indian population system	To project the population trends to 2026 with different policies, including: 1) different levels of family planning provision intensity; 2) increase in marriage age; and 3) improving equity on income distribution.	System dynamics	India	1) population is disaggregated into 15 age levels and 4 income groups; 2) births depend on fertility rates and the number of women of child-bearing age; 3) deaths depend on age-specific mortality rates and life expectancy; 3) life expectancy is influenced by nutrition and health care availability; 4) various birth control policies are modeled as scenarios.	1) different intensities of birth control policies; 2) increase in marriage age; 3) redistribution of income.	Population growth, birth and death rates, age structure, and total couples to be covered by the family planning programme.	1) moderate intensity birth control policies can stabilize the population at a higher level earlier than high-intensity policies; 2) increasing marriage age and income redistribution have significant impacts on population dynamics; 3) high-intensity birth control policies can reduce the population to lower levels but take longer to stabilize.	S: 1) comprehensive model incorporating multiple demographic and socioeconomic factors; 2) provides insights into the long-term impacts of various birth control policies. L: 1) assumptions may not fully capture the complexity of real-world dynamics; 2) data limitations and the need for more detailed and updated information.

Teel (1984)	Simulation modeling perspectives of the Bangladesh family planning and female education system.	To represent contributions of the interactions between an array of social subsystems (i.e., family planning, education, marriage formation) in explaining high fertility rates in a developing country.	System dynamics	Bangladesh	1) high fertility rates are influenced by multiple dynamically interrelated variables; 2) female education is crucial for population control, improved health, and quality of life; 3) the model was initialized for 1972 with projections over a 30-year period (1972-2002).	1) increased female education and welfare; 2) higher levels of nutrition and per capita income; 3) various intensities of family planning programs.	Fertility rates	1) female education significantly impacts population growth, delaying marriage, increasing contraceptive acceptance, and improving health and welfare; 2) family planning programs need to be integrated with female education initiatives for maximum effectiveness; 3) economic development and improved nutrition are also essential for controlling population growth.	S: 1) comprehensive integration of multiple social subsystems; 2) use of innovative methodologies like fuzzy profiles and interpretive impact matrices; 3) emphasis on non-economic societal forces in addressing population growth. L: 1) data limitations due to historical gaps and inconsistencies; 2) assumptions may not fully capture the complexity of real-world dynamics.

Hu (2007)	The costs, benefits, and cost-effectiveness of interventions to reduce maternal morbidity and mortality in Mexico	To compare the health outcomes and costs associated with the current maternal health intervention coverage levels in Mexico.	Markov modelling	Mexico	1) infertility can result following a sexually transmitted infection, unsafe abortion, or sepsis; 2) 68% of women ages 20–45 years use some method of birth control with 9% employing traditional methods; 3) 15% pregnancies end in miscarriage.	1) Upgrading selected strategies to achieve coverage levels recommended in the WHO Mother Baby Package; and 2) increasing coverage of selected interventions alone (e.g., enhanced access to safe abortion) and in the context of strategic packages (e.g., increased family planning, enhanced safe abortion, improved access to emergency obstetric services). Selected strategies: provision of family planning; safe abortion; prenatal care (e.g., four to six prenatal visits including physical exam, urine protein screen, screening and treatment for anemia and syphilis, iron/folate supplementation, tetanus vaccination, and if indicated, treatment for sexually transmitted infections; high quality intrapartum care including access to skilled attendants and emergency obstetric care (e.g., timely access to a facility with surgical expertise, critical care capability including blood transfusions, and ability to manage serious obstetric complications that can cause death); and postpartum care.	Intermediate clinical events (e.g., unsafe abortion, severe preeclampsia/eclampsia, obstructed labor, hemorrhage, sepsis) and long-term outcomes (e.g., life expectancy, disability-adjusted life expectancy, lifetime costs).	The Mother-Baby Package is both more effective and less costly than the current standard of care.	S: model parameterised with Mexico data; current programme compared against existent standard of care. L: the model makes no attempt to estimate the feasibility of scaling up the family planning and safe abortion strategies.

Goldie (2010)	Alternative strategies to reduce maternal mortality in India: A cost-effectiveness analysis	Estimate the cost-effectiveness of interventions devised to reduce maternal mortality, from family planning and access to safe abortion/post-abortion care, to integrated/stepwise approach (i.e., increased skilled deliveries, facility births, access to antenatal/postpartum care, improved recognition of referral need, transport, and availability quality of emergency obstetric care).	Markov modelling	India	1) incidence and case fatality rates of pregnancy-related complications; 2) effectiveness of interventions to reduce complications and case fatality rates; 3) costs of interventions and maternal complications; 4) access to services and facilities.	1) increased family planning; 2) safe abortion; 3) integrated services including skilled birth attendants, antenatal/postpartum care, facility-based births, and emergency obstetric care (EmOC).	Clinical events (e.g., pregnancies, live births, maternal complications), measures of maternal mortality (e.g., maternal mortality ratio), population outcomes (e.g., life expectancy), and economic costs.	1) increasing family planning is the most effective individual intervention, potentially preventing over 150,000 maternal deaths and saving more than US$1 billion in 5 years; 2) an integrated, stepwise approach could prevent nearly 80% of maternal deaths, with cost-effectiveness ratios well below India's per capita GDP.	S: 1) comprehensive model incorporating multiple data sources; 2) consideration of both urban and rural settings; 3) identification of cost-effective strategies. L: 1) altough the results point to the efficiency of the combination of strategies (family planning plus universal access to safe abortion) on maternal outcomes and medical costs, the model makes no attempt to estimate the feasibility of scaling up the family planning and safe abortion strategies. This is different to the scale-up of emergency obstetric care, where some form of feasibility analysis is present. 2) potential underestimation of effectiveness and cost-effectiveness by not including neonatal health and survival benefits.
Thomas (2011)	Estimating the effects and costs of three pregnancy-prevention programs	To assess the effectiveness and cost-efficiency of three interventions: 1) a mass media campaign encouraging contraceptive use; 2) an evidence-based teen pregnancy prevention program; 3) and expanded access to Medicaid-funded family planning services.	Agent-based modelling	United States	1) effects of interventions were derived from prior small-scale, rigorously evaluated programs; 2) assumptions were made regarding the costs and impacts of scaling these programs nationally; 3) impacts measured were on contraceptive use, sexual behavior, and associated outcomes.	1) teen pregnancy prevention through education and skills training; 2) mass media campaigns promoting contraceptive use; 3) increased availability of Medicaid-funded family planning services.	1) changes in rates of contraceptive use and sexual behavior; 2) cost-effectiveness of interventions; 3) reduction in teen pregnancies.	1) programs collectively increased contraceptive use by approximately 25%; 2) sexual activity reduced by 15% among participants; 3) cost-effectiveness varied across interventions, with scaled implementation potentially	S: inclusion of diverse intervention types. L: 1) assumptions on scalability and consistency of impacts may not fully generalize; 2) some evaluations lack sufficient replication data for validation.

								reducing impacts.	
Welti (2017)	How increasing the use of effective contraception could reduce unintended pregnancy and public health care costs	To estimate nationwide pregnancy outcomes and associated costs if women not seeking pregnancy used the same mix of effective contraceptive methods as women in Planned Parenthood clinics with enhanced contraceptive access.	Microsimulation model with daily periodicity, simulating individual-level fertility behaviors and outcomes.	United States	1) baseline contraceptive distribution matches 2006-2010 National Survey of Family Growth data; 2) proportional effects would be similar in 2017 as in 2008; 3) 68% of unintended births are publicly funded; 4) USD17k saved per averted public unintended birth in 2015 dollars.	Baseline: actual US contraceptive method distribution. Intervention: Distribution matching Planned Parenthood clinics post-intervention (higher long-acting reversible/hormonal use).	Unintended pregnancy, birth and abortion rates; maternal/child health outcomes; public healthcare cost savings.	1) 64% reduction in unintended pregnancies; 2) 63% reduction in unintended births; 3) 67% reduction in abortions; $12 billion annual public health care cost savings; 22% reduction in births into poverty.	S: 1) comprehensive simulation incorporating multiple demographic factors; 2) detailed cost analysis. L: 1) cannot explicitly model pregnancy intentions; 2) no reduction found in rates of adverse outcomes; 3) based on select clinic population that sought services; 4) assumes similar proportional effects over time.
Thomas (2012)	Three strategies to prevent unintended pregnancy	To compare the impact of three interventions to prevent unintended pregnancies.	Agent-based modelling	United States	1) information campaigns affect the behaviour of population in 3%; 2) sex education reduces risk sexual behaviour in 33%; 3) expanding family planning services has the same effect amongst members of the population (youngsters and adults).	1) Information and education campaigns, 2) pregnancy intervention directed at high risk younger individuals, 3) expansion of Medicaid family planning services.	Unintended pregnancy	Medicaid expansion yields higher cost-benefit ratios.	S: highly detailed model structure. L: 1) high dose of uncertainty around estimates; 2) positive externalities not accounted for.
Babigumira (2012)	Potential cost-effectiveness of universal access to modern contraceptives in Uganda	To compare the cost-effectiveness of granting universal access to modern contraception, compared with the current scenario (traditional methods and unmet need still occurring).	Markov modelling	Uganda	1) the tested contraceptive programme holds the same contraceptive distribution availability as the current programme; 2) a constant contraceptive mix is assumed through time.	Universal access to modern contraception in comparison to current levels of access.	Unintended pregnancy	1) in a cohort of 100k women, the new contraceptive programe would save more than USD 8 million; 2) the new programme is economically dominant.	L: 1) no attempt to estimate the feasibility of scaling up the family planning and safe abortion strategies; 2) fertility intentions do not change over time; 3) no externalities of contraception were measured.

Erim (2012)	Assessing health and economic outcomes of interventions to reduce pregnancy-related mortality in Nigeria	Provide insights into the most efficient strategies to meet the Millenium Development Goal 5.	Markov modelling	Nigeria	1) separate models for Southwest and Northeast zones; 2) coverage of effective interventions, including improved logistics; 3) incremental cost-effectiveness ratios calculated; 4) sensitivity analyses and Monte Carlo simulations conducted.	1) increasing family planning coverage; 2) improving intrapartum care; 3) integrated approach combining family planning, safe abortion, and intrapartum care.	Same as in Goldie (2010)	1) increasing family planning is the most effective and cost-saving intervention; 2) integrated strategies can prevent 4 out of 5 maternal deaths; 3) economic benefits range from cost-saving to incremental cost-effectiveness ratios less than $500 per year of life saved.	S: 1) comprehensive model considering various interventions; 2) region-specific analysis; 3) cost-effectiveness analysis provides actionable insights. L: 1) estimates based on current data, not future preferences; 3) limited data on the frequency of unsafe abortion and unmet need for contraception.
Trussell (2013)	Burden of unintended pregnancy in the United States: Potential savings with increased use of long-acting reversible contraception.	To evaluate total costs of unintended pregnancy (UP) from third-party payer perspective and estimate potential cost savings from increased LARC adoption.	Economic cost model (decision tree modelling) estimating direct medical costs of unintended pregnancy outcomes and contraceptive methods, incorporating perfect v typical use effectiveness rates.	United States	1) 50% of ectopic pregnancies/spontaneous abortions assumed from unintended pregnancy; 2) no contraceptive switching during analysis period; 3) annualized costs for multi-year methods (long-acting); 4) only first-year failure rates considered.	Three 10% switching scenarios amongst women aged 20-29 years: 1) oral contraceptive users to long-acting; 2) short-acting contraceptive users to long-acting; 3) short-acting/no method users to long-acting.	1) direct medical costs of unintended pregnancy outcomes; 2) contraceptive costs; 3) unintended pregnancy rates and costs attributable to imperfect adherence; 4) cost impact of increased long-acting reversible contraception uptake.	1) annual unintended pregnancy medical costs: USD 4.6 B; 2) 53% of unintended pregnancy costs (USD 2.47B) attributed to imperfect adherence; 3) 10% switch from short-acting/no method to long-acting could save USD 436M annually; 4) cost neutrality achieved in 1.3-1.9 years post-long-acting contraception switch.	S: 1) comprehensive cost components included; 2) mMultiple sensitivity analyses; 4) detailed age stratification. L: 1) exclusion of prenatal/long-term costs; 2) side effects costs not included; 3) no contraceptive switching considered; 4) only first-year failure rates used; 5) limited to direct medical costs.

Kennedy (2013)	The case for investing in family planning in the Pacific: Costs and benefits of reducing unmet need for contraception in Vanuatu and the Solomon Islands	Measure impact of scaling-up the current family plannign programme	Demographic modelling	Vanuatu and Solomon Islands	1) base-year (2010) data from census reports, DHS, UN agencies; 2) unmet need: 30% Vanuatu, 11% Solomon Islands; 3) front-loaded reduction in unmet need; 4) contraceptive method mix adjusted for planned changes; 5) economic/health expenditure projected to reach East Asia/Pacific average by 2054.	1) no change in unmet need; satisfying unmet need for contraception by 2) 2020 and 3) 2050.	Contraceptive prevalence and number of users per method, family planning costs, health outcomes (i.e., unintended pregnancies, induced abortions, total births, births with any avoidable risk, and maternal and infant deaths), total fertility rate, population growth, dependency ratio, and annual public sector health and education expenditure.	1) meeting needs by 2020 would cost $5.19M (Vanuatu) and $3.36M (Solomon Islands); 2) would avert 2,573 maternal and infant deaths; 3) every $1 spent would save $9-16 in health/education costs; 4) substantial reductions in unintended pregnancies and fertility rates.	S: 1) comprehensive sensitivity analysis; 2) country-specific data and expert input; 3) multiple outcome measures. L: 1) excludes system strengthening costs; 2) limited unmet need data for Vanuatu; 3) small absolute numbers affect mortality estimates; 4) cannot account for all fertility determinants; 5) constant costs assumption throughout projection period.
Carvalho (2013)	National and sub-national analysis of the health benefits and cost-effectiveness of strategies to reduce maternal mortality in Afghanistan	To assess health outcomes and cost-effectiveness of strategies to improve pregnancy and childbirth safety in Afghanistan by evaluating single interventions and integrated service packages.	Markov modelling	Afghanistan	2) case fatality rates conditional on complication type/severity and comorbidities; 2) effectiveness of interventions dependent on access to services and facility capabilities; 3) stepped implementation of integrated service packages feasible over time; 4) upper threshold of 60% contraceptive coverage.	1) progress assessment between 1999-2002 and 2007-08; 2) single interventions (e.g., family planning alone); 3) integrated packages combining multiple interventions in phased approach (family planning + skilled attendance + transport + EmOC).	1) pregnancy-related complications; 2) maternal deaths and mortality ratios; 3) cost per year of life saved; 4) proportionate mortality ratio; 5) lifetime risk of maternal death.	1) Family planning most effective single intervention - could prevent 1 in 3 maternal deaths at 60% coverage; 2) 30-40% mortality reduction threshold without emergency obstetric care access; 3) phased approach combining family planning and incremental improvements in skilled attendance, transport, referral and care quality could prevent 75% of maternal deaths.	S: 1) comprehensive model incorporating multiple intervention components; 2) sub-national analysis accounting for regional variations; 3) rigorous cost-effectiveness analysis; 4) policy-relevant phased implementation approach. L: 1) limited quality/availability of country-level data; 2) exclusion of neonatal outcomes; 3) uncertainty in timeframes for implementing later phase improvements; 4) limited abortion data due to cultural sensitivity; 5) does not capture mortality reductions from improved underlying health status.

Manlove (2014)	Male involvement in family planning: the estimated influence of improvements in condom use and efficacy on nonmarital births among teens and young adults	Estimate the effects of increasing contraceptive use (condom) among sexually active men.	Agent-based modelling	United States	1) young men aged 15–24 constitute a key population for changes in condom use; 2) modeled scenarios include moving non-users to condom users and improving use efficacy among current users.	1) 50% of non-condom users begin using condoms; 2) 100% of non-condom users begin using condoms; 3) typical use failure rates among all current users; 4) perfect use failure rates among all current users.	Incidence of nonmarital pregnancy, abortion, childbearing, and child poverty rates.	Increased condom use and efficacy significantly reduce nonmarital pregnancies (23–47%), abortions (10–48%), and child poverty rates (5.7–12.5%).	S: 1) employs a robust microsimulation model to estimate individual and population-level effects; 2) provides actionable insights for policy interventions. L: assumes substantial behavioral changes, which may not fully capture real-world barriers to condom adoption and consistent use.
Thomas (2014)	The role of mass media campaigns in preventing unintended pregnancy	Estimate the impact of information-education campaigns in unintended pregnancy reduction.	Agent-based modelling	United States	1) 3% increase in condom use among unmarried men (based on conservative estimates from literature); 2) campaign costs estimated at $100M-$250M annually (based on comparable national campaigns); 3) only considered unmarried population (excluded married couples); 4) benefits calculated through avoided taxpayer costs for Medicaid/means-tested programs up to child age 5.	Nationwide year-round media campaign promoting condom use under two cost assumptions ($100M vs $250M annually).	Unintended pregnancy	1) 4% reduction in teen pregnancies and abortions; 2) 2.2% reduction in children born into poverty (~23,000 fewer annually); 3) benefit-cost ratio of 1.7-4.3 (varying by cost assumption); 4) cost per avoided pregnancy: $900-$2,300; 5) annual taxpayer savings: $431M.	S: 1) robust simulation methodology with multiple runs; 2) conservative assumptions; 3) comprehensive cost-benefit analysis; 4) validation against real-world benchmarks. L: 1) excludes married population effects; 2) benefits only calculated up to child age 5; 3) does not account for private benefits; 4) limited to condom use only.

Diamond-Smith (2014)	Reducing Unintended Pregnancies: A Microsimulation of Contraceptive Switching, Discontinuation, and Failure Patterns in France	To test the effectiveness of three behavioural interventions in reducing unintended pregnacy.	Microsimulation	France	1) mortality and migration rates set to zero; 2) every woman experienced a monthly probability of switching to any other state. This differed by method type and length of time on that method.	1) Reducing method failure; 2) increasing time using effective methods; and 3) increasing switching from less effective to more effective methods.	Number of unintended and intended pregnancies, total fertility rate.	1) Scenario 1 reduced unintended pregnancies in 6.9 percentage-points, whilst 2 and 3 reduced 1.2 and 1.4 percentage-points, respectively.	S: 1) policy recommendations are detailed; 2) simulations replicate actual data used to parameterise the model. L: 1) no age-specific method switching rates; 2) does not account for women's parity to assign baseline contraceptive method.
Black (2015)	The Cost of Unintended Pregnancies in Canada: Estimating Direct Cost, Role of Imperfect Adherence, and the Potential Impact of Increased Use of Long-Acting Reversible Contraceptives.	1) quantify direct cost burden of unintended pregnancies in Canada; 2) determine proportion of unintended pregnancies/costs attributable to imperfect contraceptive adherence; 3) estimate potential cost savings from increased long-acting contraception usage.	Economic cost model	Canada	1) base case analysis for women aged 20-29 years; 2) one-year analysis period for comparability; 3) pregnancy outcomes: birth, induced abortion, miscarriage, ectopic pregnancy; 4) perfect vs. typical use failure rates from literature; 5) direct costs only (public payer perspective).	Three intrauterine device (IUD) uptake scenarios where 10% of users switch from: 1) oral contraceptives to IUD; 2) any short-acting reversible contraceptive to IUD; 3) either no method or any short-acting method to IUD.	1) annual number and costs of unintended pregnancies; 2) proportion of costs due to imperfect adherence; 3) potential cost savings from increased IUD use; 4) time to cost neutrality for IUD adoption.	1) annual number of unintended pregnancies in Canada: 180,733 ($320M cost); 69% of costs ($220M) due to imperfect adherence; 3) up to $35M potential annual savings with 10% IUD uptake; 4) cost neutrality achieved in ~12 months for all scenarios.	S: 1) first Canadian UP cost burden study; 2) comprehensive sensitivity analyses. L: 1) only first-year failure rates used; 2) direct costs only (no social/long-term costs); 4) discontinuation rates not considered; 5) some US data used where Canadian data unavailable.

Henry (2015)	Cost of unintended pregnancy in Norway: a role for long-acting reversible contraception	To quantify economic burden of unintended pregnancies in Norway and estimate cost savings potential from increased long-acting reversible contraception uptake.	Economic model estimating UPs and associated costs based on contraceptive failure rates, method mix, and pregnancy outcomes	Norway	1) perfect vs typical use failure rates difference represents adherence-related failures; 2) four pregnancy outcomes: live birth, induced abortion, spontaneous abortion, ectopic pregnancy; 3) costs include direct medical costs and indirect work productivity losses; 4) long-acting contraception requires 1.28 years of use to achieve cost neutrality vs short-acting.	Base case: Current contraceptive method mix 1) 5% switch from short-acting to long-acting in women aged 15-24 years; 2) sensitivity analyses with 10% and 100% SARC to LARC switch.	1) total unintended pregnancy costs; 2) proportion of unintended pregnancies due to imperfect adherence; 3) cost savings from increased long-acting contraception uptake.	1) total unintended pregnancy costs: NOK 617M (ages 15-44) and NOK 144M (ages 15-24); 2) 81.7% of unintended pregnancies in ages 15-24 due to imperfect adherence; 5% short-acting to long-acting switch saves NOK 6.5M in ages 15-24.	S: 1) comprehensive cost analysis including both direct and indirect costs; 2) extensive sensitivity analyses; 3) policy-relevant findings. L: 1) USA data used for some parameters due to lack of Norwegian data; 2) only first-year contraceptive failure rates available; 3) longer-term outcomes not considered; 4) side effects and contraceptive switching not modeled.
Manlove (2015)	Linking Changes in Contraceptive Use to Declines in Teen Pregnancy Rates	Explore how changes in contraceptive mix offered to teenagers contributed to the reduction in teen pregnancy rates between 2002-2010 in the United States.	Agent-based modelling	United States	1) no changes in coital frequency, demographics, or contraceptive discontinuation rates (except for long-acting/injectable category); 2) dual-method use patterns remained constant; 3) pregnancy risks based on typical-use failure rates; 4) method switching allowed between contraceptive categories.	1) baseline 2002 contraceptive distribution; 2) increased condom use; 3) increased pill/patch/ring (PPR) use; 4) increased LARC/injectable use; 5) counterfactual: moving condom users to more effective methods.	1) changes in pregnancy rates per 1,000 teen women; 2) relative contribution of different contraceptive method changes to overall decline.	1) contraceptive changes accounted for 48% of teen pregnancy rate decline; 2) 58% of contraceptive effect due to increased condom use; 3) reduction in non-use had greater impact than switching to more effective methods; 4) overall decline of 8.1 pregnancies per 1,000 teens attributable to contraceptive changes.	S: 1) comprehensive modeling of multiple contraceptive behaviors; 2) validation against real-world benchmarks; 3) ability to isolate effects of specific method changes. L: 1) cannot separate long-acting reversible contraception from injectable effects due to sample size; 2) does not model changes in dual method use over time; 3) does not account for changes in consistency/correctness of use; 4) may underestimate total contraceptive effect by focusing only on method mix changes.

Thomas (2016)	The intensive and extensive margins of contraceptive use: comparing the effects of method choice and method initiation	Study the effects of contraceptive use on nonmarital pregnancy rates.	Agent-based modelling	United States	1) perfect use assumed for new LARC users, typical use for other methods; 2) unmarried status used as proxy for unintended pregnancy risk; 3) model parameterized using 2006-2010 NSFG data; 4) contraceptive switching allowed monthly; 5) daily updating of menstrual cycles and age-adjusted fecundity.	Moving 5% of at-risk unmarried women from: 1) No method to condoms/PPR/long-acting reversible; 2) condoms to PPR/long-acting reversible; 3) PPR to long-acting reversible. Each scenario run with/without method switching.	Unintended pregnancies	1) extensive margin changes (initiating any method) had larger impacts than intensive margin changes (switching to more effective methods); 2) moving non-users to condoms reduced pregnancies more than moving pill users to long-acting reversible; 3) difference between adopting long-acting vs. PPR methods was modest compared to difference between using no method vs. any method.	S: 1) comprehensive validation against real-world benchmarks; 2) robust sensitivity analyses; 3) daily periodicity capturing detailed behavioral dynamics. L: 1) unable to directly model pregnancy intentions; 2) limited to 1-year validation period; 3) cannot track method switching within categories; 4) results may vary for specific subpopulations.
Karpilow (2017)	Reassessing the importance of long-acting contraception	To estimate the CHOICE programme's impact on pregnancy risk and to simulate the counterfactual effect of moving all nonusers and condom users onto shorter-acting, female-controlled methods.	Agent-based modelling	United States	Assumed demographic characteristics matching CHOICE participants, including reductions in nonuse and condom use, and adoption of female-controlled methods.	1) preenrollment contraceptive use; 2) postenrollment LARC adoption; 3) hypothetical adoption of shorter-acting methods by nonusers and condom users.	Unintended pregnancies	Over 70% of the CHOICE Project's effect on pregnancy risk could be achieved without increasing long-acting contraception use, emphasizing the role of female-controlled methods over nonuse and condom use.	S: comprehensive microsimulation, aligning closely with real-world demographic data. L: focused on one-year outcomes, limiting assessment of long-term contraceptive effectiveness differences.

Keen (2017)	Scaling up family planning in Sierra Leone: A prospective cost–benefit analysis	Use a compartmental modelling tool to estimate the programmatic and financial costs needed to scale-up FP strategies in al low-income country.	Spreadsheet modelling	Sierra Leone	1) family planning services are scaled up to currently married women aged 15–49 years; 2) two scenarios: medium (contraceptive prevalence rate reaching 34% by 2035) and high (contraceptive prevalence rate reaching 50% by 2035); 2) costs include direct costs, health facility overheads, and program costs; 3) benefits include cost savings in primary education, child immunization, malaria prevention, maternal health services, and improved drinking water.	Two levels of coverage: 1) one 'medium' (34% coverage); 2) and one 'high' (50%) which were compared to a 'counterfactual' scenario of no change in current trends to the year 2035.	Demographic: population size and structure, family planning use and fertility rates. Health outcomes: Potential reductions in maternal and infant deaths. Eonocmic: projection of the governmental costs of providing primary education, child immunisation, malaria prevention, maternal health services and improved drinking water in the different scenarios. 'Benefits': cost savings from fewer people requiring these five essential services, following the scale-up of FP coverage.	1) by 2035, the high scenario could result in 1400 fewer maternal deaths and 700 fewer infant deaths annually compared to the counterfactual; 2) total cost of family planning services will increase from US$4.2 million in 2013 to US$10.6 million annually by 2035 in the high scenario; 3) for every dollar spent on family planning, Sierra Leone could save US$2.10 in expenditure on the five selected social services over the period 2013–2035.	S: comprehensive cost-benefit analysis including direct and program costs, and benefits across multiple social services. L: 1) does not account for the dynamics of the system devised to provide services; 2) resources needed to scale-up were not expicitly modelled; 3) does not test for alternative arrangements to optimise resource use; 4) feasibility of achieving coverage levels of scenarios modelled was not explained.
Zakiyah (2019)	Cost-Effectiveness of Scaling Up Modern Family Planning Interventions in Low- and Middle-Income Countries: An Economic Modeling Analysis in Indonesia and Uganda	Analyse the cost-effectiveness of four incremental scenarios of FP scale-up: 25, 50, 75% and full coverage; they compared them to the current coverage levels in Indonesia and Uganda	Markov modelling	Indonesia and Uganda	1) women's reproductive years as time horizon; 2) modern contraception coverage increased by specific proportions; 3) healthcare payer perspective, including only medical costs; 4) women may move between five different states (sexually inactive, wanting to delay pregnancy, non-user; wanting to delay pregnancy, user; trying a pregnancy, non-user; pregnant).	25, 50, 75, and 100% increments in contraceptive coverage relative to status quo.	1) intermediate: pregnancies, livebirths (vaginal and caesarean), induced abortions, spontaneous abortions, stillbirth, maternal death; 2) final: disability-adjusted life years, costs.	1) eliminating FP results in 2483-9597 avoided pregnancies in Indonesia, and 15888-52014 in Uganda; total costs of eliminating unmet need for contraception are lower than current programme costs.	S: 1) the study models the movements between different states along the reproductive years of women; findings consistent with other studies. L: 1) no attempt to estimate the feasibility of scaling up the family planning; 2) discrepancies on definition of current method use in both countries; 3) not included other costs, e.g., out-of-pocket.

Engstrand (2018)	Cost of unintended pregnancy in Sweden — a possibility to lower costs by increasing LARC usage	To estimate costs of unintended pregnancy in Sweden and potential cost savings from 5% switch from short-acting reversible contraception to long-acting reversible contraception	Economic model	Sweden	1) population: Women 15-44 years requiring reversible contraception; 2) unintended pregnancy outcomes: birth, spontaneous abortion, induced abortion, ectopic pregnancy; 3) contraceptive failure rates from US data; 4) direct costs (healthcare, out-of-pocket) + indirect costs (work time lost); 5) long-acting contraception costs annualized over product lifetime; 6) 92% of abortions assumed unintended.	Base case + 5% switch from non-long-acting to long-acting methods in: 1) all women aged 15-44; 2) women aged 20-29 (high abortion rate subgroup).	1) number of unintended pregnancies; 2) direct medical costs; 3) indirect costs; 4) cost savings from method switching.	1) estimated 73,989 annual unintended pregnancies costing €158M; 2) 5% switch to long-acting would prevent 3,500 unintended pregnancies annually; 3) generated savings of €7.7M (2.4% of UP costs); 4) cost neutrality achieved at 2.09 years (all women).	S: 1) uses recent Swedish contraceptive usage data; 2) comprehensive cost perspective; 3) sensitivity analyses confirm robustness. L: 1) adherence rates not age-specific; 2) mental health impacts excluded; 3) early LARC discontinuation may be underestimated; 4) costs of pregnancy complications not included.

2.1 OR/MS simulation approaches applied to the study of contraception and fertility: first historical approaches

The simulation of human fertility under contraception attracted the attention of the OR community since the 1960s when most family planning programmes began around the globe. The span of different settings includes low- and middle-income countries (LMICs) and high-income countries (or developing and developed countries, respectively, as per the formerly accepted nomenclature.) Chosen techniques are diverse and include discrete-event simulation, system dynamics, and agent-based simulation. Whilst early work considered only the case of married women, more recent studies expanded the scope to address the case of non-married and cohabitating women, given that modern data sources report sexual activity levels for a wide variety of marital statuses. This responds to a shift in perspective to analysing exposure to unintended pregnancy: sexual activity is a characteristic of women of all reproductive ages, disregarding their marital status.

The Population Simulation (POPSIM) model was developed by the Research Triangle Institute and introduced in 1969, starting as a discrete-event simulation demographic model (i.e., generating births probabilistically) that evolved into the Population Representation (POPREP) model to depict reproductive milestones of women (e.g., conception, sterility) (Lachenbruch et al., 1974). The model was able to simulate contraceptive adoption and switching patterns, and its typical application was the estimation of fertility indicators such as crude birth/general fertility rates due to different policy configurations of contraceptive provision programmes (Sarma, 1970). Further uses consisted in estimating the necessary number of contraceptive users to attain fertility goals in a fictional setting (Rao et al., 1973). Despite its realistic representation of events in the reproductive lifecycle, it was deemed overly complicated for most applications on which was tested, requiring a non-trivial amount of data sources to reconstruct the life histories of its simulated populations (Treadway, 1978).

In 1972, Vertinsky et al. introduced The Costa Rica Population Control Model (Vertinsky et al., 1972), a microsimulation model which employs a decision-making algorithm in response to pregnancy susceptibility (as a function of the number of children, urban/rural setting of residence and assuming that an additional pregnancy poses disutility to exposed couples). The model estimated a matrix of contraceptive adoption probabilities adjusted to women's age and their number of children to conduct two experiments: testing the effect of distance to clinics and of information, education, and communication (IEC) campaigns in increasing contraceptive use. The authors found that both strategies could expand the number of contraceptive users in the country.

Another microsimulation model, the Fertility Modeling under Family Planning (FERMODP) model, estimated the change in fertility rates after introducing intrauterine devices as the only contraceptive option for a cohort of Taiwanese married couples (Feinberg, 1973).

The first identified application of SD goes back to 1982 in India. Subbayyan et al. (Subbayyan et al., 1982) devised a high-level model to explain the influence of the contraceptive provision programme (represented with allocated per capita spending), food/crowding, and health services available on births and deaths. The authors concluded that a 10% increase in contraceptive and health services spending would take birth and death rates to manageable levels. Again, in India, Patil et al. proposed a different SD model to project population trends (Patil et al., 1983). They projected the population development until 2026 under different policies: modifying the intensity of contraceptive provision, increasing marriage age, and improving equity in income distribution. Their main finding was the positive impact of improving contraceptive provision. Finally, a third SD model was applied to the Bangladeshi context by Teel and Ragade to represent the interactions of contraceptive provision, education, and marriage formation in explaining high fertility rates (Teel & Ragade, 1984). The main finding was the positive influence of school enrolment in diminishing birth rates. Although not formally tested, the authors suggested that improving other social subsystems, such as contraceptive provision, was necessary.

2.2 Contraceptive, sexual, and reproductive dynamics representation and unintended pregnancy estimation

Available models have approached the study of contraceptive, sexual, and reproductive dynamics in some form. All have estimated unintended pregnancies as the consequence of contraception failure or non-use. In their simplest form (Black et al., 2015; Engstrand & Kopp Kallner, 2018; Henry et al., 2015; Trussell et al., 2013), they are spreadsheet models used to investigate the economic impact of policies addressing method switching from behavioural-dependent or traditional contraception to long-acting reversible contraception (LARC) over a single-year timeframe.

Although these models are a good starting point in the investigation of method switching, they leave important unanswered questions regarding how the policy might develop over time in the likely event of method discontinuation and thus represent an incomplete view of the aspect of an ambitious switching policy.

A possible improvement to these models would be to extend the simulation period, perhaps within the bounds of a LARC's useful life -five to ten years- and include strategies with differing levels of LARC adherence. It has been argued that evaluating the efficiency of providing contraceptives that confer long-term protection against unintended pregnancies, such as LARCs, using a short period is inappropriate and might be a source of effectiveness overestimation, given discontinuation rates are higher soon after positioning them (Mavranezouli, 2009).

The *FamilyScape* agent-based model, developed at The Brookings Institution, evolved from explaining family formation patterns among couples (Thomas, 2011, 2012) to a more general model representing their sexual behaviours (Thomas & Karpilow, 2015). Its first form was used to explore the impact of increasing male condom use on live birth, abortion, and child poverty rates (Manlove et al., 2014). The model was also used to estimate the impact of information-education-communication campaigns in reducing unintended pregnancy (Thomas, 2014) and exploring how changes in the contraceptive use mix among teenagers contributed to reducing pregnancy rates in the United States (Manlove et al., 2015).

The next version of the model (Thomas & Karpilow, 2016) was used to test the impact of different contraceptive provision policies on unintended pregnancy: expanding LARC use to all method users, motivating non-users and condom users to switch to LARCs (Karpilow & Thomas, 2017), and of modifying the contraceptive use mix (Welti et al., 2011).

The model is interesting because it accounts for the dynamic contraceptive behaviour of a set of simulated women. However, and although the estimation of the adoption, switching, and discontinuation patterns was conducted using state-of-the-art regression techniques applied in longitudinal data sources (i.e., discrete-time hazard models), the data available to parameterise the model comprised only two of the 35 years of the total reproductive lifespan (Thomas & Karpilow, 2015). In this way, the model does not account, for instance, for switching from LARCs to other methods in response to changing fertility intentions. The authors do not expand on this data limitation, given that they do not recognise it as such.

The model also overlooks the most dramatic outcome of unintended pregnancy, i.e., maternal death, despite the phenomenon being still prevalent and of public health relevance in the United States (Joseph et al., 2021), where the model was devised and parameterised.

Diamond-Smith et al. (Diamond-Smith et al., 2014) developed a microsimulation model of contraceptive behaviour in France to test the impact of three interventions: reducing method failure, reducing the discontinuation rates of more effective methods, and switching from less to more effective methods. The model was parameterised with data from a local cohort study and did not use age-specific method switching/discontinuation rates. Despite that significant limitation, the authors concluded that all three interventions could reduce unintended pregnancy, being improved effectiveness of methods the most beneficial.

Applying the *OneHealth Tool* (Avenir Health, 2012), a modular compartmental model devised to estimate the resources needed to scale up health services, (Keen et al., 2017) compared the hypothetical monetary benefits of contraceptive policies aimed at increasing adoption rates and thus escalating coverage in two alternative strategies in Sierra Leone: one to 34% and another to 50% from its current baseline. Setting the year 2035 as the endpoint, they found both strategies cost saving in primary education, child immunisation, malaria prevention, maternal health services, and improved drinking water, coming from the reduction in live births. However, they fail to describe which mechanisms or policy arrangements would motivate contraceptive adoption rates to increase, although the study's objective was to present a case favouring increasing donor investments in settings where the unmet need for contraception is high.

The former is not uncommon in sexual and reproductive health modelling, where most models advocating for expansive financial commitments towards contraception lack a discussion of what is feasible to realise.

Similarly to the previous approach, Kennedy et al. (Kennedy et al., 2013) employed demographic modelling to establish the potential health (e.g., UP, induced abortions), demographic (e.g., total fertility rate) and financial (e.g., public sector health and education expenditure) outcomes accrued with two strategies of universal contraceptive coverage in the Solomon Islands, in 2020 and 2050, compared to baseline levels. It was concluded that contraception applied to scale would positively impact the analysed outcomes. However, it was assumed that adoption rates can only improve over time.

In two similar models devised to analyse the case of Uganda and Indonesia, Babigumira et al. and Zakiyah et al. (Babigumira et al., 2012; Zakiyah et al., 2019) devised separate Markov models to estimate the cost-effectiveness of universal contraceptive coverage, resulting from eliminating the traditional contraceptive use and unmet need for modern contraception. The authors concluded that universal access to contraceptives would save costs and disability-adjusted life years (DALYs) besides averting UP, neonatal, and maternal deaths.

Although these two models depict the dynamics between contraceptive use and non-use, they do so by aggregating users into a single, broad category. However, method users behave differently according to method type, given that their choice responds to their reproductive needs. What is more, there are different timescales involved in using different method types as, for instance, LARCs can last up to ten years, whilst condoms are single-use methods. It is unclear how the authors dealt with such a limitation, yet they justified their approach in lacking trustable data.

Finally, Goldie et al. (Goldie et al., 2010), Hu et al. (Hu et al., 2007), Carvalho et al. (Carvalho et al., 2013), and Erim et al. (Erim et al., 2012) have used the *Computer Global Maternal Health Policy Model* in India, Mexico, Afghanistan, and Nigeria, respectively.

The model was devised as a Markov chain representing the reproductive lifecycle of women of reproductive age and allowed to estimate the cost-effectiveness of a set of public health interventions intended to reduce maternal mortality: contraceptive provision, access to safe abortion/post-abortion care, and an integrated approach comprised by a sort of improved pregnancy and delivery services, from antenatal care to emergency obstetric care.

The common conclusion among these studies was that a combination of strategies is the best way to address maternal mortality. Scaled-up contraception, however, was the most efficient single intervention. As with all reviewed studies in the present section, there is no attempt to discuss how feasible it is to scale contraception considering the full contraceptive dynamics instead of assuming ever-increasing adoption rates.

To conclude the chapter, the following list summarises the detected limitations of available models which have represented just a component or the full contraceptive dynamics, implicitly or explicitly:

1. Most studies approach the contraceptive dynamics assuming that contraceptive adoption rates can only increase over time. The role of contraceptive switching and discontinuation is not stated clearly nor discussed and is thus assumed to be absent in these models.
2. A fair number of the models reviewed have a very short timeframe of one year, on which there is a narrow margin to discuss contraceptive dynamics and their outcomes. Moreover, with such a short timeframe, it is uncertain to know the efficiency of implementing ambitious contraceptive policies, for instance, increasing LARC use, as is argued in these studies' conclusions. Thus, a short timeframe is inappropriate to the proper study of the return of investment of contraceptive provision.
3. Maternal death as an outcome of pregnancy is absent in some of the revised models.
4. In models accounting explicitly for the dynamics of contraception, limited data sources to produce long-term contraceptive behaviours were used.
5. The dynamics of contraceptive use are assumed to be restricted to broad categories (use/non-use), thus neglecting the variable necessities that different contraceptive methods satisfy.

The model devised in the present research will address each of the former limitations described by expanding its timeframe to the entire reproductive lifespan, by investigating the effect of the full contraceptive dynamics in health and economic outcomes, by deriving long-term contraceptive behaviours from a cross-sectional data source that covers the full reproductive lifespan of women, and by differentiating between contraceptive method categories.

2.3 Chapter summary

The first part of chapter two presented an account of historical Operational Research/Management Science approaches used in investigating Sexual and Reproductive Research topics. The second part presented a critical review of previous simulation modelling efforts that explicitly or implicitly addressed contraceptive, sexual, and reproductive behaviours. Limitations in these approaches are identified as the gaps to fill by the simulation model developed in this research.

Chapter 3 Conceptual framework

The present chapter introduces the necessary concepts to analyse the events over the female reproductive lifespan, theoretically bounded between the start of adolescence and until menopause. This is between 15 and 49 years (World Health Organization, 2006). Various processes interact during these years, and the dynamics between three of them motivate the present research: contraceptive, sexual, and reproductive behaviours.

The chapter also introduces concepts related to simulation modelling and a critical appraisal of this research approach.

3.1 Contraceptive, sexual, and reproductive dynamics in the reproductive life years

Considering the reproductive lifespan as a continuum, we can use contraceptive, sexual, and reproductive behaviours to explain the movements women can make between different states during their reproductive years. The possible states women visit can, in turn, be broadly categorised in sexual activity/inactivity, contraceptive use/non-use, and wanting/not wanting a pregnancy. Naturally, the sexual activity category intersects with others, and thus at any time the following can be observed:

- Sexually active women wanting a pregnancy.
- Sexually active women not wanting a pregnancy.
    - Sexually active women, not wanting a pregnancy and not using contraception.
    - Sexually active women, not wanting a pregnancy and using contraception.

Sexual inactivity was assumed not to intersect with other states in the model, reflecting the specific scope of this research on estimating unintended pregnancies in sexually active women due to either a) contraceptive failure or b) non-use of contraception despite not wanting to become pregnant. Thus, the categorisation of sexual activity is binary in the model, separating sexually inactive from sexually active women. This simplification was made to focus on contraceptive use and its impact on unintended pregnancies, which inherently applies only to sexually active women. It should be acknowledged that contraceptives may also be used for non-contraceptive purposes, such as addressing menstrual disorders or other medical indications, the former being reported by 8.9% of Mexican women in the National Survey on Demographic Dynamics (Instituto Nacional de Estadística y Geografía, 2019c), this aspect falls outside the model's scope as it does not directly influence the primary outcome of unintended pregnancies.

Contraceptive use is the exposure to any device, medication, or surgical procedure to intentionally limit or postpone natural fertility. There are many different types of contraceptives, and access to them depends on many factors: condom (female and male), injectable, pill, diaphragm, implant, intrauterine device (IUD), patch, foam, traditional (e.g., calendar method), and permanent (female and male sterilisation). These can be classified in a variety of ways. However, for this thesis, the classification used, from most to least effective, is as follows (National Institute for Health and Care Excellence, 2016; United Nations, 2020b):

- Permanent contraception. Includes female and male sterilisation conferring almost perfect protection against pregnancy. In most studies, the assumption is of total protection. Such assumption is also used in the present thesis.
- Long-acting, reversible contraception, and injectables (LARC). IUDs, implants, and injectables compose this category. Once positioned or applied, their effectiveness is not linked to user behaviour.
- Behaviour-dependent contraception. This category is composed of condoms and pills. Unlike LARCs, their effectiveness is linked to correct use, e.g., an incorrectly positioned condom increases the risk of pregnancy.
- Traditional contraception. This category includes many methods, being the main two calendar methods and withdrawal. They are also linked to user behaviour, but unlike condoms or pills, they do not function as an explicit barrier or medicated hormones to reduce the risk of pregnancy.

LARCs, behavioural and permanent methods are further considered *modern* methods, and family planning managers worldwide consider them to be the main tools to reduce unintended pregnancy (UP), conceptually defined as the result of a mistimed (i.e., desired later) or unwanted (i.e., not desired at all) pregnancy (Santelli, Rochat, Hatfield-Timajchy, et al., 2003). This leaves the rest of pregnancies as intended (IP), or those occurring at the right time and when desired.

Current estimates based on DHS datasets reported the global proportion of UP at 41% in 2008 (Singh et al., 2010), with variations by geographic area. In Latin America, the proportion of UP reached 58% that same year (Singh et al., 2010). In Mexico, the proportion was estimated at 55% in 2009 (Juárez et al., 2013).

We use the term *unintended pregnancy* throughout this thesis to refer to pregnancies occurring when they were either unplanned/unwanted and mistimed (Santelli, Rochat, Hatfield, et al., 2003). In practice there is an important difference between *mistimed* pregnancies, i.e., those occurring earlier than desired, and *unwanted* pregnancies, where there is no desire for childbearing at all (Moreau, Bohet, Le Guen, et al., 2014). Mistimed pregnancies often reflect more flexible preferences for avoiding conception, whereas unwanted pregnancies tend to signify a stronger and more definitive intent to prevent childbearing (Samari et al., 2020). This distinction has important implications for contraceptive adoption and switching behaviours. For instance, women experiencing mistimed pregnancies may gravitate towards short-term or reversible contraceptive methods, such as behavioural methods, rather than long-term or permanent. By contrast, women with stronger preferences to avoid pregnancy may be more inclined to adopt highly effective methods, e.g., long-acting reversible contraceptives or permanent.

Further, in the present research, unintended pregnancies are defined as pregnancies that occur in sexually active women who do not wish to become pregnant, either as a result of not using contraception or through method failure (Santelli, Rochat, Hatfield-Timajchy, et al., 2003). This approach provides a practical framework for focusing on what can be addressed through contraceptive provision strategies and diffusion campaigns.

Among the possible outcomes of pregnancy, live birth, miscarriage, and unsafe abortion are the most frequent. A live birth is a product of gestation that shows any sign of life after childbirth (i.e., breathing); a miscarriage is an abortion occurring due to natural circumstances at any time before 20 weeks of gestation (American Pregnancy Association, 2015).

Unsafe abortion is the intentional termination of a pregnancy outside of the health system and performed by unskilled personnel (Ganatra et al., 2014). Unsafe abortion is another public health concern, documented to occur when pregnancy is unintended (Santelli, Rochat, Hatfield-Timajchy, et al., 2003).

Other, less frequent, albeit important outcomes from pregnancy are maternal deaths and secondary infertility. Maternal deaths are defined as the *"[...] number of female deaths from any cause related to or aggravated by pregnancy or its management (excluding accidental or incidental causes) during pregnancy and childbirth or within 42 days of termination of pregnancy, irrespective of the duration and site of the pregnancy"* (World Health Organization, 2024b). These deaths are classified using specific codes of the International Classification of Diseases and can be estimated using well-maintained administrative registries (World Health Organization, 2012).

Secondary infertility occurs at different incidence rates due to the modality of pregnancy termination (i.e., live birth, unsafe abortion, miscarriage).

As previously mentioned, women can visit different states whilst they are in their reproductive years. In practice, these states might be visited more than once, implying several spells of exposure to unintended pregnancy along the reproductive continuum. This, in turn, increases exposure to unintended live births, unsafe abortion, or even maternal death in the most neglected settings.

The main objective of any contraceptive provision programme is to reduce such exposure spells to a minimum whilst respecting women's voluntary choice of contraception. Delivering contraceptives is, thus, a balancing act between what is better suited to a particular woman's case, what is available in each setting, her fertility intentions, the quality of the counselling she receives, her social circle's influence, among other intervening factors which are not always observable. Interactions between these factors give rise to verifiable and fundamental phenomena in explaining the consequences of contraception at the population level: adoption, switching, and discontinuation.

Contraceptive adoption is defined as the first-time or subsequent uptake of any contraceptive method and its uninterrupted use. Contraceptive discontinuation is the interruption of contraceptive use, and it is of concern for programme planners when a pregnancy is not yet desired, if at all, given the increased exposure to the risk of unintended pregnancy.

Contraceptive switching refers to the movement between different contraceptive methods, which vary in effectiveness. The model assumes that switching to a less effective method increases exposure to unintended pregnancy, simplifying the nuanced and multifaceted decision-making process underlying contraceptive choices. In practice, such decisions are influenced by a range of factors, including individual preferences, values, and circumstances, which may not prioritise effectiveness as the sole or primary consideration (Egarter et al., 2013; C. Marshall et al., 2018; Pariani et al., 1991).

For instance, behavioural methods may be chosen over long-acting reversible contraceptives or permanent methods due to concerns over side effects, cultural or religious beliefs, or the desire for greater autonomy and control (Alvergne & Stevens, 2021). These choices reflect prioritisation of factors other than method effectiveness, highlighting the need to respect the diversity of women's needs and motivations.

It must be recognised that contraceptive decision-making is based on what women perceive to be most appropriate to their personal circumstances and overall objectives (Hoyt et al., 2022). Whilst outside of the scope of this thesis, future iterations of the model could benefit from incorporating the utility framework underlying contraceptive choice, acknowledging that effectiveness is but one component of a complex decision-making process.

Women currently not using a contraceptive method, being sexually active, and not wanting a pregnancy are considered to have an unmet need for contraception (Bradley & Casterline, 2014).

The metric has been dominant in measuring the performance of contraceptive programmes worldwide, and it is estimated cross-sectionally through DHS and other sources. Recent estimates of unmet need for contraception situate it at 14.2% worldwide (Kantorová et al., 2020) in 2019, around 13% in Latin America that same year (Kantorová et al., 2020), and 11.1% in Mexico in 2018 (Consejo Nacional de Población, 2019).

On the other hand, the contraceptive prevalence rate (CPR) measures the current contraception users among the sexually active population, and it is also important in determining how well a contraceptive programme is performing. A more specific metric, modern contraceptive prevalence rate (mCPR), measures only modern contraceptive use, as these are more effective in preventing unintended pregnancy (World Health Organization, 2019).

3.2 Long-term contraceptive, sexual and reproductive dynamics

Determining the long-term development of the contraceptive, sexual and reproductive dynamics within a society, along with its public health and demographic consequences, is possible considering some grand-scale drivers: values about fertility, improved and improving schooling rates, intergenerational economic and living conditions, as well as access to contraceptives. The velocity of change of these factors varies, resulting in the convergence of mixed patterns that respond to each birth cohort's particular characteristics.

In the present thesis, no attempt is being made to represent each factor, and instead, birth cohort and women's ages are used as proxies to represent them jointly. This approach is expected to produce less accurate results, but the general objective, visualising the long-term outcomes of contraceptive, sexual, and reproductive dynamics on society, will be met. Future research efforts will be directed towards increasing the model's structure to address additional questions.

It can be argued that contraceptive use increases over time, and this can be observed, for instance, in new birth cohorts starting their use earlier on each generation (Brugeilles & Rojas, 2020). However, little is known on how this fact affects the whole contraceptive dynamics. Many still unanswered questions merit some reflection: Does adopting a contraceptive earlier predict less exposure to unintended pregnancy periods at an older women's age? Does it reduce the time until discontinuation? Does it predict less switching? Is a contraceptive provision programme better-off generating new and younger users, or should it direct its efforts to retain its current user base? What are the consequences of failing to retain the youngest users? What are the consequences of failing to retain older users?

These and other enquiries are key to improving understanding of contraceptive dynamics and can be investigated via simulation modelling, using *what-if* strategy testing.

Simulation modelling, as will be described in the next section, is particularly useful when there is uncertainty associated in the development of the studied phenomena.

3.3 Simulation modelling

Simulation modelling involves the abstraction of the principal components of an actual process, its mathematical representation, and its use to conduct strategy analysis of the hypothetical course of action of the studied phenomenon. Its application has increased in various disciplines, initially starting in those from the natural/physical sciences. The practice then moved to other disciplines as more powerful computing capabilities became widely available to researchers (Küppers et al., 2006).

Simulation modelling is best suited to the study of phenomena when an experimental design is impractical, for instance, due to ethical concerns, to an extended timescale of the studied phenomenon, its complexity, or to a limited time to decision-making, to name a few reasons. A particular strength of simulation modelling in social science research is the possibility to test different policies in a typically less resource-consuming manner than in experimental designs.

Although simulation modelling is conducted *in silico*, this does not preclude researchers from conducting virtual experimental research (Sobolev et al., 2012), constituting an additional advantage over real-world experimental designs. The data generated in virtual experiments can be analysed using standard statistical tools employed in other quantitative approaches.

Simulation models are synthetic-data generation mechanisms. Their internal structure defines a parameter space populated from various sources, ranging from experimental studies and topic-specific literature to expert opinions. The differential quality of these sources gives rise to model uncertainty, thus requiring researchers to tighten or relax the assumptions that originate the simulation's results. This is not without limitations, for parameter variation may lead to a model that does not relate to reality despite fitting well to the empirical data (Humphreys, 2004a).

Another source of uncertainty comes from the internal structure of a simulation model since it results from explicit and implicit processes undertaken by researchers and their understanding of the problem under study. As a result, two additional limitations might arise (Humphreys, 2004b). The first has to do with the acceptability of simulation models: if an external observer receives only limited information about the working mechanism generating the model's behaviour, they may grow suspicious about its merits. The second has to do with empirical underdetermination, as many different model structures can explain the same phenomenon of interest and their observed behaviour.

In general, the modeller undergoes two formal processes to keep the simulation results credible: sensitivity analysis and verification-validation. The first is intended to deal with uncertainty in the parameter space and identify which parameters most influence the model's results. The second, to secure that the model reproduces reality *"for the right reasons"* (Sterman, 2000a).

3.3.1 Alternative to simulation modelling studies

The closest alternative to a simulation study of the type proposed in the present thesis comes under the umbrella term "impact evaluation." This kind of analysis aims at measuring the effect that the implementation of a policy exerts on the population exposed to it. Further, it uses a counterfactual approach to outcome measurement, where the benefits are compared against what would have happened should the programme had been absent (Morgan & Winship, 2015). Ultimately, impact evaluation intends to address causality between the observed outcome and the policy being tested.

Experimental designs are the highest regarded of the available impact evaluation tools (Morgan & Winship, 2015). In such studies, individuals are randomised and assigned to an intervention or control group. The intervention group gets exposed to the policy, whilst the second group goes unexposed. The number of different interventions determines the number of groups created.

Alternative designs to impact evaluation are non-experimental, including quasi-experimental and pre-post designs. On the first one, an intervention is not assigned randomly but based on other characteristics of the intervened population. There is no control group in pre-post designs; instead, the outcome is evaluated for the same group before and after the intervention (Morgan & Winship, 2015).

All the former approaches are evaluated with econometric techniques and have been applied to various public policy problems, mostly related to welfare economics (H. White, 2006). Its main limitation comes from ethical concerns, as it is difficult to justify that, after randomisation, certain groups are treated with a potentially beneficial policy whilst relegating others who are equally in need.

Another significant limitation is that they can be time- and resource-intensive as they usually run on entire geographic regions. Additionally, unless an adequate timeframe for the evaluation is established, it is unlikely they can capture all the relevant developments involved in the evaluation. Finally, establishing causality might not be secured unless finding a proper counterfactual, which is still debated in such designs (H. White, 2006).

3.3.2 Dynamic simulation modelling

The dynamic simulation modelling (DSM) paradigm deals with the representation of the behaviour of systems over time, facilitating analysis of their temporal and systemic complexities. There are three main DSM techniques, namely, system dynamics (SD), discrete-event simulation (DES), and agent-based modelling (ABM) (D. A. Marshall et al., 2015). Each technique embodies distinct principles, excels in specific applications, and has unique strengths and limitations.

These three techniques have been applied to analyse different aspects of healthcare and public health (Darabi & Hosseinichimeh, 2020) in single- or hybrid-technique approaches to enhance their particular capabilities, although the potential of this latter is yet to be realised (S. Brailsford et al., 2010; S. C. Brailsford et al., 2013, 2019).

Discrete event simulation (DES) is built around the representation of systems as sequences of discrete events, each of which occurs at a specific time and alters the state of the system (S. Brailsford et al., 2010). DES models are composed of entities, events, and queues, making the technique particularly adept at analysing processes in which timing, resource constraints, and workflow efficiency are central considerations (Banks & Carson, 1986).

DES is frequently applied at the tactical and operational levels, particularly in scenarios requiring detailed process optimisation (Sharma, 2015). In healthcare, DES has been instrumental in modelling patient flows, resource utilisation, and logistical processes, such as emergency department operations or surgical scheduling (Günal & Pidd, 2010; Jun et al., 1999; Zhang, 2018). By incorporating stochastic variability into event timing and outcomes, DES captures the uncertainty inherent in real-world processes, providing decision-makers with realistic and actionable insights.

Despite its strengths in operational contexts, DES is less suited to modelling feedback loops or emergent phenomena that arise from interactions between system components, thereby limiting its applicability in strategic and macro-level analyses.

Agent-based modelling differs fundamentally from both SD and DES by focusing on the behaviours and interactions of autonomous agents within a simulated environment (Gilbert &

Terna, 2000). Agents are typically heterogeneous, governed by individual decision rules, and capable of adaptive behaviour. Interactions among agents and with their environment give rise to emergent system-level properties, making ABM particularly suitable for analysing complex systems where micro-level dynamics significantly influence macro-level outcomes (Richiardi et al., 2023).

ABM is highly versatile, with applications spanning strategic, tactical, and operational levels (Macal & North, 2008). In healthcare, ABM has been used to study phenomena such as disease spread, healthcare-seeking behaviour, and the diffusion of innovations within populations (Cassidy et al., 2019; Li et al., 2016; Tracy et al., 2018). Its capacity to model heterogeneity and dynamic interaction enables researchers to explore the emergent consequences of individual behaviours.

3.3.2.1 System dynamics modelling

The SD modelling paradigm allows representing the evolution of systems over time using feedback, delays, and accumulation (Sterman, 2000; Marshall, Burgos-Liz, Ijzerman, Osgood, *et al.*, 2015; (Sterman, 2000; Homer and Hirsch, 2006; Marshall, Burgos-Liz, Ijzerman, Crown, *et al.*, 2015).

The technique was developed in the 1950s by Jay Forrester at the Massachusetts Institute of Technology to analyse industrial dynamics, moving into other fields afterwards. SD has been applied to many health-related topics, from modelling the dynamics of infectious and chronic diseases to depicting whole healthcare systems (Chang et al., 2017; Darabi & Hosseinichimeh, 2020).

The basic structures in SD are stocks and flows, originally represented graphically as bathtubs and faucets through which water moves (i.e., flows) or accumulates (i.e., stocks). Mathematically, SD models are systems of ordinary differential equations solved numerically (Sterman, 2000b). A fundamental notion of the SD modelling paradigm is feedback, which can be reinforcing or balancing (Sterman, 2006). Reinforcing feedback promotes indefinite growth or decay, whilst balancing feedback limit a quantity to grow or deplete indefinitely.

For instance, consider a simple system representing the population growth, where the current population number is represented by a stock, increased by an inflow of births, and depleted by an outflow of deaths. The population number is multiplied by a birth or death fraction to determine how many births are aggregated to or how many deaths are deducted from the total population. Call the first a “birth loop”, and the second and “death loop”. The birth loop is reinforcing, promoting population growth, and in turn, the population is prevented from growing indefinitely -and unrealistically- by the balancing loop of deaths. If more births than deaths occur, the reinforcing loop is predominant, and the population will still grow.

On the other hand, if more deaths than births happen, the population will decay. A third option is for the population to eventually stabilise if births and deaths happen at the same rate.

Unlike DES and ABM, SD is mostly a deterministic simulation technique, meaning that the results will be the same each time the model runs. Each stock represents a group of homogenous individuals who share the same characteristics and are indistinguishable from each other. This may imply the need to define multiple stocks to represent specific population groups with different characteristics. Time handling is continuous in SD models, and the technique is best suited to represent phenomena at the strategic or policy level.

3.4 Chapter summary

Chapter three introduced the main sexual and reproductive health, and simulation modelling concepts used throughout the thesis. The chapter closes with a critical appraisal of the simulation modelling methodology, explaining the main differences amongst SD, DES, and ABM techniques, which are rooted in their respective modelling approaches. SD is inherently aggregate and deterministic, ideal for high-level policy analysis but limited in capturing micro-level variation. DES excels in process-centric, operational analyses, offering precision in resource and workflow modelling but lacking the capacity to model feedback and emergent behaviours. ABM, with its focus on heterogeneity and interaction, is inherently stochastic and the most flexible but computationally demanding technique.

Chapter 4 Simulation Model Development

This chapter presents a novel system dynamics model developed to address the interplay between contraceptive-sexual-reproductive behaviours and their respective health outcomes. Building upon previous modelling approaches in reproductive health (Babigumira et al., 2012; Goldie et al., 2010; Zakiyah et al., 2019), the proposed model structure combines two components: demographic and contraceptive-sexual-reproductive dynamics. This structure was chosen based on evidence that contraceptive behaviours significantly influence population dynamics through their impact on fertility rates (Darney et al., 2022), while demographic changes affect contraceptive needs and access patterns (Serván-Mori et al., 2022).

The demographic component is a multicohort, single-year age-group model aiming to simulate the evolution of the female population from the year 2006 until 2050. Multicohort models are most adequate in representing the dynamic evolution of distinct birth cohorts and their shifting characteristics over time, enabling a more nuanced and comprehensive analysis of population behaviours than traditional models, which often fail to account for such complexities (Dewilde & Anderson, 2004). The single-year age-group structure was selected to account for variations in reproductive behaviours and contraceptive needs across age groups (Kim & Kim, 2020). Empirical evidence demonstrates that different age cohorts exhibit distinct patterns in contraceptive use and reproductive health outcomes (Phipps et al., 2008), underscoring the importance of this level of granularity imprinted in the model.

The evolution of the population in the demographic component is accomplished using an ageing mechanism by which the different age groups (also called *age cohorts* or *age classes* interchangeably throughout this thesis) are shifted forward as time progresses, and after discounting outflows due to death, net migration, and menopause (end of reproductive life).

The second component deals with the estimation of unintended pregnancies, unsafe abortions, maternal deaths, and economic impact due to the three fundamental behaviours in contraceptive practice: adoption, switching, and discontinuation. Given these are interrelated with the reproductive and sexual behaviours of women of reproductive age (WoRA), they are represented as multiple states women can visit during their reproductive life, assumed to span from age 15 to 49 (World Health Organization, 2023b).

Such an assumption is widely used in demographic and reproductive health studies due to its general applicability and data availability (Corsi et al., 2012), for this age range captures the majority of childbearing years for women globally, including in Mexico where 99.5% of all births occur within this age range (Instituto Nacional de Estadística y Geografía, 2020).

It is important to note, however, that whilst a relatively rare event, some women may experience pregnancies outside the bounds studied in this thesis. In Mexico, early adolescent childbearing (i.e., before 15 years of age), with its significant health, social, and economic implications, accounts for 0.4% of total yearly live births. Similarly, variations in age at menopause can influence fertility at the upper limit of the reproductive age range, resulting in 0.01 to 0.065% of total yearly live births (Instituto Nacional de Estadística y Geografía, 2020).

Further, the average age of menopause ranges between 47-49 years in Mexico (Garrido-Latorre et al., 1996; Legorreta et al., 2013; Sievert & Hautaniemi, 2003) and Latin America (Blümel et al., 2006), making the selected end of reproductive life a reasonable approximation. Future refinements to the model could incorporate the cases presented outside the assumed age range of 15 to 49 years to improve its comprehensiveness. The current range, though, provides a reasonable scope for analysing unintended pregnancies amongst the majority of women in reproductive age allowing for reliable parameter estimation due to robust data availability.

New WoRA are introduced into the model endogenously by estimating the number of pregnancies -intended or unintended- ending in a livebirth of a girl who matures to become age 15, thus starting her reproductive years. Linking the demographic and contraceptive-sexual-reproductive components was key to better understand the impact of current and hypothetical contraceptive provision practices, as will be seen in Chapter 7.

4.1 Model description

An endogenously driven, age-structured, and time-varying system dynamics simulation model was developed to depict the multiple states related to contraceptive, sexual, and reproductive behaviours occurring during Mexican women's reproductive lifespan.

The model's state structure (Figure 4.1) represents the complex pathways through which women navigate their reproductive years, informed by both theoretical frameworks and empirical evidence. The 13 mutually exclusive states represented were selected on the basis of previous related research, for instance (Babigumira et al., 2012; Goldie et al., 2010; Zakiyah et al., 2019) who have devised single-cohort models to represent movements between contraceptive use, non-use, and pregnancy. A key difference from those is that the model proposed in this thesis explicitly distinguishes contraception use in four different method categories, which come at different levels of effectiveness (Centers for Disease Control and Prevention, 2024), posing different implications to programme planning, and practical considerations for policy intervention points.

This feature allows us to understand how the interaction of traditional and modern contraceptive method categories influence the observed health outcomes of interest to this research. Delving deeper, it also allows us to understand the influence on outcomes of different modern method categories, further helping to inform policies based on their adoption-discontinuation-switching patterns (Alvergne & Stevens, 2021).

The state transitions were designed to capture both planned and unplanned changes in contraceptive use (Swiatlo et al., 2023), leading to the exposure to unintended pregnancy and related health impacts. According to the devised model structure shown in Figure 4.1, WoRA can move between 13 mutually exclusive states: sexually active, non-user of contraception (*NU*); sexually active, user of long-acting reversible contraception (*LARC*); sexually active, user of behavioural-dependent contraception (*BEH*); sexually active, user of traditional contraception (*TRAD*); sexually active, user of permanent contraception (*PERM*); sexually inactive (*SI*); sexually active, non-user of contraception, and intending pregnancy (*INT*); intentionally pregnant (*IP*); infertile due to intended pregnancy (secondary infertility due to IP, *INF_IP*); dead as a result of an intended pregnancy (maternal death due to IP, *M_DTH_IP*); unintentionally pregnant (*UP*); infertile due unintended pregnancy (secondary infertility due to UP, *INF_UP*); and dead as a result of unintended pregnancy (maternal death due to UP, *M_DTH_UP*). *M_DTH_IP* and *M_DTH_UP* are coloured in grey to represent their absorbing nature, i.e., there is no possible outflow from death.

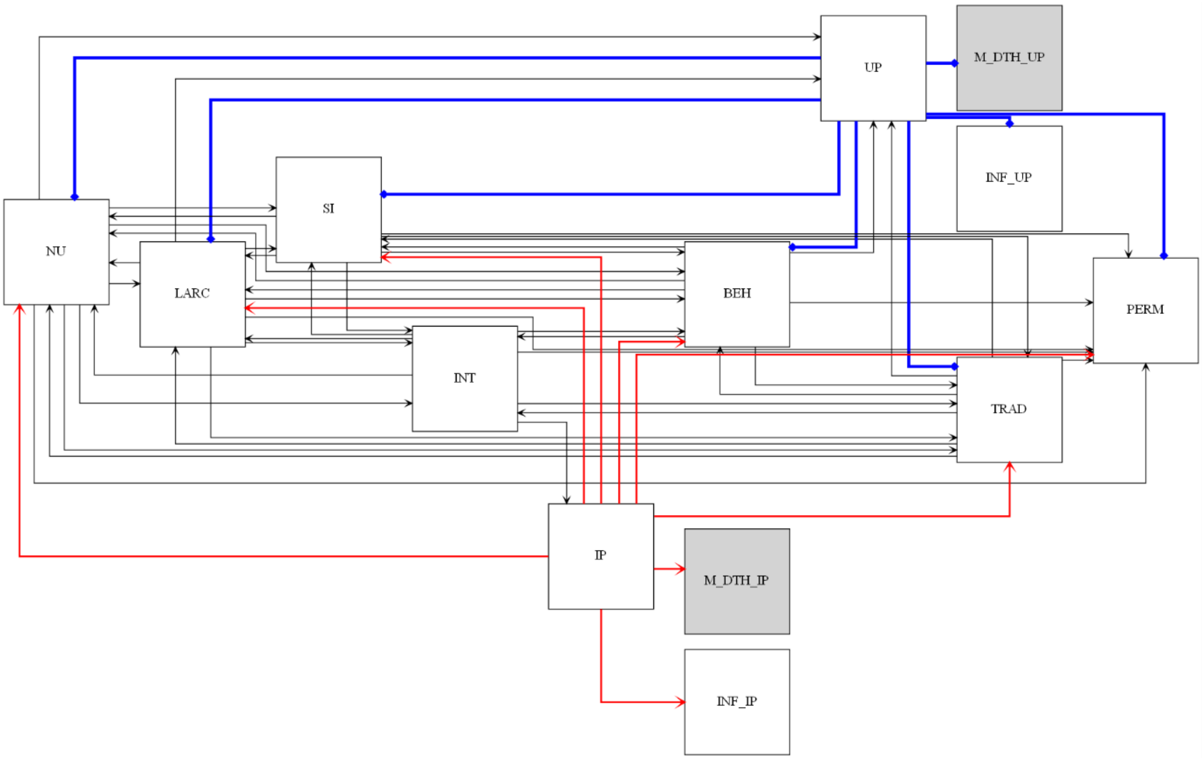


Figure 4.1. Contraceptive, sexual, and reproductive dynamics model overview.

Note: The boxes represent the mutually exclusive, multiple states women might occupy during their reproductive years. ***NU****: Sexually active, non-user of contraception;* ***LARC****: Sexually active, user of long-acting reversible contraception;* ***BEH****: Sexually active, user of behavioural-dependent contraception;* ***TRAD****: Sexually active, user of traditional contraception;* ***PERM****: Sexually active, permanent contraception user;* ***SI****: Sexually inactive;* ***INT****: Sexually active, non-user of contraception, and willing to be pregnant;* ***IP****: Pregnant, intentionally;* ***INF_IP****: Secondary infertility due to IP,* ***M_DTH_IP****: Maternal death due to IP;* ***UP****: Pregnant, unintentionally;* ***INF_UP****: Secondary infertility due to UP;* ***M_DTH_UP****: Maternal death due to UP. Boxes coloured in grey (****M_DTH_IP, M_DTH_UP****) are absorbing states, and thus there is no possible outflow from them.*

Outflows from *UP* and *IP* are highlighted in blue and red, respectively. Unintended pregnancy might lead to death by a number of causes: complications of the gestational period, childbirth, treatment of unsafe abortion, miscarriage, an abnormal product of gestation, stillbirth, puerperal period, or other (Figure 4.2). Women dying during a pregnancy classified as unintended move into the maternal death state (Singh et al., 2009).

Movements into other non-absorbing (i.e., *NU, LARC, BEH, TRAD, SI*) and absorbing states (i.e., INF_UP, PERM) from an unintended pregnancy are possible after pregnancy ends in childbirth, unsafe abortion, miscarriage, or stillbirth (Swiatlo et al., 2023). For instance, movement from UP into secondary infertility due to UP (*INF_UP)* occurs after pregnancy ends for the mentioned causes (Figure 4.2). Movements into the remaining stocks, i.e., non-absorbing, follow the same logic as exemplified.

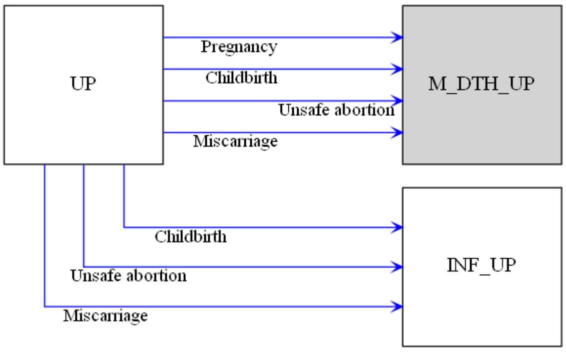


Figure 4.2. Outflow pattern from unintended pregnancy.

Note: Due to the diagram's space constraints, only four out of eight causes of maternal death are presented. Likewise, stillbirth is not shown amongst the inflows from UP to INF_UP.

Outflows from intended pregnancy are understood exercising the same logic, with a single distinction: it is assumed that an intended pregnancy does not terminate by unsafe abortion (Bearak et al., 2020) (Figure 4.3). As with the previous figure, the diagram presents the outflow pattern to maternal death and just one out of the remaining eight possible states (*INF_IP*.)

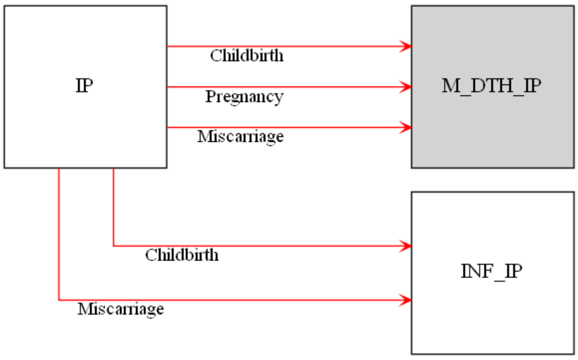


Figure 4.3. Outflow pattern from intended pregnancy.

Note: Due to the diagram's space constraints, only three out of seven causes of maternal death are presented. Likewise, stillbirth is not shown among the inflows from UP to INF_UP.

NU, *LARC*, *BEH*, *TRAD*, *PERM*, *UP*, *INF_UP*, *INT*, *IP*, *INF_IP*, *SI* might also lead to a fourteenth state (Figure 4.4), all-cause death (*Gnrl_DTH*), which excludes maternal-specific death causes and it is absorbing.

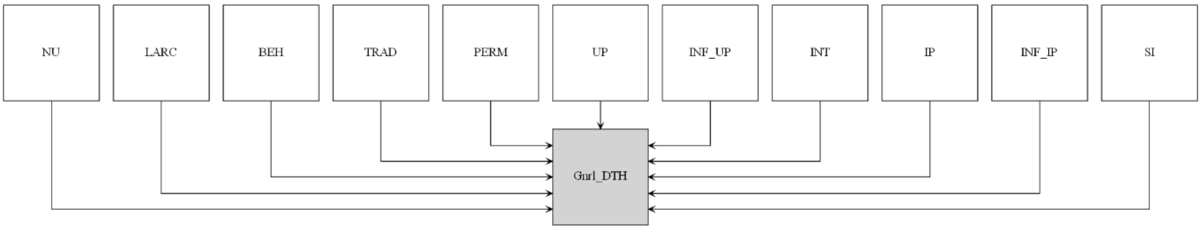


Figure 4.4. Inflows from transitory states to all-cause death state (Gnrl_DTH).

Although not represented in the former diagrams (Figure 4.1 to Figure 4.4), women might additionally flow out due to a net migration rate, which is the difference between immigration and emigration, consistently negative in Mexico across all ages, and projected to remain so in the future (Consejo Nacional de Población, 2023).

Amongst women of reproductive age, those undergoing intended or unintended pregnancies might give birth to girls ($U15_0$) who mature until reaching their reproductive years (Figure 4.5). To accomplish this, newly born girls are moved into the first position -$U15_0$- of a stratified stock -divided from $U15_0$ to $U15_{14}$- where they are shifted forward until age 15 to initiate their reproductive years. Women can start their reproductive years through any stock excepting these denoting deaths (i.e., *Gnrl_DTH, M_DTH_UP, M_DTH_IP*). As in the rest of the model, women below reproductive ages mature into the next age class after subtracting deaths from all causes and net migration.

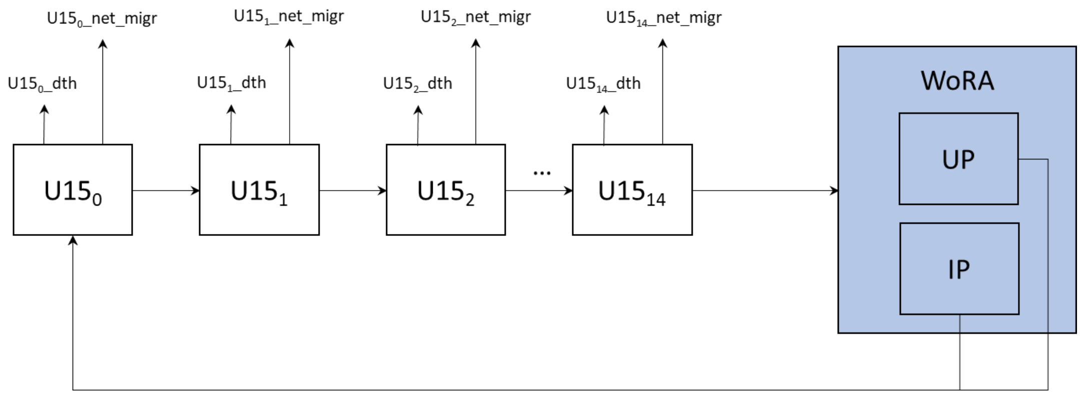


Figure 4.5. Endogenous live birth generation and maturation into reproductive ages.

Note: ***U15****: Girls below reproductive age;* ***WoRA****: women of reproductive age;* ***UP****: unintended pregnancy;* ***IP****: intended pregnancy.*

Internally, each transient state is compartmentalised into 35 chained single-year age-group stocks to represent ageing from 15 to 49 years (Ansah et al., 2017). Women are shifted forward through the stocks after spending a year on each and eventually flow out the chain at 50 years of age, i.e., at menopause (Legorreta et al., 2013). See Figure 4.6.

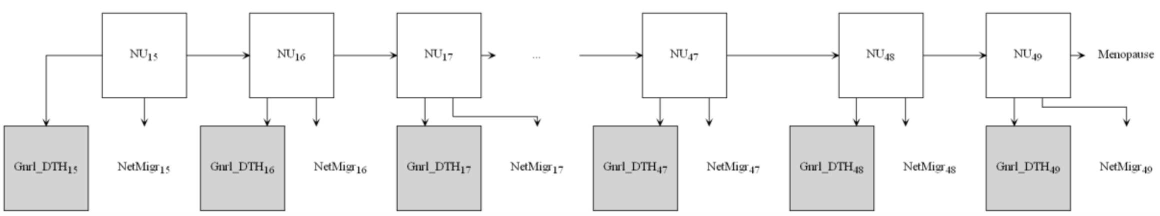


Figure 4.6. Illustration of the internal structure of the ageing chain. Example: sexually active, non-users of contraception.

4.1.1 Model dynamics: a qualitative understanding

The previously described processes and the interplay between each of the different potential states in women's reproductive years are represented mathematically below in equations 4.1 to 4.16. This structure captures key dynamics that reflect contraceptive-sexual-reproductive behaviours observed in Mexico and elsewhere. Thus, these equations represent distinct but interdependent processes.

Equations 4.1 to 4.5 reflect evidence that contraceptive non-use is not static but rather a dynamic condition, where those who have recently discontinued contraception, those who have never used it, or those transitioning from other states, e.g., (un)intended pregnancy, shape observed fertility in any point in time.

Equations 4.6 to 4.10 represent the pathways through unintended and intended pregnancies. The structure acknowledges that pregnancy outcomes are significantly influenced by sexual and contraceptive behaviours (D'Souza et al., 2022). For instance, equation 4.6 shows how non-use, together with traditional/modern contraceptive use *fuel* the presence of unintended pregnancies.

Equation 4.11 represents sexual inactivity, recognising that women move in and out of this state, and contributes to depict how sexual activity patterns, together with pregnancy intent influence contraceptive needs and choices (Harvey et al., 2006).

The separate treatment of different causes of death shown in equations 4.12 to 4.14 (i.e., maternal deaths from unintended pregnancy, intended pregnancy, and all-cause) allows the model to capture the distinct risk profiles associated with different reproductive states.

Finally, population renewal equations 4.15 and 4.16 model how the WoRA cohort maintains itself via births and maturation. The structure acknowledges the intergenerational aspects of reproductive health, showing how current pregnancy outcomes influence future population dynamics (Lunenfeld & Van Steirteghem, 2004).

The symbols for the different parameters used in the model are specified in Appendix A, whilst parameter estimation is presented in the next section (4.2). All equation elements are to be understood in their matrix form: NU, $LARC$, BEH, $TRAD$, $PERM$, UP, INF_UP, INT, IP, INF_IP, SI, M_DTH_UP, M_DTH_IP, and $Gnrl\_DTH$ are 35×35 matrices holding the absolute numbers of WoRA. $U15$ is a 15×35 matrix holding the absolute number of girls aged 0 to 14 years. Parameters related to WoRA are 35×35 diagonal matrices, and parameters related to U15 females are diagonal matrices of size 15×35 (see section 4.3).

To reduce the visual burden of the equations, $prev$ represents the previous values of the elements in the right-hand side, i.e., $(t - dt)$; dt is the time step. $s2 - s79$ are transition probabilities, and Greek characters are stratified causes of maternal death (α, δ), pregnancy outcomes (β, ε), secondary infertility (χ, ϕ), proportion of females born (γ), all-cause death rates for under-fifteens (η), maturation fractions for under-fifteens (ι), migration rates for WoRA and under-fifteens (φ, κ), and stocks where females might initiate their reproductive years (λ) (see Appendix A).

$$NU(t) = NU_{prev} + [(-age_{NUout} + age_{NUin} - (s2+\ldots+s9) - \kappa)NU_{prev} + s10LARC_{prev} + s19BEH_{prev} + s28TRAD_{prev} + s39(\beta_1+\ldots+\beta_4)UP_{prev} + s51INT_{prev} + s60(\varepsilon_1 + \varepsilon_2 + \varepsilon_3)IP_{prev} + s72SI_{prev} + \lambda_1 U15_{prev}]dt \tag{4.1}$$

$$LARC(t) = LARC_{prev} + [(-age_{LARCout} + age_{LARCin} - s10 - (s12 + \ldots + s18) - \kappa)LARC_{prev} + s2NU_{prev} + s20BEH_{prev} + s29TRAD_{prev} + s40(\beta_1+\ldots+\beta_4)UP_{prev} + s52INT_{prev} + s61(\varepsilon_1 + \varepsilon_2 + \varepsilon_3)IP_{prev} + s73SI_{prev} + \lambda_2 U15_{prev}]dt \tag{4.2}$$

$$BEH(t) = BEH_{prev} + [(-age_{BEHout} + age_{BEHin} - s19 - s20 - (s22 + \ldots + s27) - \kappa)BEH_{prev} + s3NU_{prev} + s12LARC_{prev} + s30TRAD_{prev} + s41(\beta_1+\ldots+\beta_4)UP_{prev} + s53INT_{prev} + s62(\varepsilon_1 + \varepsilon_2 + \varepsilon_3)IP_{prev} + s74SI_{prev} + \lambda_3 U15_{prev}]dt \tag{4.3}$$

$$TRAD(t) = TRAD_{prev} + [(-age_{TRADout} + age_{TRADin} - s28 - s29 - s30 - (s33 + \ldots + s36) - \kappa)TRAD_{prev} + s4TRAD_{prev} + s13LARC_{prev} + s22BEH_{prev} + s42(\beta_1+\ldots+\beta_4)UP_{prev} + s54INT_{prev} + s63(\varepsilon_1 + \varepsilon_2 + \varepsilon_3)IP_{prev} + s75SI_{prev} + \lambda_4 U15_{prev}]dt \tag{4.4}$$

$$PERM(t) = PERM_{prev} + [(-age_{PERMout} + age_{PERMin} - s38 - \kappa)PERM_{prev} + s5NU_{prev}s14 + LARC_{prev} + s23BEH_{prev} + s32TRAD_{prev} + s43(\beta_1+\ldots+\beta_4)UP_{prev} + s55INT_{prev} + s64(\varepsilon_1 + \varepsilon_2 + \varepsilon_3)IP_{prev} + s76SI_{prev} + \lambda_5 U15_{prev}]dt \tag{4.5}$$

$$UP(t) = UP_{prev} + \big[(-(\beta_1 + \dots + \beta_4)(s39 + \dots + s43 + s46) - s45(\chi_1 + \dots + \chi_4) - s47(\alpha_1 + \dots + \alpha_8) - s48 - \kappa)UP_{prev} + s6NU_{prev} + s15LARC_{prev} + s24BEH_{prev} + s33TRAD_{prev} + \lambda_6 U15_{prev}\big]dt$$

4.6

$$INF\_UP(t) = INF\_UP_{prev} + \big[(-age_{INFUPout} + age_{INFUPin} - s50 - \kappa)INF\_UP_{prev} + s45(\chi_1 + \dots + \chi_4)UP_{prev} + \lambda_7 U15_{prev}\big]dt$$

4.7

$$INT(t) = INT_{prev} + \big[(-age_{INTout} + age_{INTint} - (s51 + \dots + s55) - (s57 + \dots + s59) - \kappa)INT_{prev} + s7NU_{prev} + s16LARC_{prev} + s25BEH_{prev} + s34TRAD_{prev} + s77SI_{prev} + \lambda_8 U15_{prev}\big]dt$$

4.8

$$IP(t) = IP_{prev} + \big[(-(\varepsilon_1 + \dots + \varepsilon_3)(s60 + \dots + s64 + s67) - s66(\phi_1 + \dots + \phi_3) - s68(\delta_1 + \dots + \delta_7) - s69 - \kappa)IP_{prev} + s57INT_{prev} + \lambda_9 U15_{prev}\big]dt$$

4.9

$$INF\_IP(t) = INF\_IP_{prev} + \big[(-age_{INFIPout} + age_{INFIPin} - s71 - \kappa)INF\_IP_{prev} + s66(\phi_1 + \dots + \phi_3)IP_{prev} + \lambda_{10} U15_{prev}\big]dt$$

4.10

$$SI(t) = SI_{prev} + \big[(-age_{SIout} + age_{SIin} - (s72 + \dots + s77) - s79 - \kappa)SI_{prev} + s8NU_{prev} + s17LARC_{prev} + s26BEH_{prev} + s35TRAD_{prev} + s46(\beta_1 + \dots + \beta_4)UP_{prev} + s58INT_{prev} + s67(\varepsilon_1 + \varepsilon_2 + \varepsilon_3)IP_{prev} + \lambda_{11} U15_{prev}\big]dt$$

4.11

$$M\_DTH\_UP(t) = M\_DTH\_UP_{prev} + s47(\alpha_1 + \dots + \alpha_8)UP_{prev}dt$$

4.12

$$M\_DTH\_IP(t) = M\_DTH\_IP_{prev} + s68(\delta_1 + \dots + \delta_7)IP_{prev}dt$$

4.13

$$Gnrl\_DTH(t) = Gnrl\_DTH_{prev}$$
$$+ [s9NU_{prev} + s18LARC_{prev} + s27BEH_{prev} + s36TRAD_{prev} + s48UP_{prev}$$
$$+ s50INF\_UP_{prev} + s59INT_{prev} + s69IP_{prev} + s71INF\_IP_{prev} + s79SI_{prev}]dt$$

4.14

$$U15(t) = U15_{prev}$$
$$+ [(-age_{U15out} + age_{U15in} - \eta - \varphi)U15_{prev}$$
$$+ (s39 + \dots + s43 + s45 + s46)\gamma\beta_1 UP_{prev}$$
$$+ (s60 + +s64 + s66 + s67)\gamma\beta_1 IP_{prev}]dt$$

4.15

$$Gnrl\_DTH\_U15(t) = Gnrl\_DTH\_U15_{prev} + [\eta U15_{prev}]dt$$

4.16

The detailed parameterisation of the model is described in the following section (4.2). In general, transitions into and out of each stock are determined by the following:

1. Model mechanics:
    a. In NU, $TRAD$, BEH, $LARC$, $PERM$, INF_UP, INF_IP, SI, and INT, women ageing into the next age group are estimated at the end of each simulated year after subtracting all-cause deaths and net migration.
    b. In the case of UP and IP, there is no possibility of ageing, i.e., women do not remain pregnant indefinitely.
    c. Time spent in each stock is one year in all cases. This specification is trivial in the case of absorbing stocks (i.e., M_DTH_UP, M_DTH_IP, and $Gnrl\_DTH$), from which there is no outflow.
    d. Girls born from unintended or intended pregnancies that flow into the $U15$ stock are estimated by multiplying the number of such pregnancies by a female live birth fraction, and the fraction of pregnancies ending in a live birth (see section 4.2.3).
2. Assumptions:
    a. Only sexually active women who do not want to be pregnant can move into the unintended pregnancy stock. These women might come from a reversible contraceptive-user stock (i.e., $LARC$, BEH, $TRAD$) or non-use (NU). A contraceptive failure rate associated with each method category controls such movements (Bradley et al., 2019) (see section 4.2.2 and Appendix B).
    b. Only women trying to become pregnant (*INT*) can move into the intended pregnancy (*IP)* stock (Zakiyah et al., 2019).
    c. Movements into and between the method user categories (i.e., $LARC$, BEH, $TRAD$, $PERM$) are possible by using the adoption and switching transition probabilities corresponding to each (see section 4.2.2 and Appendix B).
    d. Moving to a different stock from the method user categories is possible by using a discontinuation fraction, specific to each method category (see section 4.2.2 and Appendix B).
    e. Given its very low failure rate, $PERM$ grants full protection from pregnancy (Centers for Disease Control and Prevention, 2024) and thus does not have other

outflows than to the next age group, all-cause deaths, net migration, and menopause.

f. Causes of infertility other than pregnancy complications are excluded, i.e., the model only accounts for secondary infertility (see section 4.2.2). Further, secondary infertility after an intended or unintended pregnancy was assumed to be permanent given structural barriers of access to infertility treatment in the country (Farland et al., 2023; Lunenfeld & Van Steirteghem, 2004). Thus, women with secondary infertility do not flow out to other stocks except those of the next age group, all-cause deaths, net migration, and menopause.

4.2 Parameter estimation

The model's parameterisation strategy reflects the complex, multi-dimensional nature of reproductive health dynamics. Drawing from diverse evidence sources, the parameters were categorised to capture distinct yet interrelated aspects of reproductive behaviour and outcomes. The categorisation framework was structured to enable systematic parameter estimation and validation.

Parameters may fall in one of the following broad categories:

1. Demographic.
2. Contraceptive method effectiveness, i.e., failure rates.
3. Behavioural.
    a. Contraceptive adoption.
    b. Contraceptive switching.
    c. Contraceptive discontinuation.
    d. Reproductive intentions.
    e. Contraceptive non-use.
    f. Sexual activity.
4. Clinical.

The Demographic category of parameters was involved in female population growth via the ageing mechanism. Categories two and three represent the contraceptive, sexual, and reproductive dynamics and are closely correlated, thus their parameters were estimated jointly. The second category controls the generation of new unintended pregnancies by representing first-year-of-use contraceptive failure fractions attributable to non-use, *LARC*, *BEH* and *TRAD*. In category 3a, parameters are used to simulate contraceptive uptake following a non-use spell, when pregnancy ends, or once sexual activity is resumed. Category 3b includes the parameters required to simulate contraceptive switching among users of *LARC*, *BEH*, *TRAD*, and *PERM*. Contraceptive discontinuation parameters (3c) are used to represent movements of women to

NU and becoming exposed to unintended pregnancy due to interrupting contraceptive use. The *Reproductive intentions* parameters (3d) control transitions from *NU* to the intending pregnancy state (*INT*) and from *INT* into *IP*. Category 3e includes those parameters needed to simulate movements to *NU* after intended/unintended pregnancy ends, when women drop their pregnancy intentions, or after resuming sexual activity without using contraception despite not wanting a pregnancy. Parameters in category 3f represent women becoming sexually inactive after a pause in their sexual lives, or after an unintended/intended pregnancy ends, and vice versa. Finally, the fourth category of parameters generate cause-stratified maternal deaths and distribute women according to their pregnancy outcomes (e.g., live birth, miscarriage).

To better represent the evolution of trends in population growth and unintended pregnancy, parameters in the model were allowed to vary inter-annually from 2006 to 2018/19/20, depending on the last year of data available in the corresponding sources. This was implemented with linear interpolation. See sections 4.2.1, 4.3, and 5.2.2.2.

This is a more realistic approach given that, for instance, there is evidence on changing temporal dynamics: under-15 death rates have improved over time: newborn death rates have reduced 30% from 2006 to 2020 (Instituto Nacional de Estadística y Geografía, 2019b). A steady-state model architecture would have certainly led to missing these and other significant improvements; thus, a time-varying parameter structure was deemed more appropriate. Parameters were fixed constant for the remainder of simulation years, from 2019/20/21 to 2050 to simplify the model structure (see section 4.3) whilst keeping the model relevant for policy analysis. This approach allows for clearer attribution of policy effects at the time that acknowledges the increasing uncertainty in longer-term projections (Oosthuizen & Magero, 2021).

Time-series data from 2006 to 2018/19/20 were collected for all parameters, except where there was no source to gather time-varying data. In those cases, parameters remained fixed during the whole simulation period.

4.2.1 Demographic parameters

The demographic parameters form the model's foundational structure, capturing both mortality patterns and population dynamics (Table 4.1). All-cause death fractions were estimated for both WoRA, and girls aged 0 to 14 years using data from 2006 to 2019. Thus, a different parameter was used in the model for each age class from 0 to 49 years, and from 2006 to 2019. The data source was the official death registry maintained by the Mexican Institute of Statistics and Geography (INEGI).

Maternal death fractions were excluded from the estimation of all-cause deaths and estimated independently using the same source (see next section). To estimate a fraction of all-cause and maternal deaths, the absolute numbers were divided by the population counts available from the National Census of Population and Households (2010, 2020), and the National Survey on the Demographic Dynamics (ENADID 2006, 2009, 2014, 2018). Missing years of population counts within the interval 2006-2019 were derived by linear interpolation to address temporal gaps.

Table 4.1. Demographic parameters in the contraceptive, sexual, and reproductive dynamics model.

Parameter	Population group	Source
All-cause deaths	WoRA[2], 0-14-year-old girls	Death registry, INEGI[3]
Maternal deaths	WoRA[2]	Death registry, INEGI[3]
Female live births[1]	WoRA[2]	Live births registry, INEGI[3]
Net migration	WoRA[2], 0-14-year-old girls	1950-2050 population projections, CONAPO[4]

[1]The yearly fraction of girls born was estimated by dividing the number of girls born by the total live births each year, and consistently fell at around 0.49 during the period 2006-2019 for all age classes; [2]Women of Reproductive Age; [3]Statistics and Geography (Mexico); [4]National Population Council (Mexico).

The time series in Figure 4.7 show the estimated all-cause death rates for WoRA. The rates are shown as a function of age, with each line representing a different year. The figure reveals an exponential increase in death rates as WoRA grow older, likely due to cumulative health vulnerabilities (Ledberg, 2020). While the age-based pattern is consistent across years, the lines diverge at older ages (40–50), indicating a temporal rise in all-cause mortality for this group. This trend suggests potential drivers such as changes in health system performance, or a growing burden of chronic diseases (Bello-Chavolla et al., 2017).

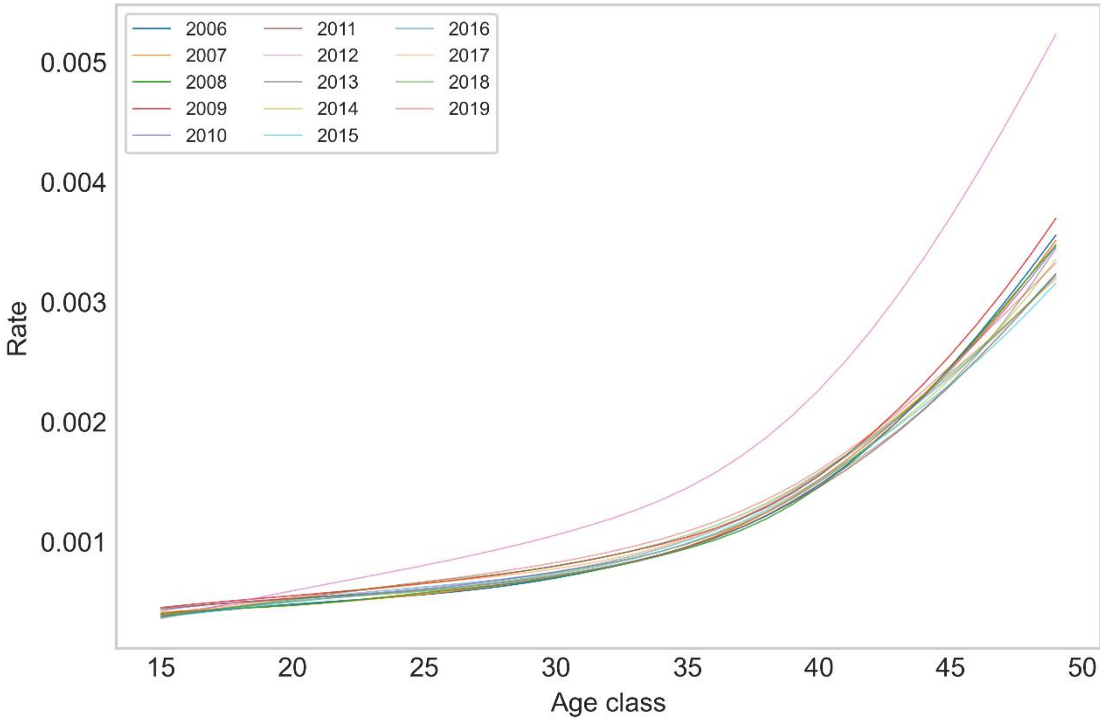


Figure 4.7. Interpolated all-cause death fractions, WoRA. Age-stratified, 2006-2019.

Figure 4.8 shows the estimated trends for females aged 0 to 14. Contrary to the trend observed in WoRA, all-cause death rates show a decreasing pattern over time and as women age, reflecting the impact of public health initiatives and improved access to care (Celhay et al., 2019).

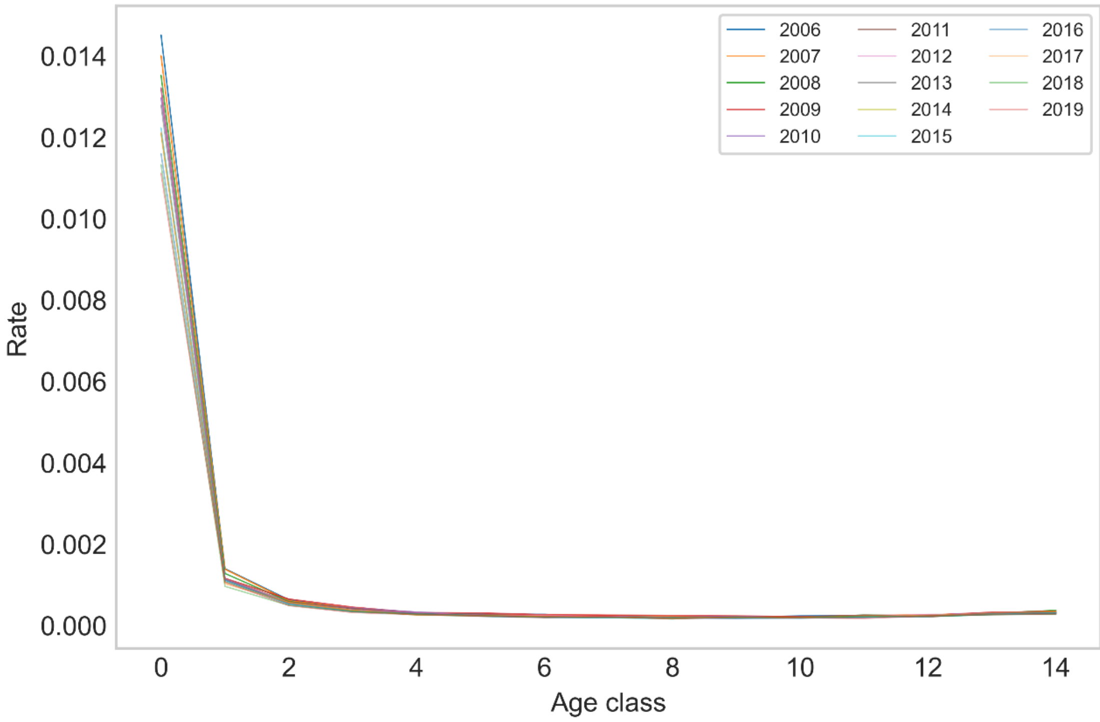


Figure 4.8. Interpolated all-cause death fractions for under-fifteen females. Age-stratified, 2006-2019.

Net migration was estimated by subtracting the number of emigrants from the number of immigrants reported in population projections made by CONAPO (Consejo Nacional de Población, 2023). Given CONAPO reports these data in five-year bands (e.g., 2005-2009, 2010-2014, 2015-2019, 2020-2024) and five-year age groups (e.g., 0 to 4, 5 to 9, 9 to 14), they were further adjusted to yearly time intervals and single-year age classes with successive divisions by five. This resulted, for instance, in having equal net migration rates between 2006 and 2009 across WoRA aged 15 to 19 (Figure 4.9). The former is also the case for girls aged 0 to 14 (Figure 4.10).

Both WoRA (Figure 4.9) and girls aged 0 to 14 (Figure 4.10) are estimated to present more emigrants than immigrants, hence the positive net migration rates observed in both graphs. Their specific trends are opposite, likely reflecting different underlying patterns. The higher emigration rates among younger WoRA may be driven by economic opportunities and labour market dynamics, while the pattern for girls likely reflects family migration decisions (Cerrutti & Massey, 2001).

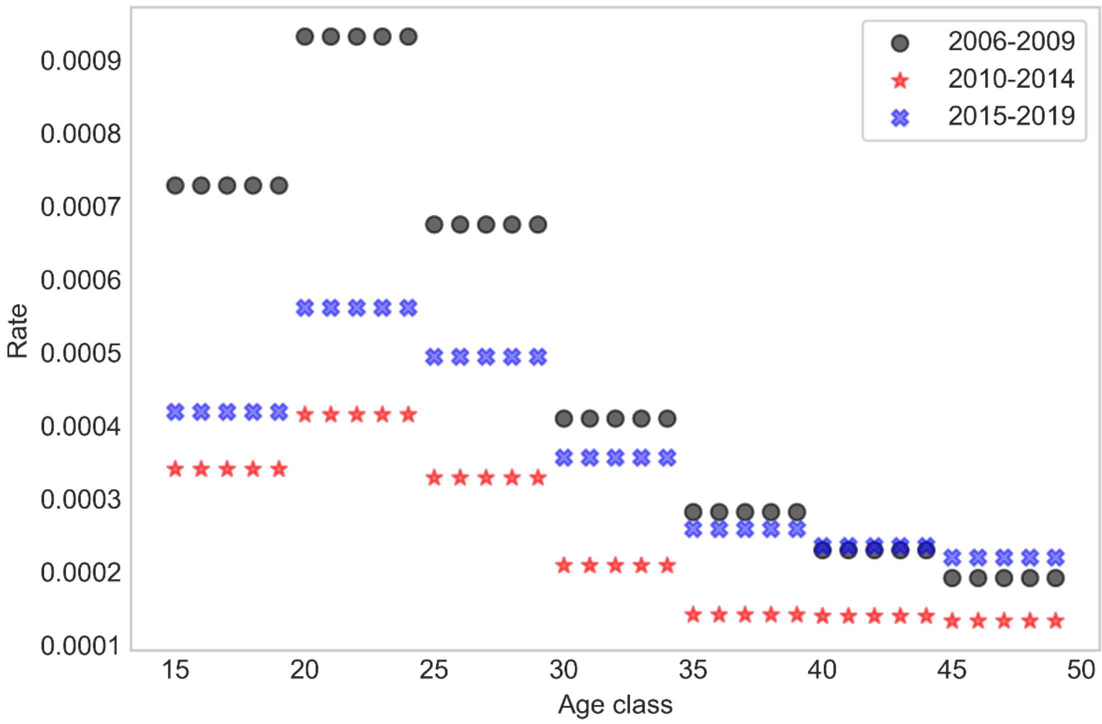


Figure 4.9. Net migration rates for women of reproductive age. Age-stratified, 1990-2020.

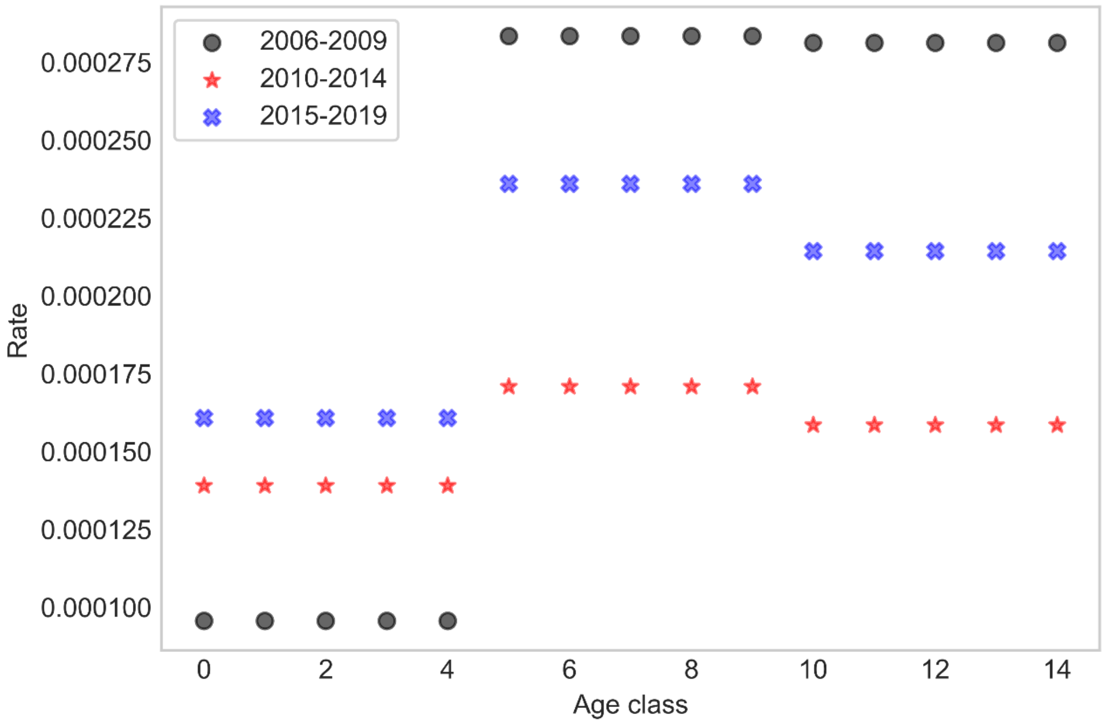


Figure 4.10. Net migration rates for under-fifteen females. Age-stratified, 1990-2020.

4.2.2 Contraceptive, sexual, and reproductive dynamics parameters

The estimation of transition probabilities between different contraceptive, sexual, and reproductive states (Figure 4.1) presents unique methodological challenges. Whilst longitudinal studies would ideally provide direct measures of these transitions (Srivastava et al., 2021), such data are rarely available in low and middle-income countries due to resource constraints (Zakiyah et al., 2019).

Given this is a recurrent multistate model parameterised with the transition probabilities shown in Appendix B, and there is no readily available source reporting such data, these were estimated by using the 2006, 2009, 2014, and 2018 ENADID waves to solve an underdetermined system of equations with the Moore-Penrose (M-P) pseudoinverse (Chen X, 2015; Feng Lin, 2013; Khosravi et al., 2016; Lin & Chen, 2010).

The M-P pseudoinverse is used to compute solutions for systems of linear equations that may be over/underdetermined, or ill-conditioned. Unlike the regular matrix inverse, which only exists for square, non-singular matrices, the M-P pseudoinverse can be applied to any rectangular matrix. It is particularly useful for solving systems of equations of the form $\boldsymbol{Ax} = \boldsymbol{b}$, where $\boldsymbol{A}$ is the coefficient matrix, $\boldsymbol{x}$ is the vector of unknowns, and $\boldsymbol{b}$ is the outcome vector. The method provides a solution $\boldsymbol{x} = \boldsymbol{A}^{+}\boldsymbol{b}$, where $\boldsymbol{A}^{+}$ denotes the pseudoinverse of $\boldsymbol{A}$ (Barata & Hussein, 2012). This solution either: 1) minimises the Euclidean norm of the residual $\|\boldsymbol{Ax}-\boldsymbol{b}\|^2$ if no exact solution exists, or 2) gives the least-squares solution when multiple solutions are possible (MacAusland, 2014). In this way, the difference between estimated probabilities and observed data is minimised, given the constraints established by the solved system of equations (MacAusland, 2014).

The M-P pseudoinverse has been previously applied in the absence of a longitudinal data source from which hazard models or multiple increment-decrement life tables are constructed to estimate transition probabilities. The approach offers a reasonable workaround (Erdmann et al., 2020) to this estimation problem by taking advantage of cross-sectional data sources, which are less time- and financially demanding to collect, and thus more abundant.

Using the M-P approach, transition probabilities were estimated at four different years, corresponding to the ENADID waves available for the whole simulation period to denote the evolving nature of the contraceptive, sexual, and reproductive dynamics (Benagiano et al., 2007).

For each age class i from 15 to 49 years, and each jth ENADID wave, an underdetermined system of equations (Taylor & Francis, 2024) was defined to obtain the set of 79 transition probabilities presented in Appendix B. NU, $LARC$, BEH, $TRAD$, $PERM$, UP, INF_UP, INT, IP, INF_IP, and SI are coefficients representing the prevalence of each stock reported at age class i and jth ENADID wave:

$$NU_{i+1,j} = NU_{i,j} - NU_{i,j}\left(s2_{i,j} + s3_{i,j} + \ldots + s9_{i,j}\right) + LARC_{i,j}s10_{i,j} + BEH_{i,j}s19_{i,j} + TRAD_{i,j}s28_{i,j} + UP_{i,j}s39_{i,j} + INT_{i,j}s51_{i,j} + IP_{i,j}s60_{i,j} + SI_{i,j}s72_{i,j}$$

$$LARC_{i+1,j} = LARC_{i,j} - LARC_{i,j}\left(s10_{i,j} + s12_{i,j} + s13_{i,j} + \ldots + s18_{i,j}\right) + NU_{i,j}s2_{i,j} + BEH_{i,j}s20_{i,j} + TRAD_{i,j}s29_{i,j} + UP_{i,j}s40_{i,j} + INT_{i,j}s52_{i,j} + IP_{i,j}s61_{i,j} + SI_{i,j}s73_{i,j}$$

$$BEH_{i+1,j} = BEH_{i,j} - BEH_{i,j}\left(s19_{i,j} + s20_{i,j} + s22_{i,j} + s23_{i,j} + \ldots + s27_{i,j}\right) + NU_{i,j}s3_{i,j} + LARC_{i,j}s12_{i,j} + TRAD_{i,j}s30_{i,j} + UP_{i,j}s41_{i,j} + INT_{i,j}s53_{i,j} + IP_{i,j}s62_{i,j} + SI_{i,j}s74_{i,j}$$

$$TRAD_{i+1,j} = TRAD_{i,j} - TRAD_{i,j}\left(s28_{i,j} + s29_{i,j} + s30_{i,j} + s32_{i,j} + s33_{i,j} + \ldots + s36_{i,j}\right) + NU_{i,j}s4_{i,j} + LARC_{i,j}s13_{i,j} + BEH_{i,j}s22_{i,j} + UP_{i,j}s42_{i,j} + INT_{i,j}s54_{i,j} + IP_{i,j}s63_{i,j} + SI_{i,j}s75_{i,j}$$

$$PERM_{i+1,j} = PERM_{i,j} - PERM_{i,j}s38 + NU_{i,j}s5 + LARC_{i,j}s14 + BEH_{i,j}s23 + TRAD_{i,j}s32 + UP_{i,j}s43 + INT_{i,j}s55 + IP_{i,j}s64 + SI_{i,j}s76$$

$$UP_{i+1,j} = UP_{i,j} - UP_{i,j}\left(s39_{i,j}+\ldots+s42_{i,j} + s43_{i,j} + s45_{i,j}+\ldots+s48_{i,j}\right) + NU_{i,j}s6_{i,j} + LARC_{i,j}s15_{i,j} + BEH_{i,j}s24_{i,j} + TRAD_{i,j}s33_{i,j}$$

$$INF\_UP_{i+1,j} = INF\_UP_{i,j} - INF\_UP_{i,j}s50_{i,j} + UP_{i,j}s45_{i,j}$$

$$INT_{i+1,j} = INT_{i,j} - INT_{i,j}\left(s51_{i,j}+\ldots+s55_{i,j} + s57_{i,j} + s58_{i,j} + s59_{i,j}\right) + NU_{i,j}s7_{i,j} + LARC_{i,j}s16_{i,j} + BEH_{i,j}s25_{i,j} + TRAD_{i,j}s34_{i,j} + SI_{i,j}s77_{i,j}$$

$$IP_{i+1,j} = IP_{i,j} - IP_{i,j}\left(s60_{i,j}+\ldots+s64_{i,j} + s66_{i,j}+\ldots+s69_{i,j}\right) + INT_{i,j}s57_{i,j}$$

$$INF\_IP_{i+1,j} = INF\_IP_{i,j} - INF\_IP_{i,j}s71_{i,j} + UP_{i,j}s66_{i,j}$$

$$SI_{i+1,j} = SI_{i,j} - SI_{i,j}\left(s72_{i,j}+\ldots+s77_{i,j} + s79_{i,j}\right) + NU_{i,j}s8_{i,j} + LARC_{i,j}s17_{i,j} + BEH_{i,j}s26_{i,j} + TRADs35_{i,j} + UP_{i,j}s46_{i,j} + INT_{i,j}s58_{i,j} + IP_{i,j}s67_{i,j}$$

$$s1_{i,j} + s2_{i,j}+\ldots+s9_{i,j} = 1$$

$$s10_{i,j} + s11_{i,j}+\ldots+s18_{i,j} = 1$$

$$s19_{i,j} + s20_{i,j}+\ldots+s27_{i,j} = 1$$

$$s28_{i,j} + s29_{i,j}+\ldots+s36_{i,j} = 1$$

$$s37_{i,j} + s38_{i,j} = 1$$

$$s39_{i,j} + s40_{i,j}+\ldots+s48_{i,j} = 1$$

$$s49_{i,j} + s50_{i,j} = 1$$

$$s51_{i,j} + s52_{i,j}+\ldots+s59_{i,j} = 1$$

$$s60_{i,j} + s61_{i,j}+\ldots+s69_{i,j} = 1$$

$$s70_{i,j} + s71_{i,j} = 1$$

$$s72_{i,j} + s73_{i,j}+\ldots+s79_{i,j} = 1$$

4.17

Two things must be noticed in the system of equations presented above in equation 4.17. First, the prevalence at age $i + 1$ at any stock is dependent upon prevalence of the stock one year prior. Take the equation to estimate the prevalence of non-users (NU) at age 16 (first in the system of equations) as an example: the equation establishes its dependence to the prevalence at age 15, together with outflows from and inflows into the NU stock at that same age. Second, the sum of transition probabilities denoting allowed outflows from each stock must add up to one, e.g., $s1_{i,j} + s2_{i,j} + \ldots + s9_{i,j} = 1$.

To estimate the coefficients for NU, $LARC$, BEH, $TRAD$, $PERM$, UP, INF_UP, INT, IP, INF_IP, and SI, the absolute number of females at the different stocks were obtained from each wave of the ENADID survey using the classification algorithm presented in Figure 4.11. After being asked about their current contraceptive use, females are further asked about the type of method used if they answered affirmatively. If they answer, "*Not using contraception at present*," they are presented with a variety of reasons not to use any contraceptive. Current pregnancy, intending to be pregnant, and sexual inactivity reasons were used to classify them at the corresponding stock. Infertility was estimated with option 5 of question 7.9 in the survey: *"Why are you unable to have children: 1) health problems; 2) the woman/partner has a permanent contraceptive method; 3) no current partner/she is single; 4) menopause; 5) the woman/partner is infertile; 6) other reason (specify)"*. Albeit infertility and menopause are two different response options in question 7.9, some overlap between the two is possible given they were obtained with self-report, instead of clinical examination. The remaining females are assumed to be non-pregnant, not intending pregnancy, sexually active, fertile non-users.

Contraceptive failure fractions reported by (Bradley *et al.*, 2019) were used to further adjust the number of current pregnancies as per their intention. Since the absolute numbers reported in the ENADID survey correspond to alive-only women and girls, the absolute number of all-cause and maternal deaths during 2006, 2009, 2014 and 2018 was retrieved from the Death registry maintained by INEGI (Instituto Nacional de Estadística y Geografía, 2019b). The number of maternal deaths was stratified with the distribution of intended/unintended pregnancies found after adjusting pregnancies per intention, assuming these maintain for alive and deceased women. All-cause deaths and maternal deaths stratified per pregnancy intention were then incorporated into the coefficients table.

Finally, and prior to converting them into prevalence coefficients, the data were smoothed to reduce the random variations observed in raw data coming from the ENADID survey waves, thus extracting the underlying trends, and ensuring that further modelling results and their interpretation are not influenced by the extreme nature of raw data. Kernel regression was used to smooth the data, as this technique is common in public health research (Zeger & Diggle, 1994), and suitable for survey data given no functional form is assumed before its use.

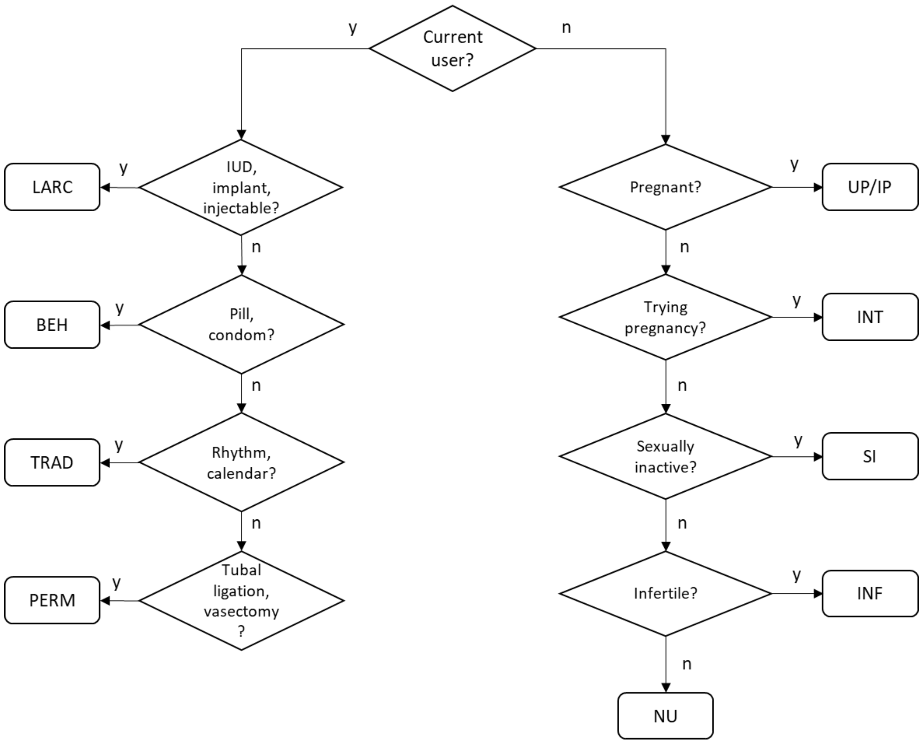


Figure 4.11. Classification algorithm to define the current state of women in ENADID survey.

After smoothing the data, each system of equations was converted into a matrix equation of the form $\boldsymbol{A}_{i,j}\ \boldsymbol{s}_{i,j} = \boldsymbol{b}_{i,j}$, where $\boldsymbol{A}_{i,j}$ holds the prevalence coefficients at each stock, $\boldsymbol{s}_{i,j}$ is the solution vector for the system of equations, and $\boldsymbol{b}_{i,j}$ is a vector with the right-hand side of each equation in the system presented in equation 4.17. A Python script was devised to automate the process and ultimately obtain age-stratified transition probability matrices for each ENADID wave. The script also allowed to normalise the data whenever negative probabilities were found with the M-P algorithm.

The estimated transition probabilities from non-use are presented in Figure 4.12. There are no substantial between-year differences, except for the end of reproductive years when an upward trend of women remaining as non-users (s1) or an abrupt decline in the transit from non-use to sexual inactivity (s8) were observed. There is also a slight but noticeable movement from non-use to intending a pregnancy (s7) halfway through the reproductive years. The stability in contraceptive adoption probabilities across age groups (s2-s4) suggests that barriers to contraceptive uptake persist throughout women's reproductive years. However, the increasing probability of permanent contraception adoption with age (s5) reflects life-stage family planning decisions based on accomplishing desired fertility goals. Transition probabilities from non-use to unintended pregnancy (s6) were already reported by (Bradley *et al.*, 2019) and assumed to hold for Mexico. Transitions to all-cause death (s9) were negligible compared with the rest of estimated probabilities, and thus are presented at their original scale to visualise them along the rest of estimates.

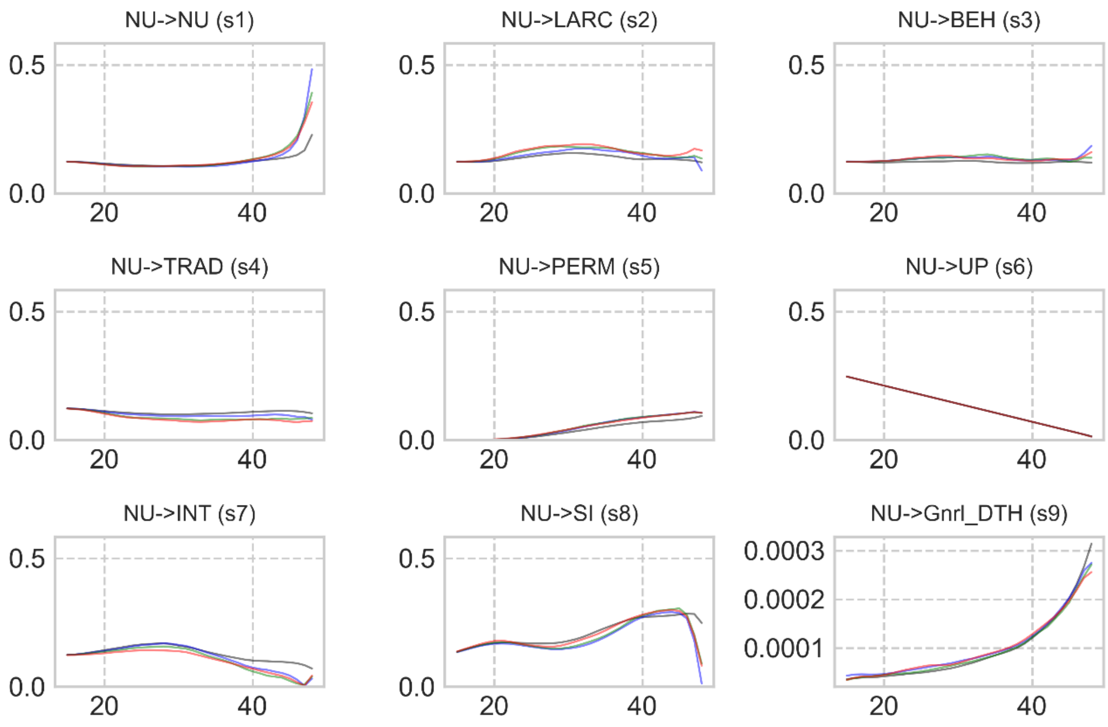


Figure 4.12. Transition probabilities from contraceptive non-use estimated with the M-P approach.

Notes: 1) ***NU****: non-users;* ***LARC****: long-acting, reversible contraception users;* ***BEH****: behavioural contraception users;* ***TRAD****: traditional contraception users;* ***PERM****: permanent contraception users;* ***UP****: unintended pregnancy;* ***INT****: trying to be pregnant;* ***SI****: sexually inactive;* ***Gnrl_DTH****: all-cause death. 2)Transition probabilities for 2006, 2009, 2014, and 2018 are coloured in black, blue, green, and red, respectively. 3) Transition probabilities in s9 are presented in their original scale to allow their visualization. 4) x-axis represents age classes; y-axis represents probabilities between 0 and 1.*

Transition from long-acting, reversible contraception, which can be both due to switching to a different contraceptive or to method discontinuation, are shown in Figure 4.13. Contrary to the case of non-use, differences between years are more pronounced in this case, especially at the middle of the reproductive years in s11, and s12, and throughout the reproductive lifespan in s16 and s17. The observed patterns in LARC discontinuation may reflect several underlying factors. The higher discontinuation rates at reproductive span extremes could point to different motivation: younger women may discontinue due to side effects or desire for pregnancy, while older women may transition to permanent methods. The between-year variations in transition probabilities highlight evolving contraceptive preferences and potentially changing healthcare access patterns.

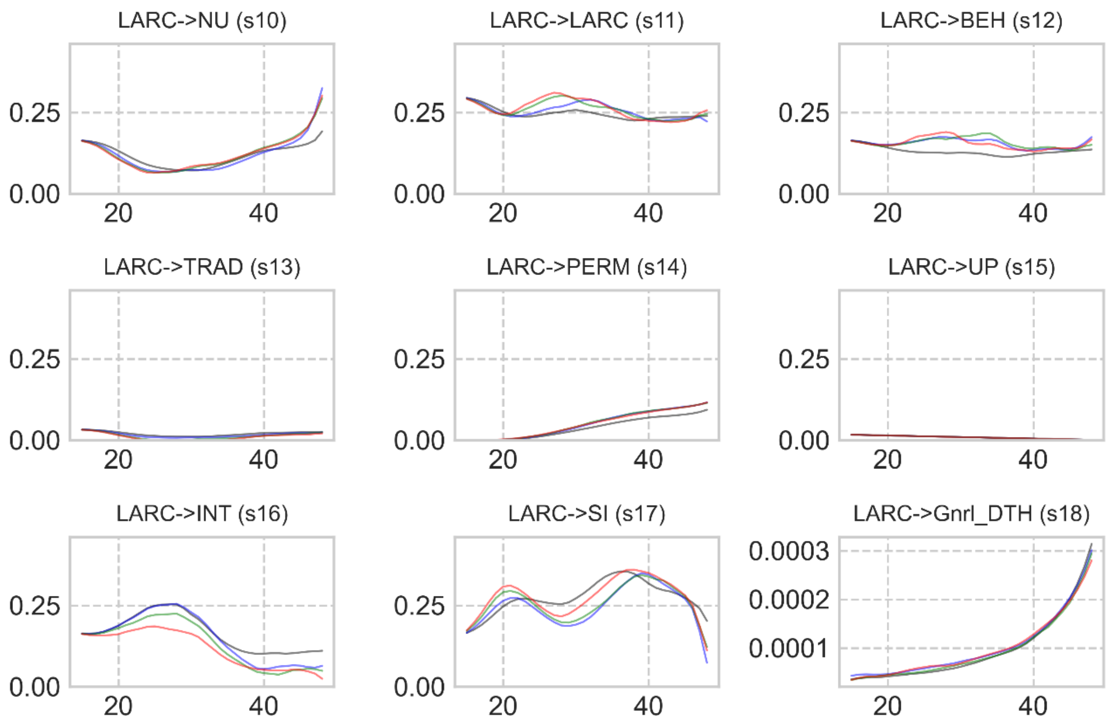


Figure 4.13. Transition probabilities from long-acting, reversible contraception estimated with the M-P approach.

Note: 1) ***NU:*** *non-users;* ***LARC:*** *long-acting, reversible contraception users;* ***BEH:*** *behavioural contraception users;* ***TRAD:*** *traditional contraception users;* ***PERM:*** *permanent contraception users;* ***UP:*** *unintended pregnancy;* ***INT:*** *trying to be pregnant;* ***SI:*** *sexually inactive;* ***Gnrl_DTH:*** *all-cause death. 2) Transition probabilities for 2006, 2009, 2014, and 2018 are coloured in black, blue, green, and red, respectively. 3) Transition probabilities in s18 are presented in their original scale to allow their visualization. 4) x-axis represents age classes; y-axis represents probabilities between 0 and 1.*

The variability in transitions from behavioural methods across survey years (Figure 4.14, particularly s20, s25, s26) likely reflects evolving contraceptive preferences and healthcare system changes in Mexico. The increasing trend of switching from behavioural to LARC methods (s20), particularly among mid-reproductive age women, suggests improved access to and acceptance of more effective contraceptive options.

The preference for maintaining behavioural methods over switching to traditional methods (s22) suggests these contraceptives offer advantages that users value, such as high efficacy, or partner cooperation (Shattuck et al., 2011). However, the steady increase in transitions to permanent contraception across age groups (s23) indicates that women ultimately seek more definitive contraceptive solutions as they complete their desired family size (Kane et al., 2009).

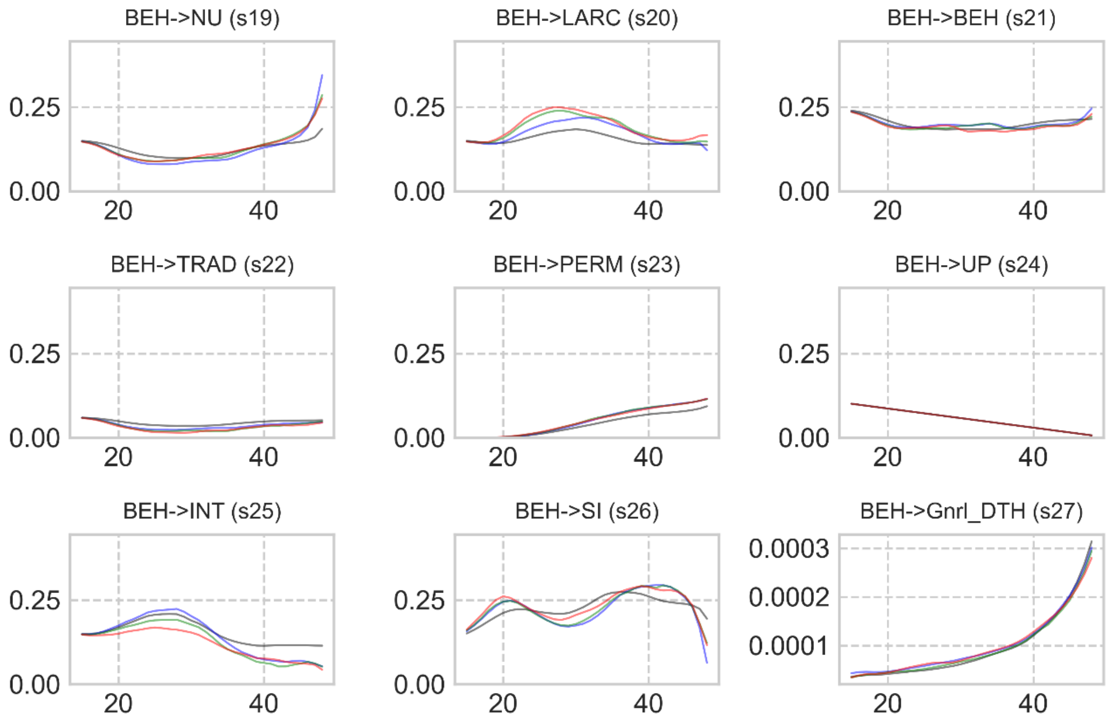


Figure 4.14. Transition probabilities from behavioural contraception estimated with the M-P approach.

Note: 1) ***NU****: non-users;* ***LARC****: long-acting, reversible contraception users;* ***BEH****: behavioural contraception users;* ***TRAD****: traditional contraception users;* ***PERM****: permanent contraception users;* ***UP****: unintended pregnancy;* ***INT****: trying to be pregnant;* ***SI****: sexually inactive;* ***Gnrl_DTH****: all-cause death. 2) Transition probabilities for 2006, 2009, 2014, and 2018 are coloured in black, blue, green, and red, respectively. 3) Transition probabilities in s27 are presented in their original scale to allow their visualization. 4) x-axis represents age classes; y-axis represents probabilities between 0 and 1.*

No great difference between years was found in the movements out of traditional contraception (Figure 4.15) except for the trend shown by s35. Movements from traditional contraception to non-use (s28) were found to occur more frequently at the end of the reproductive span, possibly reflecting a reduced pregnancy risk perception at these older age groups (Gemmill & Cowan, 2021). The higher probability of switching to more effective methods (s29, s30, s32) compared to maintaining traditional method use (s31) suggests that traditional methods are regarded only as temporary solutions to avoid pregnancy along women's reproductive years and consistent with trends in use in the recent era (F. Juarez et al., 2018).

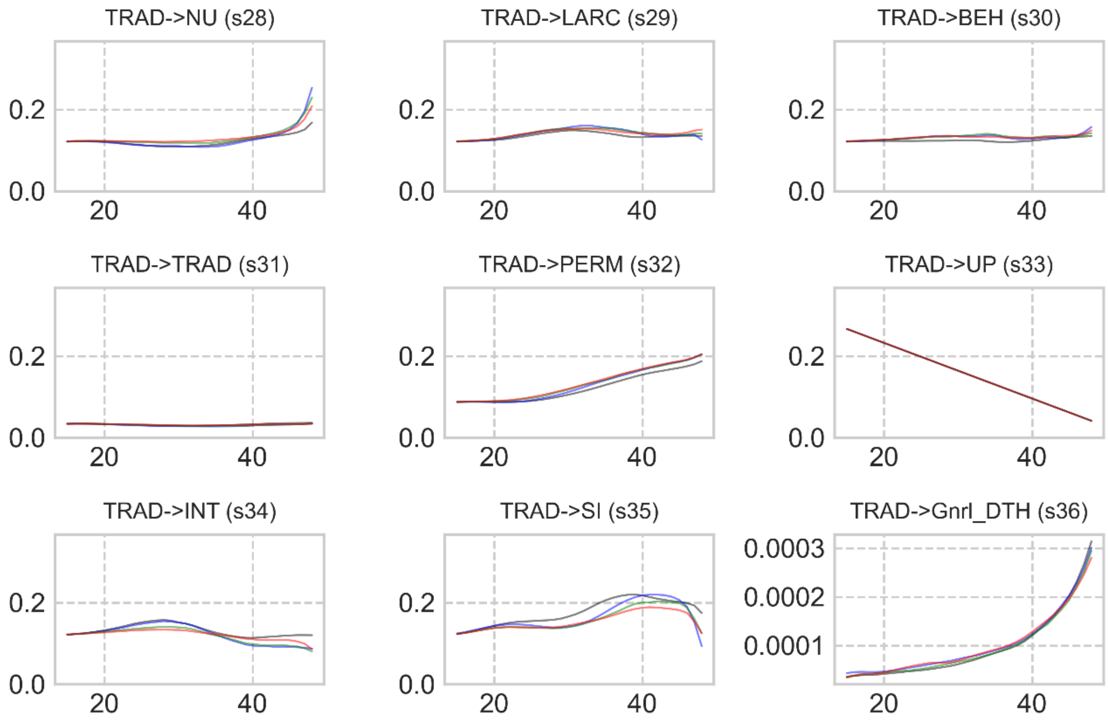


Figure 4.15. Transition probabilities from traditional contraception estimated with the M-P approach.

*Note: 1) **NU**: non-users; **LARC**: long-acting, reversible contraception users; **BEH**: behavioural contraception users; **TRAD**: traditional contraception users; **PERM**: permanent contraception users; **UP**: unintended pregnancy; **INT**: trying to be pregnant; **SI**: sexually inactive; **Gnrl_DTH**: all-cause death. 2) Transition probabilities for 2006, 2009, 2014, and 2018 are coloured in black, blue, green, and red, respectively. 3) Transition probabilities in s36 are presented in their original scale to allow their visualization. 4) x-axis represents age classes; y-axis represents probabilities between 0 and 1.*

Given the low frequency of all-cause deaths, practically all permanent contraception users remain in the stock and age as the simulation progresses (Figure 4.16). No other transitions from this stock are possible since it was assumed that permanent contraception offers perfect protection against unintended pregnancy.

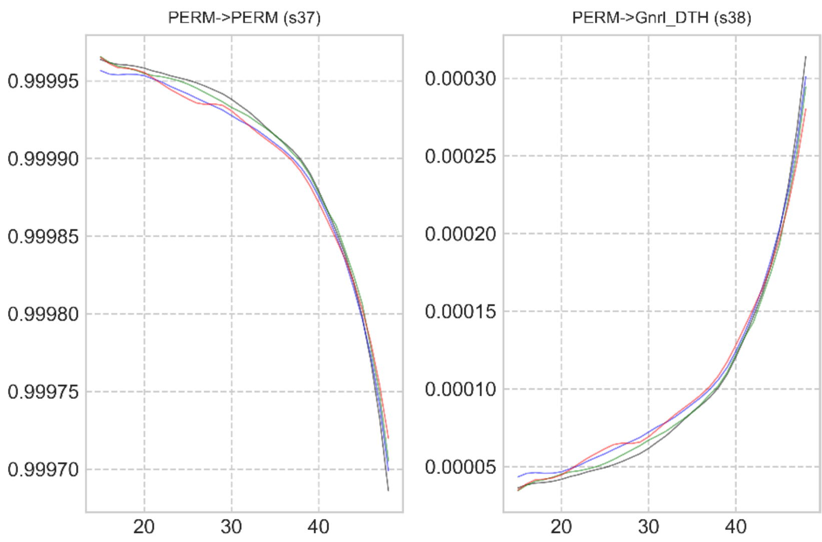


Figure 4.16. Transition probabilities from permanent contraception estimated with the M-P approach.

Note: 1) ***PERM****: permanent contraception users;* ***Gnrl_DTH****: all-cause death. 2) Transition probabilities for 2006, 2009, 2014, and 2018 are coloured in black, blue, green, and red, respectively. 3) Figures are presented at their original scale. 4) x-axis represents age classes; y-axis represents probabilities between 0 and 1.*

The similar probabilities of adopting LARC, behavioural, or traditional methods following unintended pregnancy (Figure 4.17) suggest that the experience of unintended pregnancy does not necessarily lead women to choose more effective contraception. Further, this pattern might reflect persistent barriers to accessing more effective methods, including cost, quality of contraceptive counselling, and misinformation (Ibáñez-Cuevas et al., 2021).

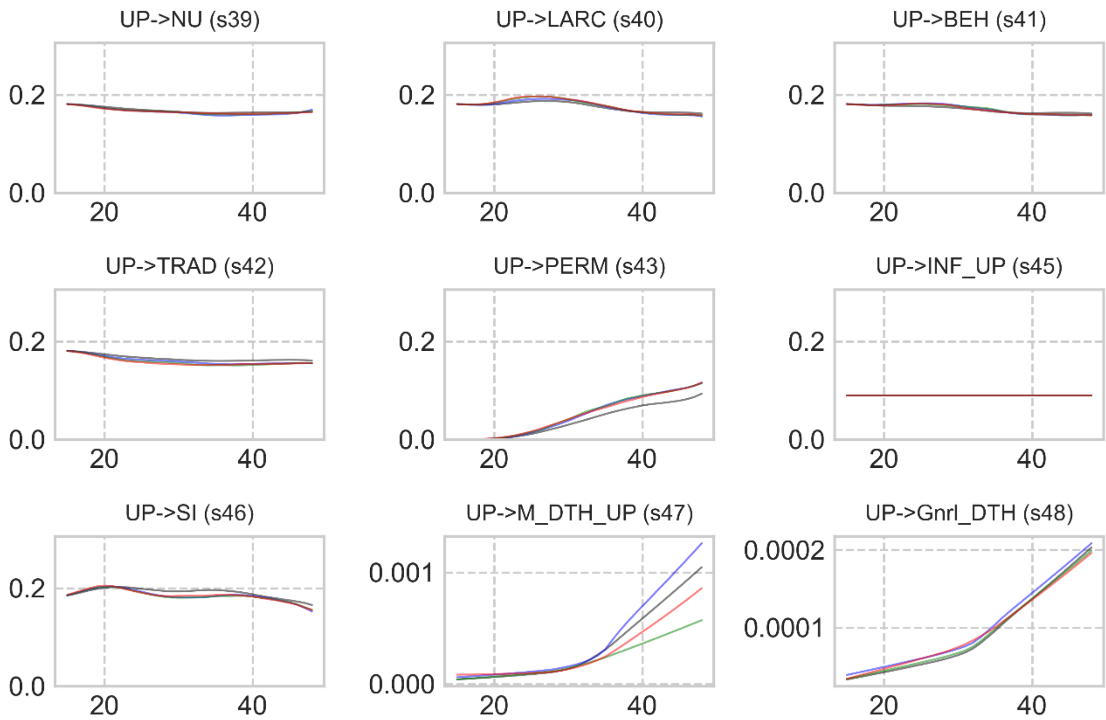


Figure 4.17. Transition probabilities from unintended pregnancy estimated with the M-P approach.

*Note: 1) **NU**: non-users; **LARC**: long-acting, reversible contraception users; **BEH**: behavioural contraception users; **TRAD**: traditional contraception users; **PERM**: permanent contraception users; **UP**: unintended pregnancy; **INT**: trying to be pregnant; **SI**: sexually inactive; **Gnrl_DTH**: all-cause death; **M_DTH_UP**: maternal death attributable to unintended pregnancy. 2) Transition probabilities for 2006, 2009, 2014, and 2018 are coloured in black, blue, green, and red, respectively. 3) Transition probabilities in s47 and s48 are presented in their original scale to allow their visualization. 4) x-axis represents age classes; y-axis represents probabilities between 0 and 1.*

Given that all-cause deaths are negligible, once they enter it, practically all women remain in the secondary infertility stock, and age as the simulation progresses (Figure 4.18). No other transitions from this stock are allowed since it was assumed that secondary infertility is permanent. Despite being a treatable condition, access to infertility treatment is largely restricted in the Mexican context with some exceptions (Farland et al., 2023).

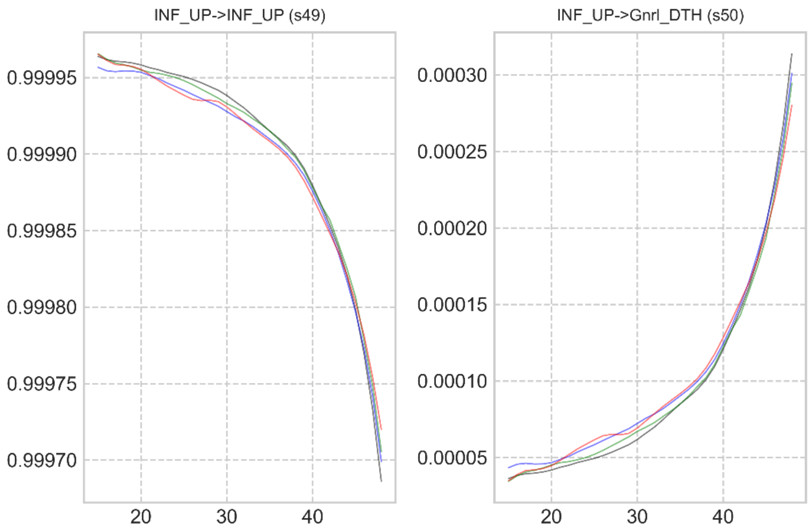


Figure 4.18. Transition probabilities from infertility secondary to unintended pregnancy, estimated with the M-P approach.

*Note: 1) **INF_UP**: infertility secondary to unintended pregnancy; **Gnrl_DTH**: all-cause death. 2) Transition probabilities for 2006, 2009, 2014, and 2018 are coloured in black, blue, green, and red, respectively. 3) Figures are presented at their original scale. 4) x-axis represents age classes; y-axis represents probabilities between 0 and 1.*

Becoming pregnant intentionally is the more frequent outcome of trying for pregnancy (s57, Figure 4.19) followed by becoming sexually inactive (s58), which shows two peaks at adolescence and before reaching the age of 40. The high probability of achieving intended pregnancy among those trying reflects the generally good fertility levels in Mexico's reproductive-age population. The bimodal pattern of transitioning to sexual inactivity likely reflects different social phenomena: in adolescence, it may represent relationship instability and educational priorities (Twenge et al., 2017), while the later peak might relate to relationship dissolution or health concerns (Bianco et al., 1996).

The increasing adoption of LARC between ages 20-40 suggests growing awareness of the need for effective spacing methods during peak reproductive years (Saavedra-Avendano et al., 2017).

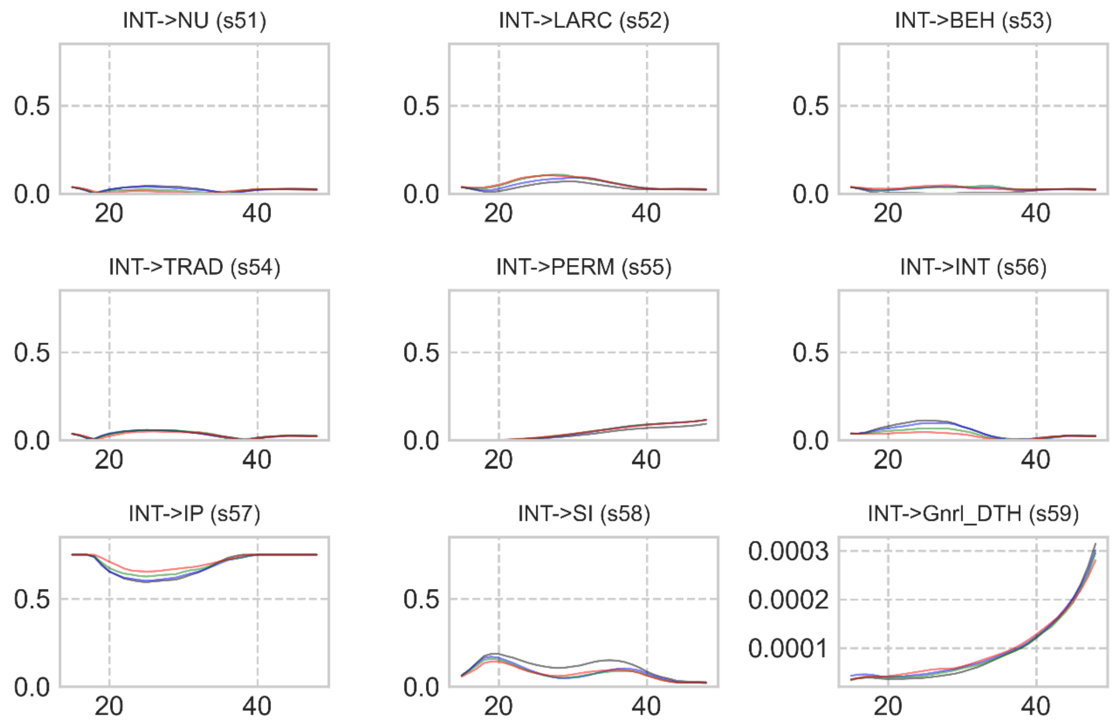


Figure 4.19. Transition probabilities from intention of pregnancy estimated with the M-P approach.

Note: 1) ***NU****: non-users;* ***LARC****: long-acting, reversible contraception users;* ***BEH****: behavioural contraception users;* ***TRAD****: traditional contraception users;* ***PERM****: permanent contraception users;* ***IP****: intended pregnancy;* ***INT****: trying to be pregnant;* ***SI****: sexually inactive;* ***Gnrl_DTH****: all-cause death. 2) Transition probabilities for 2006, 2009, 2014, and 2018 are coloured in black, blue, green, and red, respectively. 3) Transition probabilities in s58 and s59 are presented in their original scale to allow their visualization. 4) x-axis represents age classes; y-axis represents probabilities between 0 and 1.*

There were some between-year differences found in the movements from unintended pregnancy, mostly at s61, s62, and s67 (Figure 4.20). Becoming a long-acting contraception user after an intended pregnancy ends (s61) peaks at the middle-ages of the reproductive span, keeping a roughly similar probability at the extremes. In contrast, the trend of traditional contraceptive adoption after an intended pregnancy ends (s63) declines until the middle-ages to steadily grow after these, also keeping a similar probability at the extremes. Females not accepting any contraceptive and becoming non-users (s60) show a less pronounced however noticeable decline as in s63. Becoming a behavioural contraception user (s62) shows practically the same trend throughout the reproductive years.

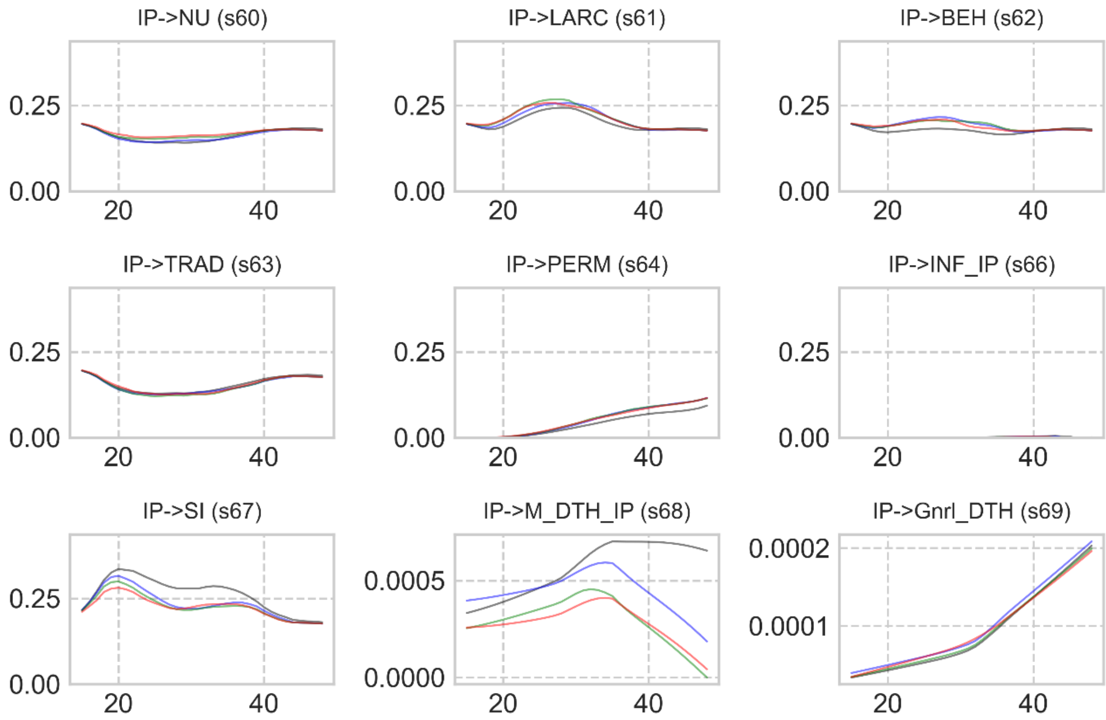


Figure 4.20. Transition probabilities from intended pregnancy estimated with the M-P approach.

Note: 1) ***NU****: non-users;* ***LARC****: long-acting, reversible contraception users;* ***BEH****: behavioural contraception users;* ***TRAD****: traditional contraception users;* ***PERM****: permanent contraception users;* ***IP****: intended pregnancy;* ***INT****: trying to be pregnant;* ***SI****: sexually inactive;* ***Gnrl_DTH****: all-cause death;* ***M_DTH_IP****: maternal death attributable to intended pregnancy. 2) Transition probabilities for 2006, 2009, 2014, and 2018 are coloured in black, blue, green, and red, respectively. 3) Transition probabilities in s68 and s69 are presented in their original scale to allow their visualization. 4) x-axis represents age classes; y-axis represents probabilities between 0 and 1.*

Given that all-cause deaths have a low frequency, once they enter it, practically all women remain in the secondary infertility stock, and age as the simulation progresses (Figure 4.21). No other transitions from this stock were allowed given access to secondary infertility treatment is scarce in Mexico, excepting for some groups (Farland et al., 2023). Thus, the condition was assumed permanent.

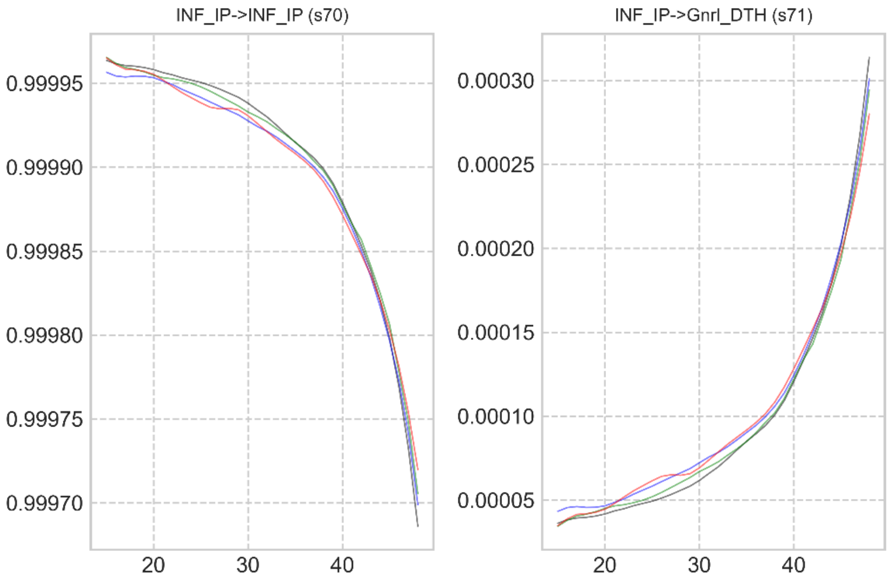


Figure 4.21. Transition probabilities from infertility secondary to intended pregnancy estimated with the M-P approach.

Note: 1) ***INF_IP****: infertility secondary to intended pregnancy;* ***Gnrl_DTH****: all-cause death. Transition probabilities for 2006, 2009, 2014, and 2018 are coloured in black, blue, green, and red, respectively. 3) Figures are presented at their original scale. 4) x-axis represents age classes; y-axis represents probabilities between 0 and 1.*

The probability of remaining sexually inactive (s78) presents an oscillating pattern, holding its maximum value at the start of the reproductive lifespan, then declining substantially until the start of age 30, increasing again until age 40, and finally decreasing from that age on (Figure 4.22). It is noticeable that adopting traditional contraception once sexual activity is resumed (s75) is not an attractive option, showing transition probabilities nearing zero.

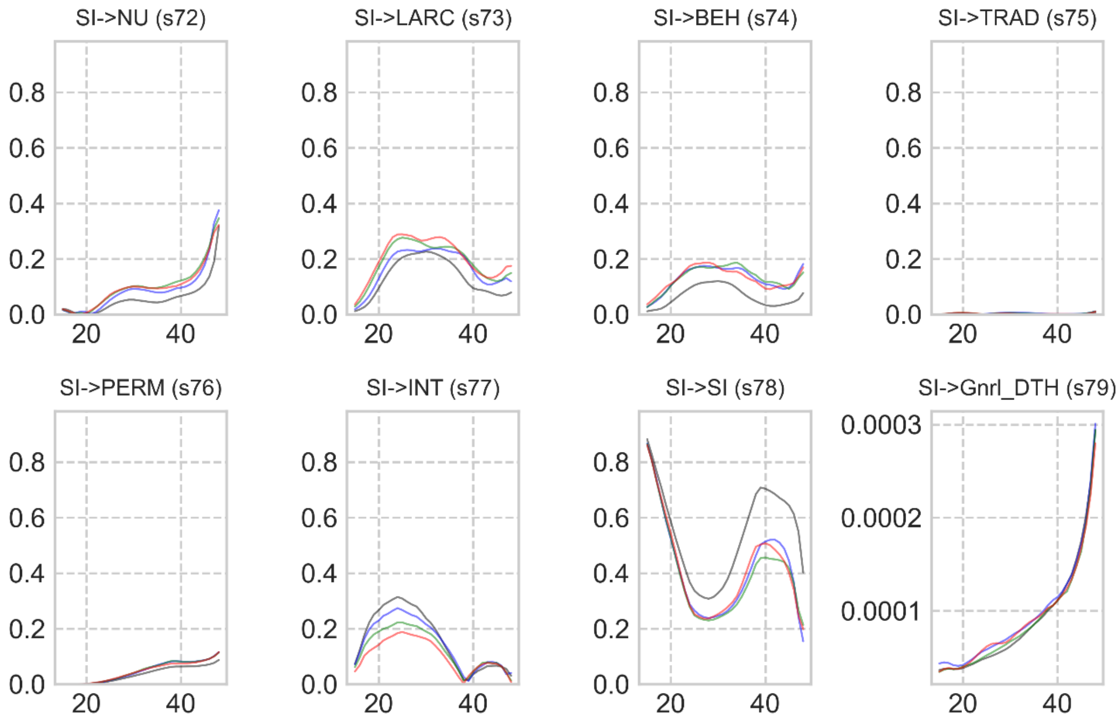


Figure 4.22. Transition probabilities from sexual inactivity estimated with the M-P approach.

Note: 1) ***NU****: non-users;* ***LARC****: long-acting, reversible contraception users;* ***BEH****: behavioural contraception users;* ***TRAD****: traditional contraception users;* ***PERM****: permanent contraception users;* ***INT****: trying to be pregnant;* ***SI****: sexually inactive;* ***Gnrl_DTH****: all-cause death. 2) Transition probabilities for 2006, 2009, 2014, and 2018 are coloured in black, blue, green, and red, respectively. 3) Transition probabilities in s79 are presented in their original scale to allow their visualization. 4) x-axis represents age classes; y-axis represents probabilities between 0 and 1.*

Collectively, these transition patterns reveal a complex interplay between age, fertility intentions, and contraceptive preferences. The estimated probabilities suggest three key phenomena: 1) a general progression toward more effective methods over time, particularly among mid-reproductive age women; 2) age-specific patterns in method switching that align with life-course fertility intentions; and 3) persistent method-specific discontinuation patterns that may indicate areas for targeted intervention in the Mexican contraceptive programme.

4.2.3 Clinical parameters

As mentioned in the introduction to the different model parameters, this category relates to outcomes of intended and unintended pregnancy. Recall from the previous chapter that, once a pregnancy ends, women of reproductive age end in one of three different stock categories: dead; alive, infertile secondary to pregnancy; and alive non-infertile, which implies moving to *NU, LARC, BEH, TRAD, PERM, INT,* and *SI*. See Figure 4.2 and Figure 4.3. The possible ways a pregnancy might end and lead to death or otherwise are presented in Section 4.1.

The different causes of maternal death of WoRA were classified as per their frequency of occurrence and derived from the Maternal-related deaths registry maintained by the Health Secretariat (Secretaría de Salud, 2022) using the International Classification of Diseases 11th revision (World Health Organization, 2024a). The dataset covers the years 2002 to 2022, and documents N=23,278 maternal deaths occurred during the period. Given that maternal death is a relatively rare phenomenon in Mexico, some of the causes of death had a pronouncedly low frequency of occurrence, thus rendering figures too noisy to present yearly and age-stratified estimates. A workaround for this paucity of data was to pool the estimates for the whole period and parameterise the model with the average proportions from 2002-2017.

Table 4.2. Clinical outcomes of intended and unintended pregnancy.

Status after pregnancy	Pregnancy outcome/Cause of death	Source(s)
Dead	Abnormal product of conception	Maternal deaths registry[2]
	Childbirth	Maternal deaths registry[2]
	Miscarriage	Maternal deaths registry[2]
	Gestational period	Maternal deaths registry[2]
	Unsafe abortion[1]	Maternal deaths registry[2]
	Stillbirth	Maternal deaths registry[2]
	Puerperal period	Maternal deaths registry[2]
	Other causes	Maternal deaths registry[2]
Alive, infertile secondary to pregnancy	Childbirth	Calibration
	Miscarriage	Calibration
	Unsafe abortion[1]	Calibration
	Stillbirth	Calibration
Alive, non-infertile	Childbirth	ENADID[3]
	Miscarriage	ENADID[3]
	Unsafe abortion[1]	ENADID[3], (Lara et al., 2006)
	Stillbirth	ENADID[3]

[1]Unsafe abortion only relates to intended pregnancy; [2]This registry spans from 2002-2022; [3]National Survey on the Demographic Dynamics, 2006, 2009, and 2018 waves.

The estimated age-stratified causes of death for unintended pregnancies are presented in Figure 4.23 below. Overall, the most frequent causes of death observed were “Other causes” and causes attributable to the gestational period, e.g., gestational diabetes, hypertension, followed by deaths during the puerperal period, e.g., puerperal sepsis, hypovolemia. Miscarriage and stillbirth represent the smaller burden throughout the reproductive years.

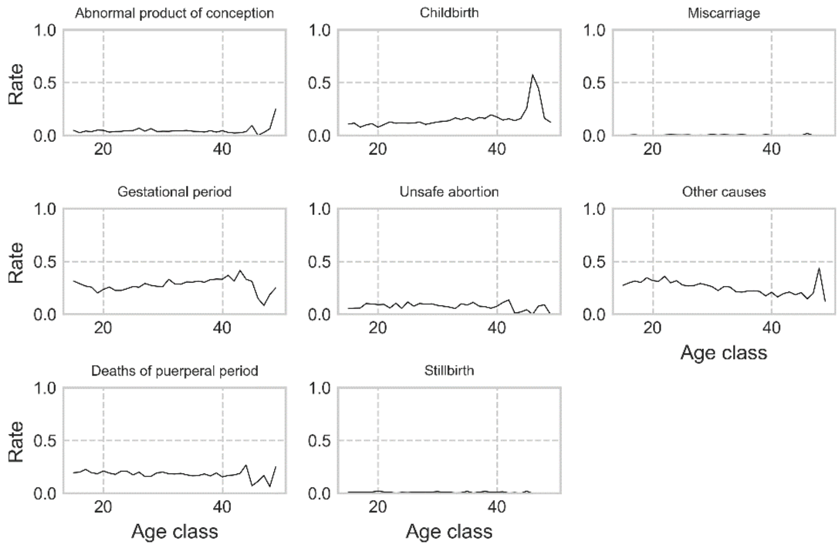


Figure 4.23. Age-stratified causes of death due to unintended pregnancy.

The estimated age-stratified causes of death for intended pregnancies are presented in Figure 4.24 below. The patterns are practically the same as for unintended pregnancies, excluding death due to unsafe abortion which was assumed not to occur in *IP*. Given that the maternal deaths registry had no reference to the intention of pregnancy of the deceased females, distinguishing deaths due to intended and unintended pregnancies was only possible by including/excluding the ICD codes presumably related to unsafe abortion (i.e., O04 Complications following (induced) termination of pregnancy, O07 Failed attempted termination of pregnancy) (World Health Organization, 2016) from the proportion estimation.

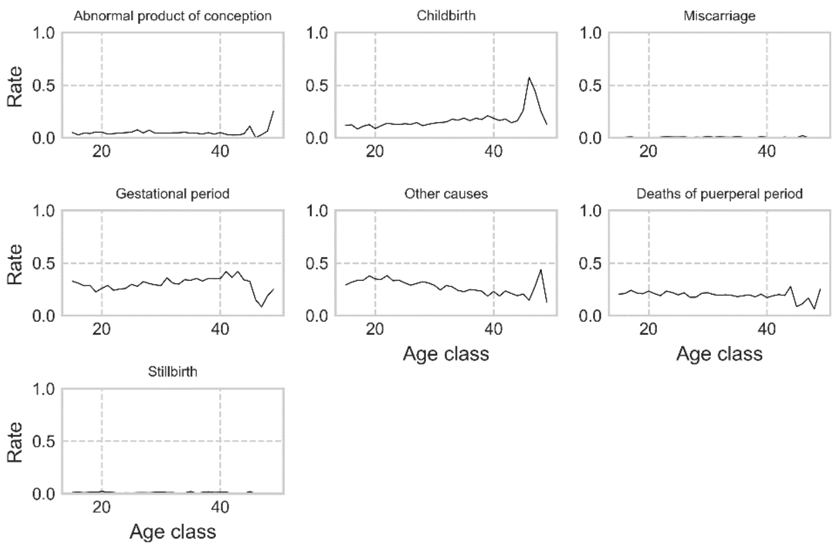


Figure 4.24. Age-stratified causes of death due to intended pregnancy.

Given no data on infertility secondary to intended/unintended pregnancy was found for the country, these proportions were hand calibrated and fixed constant across age groups and throughout the simulated years. Infertility secondary to childbirth, miscarriage, unsafe abortion, and stillbirth when pregnancy is unintended was set at 0.5, 0.025, 0.4, and 0.025, respectively. Infertility secondary to childbirth, miscarriage, and stillbirth when pregnancy is intended was set at 0.5, 0.45, and 0.05, respectively.

The 2006, 2009, 2014, and 2018 waves of the ENADID survey were used to estimate the distribution of pregnancy outcomes when a woman survives and does not develop secondary infertility. As with the estimation of maternal causes of death, a small amount of data points in some categories, e.g., stillbirth across age groups and throughout the years, made necessary to average the figures and introduce a constant distribution during the simulation period. To differentiate whether an abortion was unsafe, a proxy was obtained from ENADID survey, where women reporting a previous abortion are further asked to specify who attended/conducted the procedure. Among the possible answers, *“Nobody (herself)”* was determined to hint an unsafe abortion, according to the definition used in this research (Ganatra et al., 2014). Each age group’s proportion of unsafe abortions was further adjusted by hand until resembling the average 16% figure reported in (Lara *et al.*, 2006).

Figure 4.25 shows the estimated distribution of outcomes of unintended pregnancy. In general, and as expected, most pregnancies end with a live birth albeit the proportion diminishes as women age. In turn, miscarriages and unsafe abortions become more prevalent as women age, however the latter raise more slowly. The first phenomenon reflects diminishing biological aptitude to pregnancy as women age (Arck et al., 2008), whilst the second might be reflecting the explicit intention to limit the number of children as desired family sizes are reached, together with barriers of accessing safe abortion services in the country (Juárez et al., 2013).

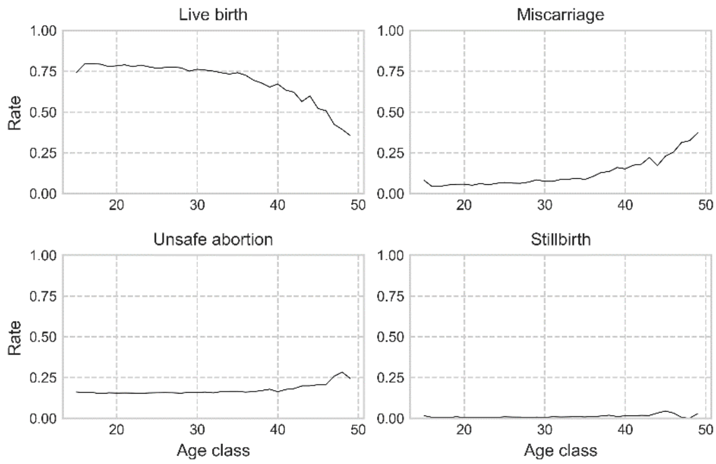


Figure 4.25. Age-stratified unintended pregnancy outcomes.

In the case of intended pregnancies (Figure 4.26), live births also show a decreasing trend as women move out of their reproductive years. As in the case of intended pregnancies, miscarriage is also more common as women age.

Figure 4.26. Age-stratified intended pregnancy outcomes.

The high dimensionality of the model and limited availability of secondary infertility data for the country rendered automated calibration too time-consuming, thus an inefficient approach to this research. Hand calibration was therefore selected as the most appropriate approach to adjust these parameters. As Figure 4.27 shows, it was implemented by first selecting an arbitrary, yet plausible value for the parameter being determined. Secondly, the full model was run for the *status quo* scenario and the correspondence between ENADID survey data and simulated results was visually evaluated (Lyneis & Pugh, 1996). The process was repeated until a fair qualitative correspondence between the simulated results and the survey data was found (see Appendix C).

After this point, the parameter table to be employed by the model, which constitutes the basis to build the rest of scenarios (see next section) was defined.

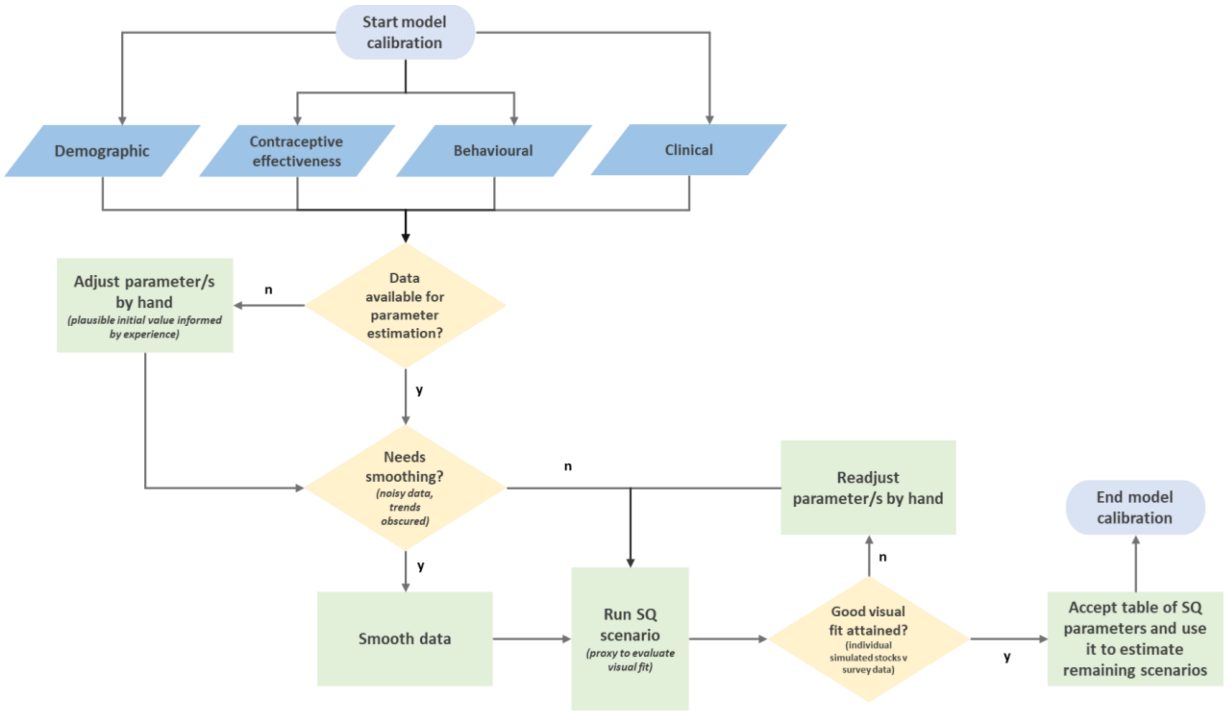


Figure 4.27. Calibration flowchart for the parameter estimation process.

4.3 Software implementation

The workflow depicted in Figure 4.28 illustrates the steps followed to derive the simulation model results arrived at in this thesis. Parameter estimation consisted in combining various datasets publicly available to the country, along with topic-specific literature to compose a table of more than a hundred parameters required by the model. If not otherwise stated, those parameters are age-stratified and time-varying.

Linear interpolation was used to fill in missing data in the contraceptive, sexual, and reproductive (C-S-R) dynamics during the 2006-2020 period. It should be recalled that the ENADID survey from which C-S-R transition probabilities were estimated has four waves: 2006, 2009, 2014, and 2018. See sections 4.2 and 4.2.2.

Microsoft Excel, Stata v17 and Python v3.9.15 served different purposes at the parameter estimation stage. Microsoft Excel was used mostly as data repository for the different Stata and Python scripts devised. Given its ready-to-use survey analysis facilities, Stata was used to analyse the different ENADID waves and extract the tables with the absolute number of women in each state, in preparation for transition probability estimation (see section 4.2).

The remaining processes in parameter estimation (i.e., clinical/demographic parameter estimation, transition probability estimation), strategy preparation, model simulation, and cost-effectiveness analysis were implemented in Python given the broad range of libraries available for data analysis, numerical solution of ordinary differential equations (ODEs), and data visualisation.

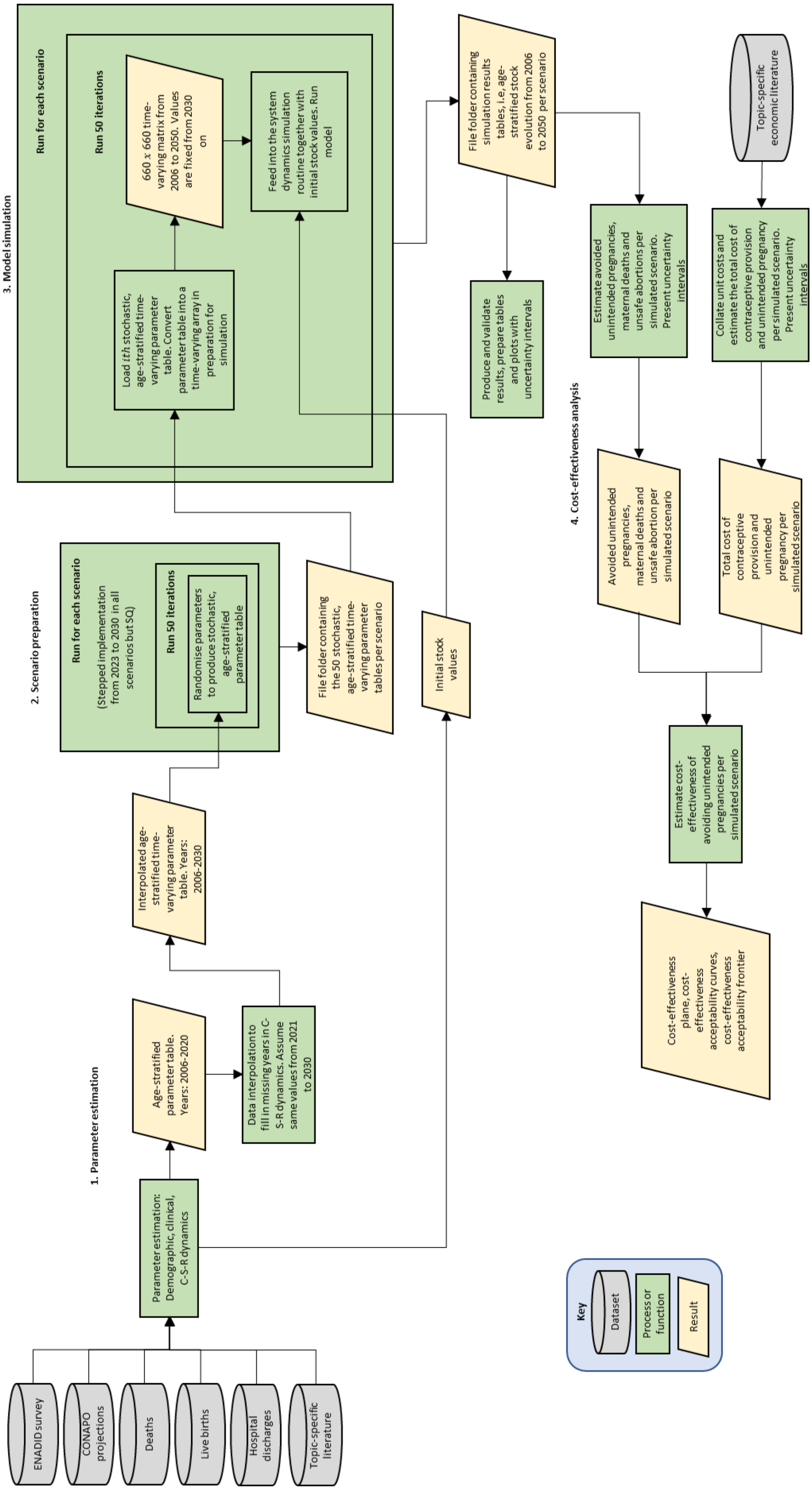


Figure 4.28. Analytical flowchart of the contraceptive provision simulation and cost-effectiveness analysis of competing strategies.

Previous versions of the system dynamics simulation model devised in this thesis used *SciPy's solve_ivp* third-party package (Virtanen et al., 2020) to solve ODEs. As the model grew in complexity and *solve_ivp* was surpassed by the need to run the model multiple times (more than 30 simulated strategies with *n* iterations each), it was decided to develop a new system dynamics platform, capable of solving systems of ODEs with vectorisation, i.e., simultaneously solving model equations using linear algebra.

Once ready, this new platform reduced the model's execution time to a reasonable extent: using a Dell Latitude 5400 laptop with 8 GB of RAM, one iteration with *solve_ivp* executes in around 17 seconds, whilst one iteration with the vectorised version executes in 265 milliseconds, or sixty-four times faster.

To illustrate the development of the vectorised system dynamics model, consider the dummy age-stratified model in equation 4.18 below. To ease its interpretation, the model does not include deaths or migration. The model depicts the endogenous generation of livebirths from three unintended pregnancy age cohorts (UP_A, UP_B, UP_C) and their further introduction into the U_A stock via coflows. Women then mature until reaching U_C and start their reproductive lifespan at SI_A where they age to reach SI_C:

$$U_A(t) = U_A(t-dt) + (aUP_A + bUP_B + cUP_C - dU_A)dt$$

$$U_B(t) = U_B(t-dt) + (dU_A - eU_B)dt$$

$$U_C(t) = U_C(t-dt) + eU_B dt$$

$$UP_A(t) = UP_A(t-dt) - gUP_A dt$$

$$UP_B(t) = UP_B(t-dt) - iUP_B dt$$

$$UP_C(t) = UP_C(t-dt) - kUP_C dt$$

$$SI_A(t) = SI_A(t-dt) + (fU_C + gUP_A - hSI_A)dt$$

$$SI_B(t) = SI_B(t-dt) + (hSI_A + iUP_B - jSI_B)dt$$

$$SI_C(t) = SI_C(t-dt) + (jSI_B + kUP_C)dt$$

4.18

Where $a - k$ are coefficients indicating the fraction of women moving between stocks.

An approximate solution to this equation system can be found numerically with the Euler's method, and can be expressed in matrix form:

$$\boldsymbol{s}(t) = \boldsymbol{s}(t-dt) + \boldsymbol{Cs}(t-dt)dt$$

4.19

Where $\boldsymbol{s}(t)$ is a vector with the model's next stock values; $\boldsymbol{s}(t-dt)$ is a vector with the stock values in the previous dt timestep; and $\boldsymbol{C}$ is a $m\ x\ m$ matrix with the $a-k$ coefficients indicating the fraction of females moving between stocks at timestep dt. The m columns and m rows are equal to the number of stocks in the model. Thus, this dummy nine-stock model will have a $9\ x\ 9$ coefficient matrix.

The equation presented in 4.19 can also be presented in matrix form:

$$\begin{pmatrix} U_A \\ U_B \\ U_C \\ UP_A \\ UP_B \\ UP_C \\ SI_A \\ SI_B \\ SI_C \end{pmatrix}(t) = \begin{pmatrix} U_A \\ U_B \\ U_C \\ UP_A \\ UP_B \\ UP_C \\ SI_A \\ SI_B \\ SI_C \end{pmatrix}(t-dt) + \begin{pmatrix} aUP_A + bUP_B + cUP_C - dU_A \\ dU_A - eU_B \\ eU_B \\ -gUP_A \\ -iUP_B \\ -kUP_C \\ fU_C + gUP_A - hSI_A \\ hSI_A + iUP_B - jSI_B \\ jSI_B + kUP_C \end{pmatrix}dt$$

4.20

The light blue box in equation 4.20 can be further expressed as the matrix multiplication of the $m\ x\ m$ coefficient matrix and the $\boldsymbol{s}(t-dt)$ vector to complete the vectorised Euler's method specification:

$$\begin{pmatrix} U_A \\ U_B \\ U_C \\ UP_A \\ UP_B \\ UP_C \\ SI_A \\ SI_B \\ SI_C \end{pmatrix}(t) = \begin{pmatrix} U_A \\ U_B \\ U_C \\ UP_A \\ UP_B \\ UP_C \\ SI_A \\ SI_B \\ SI_C \end{pmatrix}(t-dt) + \begin{pmatrix} -d & 0 & 0 & a & b & c & 0 & 0 & 0 \\ d & -e & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & e & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -g & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -i & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -k & 0 & 0 & 0 \\ 0 & 0 & f & g & 0 & 0 & -h & 0 & 0 \\ 0 & 0 & 0 & 0 & i & 0 & h & -j & 0 \\ 0 & 0 & 0 & 0 & 0 & k & 0 & j & 0 \end{pmatrix}\begin{pmatrix} U_A \\ U_B \\ U_C \\ UP_A \\ UP_B \\ UP_C \\ SI_A \\ SI_B \\ SI_C \end{pmatrix}dt$$

4.21

Finally, a time-varying version of this dummy model would have a different coefficient matrix at the ith simulated year or period:

$$\begin{pmatrix} U_A \\ U_B \\ U_C \\ UP_A \\ UP_B \\ UP_C \\ SI_A \\ SI_B \\ SI_C \end{pmatrix}(t) = \begin{pmatrix} U_A \\ U_B \\ U_C \\ UP_A \\ UP_B \\ UP_C \\ SI_A \\ SI_B \\ SI_C \end{pmatrix}(t-dt) + \begin{pmatrix} -d_i & 0 & 0 & a_i & b_i & c_i & 0 & 0 & 0 \\ d_i & -e_i & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & e_i & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -g_i & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -i_i & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -k_i & 0 & 0 & 0 \\ 0 & 0 & f_i & g_i & 0 & 0 & -h_i & 0 & 0 \\ 0 & 0 & 0 & 0 & i & 0 & h_i & -j_i & 0 \\ 0 & 0 & 0 & 0 & 0 & k_i & 0 & j_i & 0 \end{pmatrix}\begin{pmatrix} U_A \\ U_B \\ U_C \\ UP_A \\ UP_B \\ UP_C \\ SI_A \\ SI_B \\ SI_C \end{pmatrix} dt$$

4.22

Following equation 4.22, the model implemented in this thesis is an age-stratified, time-varying 520-stock model with a $520\ x\ 520$ coefficient matrix updated yearly from 2006 to 2030 and kept fixed from 2031 to 2050. It was implemented in Python with the specialised *NumPy* library, suitable for vectorised operations (Harris et al., 2020).

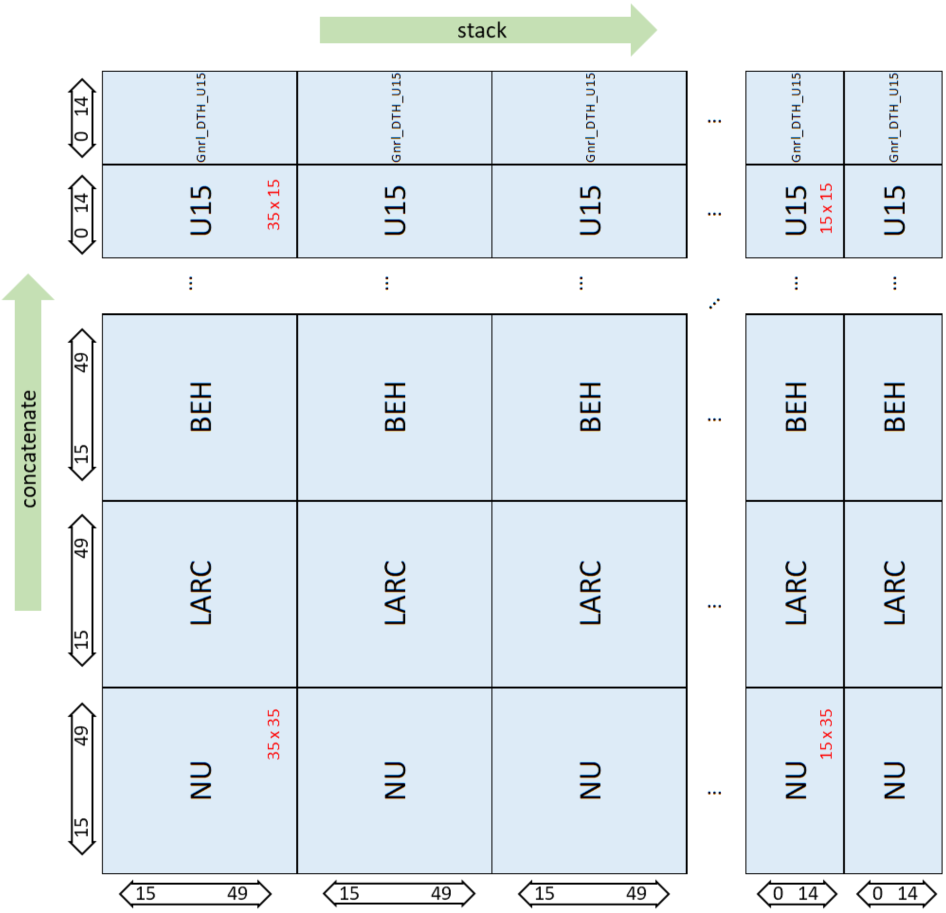
The time-varying coefficient matrix was composed with the following algorithm implemented in Python (see also Figure 4.29):

For eq in 4.1 to 4.16:
    if $eq \neq 4.15$ | $eq \neq 4.16$:
        for $summand$ in eq:
            if $summand$ has negative sign, indicating outflow:
                Generate 35×35 diagonal matrix; diagonal elements are age-stratified raw parameters.
                Save matrix to $summand_{out}$, assigning a null matrix if there are no outflows from the stock to which eq refers.
        Sum $summand_{out}$ matrices to create outflow diagonal matrix (S_{out}).
            else (summand has positive sign -inflow-):
                Generate 35×35 lagged diagonal matrix; lagged diagonal elements are maturation fractions to shift females from one age group into the next.
                Save matrix to $summand_{agein}$.
        Update S_{out} by adding the $summand_{agein}$ matrix.
                if summand does not relate to $U15$ | $Gnrl\_DTH\_U15$:
                    Generate 35×35 diagonal matrix; diagonal elements are age-stratified raw parameters.
                    Save matrix to $summand_{in}$, assigning a null matrix if there is no inflow from to the stock to which eq refers.
                else (summand relates to U15 | Gnrl_DTH_U15):
                    Generate 35×15 diagonal matrix; diagonal elements are age-stratified raw parameters.
                    Save matrix to $summand_{in}$, assigning a null matrix if there is no inflow from to the stock to which eq refers.
        Concatenate S_{out} and $summand_{in}$ matrices to create a 35×520 matrix (eq_{coeff}).
    else ($eq = 4.15$ | $eq = 4.16$):
        for $summand$ in eq:
            if $summand$ has negative sign, indicating outflow:
                Generate 15×35 diagonal matrix; diagonal elements are age-stratified raw parameters.
                Save matrix to $summand_{out}$, assigning a null matrix if there are no outflows from the stock to which eq refers.
        Sum $summand_{out}$ matrices to create outflow diagonal matrix (S_{out}).
            else (summand has positive sign -inflow-):
                Generate 15×35 lagged diagonal matrix; lagged diagonal elements are maturation fractions to shift females from one age group into the next.
                Save matrix to $summand_{agein}$.
        Update S_{out} by adding the $summand_{agein}$ matrix.
                if summand does not relate to $U15$ | $Gnrl\_DTH\_U15$:
                    Generate 15×35 diagonal matrix; diagonal elements are age-stratified raw parameters.
                    Save matrix to $summand_{in}$, assigning a null matrix if there is no inflow from to the stock to which eq refers.
                else (summand relates to U15 | Gnrl_DTH_U15):
                    Generate 15×15 diagonal matrix; diagonal elements are age-stratified raw parameters.
                    Save matrix to $summand_{in}$, assigning a null matrix if there is no inflow from to the stock to which eq refers.
        Concatenate S_{out} and $summand_{in}$ matrices to create a 15×520 matrix (eq_{coeff}).
Stack the eq_{coeff} matrices to compose the final 520×520 coefficient matrix.

The algorithm basically transforms each equation's summands (i.e., model parameters) into matrices of various sizes, their rows being the age classes in the stock referred by the equation, and columns being the number of age classes in the origin stock from which (if any) females move into the stock referred by the equation. For instance, equation 4.1 indicates the outflows from and inflows into the non-users' stock (NU). Given NU holds females aged 15 to 49, these 35 age classes are the rows of the matrices defined. Moreover, given NU receives inflows from LARC, BEH, TRAD, UP, INT, IP, SI, and U15, and this latter holds 15 age classes, whilst the rest hold 35, then the number of columns varies. The resulting matrices will have 35 rows and 35 columns, except for U15 that will have 35 rows and 15 columns. Despite there are no inflows to NU from PERM, INF_UP, INF_IP, M_DTH_UP, M_DTH_IP, Gnrl_DTH, and Gnrl_DTH_U15, null matrices must be defined in these cases to preserve the form of the final coefficient matrix and allow the correct operations to produce the simulation results. Thus, Gnrl_DTH_U15 will be a 35×15 null matrix, and the rest will be of size 35×35.

The algorithm then concatenates the individual matrices and produces a 35×520 matrix corresponding to the dynamics of NU and continues with the rest of equations.

Finally, with all the parameter equations converted into their respective matrix form, they are stacked to produce the 520×520 final coefficient matrix. These steps are repeated for each year during the simulation window, each of the 50 iterations, and each of the 31 hypothetical strategies tested.



$$NU(t) = NU_{prev} + [(-age_{NUout} + age_{NUin} - (s2 + \ldots + s9) - \kappa)NU_{prev} + s10\,LARC_{prev} + s19\,BEH_{prev} + s28\,TRAD_{prev} + s39(\beta_1 + \ldots + \beta_4)UP_{prev} + s51\,INT_{prev} + s60(\varepsilon_1 + \ldots + \varepsilon_3)IP_{prev} + s72\,SI_{prev} + \lambda_1 U15_{prev}]dt \quad (4.1)$$

summand

$$LARC(t) = LARC_{prev} + [(-age_{LARCout} + age_{LARCin} - s10 - (s12 + \ldots + s18) - \kappa)LARC_{prev} + s2\,NU_{prev} + s20\,BEH_{prev} + s29\,TRAD_{prev} + s40(\beta_1 + \ldots + \beta_4)UP_{prev} + s52\,INT_{prev} + s61(\varepsilon_1 + \ldots + \varepsilon_3)IP_{prev} + s73\,SI_{prev} + \lambda_2 U15_{prev}]dt \quad (4.2)$$

$$BEH(t) = BEH_{prev} + [(-age_{BEHout} + age_{BEHin} - s19 - s20 - (s22 + \ldots + s27) - \kappa)BEH_{prev} + s3\,NU_{prev} + s12\,LARC_{prev} + s30\,TRAD_{prev} + s41(\beta_1 + \ldots + \beta_4)UP_{prev} + s53\,INT_{prev} + s62(\varepsilon_1 + \ldots + \varepsilon_3)IP_{prev} + s74\,SI_{prev} + \lambda_3 U15_{prev}]dt \quad (4.3)$$

…

$$U15(t) = U15_{prev} + [(-age_{U15out} + age_{U15in} - \eta - \varphi)U15_{prev} + (s39 + \ldots + s43 + s45 + s46)\gamma\beta_1 UP_{prev} + (s60 + + s64 + s66 + s67)\gamma\beta_1 IP_{prev}]dt \quad (4.15)$$

$$Gnrl\_DTH\_U15(t) = Gnrl\_DTH\_U15_{prev} + [\eta U15_{prev}]dt \quad (4.16)$$

Figure 4.29. Composition of the $520x520$ coefficient matrix used in the vectorised system dynamics simulation model.

A time progression vector sized 90 ($45\ years\ x\ dt^{-1} = 90;\ where\ dt = 0.5\ years$) was defined to traverse from 2006 to 2050 and update the $\boldsymbol{s}(t)$ vector after multiplying the coefficient matrix by the vector of previous $\boldsymbol{s}(t - dt)$ values. The updated stock values are collected in a $520\ x\ 90$ matrix which reports results for each of the 50 iterations in each hypothetical policy tested in this thesis (see section 6.1, and number 3 in the workflow presented in Figure 4.28).

With the goal of balancing computational feasibility and the need to represent variability in model outputs, fifty iterations were considered to be sufficient to estimate the stochastic parameter matrices, conduct the full range of experiments, and produce the cost-effectiveness analysis. Given the described complexity of the model, which comprises more than five hundred differential equations to be solved with a matrix version of Euler's method, such a number of iterations provided visually reasonable uncertainty intervals at a reasonable running time (Currie & Cheng, 2013).

4.4 Chapter summary

Chapter four presented the working mechanisms and assumptions of the model developed in this thesis, and a detailed account of parameter estimation in three broad categories (i.e., demographic, behavioural, clinical). The full process of vectorisation to allow a stochastic, endogenously driven, age-structured, and time-varying model was also detailed in this chapter.

Chapter 5 Verification and Validation

5.1 Model initialisation

The simulation spanned 45 years, from 2006 to 2050, to include the final years of the Millennium Development Goals initiative (MDGs, 2006-2015), the full Sustainable Development Goals era (SDGs, 2015-2030), and a twenty-year window post-SDG. Initial values of stocks pertaining to WoRA (N= 28.4 million) were obtained from the 2006 wave of ENADID survey and are shown in Figure 5.1. Stocks pertaining to maternal-related deaths (i.e., *M_DTH_UP, M_DTH_IP*) and all-cause deaths (i.e., *Gnrl_DTH*) were initialised at zero, thus are not shown in the figure.

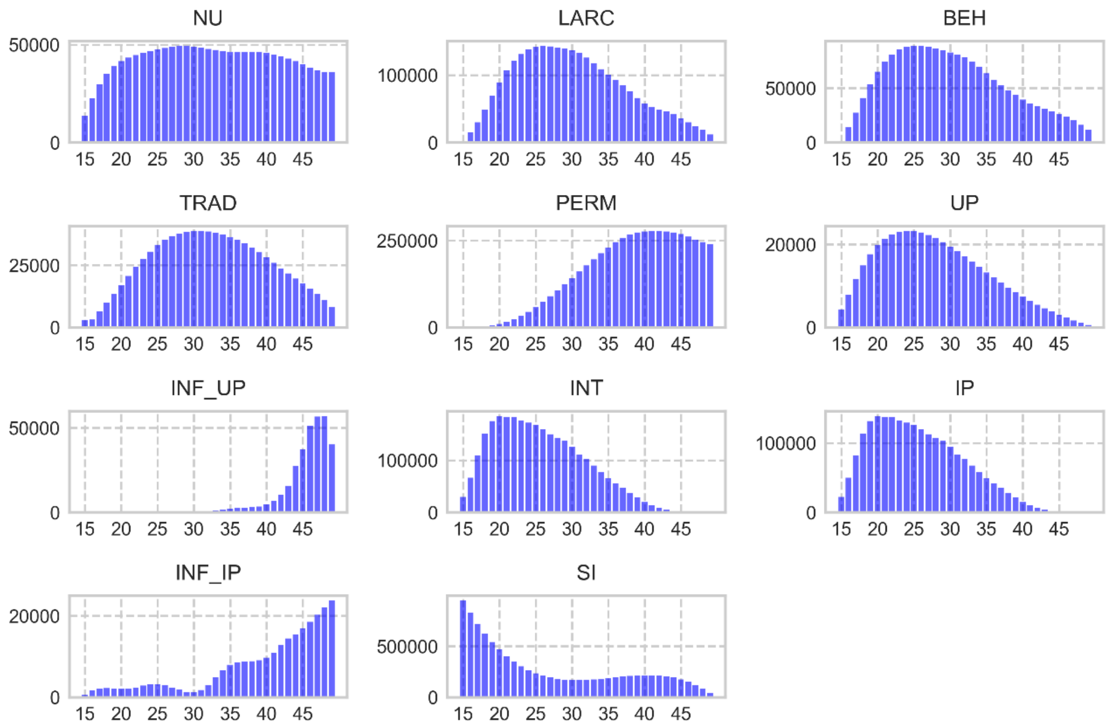


Figure 5.1. Initial values of WoRA used in the simulation model.

Note: 1) x-axis represents age classes; 2) y-axis represents population totals in absolute numbers; 3) Figure headings are ***NU***: Sexually active, Non-user of contraception; ***LARC***: Sexually active, user of long-acting reversible contraception; ***BEH***: Sexually active, user of behavioural-dependent contraception; ***TRAD***: Sexually active, user of traditional contraception; ***PERM***: Sexually active, permanent contraception user; ***UP***: Unintentionally pregnant; ***INF_UP***: Infertile secondary to unintended pregnancy; ***INT***: Sexually active, non-user of contraception, and trying to be pregnant; ***IP***: Intentionally pregnant; ***INF_IP***: Infertile secondary to intended pregnancy ends; ***SI***: Sexually inactive.

Population counts of girls aged 0 to 14 years were sourced from the National Population Council's (CONAPO) population projections 1950-2050 (Consejo Nacional de Población, 2023) (Table 5.1).

Table 5.1. Initial values for stocks related to girls aged 0 to 14 years.

Age class	Initial stock value (population total)
0	1,103,428
1	1,106,163
2	1,105,850
3	1,104,853
4	1,104,692
5	1,103,544
6	1,101,812
7	1,100,701
8	1,101,600
9	1,104,928
10	1,109,161
11	1,111,490
12	1,109,368
13	1,105,311
14	1,099,020

5.2 Verification and validation

After the full model was parameterised, tests to verify the model's ageing mechanism, behaviour against extreme values, and stock nonnegativity were conducted. These tests functioned as a first step in confirming this model's suitability in answering the proposed research questions. The next step was to compare model results against selected extant demographic and sexual and reproductive health indicators.

The present section describes the result of an iterative procedure conducted to verify and validate the model. Whenever model structure or simulation results were deemed unfeasible, its parameters and structure were revised, and the tests were reattempted until reasonable results were obtained.

5.2.1 Verification

Three main tests were conducted to verify that the model structure was working properly. The first consisted in corroborating the ageing mechanism, which is central to the model given that allows the female population to shift forward into the next age group with every timestep. To set up the test, a single cohort of one million newly born females (aged 0) was introduced to the simulation in 2006 and aged at a timestep of one year until 2050. To simplify the test, migration and death probabilities were cancelled, together with the probability of pregnancy by assuming perfect protection in all contraceptive categories, and widespread unwillingness to become pregnant. Movements between stocks were preserved. Figure 5.2 shows the results after running the simulation with these settings. As expected, the million women introduced in 2006 ages out and shifts into the next age group until the simulation ends. The simulation ends five years before women turn 49, at age 44, given the simulation period is of 45 years.

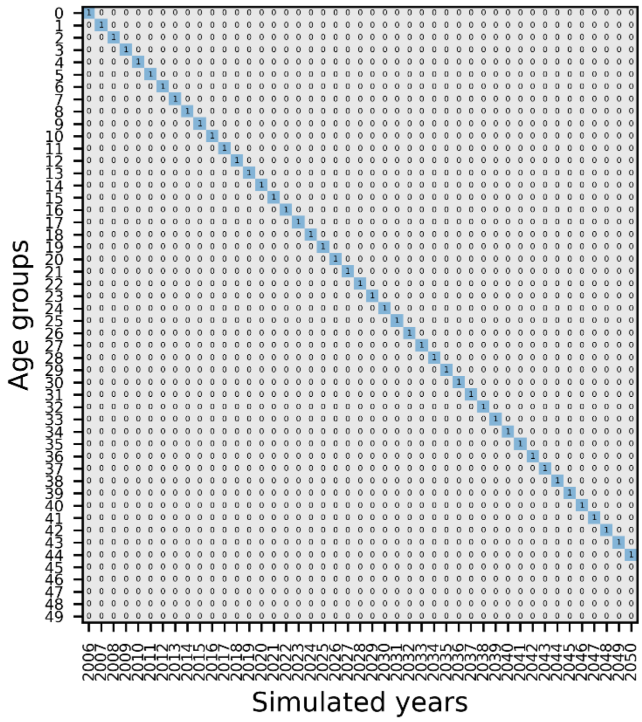


Figure 5.2. Ageing mechanism test for a single cohort of females.

Note: Numbers are scaled to millions.

The second test consisted in an extreme value test aiming to simulate a hypothetical strategy in which no girls joined the population of WoRA upon reaching the age of 15, and no female babies were born. The anticipated outcome was a gradual depletion of the WoRA cohort at each age, reflecting the natural ageing process without new female additions. To model this, the birth rate of female babies and the initial stocks of girls aged 0-14 were both set to zero.

Figure 5.3 shows the test results in a panel of subgraphs were each represent the stratified evolution of the different age groups considered in the simulation. Ages 0 to 14 show no population in concordance with how the test was devised, i.e., cancelling new female babies being born, and initialising younger-than-15-years age groups at zero. Starting at age fifteen, women move through the different age groups as they grow older, and with the cancelled introduction of new WoRA, their population counts plummet to zero as time moves forward.

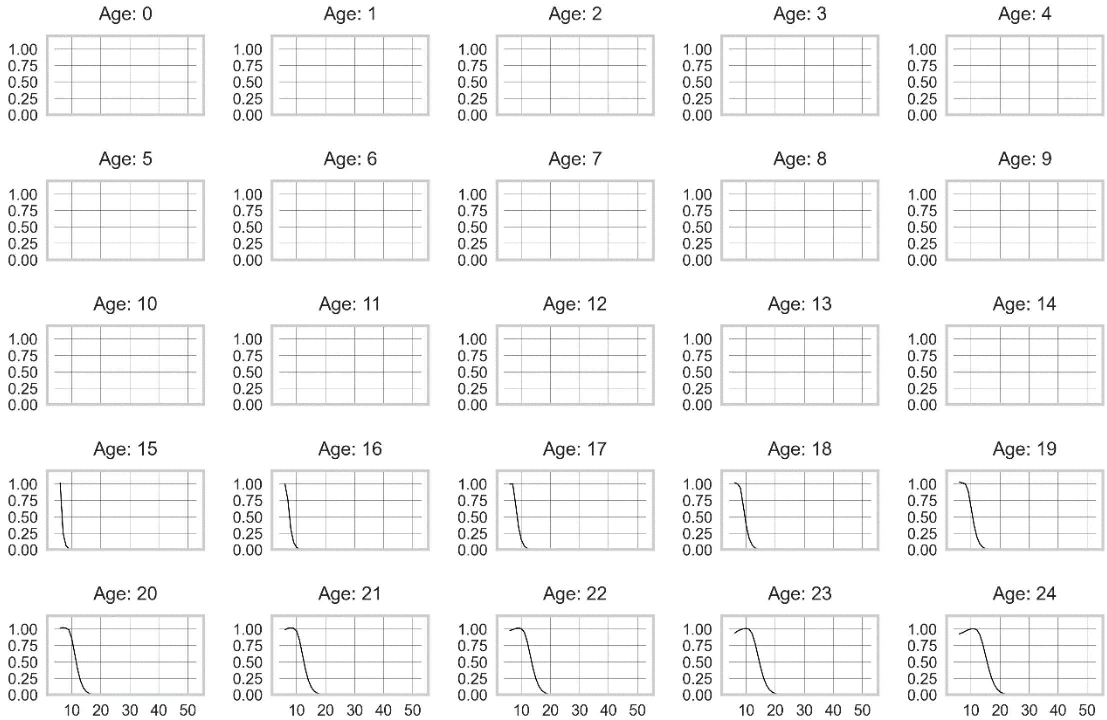


Figure 5.3. Extreme value test. Females aged 0 to 24 when introduction of new WoRA is cancelled.

Note: x-axis represents simulation years, stepped in ten-year groups; y-axis represent population totals in millions.

This behaviour is also observed in Figure 5.4, which presents the results of this test for females aged 25 to 49 years.

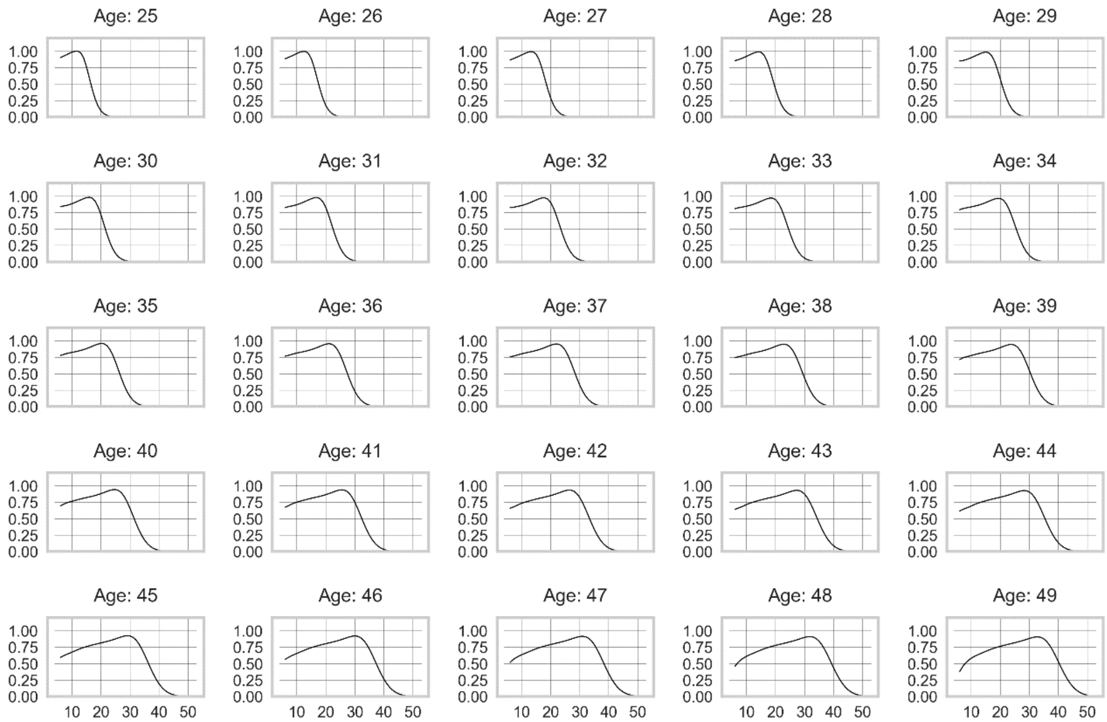


Figure 5.4. Extreme value test. Females aged 25 to 49 when introduction of new WoRA is cancelled.

Note: x-axis represents simulation years, stepped in ten-year groups; y-axis represent population totals in millions.

Finally, it was verified that no stock reached negative values throughout the simulation at any of the 50 model iterations. This is presented, for a single iteration, in a panel of heatmaps in Figure 5.5. Each panel represents a simulated stock, together with its maximum and minimum values, showing no negative values were obtained at any stock whilst running the model. Although not presented in this document, this was also assessed in the rest of model iterations with similar results and the same conclusion of stock nonnegativity.

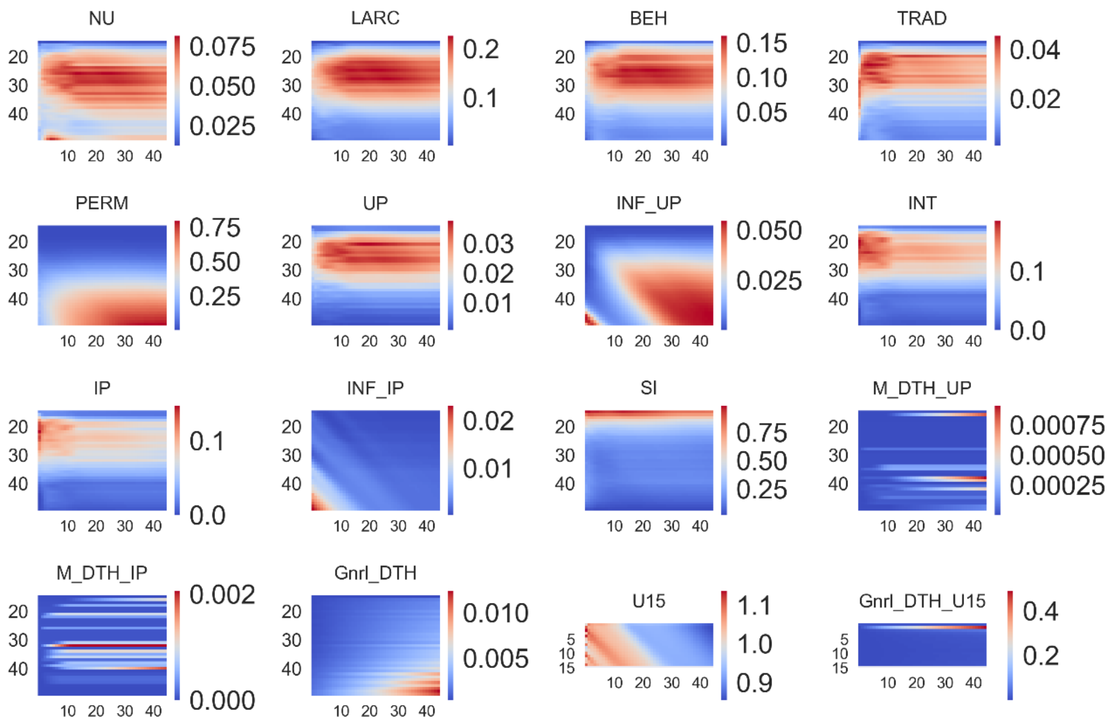


Figure 5.5. Simulation model's nonnegativity test.

*Note: In each figure, x-axis represents simulated years, and y-axis represents age groups. Y-axis is shorter in **U15** and **Gnrl_DTH_U15** given these stocks represent females aged 0 to 14. Plotted stocks: **NU**: Sexually active, non-user of contraception; **LARC**: Sexually active, user of long-acting reversible contraception; **BEH**: Sexually active, user of behavioural-dependent contraception; **TRAD**: Sexually active, user of traditional contraception; **PERM**: Sexually active, permanent contraception user; **UP**: Pregnant, unintentionally; **INF_UP**: Infertile secondary to unintended pregnancy; **INT**: Sexually active, non-user of contraception, and intending to be pregnant; **IP**: Pregnant, intentionally; **INF_IP**: Infertile secondary to intended pregnancy; **SI**: Sexually inactive; **M_DTH_UP**: Maternal death attributable to UP; **M_DTH_IP**: Maternal death attributable to IP; **Gnrl_DTH**: All-cause deaths, WoRA; **U15**: Girls aged 0 to 14 years; **Gnrl_DTH_U15**: All-cause deaths, females aged 0 to 14.*

5.2.2 Validation

To establish the robustness of the model results, these were compared against real-world benchmarks drawn from public official sources. The selected indicators fall into one of two categories: 1) Demographic, or 2) Sexual and Reproductive Health. The first category deals with population evolution over time, whilst the second includes important topic-related indicators such as crude fertility rate, and maternal mortality ratio.

5.2.2.1 Demographic indicators

The simulated population of WoRA from 2006 to 2050 was derived by composing a time series of the form:

$$WoRA = (WoRA_{2006}, WoRA_{2007}, WoRA_{2008}, \ldots, WoRA_{2050}) \tag{5.1}$$

Where every element is estimated as the sum of alive women at NU, $LARC$, BEH, $TRAD$, $PERM$, UP, INF_UP, INT, IP, INF_IP, and SI across age classes for each year. Figure 5.6 shows the simulated trend of WoRA from 2006 to 2050. The dotted, gray-coloured line and band depict simulation results and their 95% uncertainty interval (UI), respectively; the dashed, blue-coloured line represents population projection estimates, and red crosses are the single data points for population censuses.

Two diagnostic metrics are presented in the legend box as a quantitative comparison of the simulation results: mean absolute percentage error (MAPE) and R^2 score. There are important things to notice. First, the trend estimated by the CONAPO projection is consistently higher than the simulated trend and the INEGI population counts. Second, the simulation results offer a better fit to data points of the 2010, and 2020 census data. The MAPE and R^2 metrics indicate that the model follows the female population development with good agreement, given its good fit to the official benchmark data. From 2021 on, the CONAPO population projections lie within the simulation's 95% UI. Both the CONAPO projection and the simulation results show an increasing trend followed by a decline in the female population by 2050, related to decreasing fertility levels over time (see Figure 5.6).

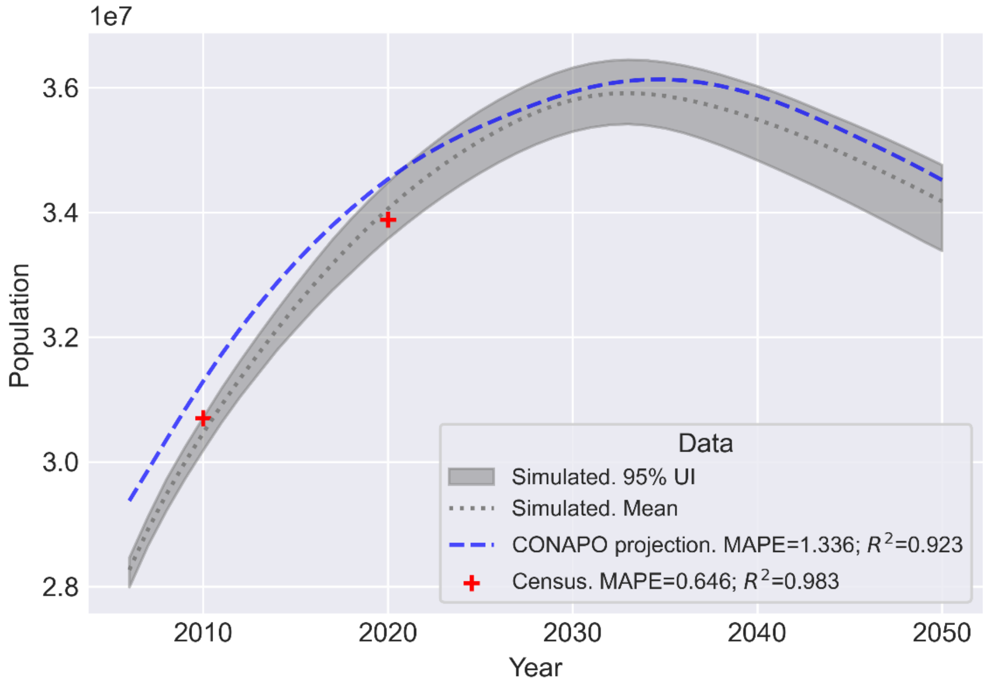


Figure 5.6. Total Mexican female population of reproductive age (15 to 49 years), 2006-2050.

The simulated $U15$ and WoRA populations were disaggregated in single-year age groups to further inspect their development and agreement to the CONAPO projections (Figure 5.7 and Figure 5.8). In general, both trends are in good correspondence, with ages 21 and older offering the best fit. The trends for newly born up to those of girls aged 14 show a consistent decrease from 2006, which is more pronounced in the simulation results, and influences the observed trends for the rest of age classes. This continues from ages 15 to 19 when there is a slight increase in the trend by 2020 to then start declining at a slower pace than the youngest age groups (newly born to 14 years).

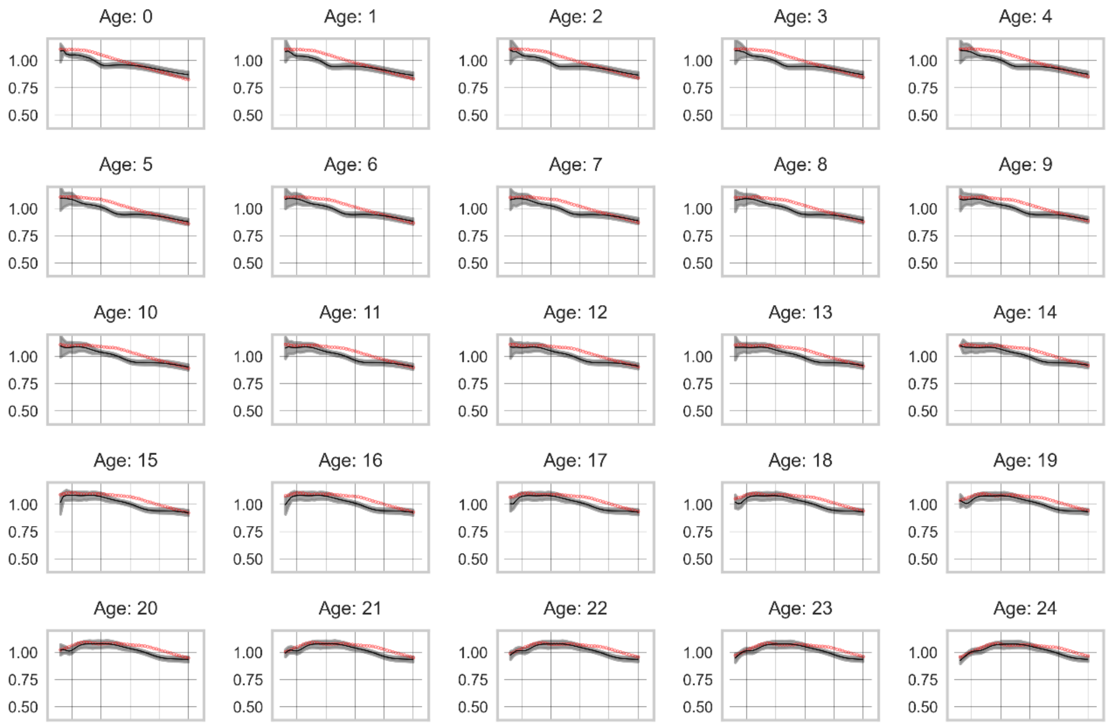


Figure 5.7. Mexican female population aged 0 to 24 years, 2006-2050.

Note: x-axis: simulated years; y-axis: female population total (in millions); the gray-coloured dotted line and band represent simulated data, and 95% uncertainty interval, respectively; red circles are the CONAPO projection data.

This peak manifests later in the older age groups, if at all. The trends for females aged 20 to 26 peak by 2020 to then start declining; females aged 27 to 30 peak between 2020 and 2030; females aged 31 to 42 have their trends peaking between 2030 and 2040.

The oldest age groups, from 43 up to 49 follow ever-increasing trends that have yet to see their peaks. As previously stated, these described patterns are influenced by the diminishing inflow of newly born females over time given declining fertility rates. This results in the population of younger/more mature females reaching a maximum value by 2020, 2030, or 2040 and then start declining. The population of older females, on the other hand, is still growing and will reach its peak at a time outside the simulation's time bounds.

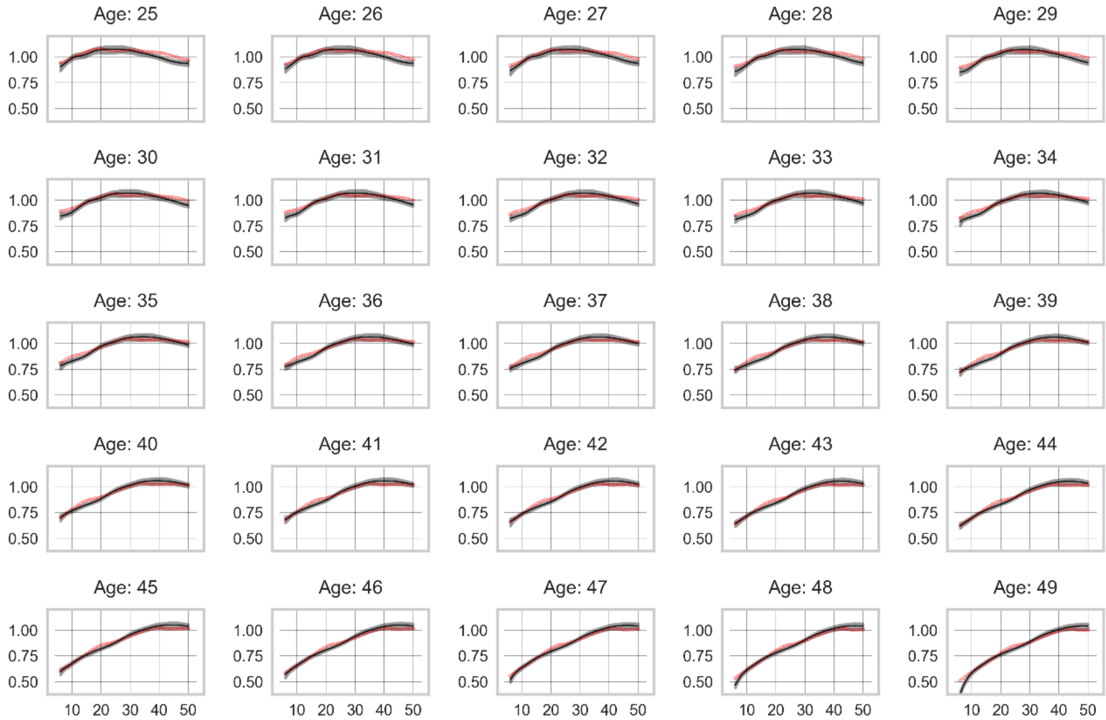


Figure 5.8. Mexican female population aged 25 to 49 years, 2006-2050.

Note: x-axis: simulated years; y-axis: female population total (in millions); the gray-coloured dotted line and band represent simulated data, and 95% uncertainty interval, respectively; red circles are the CONAPO projection data.

Table 5.2 below shows the MAPE resulting after comparing the simulation results and the CONAPO projections. As noted previously the fit is very good overall, with a MAPE of less than 5% in all analysed age groups. The youngest age groups, from newly born females to 20-year-olds, have a MAPE between 3.155% (age 20) and 4.063% (age 1). From 21 until the end of the reproductive years, the average MAPE is less than 3%, getting as low as 1.906% at age 35, and high as 2.948% at age 21.

Table 5.2. Simulation model fit to CONAPO projections, from 0 to 49 years.

Age group	MAPE[1]	Age group	MAPE[1]	Age group	MAPE[1]
0	3.825	17	3.759	34	1.938
1	4.063	18	3.616	35	1.906
2	4.045	19	3.378	36	1.876
3	4.007	20	3.155	37	1.858
4	3.937	21	2.948	38	1.843
5	3.859	22	2.762	39	1.834
6	3.809	23	2.614	40	1.849
7	3.774	24	2.491	41	1.869
8	3.758	25	2.376	42	1.868
9	3.73	26	2.284	43	1.854
10	3.697	27	2.222	44	1.832
11	3.727	28	2.147	45	1.809
12	3.704	29	2.084	46	1.831
13	3.69	30	2.025	47	1.958
14	3.602	31	1.999	48	2.189
15	3.782	32	1.967	49	2.743
16	3.809	33	1.936	-	-

[1]*Mean absolute percentage error.*

Five-year population pyramids were also prepared to verify the correspondence of the simulated population to official datasets. The population projections prepared by the Mexican National Population Council (CONAPO), and National Population Census data for 2010 and 2020 were used to contrast the simulated demographic results. The CONAPO projections range from 1950 to 2050, are obtained with time series forecasting and updated regularly, being the most recent estimate for the year 2015 (Consejo Nacional de Población, 2023). Data points obtained via the censuses are sporadic because of their collection frequency of ten years, thus only two census data points are included in the simulation timeframe, for years 2010 and 2020.

Two official data sources were used to draw reference modes and benchmark the simulation's demographic results. The first were official population counts produced by INEGI at the 2010 and 2020 national censuses. The second comparator were the 1950-2050 official population projections produced by CONAPO, from which a subset ranging from 2006-2050 was selected to align with the simulation's initiation year.

Figure 5.9 compares INEGI population censuses -red-coloured bars - against simulation data - gray-coloured -. The fit to the population censuses is very good for 2010 and 2020, both years showing a MAPE less than 2.5%. The population shows an ongoing ageing process from 2010 to 2020, expressed in an increasing proportion of females aged 25 to 49, whilst the rest of age bands saw an either stalled (20 to 24 years) or reduced proportion (newly born to 19).

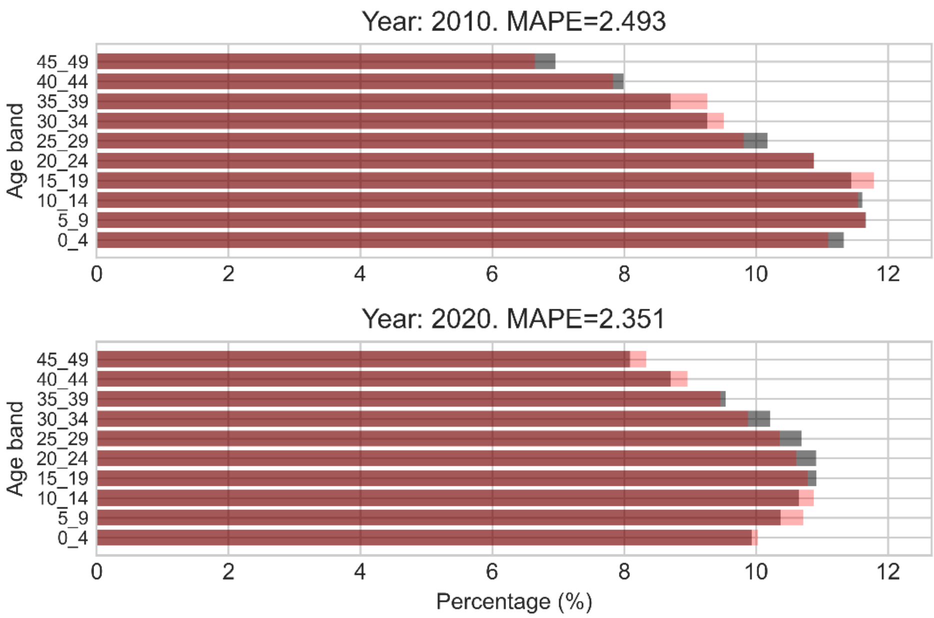


Figure 5.9. 2010 and 2020 population pyramids. INEGI censuses v simulation results.

Note: red-coloured bars represent the 2010, and 2020 INEGI population censuses; gray-coloured bars represent simulated data.

Figure 5.10 shows the population pyramids comparing the CONAPO projections (red-coloured bars) to the simulated data (grey-coloured). There are more selected decades in this comparison, from 2010 to 2050. As with the previous case, there is evidence of good fit, with the largest MAPE of 3.044% occurring in 2030. The ongoing ageing process described above becomes more evident in this figure, as female population vacate the youngest age groups to move into the oldest. Thus, the base of the pyramid is expected to become narrower and to widen at the top over time, making older female age groups the most prevalent.

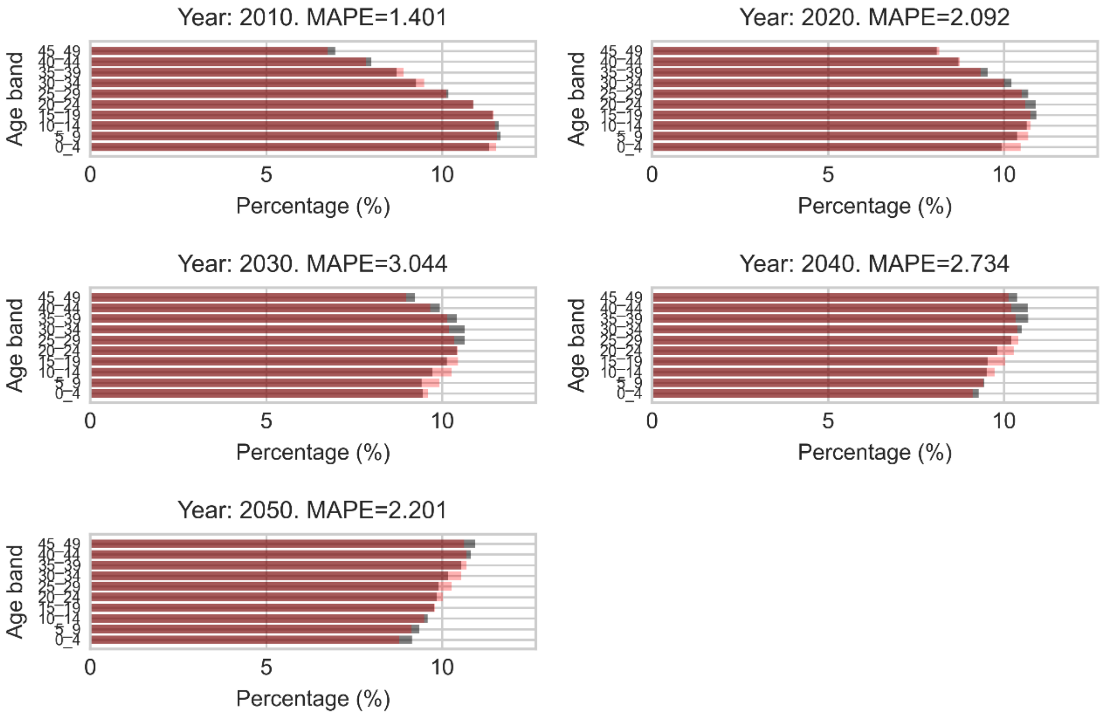


Figure 5.10. Population pyramids for selected years. CONAPO population projections v simulated population.

Note: red-coloured bars represent the 2010, and 2020 INEGI population censuses; grey-coloured bars represent simulated data.

5.2.2.2 Sexual and Reproductive Health indicators

The two indicators used to compare the performance of the contraceptive, sexual, and reproductive dynamics depicted in the simulation model were selected given their widespread use in programme planning and in topic-specific literature. Crude fertility rate (CFR) is defined as the number of livebirths compared to WoRA during a specific period (Statistics Finland, n.d.), which was yearly to this thesis. As with the demographic indicators, data from the CONAPO projections were queried from 2006 to 2050 to obtain a first CFR comparator. A second comparator was estimated from the national registry of livebirths, reporting events from 2006 until 2020, and the number of WoRA estimated via the intercensal survey 2005, and the population censuses 2010, and 2020. Since only three years were available after collecting data from the intercensal survey and censuses, linear interpolation was implemented to fill in data gaps.

To estimate CFR from the simulation model, a time series of the total yearly livebirths between 2006 and 2050 was first composed by doing:

$$LB = (LB_{2006}, LB_{2007}, LB_{2008}, \dots, LB_{2050}) \tag{5.2}$$

Where every element is estimated as follows:

$$LB_i = \sum_{j=15}^{49} LBfrUP_{i,j} \times UP_{i,j} + \sum_{j=15}^{49} LBfrIP_{i,j} \times IP_{i,j}$$

5.3

Where i represents the year, from 2006 to 2050, and j is the age class, from 15 to 49 years; $LBfrUP_{i,j}$ and $LBfrIP_{i,j}$ are the probabilities of unintended/intended pregnancies ending in a livebirth at year i and age j, respectively; and $UP_{i,j}$ and $IP_{i,j}$ are the stocks containing unintended/intended pregnancies at year i and age j, respectively.

Finally, CFR was estimated by doing:

$$CFR_i = \frac{LB_i}{WoRA_i} \times 1000$$

5.4

Where i represents the year, from 2006 to 2050; LB_i are livebirths estimated with equation 5.3 at year i; $WoRA_i$ are women of reproductive age estimated as the sum of alive women at NU, $LARC$, BEH, $TRAD$, $PERM$, UP, INF_UP, INT, IP, INF_IP, and SI across age classes for each year i. The ratio is presented as births per thousand women in Figure 5.11 below.

The agreement between the simulated and the official sources of data shown in the figure is fair, with a MAPE below 7%, and an average R^2 score of 0.725. The simulated CFR always underestimates the 2006-2020 CFR estimated from the official live birth registry maintained by INEGI. Better metrics are obtained when comparing the simulated CFR against the CFR estimated from the CONAPO projection; in such case, the MAPE is below 4.5% and R^2 score around 0.85, with the trend being noticeably underestimated in the simulation model most of the time. In the later simulation years, however, both trends tend to converge until crossing by 2039. In the final years, the CFR estimated with CONAPO data tend to decrease at a faster pace than simulated data to reach a minimum of around 48 live births per thousand women. In contrast, the simulated CFR seems to reduce at a slower pace and even stabilise at around 51 live births per thousand females by 2050.

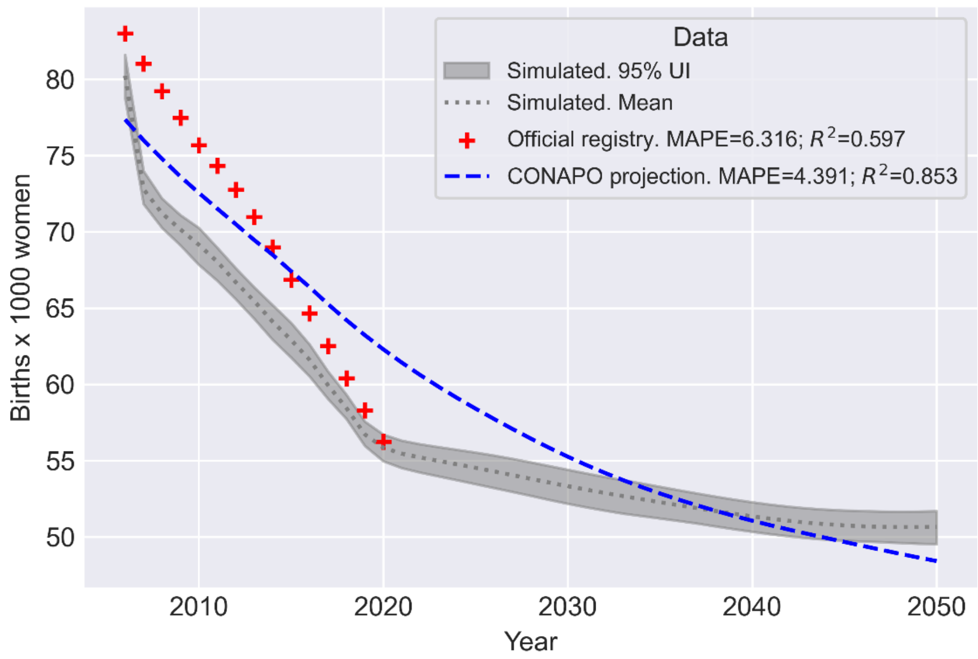


Figure 5.11. Crude fertility rate. Mexico, 2006-2050.

Maternal mortality ratio (MMR) is the number of maternal deaths compared to livebirths during a specific period, typically one year (World Health Organization, 2024c). To estimate MMR with official sources, reported figures of maternal deaths during 2006-2020 were obtained from the death registry maintained by INEGI (Instituto Nacional de Estadística y Geografía, 2019b). Yearly livebirths during 2006-2020 were obtained from the national registry of livebirths.

To estimate MMR from the simulation model, a time series with the number of maternal deaths was first composed by doing:

$$MatDth = (MatDth_{2006}, MatDth_{2007}, MatDth_{2008}, \dots, MatDth_{2050}) \quad 5.5$$

Where every element is estimated as:

$$MatDth_i = \sum_{j=15}^{49} MatDthfrUP_{i,j} \times UP_{i,j} + \sum_{j=15}^{49} MatDthfrIP_{i,j} \times IP_{i,j} \quad 5.6$$

Where i represents the year, from 2006 to 2050, and j is the age class, from 15 to 49 years; $MatDthfrUP_{i,j}$ and $MatDthfrIP_{i,j}$ are the probabilities of unintended/intended pregnancies ending in a maternal death at year i and age j, respectively; and $UP_{i,j}$ and $IP_{i,j}$ are the stocks containing unintended/intended pregnancies at year i and age j, respectively.

Finally, MMR was estimated as:

$$MMR_i = \frac{MatDth_i}{LB_i} \times 100{,}000$$

5.7

Where i represents the year, from 2006 to 2050; $MatDth_i$ are maternal deaths estimated with equation 5.6 at year i; LB_i are livebirths estimated with equation 5.3 at year i. The ratio is presented as deaths per 100k livebirths in Figure 5.12.

Agreement between the simulated and the official MMR is also fair, with a MAPE of 5.265 and R^2 score of 0.68. From 2006 to 2019 the simulated and official MMR are very similar, disagreeing noticeably during the two following years (2020, 2021) on which the official MMR spiked as a likely outcome of the COVID-19 pandemic. The simulated MMR's broad uncertainty interval, however, includes these two extreme data points. From 2020 on, the simulated MMR stabilises at roughly 35 maternal deaths per 100k thousand live births, with lower and upper bounds of roughly 14 and 60, respectively.

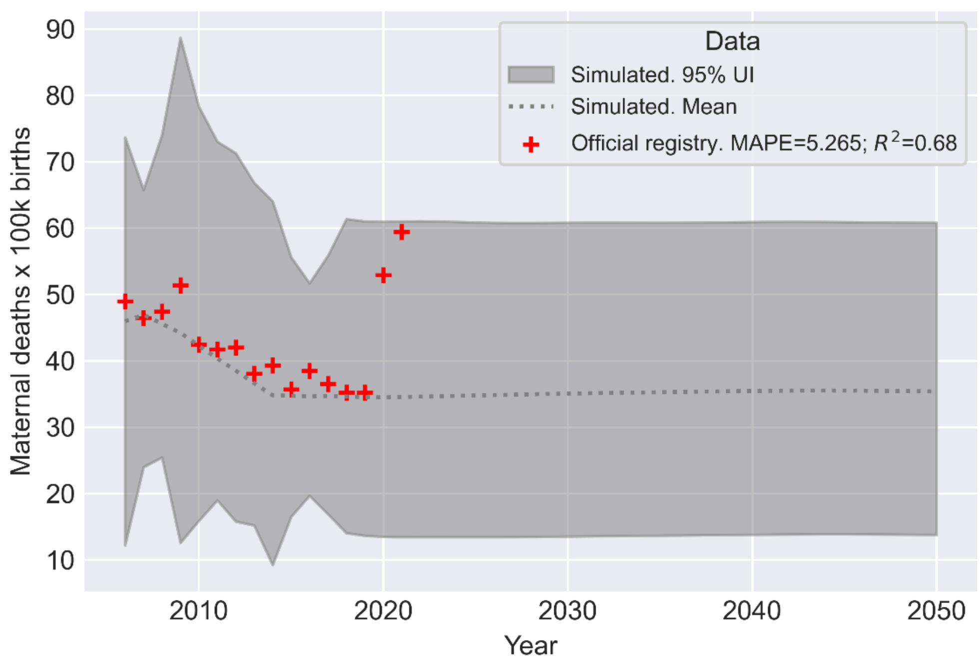


Figure 5.12. Maternal mortality ratio. Mexico, 2006-2050.

5.3 Chapter summary

Chapter five presented the initial values of parameters used to initialise the model. Verification of model structure, together with validation of results against demographic, sexual and reproductive health indicators are also presented.

Chapter 6 Experimentation and Cost-Effectiveness Analysis

After model results were deemed satisfactory via verification and validation, the contraceptive, sexual and reproductive dynamics model was used to test a set of policies aimed at reducing unintended pregnancies, maternal deaths, and unsafe abortions across all age groups. This chapter firstly introduces the hypothetical strategies tested, including their actual implementation in the simulation model.

Afterwards, the simulation model devised is used to conduct a cost-effectiveness analysis (CEA) of a variety of contraceptive provision strategies, all relevant to the Mexican context. A CEA is, basically, a comparison of the differential costs and consequences that arise when comparing different strategies against the *status quo,* or business-as-usual strategy. The specifics of health outcome, total cost, and cost-effectiveness estimation, together with a sensitivity analysis, are detailed in sections 6.2.1, 6.2.2, 6.2.3, 6.2.4,respectively.

6.1 Rationale and proposed policies

Compared to competing interventions such as sexual abstinence or delaying sexual debut to an older age, contraception has been demonstrated to be the most efficient intervention in avoiding unintended pregnancy in countries of all income levels, with health- and economic-related benefits associated to its practice (see Introduction). Because of this frequently documented result, only contraceptive provision strategies were tested in this thesis.

Those provision strategies can be categorised using the three characteristic phenomena of the contraceptive, sexual, and reproductive dynamics: 1) Contraceptive switching; 2) Discontinuation; 3) Adoption. The list of disaggregated hypothetical strategies includes feasible policies[1] for the Mexican context, given its provisioning system's infrastructure and available resources. Some of them are already underway (Kuri-Morales et al., 2020), and this research investigates their long-term effect on selected outcomes.

1. Contraceptive switching, which addresses current contraceptive users and consists in preventing users of more effective, modern reversible contraceptives from changing their contraceptive method to traditional. There are two instances of this strategy:
    a. Moving from long-acting, reversible contraception (LARC) to traditional contraception (TRAD).
    b. Moving from behaviour-dependent contraception (BEH) to TRAD.
2. Method discontinuation, which also addresses current contraceptive users and consists in preventing users of any contraceptive, modern or traditional, from becoming non-users despite they do not intend to become pregnant and being sexually active. There are three instances of this strategy:
    a. Prevent LARC users moving to non-use (NU).
    b. Prevent BEH users moving to NU.
    c. Prevent TRAD users moving to NU.
3. Contraceptive adoption, which addresses current non-users that are sexually active, and do not want to become pregnant. The strategy consists in incentivising non-users to become modern contraceptive users across all age groups.
4. Modern contraceptive adoption in hospital settings, which addresses contraceptive uptake after an intended or unintended pregnancy ends in childbirth, stillbirth, or abortion. The first two cases (i.e., childbirth, stillbirth) refer to post-partum contraception, and the methods on offer are the same as those available at health clinics (i.e., LARC, BEH) plus female sterilisation (PERM). The latter case refers to post-abortion contraception of women developing the most severe complications of abortion and thus end up receiving healthcare at the hospital level. Like in post-partum contraceptive provision, the contraceptives on offer are the same as in health clinics plus female sterilisation.
5. Switching, discontinuation, and adoption. The strategy combines all the above to produce an integral policy aiming to deter switching from modern to traditional

[1] All policies refer to voluntary, non-coercive contraception. Intention to become pregnant always govern modifications to contraceptive practices.

contraceptive methods, prevent discontinuation, and raise uptake at all age groups, and in hospital settings.

6. Do nothing, i.e., status quo (SQ). This strategy implies that no additional effort is undertaken to improve contraceptive coverage levels, and thus reducing unintended pregnancies.

The strategies were implemented in a stepwise logic to linearly improve coverage by 25%, 50%, or 75% between 2023 and 2030, remaining fixed thereafter until 2050. Under this logic, a desired improvement by 2030 was set (e.g., 50% improvement from its original level in 2022) and was distributed evenly between the eight years in the 2023-2030 period. In this way, with a desired improvement of fifty percent by 2030, the yearly improvement rate needed to be 6.25%. The improvement set by 2030 was then fixed until 2050.

Such an approach allowed to estimate the effect of an ambitious, gradually increasing commitment during the final years of the Sustainable Development Goals era (2023-2030) and a consistent and long-lasting effort towards maintaining this contraceptive coverage level two decades past (2031-2050). This is a more credible approach than assuming an immediate change between consecutive years (see section 2.2), which may imply an abrupt modification of the operating conditions of the contraceptive provision programme.

6.2 Cost-effectiveness analysis

A full economic evaluation of any form, i.e., cost-effectiveness, cost-benefit, cost-utility analysis, is complete after total costs and health outcomes are estimated, compared in a marginal analysis, and expressed as a ratio, i.e., the incremental cost-effectiveness (ICER), cost-benefit, cost-utility ratio. With this comparison it is possible to establish the extra costs or savings incurred with each strategy and establish the health return in exchange for the money invested in it (M. Drummond & McGuire, 2001).

The remaining sections in this chapter detail the methods followed to conduct a cost-effectiveness analysis (CEA) of different contraceptive coverage policies, using avoided unintended pregnancies as the main health outcome. Other metrics such as avoided unsafe abortions and avoided maternal deaths were also estimated given their importance in programme planning, albeit they were not included in the ICER estimation.

The analysis was conducted from the perspective of the health system, including direct medical and contraceptive provision costs. Unit costs were sourced from topic-specific literature and adjusted to 2021 US dollars. Total costs and health outcomes were estimated from 2023 to 2050 and were discounted (Severens et al., 2004) at a 5% yearly rate, as established in Mexican guidelines for the conduction of economic studies (Consejo de Salubridad General, 2023).

6.2.1 Health outcomes estimation

Unintended pregnancies, unsafe abortions, and maternal deaths were estimated to compare the performance of the 31 proposed strategies. Ultimately, only UP were used to estimate ICERs in the CEA. Avoided unintended pregnancies attributable to each strategy were estimated as the absolute difference between each and SQ.

Total unintended pregnancies from 2023-2050 were estimated as the sum of UP in the jth age group, from 15 to 49 years, for each ith simulated year in the analysis period:

$$UP_{total} = \sum_{i=2023}^{2050} \sum_{j=15}^{49} UP_{i,j} \tag{6.1}$$

Total unsafe abortions, which are assumed only to occur in the case of UP in this thesis (Bearak et al., 2020), were estimated with the below formula:

$$UA_{total} = \sum_{i=2023}^{2050} \sum_{j=15}^{49} UAfr_{i,j} \times UP_{i,j}$$

6.2

Where i represents the year, from 2023 to 2050; j is the age class, from 15 to 49 years; $UAfr_{i,j}$ is the probability that an unintended pregnancy ends in unsafe abortion at age j in year i (see section 4.2.3); and $UP_{i,j}$ is the number of unintended pregnancies at year i and age j.

Finally, the total number of maternal deaths due to UP during the 2023-2050 period were estimated as:

$$MatDth_{total} = \sum_{i=2023}^{2050} \sum_{j=15}^{49} MatDthfrUP_{i,j} \times UP_{i,j}$$

6.3

Where i represents the year, from 2023 to 2050; j is the age class, from 15 to 49 years; $MatDthfrUP_{i,j}$ is the probability that an unintended pregnancy ends in a maternal death at year i and age j (see section 4.2.2); and $UP_{i,j}$ is the number of unintended pregnancies at year i and age j.

6.2.2 Cost estimation

Direct costs attributable to contraceptive provision, along with pregnancy-related care were included into the total cost estimation for the CEA. Table 6.1 presents the unit costs (UC) used to arrive at the total cost figures. Most of the sources relate to the Mexican context and cover both contraceptive provision and pregnancy/delivery care, excepting (Mavranezouli, 2008) which was conducted in the UK and used as a proxy for the unit cost of IUD and implant removal in this thesis, given the absence of evidence for Mexico or other middle-income country.

The majority of unit costs reported in the table cover one-off events, e.g., positioning IUD, vaginal/caesarean section birth, whilst the rest refer to recurrent use of contraceptives (injectables, pills, condoms) and represent a full year of use. Antenatal control cost includes all tests and procedures provided during clinical consultations prior to delivery.

Table 6.1. Unit costs included in the cost-effectiveness analysis.

Unit cost category	Mean unit cost[1] (SD[2])	Probability distribution for PSA[3]	Source
Adoption			
LARC	24.81 (3.43)	Lognormal: mean=3.2; SD[2]=0.14	5
BEH	7.81 (5.07)	Lognormal: mean=1.88; SD[2]=0.59	6
PERM	68.55 (54.87)	Lognormal: mean=3.98; SD[2]=0.7	5
Discontinuation			
LARC	17.29 (12.03)	Lognormal: mean=2.65; SD[2]=0.63	7
Recurrent use			
BEH	41.07 (29.34)	Lognormal: mean=3.51; SD[2]=0.64	8
LARC (injectable contraceptive only)	72.61 (70.06)	Lognormal: mean=3.96; SD[2]=0.81	8
Pregnancy-related			
Childbirth	804.48 (404.48)	Lognormal: mean=6.58; SD[2]=0.47	9
Miscarriage	154.23 (19.96)	Lognormal: mean=5.03; SD[2]=0.13	10
PAC[4]	388.04 (286.78)	Lognormal: mean=5.74; SD[2]=0.66	11
Stillbirth	791.21 (394.68)	Lognormal: mean=6.56; SD[2]=0.47	12
Complications	824.96 (467.12)	Lognormal: mean=6.58; SD[2]=0.53	12

[1]In 2021 US dollars; [2]Standard deviation; [3]Probabilistic sensitivity analysis; [4]Post-abortion care, in case of unsafe abortion;[5]Own estimation from (Aracena-Genao et al., 2022; Hu et al., 2007; Hubacher et al., 1999; Singh & Darroch, 2012); [6]Own estimation from (Aracena-Genao et al., 2022; Hu et al., 2007; Hubacher et al., 1999); [7]Own estimation from (Hubacher et al., 1999; Mavranezouli, 2008); [8]Own estimation from (Aracena-Genao et al., 2022; Hubacher et al., 1999; Singh & Darroch, 2012); [9]Own estimation from (Aracena-Genao et al., 2022; Hu et al., 2007; Sosa-Rubi et al., 2019); [10]Own estimation from (Hu et al., 2007, 2009a); [11]Own estimation from (Aracena-Genao et al., 2022; Hu et al., 2009b; Levin et al., 2009; Sanchez-Morales et al., 2022; Shearer et al., 2016); [12]Own estimation from (Aracena-Genao et al., 2022; Hu et al., 2007).

Contraceptive provision costs included adoption, switching and discontinuation (removal) of methods included in the different categories, excepting those in the traditional method category, which were assumed not to accrue any provision costs: these methods do not imply interactions between the contraceptive provider, i.e., the healthcare services, and potential users.

The total cost of adopting a long-acting, reversible contraceptive from 2023 to 2050 was estimated as:

$$LARC_{adopt} = \sum_{i=2023}^{2050} \sum_{j=15}^{49} (NU_{LARC_{i,j}} + BEH_{LARC_{i,j}} + TRAD_{LARC_{i,j}} + UP_{LARC_{i,j}} + INT_{LARC_{i,j}} + IP_{LARC_{i,j}} + SI_{LARC_{i,j}}) \times UC_{LARC} \quad 6.4$$

Where $NU_{LARC_{i,j}}$ is the transition probability from non-use (NU) to long-acting, reversible contraception (LARC) multiplied by the number of non-users at age j in year i; $BEH_{LARC_{i,j}}$ is the transition probability from behavioural contraception (BEH) to LARC multiplied by the number of behavioural contraception users at age j in year i; $TRAD_{LARC_{i,j}}$ is the transition probability from traditional contraception (TRAD) to LARC multiplied by the number of traditional contraception users at age j in year i; $UP_{LARC_{i,j}}$ is the transition probability from unintended pregnancy (UP) to LARC multiplied by the number of unintended pregnancies at age j in year i; $INT_{LARC_{i,j}}$ is the transition probability from intending a pregnancy (INT) to LARC multiplied by the number of women trying to be pregnant at age j in year i; $IP_{LARC_{i,j}}$ is the transition probability from intended pregnancy (IP) to LARC multiplied by the number of intended pregnancies at age j in year i; $SI_{LARC_{i,j}}$ is the transition probability from sexual inactivity (SI) to LARC multiplied by the number of sexually inactive women at age j in year i; UC_{LARC} is the unit cost of LARC adoption, estimated as the weighted average of the unit costs of LARCs reported in (Aracena-Genao et al., 2022; Hu et al., 2007; Hubacher et al., 1999; Singh & Darroch, 2012), using the distribution of users reported in ENADID 2018 as weights: IUDs (58.71%), implants (23.06%), injectables (18.23%).

The total cost of adopting a behavioural contraceptive from 2023 to 2050 was estimated as:

$$BEH_{adopt} = \sum_{i=2023}^{2050} \sum_{j=15}^{49} (NU_{BEH_{i,j}} + LARC_{BEH_{i,j}} + TRAD_{BEH_{i,j}} + UP_{BEH_{i,j}} + INT_{BEH_{i,j}} + IP_{BEH_{i,j}} + SI_{BEH_{i,j}}) \times UC_{BEH} \quad 6.5$$

Where $NU_{BEH_{i,j}}$ is the transition probability from NU to behavioural contraception (BEH) multiplied by the number of non-users at age j in year i; $LARC_{BEH_{i,j}}$ is the transition probability from LARC to BEH multiplied by the number of LARC users at age j in year i; $TRAD_{BEH_{i,j}}$ is the transition probability from TRAD to BEH multiplied by the number of traditional contraception users at age j in year i; $UP_{BEH_{i,j}}$ is the transition probability from UP to BEH multiplied by the number of unintended pregnancies at age j in year i; $INT_{BEH_{i,j}}$ is the transition probability from INT to BEH multiplied by the number of women trying to be pregnant at age j in year i; IP_{BEH} is the transition probability from IP to BEH multiplied by the number of intended pregnancies at age j in year i; $SI_{BEH_{i,j}}$ is the transition probability from SI to BEH multiplied by the number of sexually inactive women at age j in year i; UC_{BEH} is the unit cost of BEH adoption, estimated as the weighted average of unit costs reported in (Aracena-Genao et al., 2022; Hu et al., 2007; Hubacher et al., 1999), using the distribution of behavioural users reported in ENADID 2018 as weights: pills (20.62%), condoms (79.38%.) Given the unit costs of pills and condoms reported in (Aracena-Genao et al., 2022) account for a full year of use, these were further adjusted by assuming adoption represented a share of 24.11% and 14.6% for pills and condoms, respectively (Hubacher et al., 1999).

The total cost of tubal ligation (permanent contraception) from 2023 to 2050 was estimated as:

$$PERM_{adopt} = \sum_{i=2023}^{2050} \sum_{j=15}^{49} (NU_{PERM_{i,j}} + LARC_{PERM_{i,j}} + BEH_{PERM_{i,j}} + TRAD_{PERM_{i,j}} + UP_{PERM_{i,j}} + INT_{PERM_{i,j}} + IP_{PERM_{i,j}} + SI_{PERM_{i,j}}) \times UC_{PERM} \quad 6.6$$

Where $NU_{PERM_{i,j}}$ is the transition probability from NU to permanent contraception (PERM) multiplied by the number of non-users at age j in year i; $LARC_{PERM_{i,j}}$ is the transition probability from LARC to PERM multiplied by the number of LARC users at age j in year i; $BEH_{PERM_{i,j}}$ is the transition probability from BEH to PERM multiplied by the number of behavioural contraception users at age j in year i; $TRAD_{PERM_{i,j}}$ is the transition probability from TRAD to PERM multiplied by the number of traditional contraception users at age j in year i; $UP_{PERM_{i,j}}$ is the transition probability from UP to PERM multiplied by the number of unintended pregnancies at age j in year i; $INT_{PERM_{i,j}}$ is the transition probability from INT to PERM multiplied by the number of women trying to be pregnant at age j in year i; $IP_{PERM_{i,j}}$ is the transition probability from IP to PERM multiplied by the number of intended pregnancies at age j in year i; $SI_{PERM_{i,j}}$ is the transition probability from SI to PERM multiplied by the number of sexually inactive women at age j in year i; UC_{PERM} is the average unit cost of PERM adoption reported in (Aracena-Genao et al., 2022; Hu et al., 2007; Hubacher et al., 1999; Singh & Darroch, 2012).

Only LARCs were assumed to accrue costs via method removal. Behavioural and traditional contraception do not imply further interactions between users and the health services provider when they cease to be used, thus they were assumed to have no ‘removal’ cost. The total cost of LARC discontinuation from 2023 to 2050 was estimated as:

$$LARC_{disc} = \sum_{i=2023}^{2050} \sum_{j=15}^{49} (NU_{disc_{i,j}} + BEH_{disc_{i,j}} + TRAD_{disc_{i,j}} + PERM_{disc_{i,j}} + UP_{disc_{i,j}} + INT_{disc_{i,j}} + SI_{disc_{i,j}}) \times UC_{LARC_{disc}}$$

6.7

Where $NU_{disc_{i,j}}$ is the transition probability from LARC to NU multiplied by the number of LARC users at age j in the year i; $BEH_{disc_{i,j}}$ is the transition probability from LARC to BEH multiplied by the number of LARC users at age j in the year i; $TRAD_{disc_{i,j}}$ is the transition probability from LARC to TRAD multiplied by the number of LARC users at age j in the year i; $PERM_{disc_{i,j}}$ is the transition probability from LARC to PERM multiplied by the number of LARC users at age j in the year i; $UP_{disc_{i,j}}$ is the transition probability from LARC to UP multiplied by the number of LARC users at age j in the year i; $INT_{disc_{i,j}}$ is the transition probability from LARC to INT multiplied by the number of LARC users at age j in the year i; $SI_{disc_{i,j}}$ is the transition probability from LARC to SI multiplied by the number of LARC users at age j in the year i; $UC_{LARC_{disc}}$ is the weighted average cost of LARC discontinuation reported in (Hubacher et al., 1999; Mavranezouli, 2008), estimated using the distribution reported in ENADID 2018 as weights: IUDs (58.71%), implants (23.06%), injectables (18.23%). It was further assumed that injectable contraception ‘removal’ does not accrue costs to the health services provider given that contact with the health services cease once these methods are discontinued.

The total cost of recurrent use of behavioural contraception from 2023 to 2050 was estimated as:

$$BEH_{cont} = \sum_{i=2023}^{2050} \sum_{j=15}^{49} BEH_{i,j} \times UC_{BEH_{cont}}$$

6.8

Where $BEH_{i,j}$ is the number of behavioural contraception users at age j in year i; $UC_{BEH_{cont}}$ is the unit cost of BEH recurrent use, estimated as the weighted average of the unit costs of behavioural methods reported in (Aracena-Genao et al., 2022; Hubacher et al., 1999; Singh & Darroch, 2012), using the distribution of users reported in ENADID 2018 as weights: pills

(20.62%), condoms (79.38%). Given the unit costs of pills and condoms reported in (Aracena-Genao et al., 2022) account for a full year of use, including adoption, these were further adjusted by assuming their continuous use represents a share of 75.85% and 83.4% for pills and condoms, respectively (Hubacher et al., 1999).

The total cost of continued use of long-acting (injectable) contraception from 2023 to 2050 was estimated as follows:

$$LARC_{cont} = \sum_{i=2023}^{2050} \sum_{j=15}^{49} LARC_{i,j} \times UC_{Injectable} \times Injectable_{fr}$$

6.9

Where $LARC_{i,j}$ is the number of LARC users at age j in year i; $UC_{Injectable}$ is the average unit cost of injectables reported by (Aracena-Genao et al., 2022; Hubacher et al., 1999; Singh & Darroch, 2012). Given the unit cost reported in (Aracena-Genao et al., 2022) accounted for adoption, this was previously discounted by multiplying it by 75.85% (Hubacher et al., 1999); $Injectable_{fr}$ is the fraction of LARCs that correspond to injectables (18.23%), as reported in ENADID 2018.

The estimated pregnancy-related total costs from 2023 to 2050 included childbirth, miscarriage, post-abortion care after an unsafe abortion, stillbirth, and complications leading to maternal death. Only costs associated to unintended pregnancies were estimated:

$$UP_{care} = \sum_{i=2023}^{2050} \sum_{j=15}^{49} Childbirth_{i,j} \times UC_{Childbirth} + Miscarriage_{i,j} \times UC_{Miscarriage} + UA_{i,j} \times UC_{UA} + Stillbirth_{i,j} \times UC_{Stillbirth} + MatDth_{i,j} \times UC_{Compl}$$

6.10

Where $Childbirth_{i,j}$ is the number of unintended pregnancies multiplied by the fraction ending in a live birth at age j in year i; $UC_{Childbirth}$ is the unit weighted average cost of childbirth, estimated with the unit costs of vaginal and caesarean section births reported in (Aracena-Genao et al., 2022; Hu et al., 2007; Sosa-Rubi et al., 2019), using the delivery distribution reported in ENADID 2018 as weights: vaginal birth (64.1%), caesarean section (35.9%), and adding the unit cost of antenatal care; $Miscarriage_{i,j}$ is the number of unintended pregnancies multiplied by the fraction ending in miscarriage at age j in year i; $UC_{Miscarriage}$ is the average unit cost of miscarriage treatment reported by (Hu et al., 2007, 2009a); $UA_{i,j}$ is the number of unintended pregnancies multiplied by the fraction ending in unsafe abortion at age j in year i; UC_{UA} is the average unit cost of unsafe abortion treatment, i.e., manual vacuum aspiration, curettage and medicated abortion reported in (Aracena-Genao et al., 2022; Hu et al., 2009b; Levin et al., 2009; Sanchez-Morales et al., 2022; Shearer et al., 2016); $Stillbirth_{i,j}$ is the number of unintended pregnancies multiplied by the fraction ending in stillbirth at age j in year i; $UC_{Stillbirth}$ is the stillbirth average unit cost reported in (Aracena-Genao et al., 2022; Hu et al., 2007); $MatDth_{i,j}$ is the number of unintended pregnancies multiplied by the fraction ending in maternal deaths at age j in year i; UC_{Compl} is the average unit cost of pregnancy- and delivery-related complications reported in (Aracena-Genao et al., 2022; Hu et al., 2007).

Finally, the cumulative 2023-2050 total cost to the contraceptive provision programme, along with pregnancy and delivery care associated to unintended pregnancy was estimated by adding the previously estimated costs:

$$ContrProgr_{TC} = LARC_{adopt} + BEH_{adopt} + PERM_{adopt} + LARC_{disc} + BEH_{cont} + LARC_{cont} + UP_{care} \tag{6.11}$$

Where $LARC_{adopt}$ is the total cost of adopting long-acting, reversible contraception from 2023 to 2050; BEH_{adopt} is the total cost of adopting behavioural contraception from 2023 to 2050; $PERM_{adopt}$ is the total cost of adopting permanent contraception from 2023 to 2050; $LARC_{disc}$ is the total cost of interrupting use of long-acting contraception (IUDs and implants) from 2023 to 2050; BEH_{cont} is the total of cost continuing using behavioural contraception from 2023 to 2050; $LARC_{cont}$ is the total cost of continuing using long-acting contraception from 2023 to 2050; UP_{care} is the total cost of unintended pregnancy and delivery care from 2023 to 2050.

6.2.3 Cost-effectiveness estimation

Once total costs and unintended pregnancies were estimated, the incremental cost-effectiveness ratio (Paulden, 2020) was estimated by subtracting the total costs of contraceptive provision of strategy k from SQ, and dividing this by the difference between unintended pregnancies of strategy k and SQ:

$$ICER_k = \frac{ContrProgr_{TC_k} - ContrProgr_{TC_{SQ}}}{UP_k - UP_{SQ}} \tag{6.12}$$

The most efficient strategies were established by estimating the cost-effectiveness acceptability curve (CEAC) (Barton et al., 2008; Fenwick et al., 2001; Fenwick & Byford, 2005) and cost-effectiveness acceptability frontier (CEAF) (Barton et al., 2008).

6.2.4 Sensitivity analysis

A probabilistic sensitivity analysis was conducted by running fifty model iterations to calculate 95% uncertainty intervals in each strategy. The estimated transition probabilities (see Appendix B) were assigned a multinomial distribution with five hundred experiments. Unit costs were assigned a lognormal distribution (Edlin, McCabe, et al., 2015) (see Table 6.1).

6.3 Software implementation

The hypothetical strategies tested in this thesis affected the C-S-R transition probabilities estimated with the procedure described in section 4.2.2. Briefly, these transition probabilities describe the frequency with which women flow out of NU, $LARC$, BEH, $TRAD$, $PERM$, UP, INF_UP, INT, IP, INF_IP, and SI to enter another of these stocks, or remain in the same (except for UP and IP). Transition probabilities from each stock must add up to one.

To secure such a property was preserved in all strategies, adjustments were conducted whilst generating the stochastic, age-stratified time-varying parameter tables (see number 2 in Figure 4.28). In switching/discontinuation strategies, which affected the transition probabilities listed in Table 6.2, a reduction factor ($reduct$) was introduced to represent the proportional effect of the hypothetical policy, applied with linear yearly increments from 2023-2030 (see section 6.1). First, the effect of reducing the probability of adopting a less effective contraceptive (strategies 1a, 1b) or discontinuing contraception altogether (strategies 2a, 2b, and 2c) was defined as:

$$trPr_{new} = trPr_{orig} \times (1 - reduct)$$

6.13

Where $trPr_{orig}$ is the original probability of adopting a less effective contraceptive ($s13, s22$) or discontinuing contraception altogether ($s10, s19, s28$), which are the behaviours targeted and attempted to prevent by the policy; $trPr_{new}$ is the transition probability obtained after applying $reduct$, which is the reduction factor of the hypothetical policy.

Table 6.2. Transition probabilities affected by the hypothetical policies tested in this thesis.

Category	Rationale	Strategy ID	Description	Affected transition probabilities[1]
Status Quo	N/A	SQ	Do nothing. Parameters remain fixed from 2023 to 2050	N/A
Switching	Promote the use of more effective, modern contraception over a longer period	1a	Prevent women moving from long-acting, reversible contraception (LARC) to traditional contraception (TRAD)	s11, s13
		1b	Prevent women moving from behavioural contraception (BEH) to TRAD	s21, s22
Discontinuation	Reduce discontinuation of all modern (LARC, BEH) and traditional (TRAD) contraception forms	2a	Prevent LARC users moving to non-use (NU)	s11, s10
		2b	Prevent BEH users moving to NU	s21, s19
		2c	Prevent TRAD users moving NU	s31, s28
Adoption I	Promote modern contraceptive adoption (LARC, BEH) at all ages	3a	Raise adoption probability of all reversible modern methods at each age class	s1, s2, s3, s72, s75, s73, s74
Adoption II	Improve modern contraceptive adoption (LARC, BEH) in hospital settings after childbirth and as part of post-abortion care	4	Raise reversible contraceptive adoption following UP/IP	s39, s42, s40, s41, s60, s63, s61, s62
Combined	Verify the effect of an integral approach	5	Combination of all previous strategies, except SQ	s10, s13, s11, s19, s22, s21, s31, s28, s1, s2, s3, s72, s75, s73, s74, s39, s42, s40, s41, s60, s63, s61, s62

[1]See Appendix B.

With the effect of the policy established, a further adjustment was to secure that the same proportion of females prevented from switching to a less effective contraceptive or stopping its use remained in their current method (i.e., long-acting, behavioural, traditional):

$$trPr_{remain\_new} = trPr_{remain\_orig} + trPr_{orig} \times reduct \tag{6.14}$$

Where $trPr_{remain\_orig}$, and $trPr_{remain\_new}$ are the new and original probabilities of remaining a long-acting ($s11$), behavioural ($s21$), or traditional ($s31$) contraceptive user, respectively.

Strategy 3a consisted in raising uptake of modern, reversible contraceptives (i.e., long-acting -LARC-, behavioural -BEH-) in a policy addressing both contraceptives concurrently. The policy is aimed at reducing the number of sexually active, not intending pregnancy non-users (NU) remaining in NU, and sexually active females restarting sexual activity (SI) in NU or restarting as traditional contraception users.

To implement the strategy, the probability of remaining as a non-user is reduced first:

$$s1_{new} = s1_{orig} \times (1 - reduct)$$

6.15

Where $s1_{orig}$ is the original probability of staying at NU, i.e., keep being a sexually active, not intending pregnancy non-user, which is one of the two behaviours targeted and attempted to prevent by the policy; $s1_{new}$ is the new probability after applying $reduct$, which is the reduction factor of the hypothetical policy.

With the effect of the policy established for NU, a further adjustment was to secure probabilities adding up to one by having the same proportion of females prevented from maintaining their non-user status moving into LARC (equation 6.16) or BEH (equation 6.17):

$$s2_{new} = s2_{orig} + \left(\frac{s1_{orig} \times reduct}{2}\right)$$

6.16

Where $s2_{orig}$ and $s2_{new}$ are the original and new probabilities of moving from NU to LARC, respectively. Under this strategy, the reduction factor ($reduct$) is assumed to split evenly between the two forms of contraception, LARC (equation 6.16) and BEH (equation 6.17).

$$s3_{new} = s3_{orig} + \left(\frac{s1_{orig} \times reduct}{2}\right)$$

6.17

Where $s3_{orig}$ and $s3_{new}$ are the original and new probabilities of moving from NU to BEH, respectively.

The complement for this strategy deals with modern, reversible contraceptive uptake when females retake sexual activity. First, the probabilities of moving into NU (equation 6.18) or TRAD (equation 6.19) after applying the hypothetical policy are estimated:

$$s72_{new} = s72_{orig} \times (1 - reduct)$$

6.18

Where $s72_{orig}$ and $s72_{new}$ are the original and new probabilities of moving into NU from SI, respectively, after the hypothetical policy is applied ($reduct$).

$$s75_{new} = s75_{orig} \times (1 - reduct)$$

6.19

Where $s75_{orig}$ and $s75_{new}$ are the original and new probabilities of becoming a traditional contraceptive user after restarting sexual activity, respectively, once $reduct$ is applied.

With the effect of the policy established for SI, a further adjustment was to secure probabilities adding up to one by having the same proportion of females prevented from moving into NU and TRAD allocated into LARC (equation 6.20) or BEH (equation 6.21):

$$s73_{new} = s73_{orig} + \left(s72_{orig} + s75_{orig}\right) \times \frac{reduct}{2}$$

6.20

Where $s73_{new}$ and 73_{orig} are the original and new probabilities of moving from SI to LARC, respectively. Under this strategy, $reduct$ is assumed to split evenly between these two forms of contraception. Given that a fraction of females was taken from NU and TRAD initially, both must be introduced into LARC after retaking sexual activity.

$$s74_{new} = s74_{orig} + \left(s72_{orig} + s75_{orig}\right) \times \frac{reduct}{2}$$

6.21

Where $s74_{orig}$and $s74_{new}$ are the original and new probabilities of moving from SI to BEH, respectively. Under this strategy, $reduct$ is assumed to split evenly between these two forms of contraception. Given that a fraction of females was taken from NU and TRAD initially, both must be introduced into BEH after retaking sexual activity.

The fourth strategy consisted in improving modern contraceptive adoption after unintended (UP) and intended pregnancy (IP) end. To address the case of UP, the effect of the policy was first established by reducing the number of females that become sexually active, not intending pregnancy non-users, and the number of females that become traditional contraception users.

First, the effect of reducing the probability of moving into NU from UP is estimated as:

$$s39_{new} = s39_{orig} \times (1 - reduct)$$

6.22

Where $s39_{orig}$ and $s39_{new}$ are the original and new probabilities of becoming a sexually active, not intending pregnancy non-user after UP, respectively; $reduct$ is the reduction accomplished by applying the hypothetical policy.

Then, the effect of reducing the probability of moving into TRAD from UP is estimated as:

$$s42_{new} = s42_{orig} \times (1 - reduct)$$

6.23

Where $s42_{orig}$ and $s42_{new}$ are the original and new probabilities of becoming a traditional contraceptive user after UP, respectively; $reduct$ is the reduction accomplished by applying the hypothetical policy.

With the effect of the policy established for UP, a further adjustment was to secure probabilities adding up to one by having the same proportion of females prevented from moving into NU and TRAD allocated into LARC (equation 6.24) or BEH (equation 6.25):

$$s40_{new} = s40_{orig} + \left(s39_{orig} + s42_{orig}\right) \times \frac{reduct}{2}$$

6.24

Where $s40_{orig}$ and $s40_{new}$ are the original and new transition probabilities of moving from UP to LARC, respectively. Given that a fraction of females was taken from NU ($s39_{orig}$) and TRAD ($s42_{orig}$) initially, both must be introduced into LARC when unintended pregnancy ends. Under this strategy, $reduct$ is assumed to split evenly between LARC and BEH.

$$s41_{new} = s41_{orig} + \left(s39_{orig} + s42_{orig}\right) \times \frac{reduct}{2}$$

6.25

Where $s41_{orig}$and $s41_{new}$ are the original and new transition probabilities of moving from UP to BEH, respectively. Given that a fraction of females was taken from NU ($s39_{orig}$) and TRAD ($s42_{orig}$) initially, both must be introduced into BEH after unintended pregnancy ends. Under this strategy, $reduct$ is assumed to split evenly between the two forms of contraception, LARC and BEH.

A similar set of equations to those presented in 6.13 to 6.24 were used to complement the strategy and address the case of females adopting modern, reversible contraception after intended pregnancy. The affected probabilities were: 1) becoming a sexually active, not intending pregnancy non-user after intended pregnancy ends ($s60$); 2) adopting a traditional contraceptive after intended pregnancy ends ($s63$); 3) adopting a long-acting contraceptive after intended pregnancy ends ($s61$); and 4) adopting a behavioural contraceptive after intended pregnancy ends ($s62$).

Hybrid strategies were also defined as the: 1) combination of a, b instances of strategy 1 to create strategy '1ab'; 2) combination of a, b, c instances of strategy 2 to create strategy '2abc'; and 3) combination of strategies 1a, 1b, 2a, 2b, 2c, 3a, and 4 to create strategy 5. No additional formulations were required to create strategies 1ab and 2abc.

Strategy 5, however, implied overlaps in the affected transition probabilities at strategy pairs (1a, 2a) and (1b, 2b) (see Table 6.2). Thus, additional formulation was required to secure transition probabilities still added up to one in each of the two strategy pairs and at the same time not to duplicate the application of the $reduct$ factor.

The combination of strategies first started with reducing the probability of discontinuing use of modern reversible contraception (LARC -$s10$- or BEH -$s19$-) with equation 6.13. Then, the probability of moving from LARC ($s13$) or BEH ($s22$) to traditional contraception is also reduced applying the same equation. Finally, to secure the transition probability set still added up to one:

$$trPr_{new} = trPr_{orig} + \left(trPr_{orig\_disc} + trPr_{orig\_TRAD}\right) \times \ reduct \tag{6.26}$$

Where $trPr_{orig}$ and $trPr_{new}$ are the original and new transition probabilities of remaining a long-acting ($s11$) or behavioural ($s21$) contraceptive user; $trPr_{orig\_disc}$ is the probability of discontinuing use of LARC ($s10$) or BEH ($s19$); $trPr_{orig\_TRAD}$ is the probability of moving from LARC ($s13$) or BEH ($s22$) into traditional contraception; $reduct$ is the reduction factor of the hypothetical policy.

6.4 Chapter summary

Chapter five presented the set of 31 hypothetical contraceptive provision strategies to be tested, including their logic of implementation in the simulation model. The chapter continued by detailing the cost-effectiveness analysis conducted to establish the efficiency of investing resources in these 31 policies in the Mexican context. Finally, the chapter also detailed the model modifications necessary to implement the tested strategies' effectiveness.

Chapter 7 Results

The present chapter is organised in two sections with different categories of results, according to the research objectives set in this thesis[2]. The first section reports the unintended pregnancies, unsafe abortions, and maternal deaths estimated with the 31 tested policies. The section also presents the policies' impact in the proportion of total pregnancies that are unintended, and their impact in the WoRA population development. The second section presents the economic impact and cost-effectiveness analysis of the tested policies.

7.1 Comparison of strategies

Results for five categories of strategies together with SQ were estimated (Table 7.1). Recall that the tested hypothetical strategies consisted in raising contraceptive adoption (strategies 3a, and 4); preventing switching from a more to a less effective contraceptive (strategy 1); reducing discontinuation of all modern and traditional contraception (strategy 2); or a combination of all the former in a single, integral policy (strategy 5). The total absolute

---

[2] Research questions (see section 1.3):

1. Can a system dynamics model accurately represent the reproductive life years of women, capturing the dynamics of contraceptive adoption, switching, and discontinuation?
2. Which contraceptive coverage policies are most cost-effective in reducing unintended pregnancy and other important reproductive/maternal health and economic outcomes over the longer term, given the dynamics of contraceptive adoption, switching, and discontinuation among Mexican women?

Research objectives (see section 1.3):

1. Develop a conceptual model to characterise the different stages in the reproductive life years of women aged 15 to 49, and depict their interrelations with contraceptive adoption, switching, and discontinuation.
2. Translate the conceptual model into an endogenously driven, multistate, age-structured, time-varying system dynamics simulation model which represents the evolving dynamics of contraceptive, sexual, and reproductive behaviours to estimate their impact on the following outcomes:
    a. Unintended pregnancies due to contraception failure and non-use of contraception.
    b. Live births, unsafe abortions, and maternal deaths attributable to unintended pregnancy.
    c. Economic impact of contraceptive provision and unintended pregnancy from the perspective of the health provider.
3. Use the devised model to compare the cost-effectiveness of different contraceptive provision policies aiming to reduce unintended pregnancy.

numbers of unintended pregnancies, unsafe abortions, and maternal deaths were used to compare their performance at 25, 50, or 75% improvement/reduction.

Table 7.1. Description of compared strategies.

Category	Rationale	Strategy ID	Description
Status Quo	Keep the current state of things	SQ	Do nothing. Parameters remain fixed from 2023 to 2050
Switching	Promote the use of more effective, modern contraception over a longer period	1a	Prevent women moving from long-acting, reversible contraception (LARC) to traditional contraception (TRAD)
		1b	Prevent women moving from behavioural contraception (BEH) to TRAD
Discontinuation	Reduce discontinuation of all modern (LARC, BEH) and traditional (TRAD) contraception forms	2a	Prevent LARC users moving to non-use (NU)
		2b	Prevent BEH users moving to NU
		2c	Prevent TRAD users moving NU
Adoption I	Promote modern contraceptive adoption (LARC, BEH) at all ages	3a	Raise adoption probability of all reversible modern methods at each age class
Adoption II	Improve modern contraceptive adoption (LARC, BEH) in hospital settings after childbirth and as part of post-abortion care	4	Raise reversible contraceptive adoption following UP/IP
Combined	Verify the effect of an integral approach	5	Combination of all previous strategies, except SQ

For each strategy, the results also include the size of the population of women of reproductive age (WoRA) over time, and the proportion of unintended pregnancies out of total pregnancies (see section 6.1 and Table 7.1).

Figure 7.1 shows a panel of time checkpoints (i.e., 2030, 2040, 2050) with the estimated population of WoRA in that decade for each strategy. The horizontal gray bars represent the 95% uncertainty interval (UI) of the population estimate, and vertical gray bars indicate the mean estimate. The vertical dashed lines in the figure indicate the 95% UI of the status quo (SQ) strategy, used as the reference in all comparisons. There might be evidence of statistical significance, i.e., differences between the estimated populations for the SQ and other strategies, whenever the UI for any strategy is outside the dashed lines.

Amongst the tested strategies, none had a significant impact on the population of WoRA in any analysed year. By 2030 the population was estimated at 35.8 million WoRA, reducing to 35.5 million by 2040. By 2050 the population reduced further in all strategies, with strategies 5_0.5, and 5_0.75 the most impactful, respectively. This reduction, however, does not appear to be statistically significant compared with the reduction in SQ.

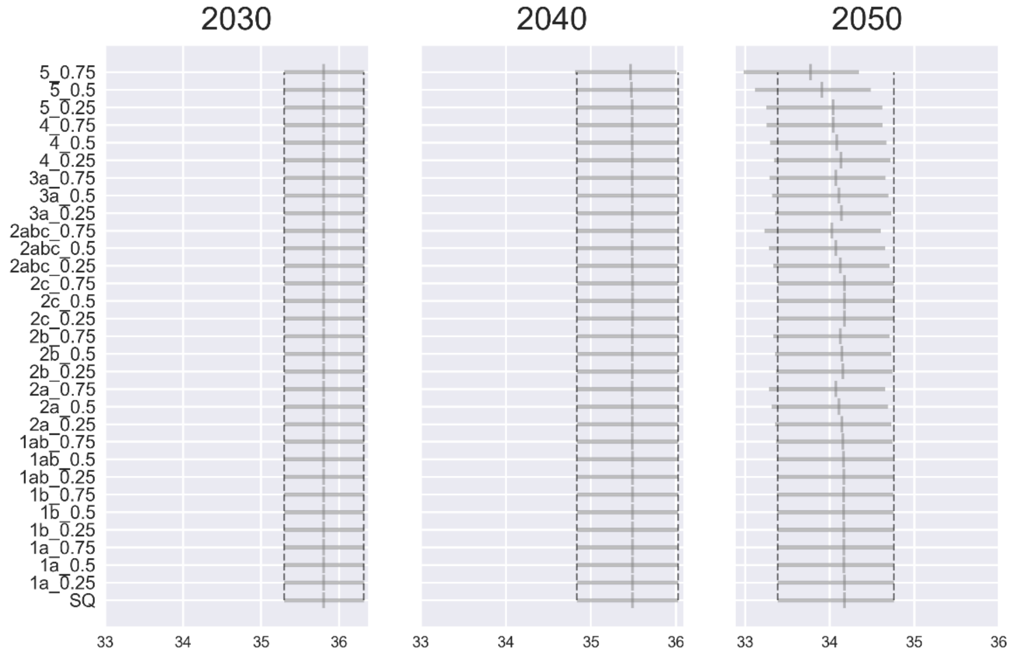


Figure 7.1. Absolute number of women of reproductive age, 2030, 2040, 2050. In millions.

Note: x-axis represents absolute numbers; y-axis represents the tested strategy; dashed line indicates the 95% uncertainty interval of the Status quo strategy to compare against the other strategies.

Unintended pregnancies (UP) estimated for each strategy are presented in Table 7.2, ranked from the most (top) to the least effective (bottom) at year 2050 (fourth column in the table). The first thing to notice is that all strategies, including SQ, achieve an annual reduction in UP from 2030 to 2050. However, continuing contraceptive provision with SQ would give the least effective reduction in annual UP, going from a total of 635k in 2030 to 577k in 2050, a reduction of 9.13%. Under this strategy, 17.2 million cumulative UP (95% UI: 16.6-17.8) would be observed between 2023 and 2050.

Located at the top of Table 7.2 is the most effective strategy, 5_0.75. This hypothetical approach would give an 18.6% reduction in annual UP, going from a total of 478k in 2030 to 389k in 2050. Under this strategy, a cumulative 12.8 million UP (12.14-13.28) would be observed between 2023-2050, a reduction of 25.7% compared with SQ. The next most effective strategy also consists of the combination of all strategies but with a 50% improvement/reduction (5_0.5).

The third most effective strategy was simultaneously reducing movements from LARC , BEH, and TRAD to NU by 75% (2abc_0.75). Under this strategy, a 12.4% reduction in annual UP was estimated, going from 580k in 2030 to 508k in 2050, and a cumulative 15.6 million UP (14.95-16.13) between 2023-2050, which is a 9.3% relative reduction compared with SQ.

Increasing the adoption of modern reversible contraception by 75% following unintended or intended pregnancy (strategy 4_0.75) was the most effective among the non-combined strategies. Under the strategy, an 11.2% annual reduction is expected, going from 580k in 2030 to 515k UP in 2050, and a cumulative 15.7 million UP (15-16.27) between 2023-2050, which is an 8.7% relative reduction compared with SQ.

Although a formal test was not conducted, unintended pregnancies estimated with the remaining ranked strategies are unlikely to differ statistically from the cumulative SQ estimate, since their uncertainty intervals (UI) overlap with the UI for SQ (Table 7.2).

Table 7.2. Unintended pregnancies[1] per tested strategy in 2030, 2040, 2050, and cumulative 2023-2050.

Strategy[2]	**Unintended pregnancies (95% UI[3])**			
	2030	**2040**	**2050**	**Cumulative 2023-2050**
5_0.75	478 (454-497)	414 (391-432)	389 (368-406)	12,776 (12,140-13,285)
5_0.5	530 (507-551)	479 (456-498)	452 (431-470)	14,267 (13,629-14,809)
2abc_0.75	580 (554-600)	537 (513-555)	508 (486-527)	15,606 (14,953-16,135)
5_0.25	583 (559-604)	544 (520-563)	515 (494-533)	15,741 (15,101-16,308)
4_0.75	580 (556-604)	543 (521-565)	515 (495-535)	15,705 (15,060-16,354)
3a_0.75	596 (574-617)	560 (539-579)	531 (510-550)	16,121 (15,525-16,671)
2a_0.75	598 (573-619)	560 (536-579)	531 (508-549)	16,136 (15,478-16,673)
2abc_0.5	599 (574-620)	562 (538-581)	532 (510-551)	16,164 (15,520-16,707)
4_0.5	598 (575-621)	564 (542-587)	535 (515-555)	16,197 (15,545-16,825)
3a_0.5	609 (586-629)	575 (553-595)	546 (524-565)	16,466 (15,855-17,018)
2a_0.5	611 (587-632)	577 (553-597)	547 (525-567)	16,508 (15,857-17,067)
2b_0.75	616 (593-638)	584 (561-605)	554 (532-575)	16,662 (16,027-17,245)
2abc_0.25	617 (593-639)	585 (562-606)	555 (533-575)	16,695 (16,052-17,265)
4_0.25	616 (593-639)	585 (563-607)	556 (535-576)	16,695 (16,045-17,306)
3a_0.25	622 (599-643)	591 (568-612)	561 (540-581)	16,825 (16,199-17,395)
2b_0.5	623 (599-645)	592 (569-613)	562 (541-583)	16,851 (16,213-17,440)
2a_0.25	623 (599-645)	592 (569-614)	562 (541-583)	16,863 (16,217-17,443)
1ab_0.75	627 (604-649)	598 (576-621)	569 (548-590)	16,993 (16,335-17,595)
2b_0.25	629 (606-651)	600 (577-622)	570 (549-591)	17,030 (16,390-17,627)
1b_0.75	630 (606-652)	601 (579-624)	571 (551-593)	17,063 (16,404-17,665)
1ab_0.5	630 (606-652)	602 (579-624)	572 (551-593)	17,069 (16,403-17,674)
1b_0.5	632 (609-654)	604 (582-627)	574 (553-596)	17,132 (16,481-17,735)
1a_0.75	631 (608-654)	604 (581-626)	574 (553-595)	17,113 (16,452-17,718)
1ab_0.25	632 (609-654)	604 (582-626)	574 (553-595)	17,125 (16,485-17,725)
1a_0.5	633 (610-655)	605 (583-628)	575 (554-597)	17,157 (16,505-17,761)
1b_0.25	633 (610-655)	605 (583-627)	575 (554-596)	17,150 (16,509-17,751)
1a_0.25	634 (611-656)	606 (584-628)	576 (555-597)	17,175 (16,533-17,778)
2c_0.5	635 (612-657)	607 (584-629)	577 (556-598)	17,207 (16,570-17,805)
2c_0.25	635 (612-657)	607 (584-629)	577 (556-598)	17,203 (16,564-17,804)
2c_0.75	636 (612-658)	607 (585-629)	577 (556-598)	17,210 (16,575-17,805)
SQ[4]	635 (612-657)	607 (584-629)	577 (556-598)	17,200 (16,557-17,804)

[1]Figures are presented in thousands;[2]preffix (before underscore) indicates the strategy ID, whilst suffix (after underscore) indicates the tested improvement/reduction; [3]95% Uncertainty interval; [4]Status quo.

The proportion of unintended pregnancies out of total pregnancies at the three different time points is shown in Figure 7.2 below. By 2030, only strategies 5_0.75 and 5_0.5 represent a relative significant difference in the proportion of unintended pregnancies, roughly 21.91% and 23.73% respectively (Figure 7.2). By 2040, strategies 5_0.25, 4_0.75, and 2abc_0.75 also showed a relative significant difference, all around 25%. Nevertheless, strategies 5_0.75 and 5_0.5 kept reducing the proportion further, reaching 19.8% and 22.6%, respectively.

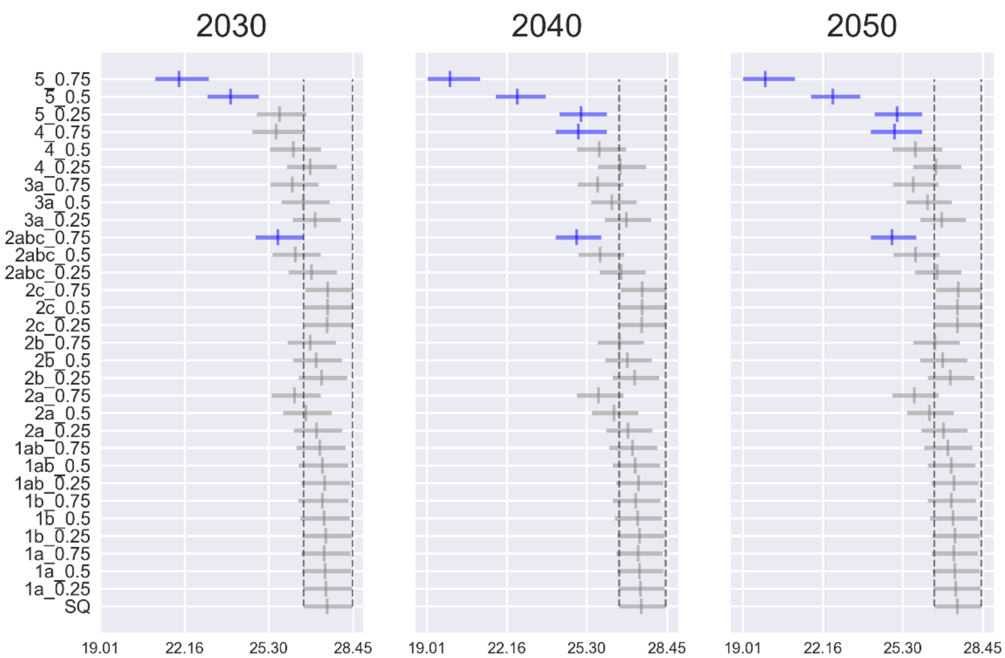


Figure 7.2. Percentage of unintended pregnancies out of total pregnancies, 2030, 2040, 2050.

Note: x-axis represents percentages; y-axis represents the tested strategy; dashed line indicates the 95% uncertainty interval of the Status quo strategy to compare against the rest of strategies.

Unsafe abortions (UA) estimated under each strategy are presented in Table 7.3, arranged from the most to the least effective by 2050. Despite being the least effective strategy, SQ reached a reduction of 8.9% in annual UA, going from a total of 102k in 2030 to 93k in 2050. Under SQ, a cumulative 2.76 million unsafe abortions (UI: 2.7-2.9) would be observed between 2023 and 2050.

Located at the top of Table 7.3 is the most effective strategy, 5_0.75. This hypothetical approach would allow an 18.4% reduction in annual UA, going from a total of 76k in 2030 to 62k in 2050. Additionally, under this strategy, a cumulative 2 million UA (1.94-2.12) would be observed between 2023-2050, representing a reduction of 25.9% compared with SQ. The next most effective strategy is 5_0.5.

Increasing the adoption of modern reversible contraception by 75% following pregnancy (strategy 4_0.75) was the most effective among the non-combined strategies. Under the strategy, a 10.8% annual reduction in unsafe abortions is expected, going from 93k in 2030 to

83k UA in 2050, and a cumulative 2.52 (2.42-2.6) million between 2023-2050, which is an 8.63% relative reduction from those observed in SQ.

Table 7.3. Unsafe abortions[1] per tested strategy in 2030, 2040, 2050, and cumulative 2023-2050.

Strategy[2]	Unsafe abortions (95% UI[3])			
	2030	2040	2050	Cumulative 2023-2050
5_0.75	76 (73-79)	66 (63-69)	62 (59-65)	2,043 (1,941-2,123)
5_0.5	85 (81-88)	77 (73-80)	73 (69-75)	2,283 (2,181-2,366)
2abc_0.75	93 (89-96)	86 (82-89)	81 (78-85)	2,499 (2,396-2,583)
5_0.25	93 (90-97)	87 (84-90)	83 (79-86)	2,520 (2,419-2,612)
4_0.75	93 (89-97)	87 (84-91)	83 (80-86)	2,518 (2,418-2,623)
3a_0.75	95 (92-98)	90 (86-93)	85 (82-88)	2,578 (2,483-2,664)
2abc_0.5	96 (92-99)	90 (86-93)	85 (82-89)	2,588 (2,486-2,678)
2a_0.75	96 (92-99)	90 (86-93)	85 (82-88)	2,584 (2,480-2,673)
4_0.5	96 (92-99)	90 (87-94)	86 (83-89)	2,596 (2,495-2,699)
3a_0.5	97 (94-101)	92 (89-95)	87 (84-91)	2,634 (2,538-2,724)
2a_0.5	98 (94-101)	92 (89-96)	88 (84-91)	2,644 (2,541-2,736)
2abc_0.25	99 (95-102)	94 (90-97)	89 (86-92)	2,674 (2,572-2,768)
4_0.25	99 (95-102)	94 (90-98)	89 (86-93)	2,675 (2,573-2,776)
2b_0.75	99 (95-102)	94 (90-97)	89 (86-92)	2,668 (2,568-2,765)
2b_0.5	100 (96-103)	95 (91-98)	90 (87-94)	2,699 (2,598-2,796)
3a_0.25	99 (96-103)	95 (91-98)	90 (87-93)	2,693 (2,594-2,788)
2a_0.25	100 (96-103)	95 (91-98)	90 (87-94)	2,701 (2,599-2,797)
1ab_0.75	100 (97-104)	96 (92-100)	91 (88-95)	2,721 (2,620-2,821)
2b_0.25	101 (97-104)	96 (93-100)	91 (88-95)	2,727 (2,627-2,826)
1ab_0.25	101 (97-105)	97 (93-101)	92 (89-96)	2,744 (2,641-2,844)
1b_0.75	101 (97-104)	96 (93-100)	92 (89-95)	2,734 (2,631-2,834)
1b_0.5	101 (97-105)	97 (93-100)	92 (89-96)	2,741 (2,638-2,841)
1b_0.25	101 (98-105)	97 (94-101)	92 (89-96)	2,748 (2,645-2,848)
1a_0.75	101 (98-105)	97 (93-101)	92 (89-96)	2,743 (2,641-2,842)
1a_0.5	101 (98-105)	97 (94-101)	92 (89-96)	2,747 (2,645-2,846)
1a_0.25	101 (98-105)	97 (94-101)	92 (89-96)	2,751 (2,649-2,851)
1ab_0.5	101 (97-104)	96 (93-100)	92 (88-95)	2,733 (2,631-2,832)
2c_0.75	102 (98-105)	97 (94-101)	93 (89-96)	2,757 (2,656-2,855)
2c_0.25	102 (98-105)	97 (94-101)	93 (89-96)	2,755 (2,654-2,855)
2c_0.5	102 (98-105)	97 (94-101)	93 (89-96)	2,756 (2,655-2,855)
SQ[4]	102 (98-105)	97 (94-101)	93 (89-96)	2,755 (2,653-2,855)

[1]Figures are presented in thousands;[2]preffix (before underscore) indicates the strategy ID, whilst suffix (after underscore) indicates the tested improvement/reduction; [3]95% Uncertainty interval; [4]Status quo.

Maternal deaths estimated with each strategy are presented in Table 7.4. Under SQ, a total of 2,535 cumulative maternal deaths (528-5,715) would be observed between 2023 and 2050. The most effective strategy was 5_0.75, allowing a 14.71% reduction in yearly maternal deaths, going from 68 in 2030 to 58 in 2050. Under this strategy, 1,850 cumulative maternal deaths (434-4,147) would be observed between 2023-2050, which represents a reduction of 27% from the cumulative deaths observed in SQ. The next most effective strategy is 5_0.5.

The third most effective strategy was 2abc_0.75. Under the strategy, an 8.3% reduction in yearly maternal deaths was estimated, going from 84 in 2030 to 77 in 2050, and a cumulative 2,290 maternal deaths (492-5,078) between 2023-2050, or a 9.5% relative reduction from those observed in SQ.

Increasing the adoption of modern reversible contraception in 75% (strategy 3a_0.75) was the most effective among the non-combined strategies. Under this strategy, an 8.24% yearly reduction is expected, going from 85 in 2030 to 78 maternal deaths in 2050, and 2,328 cumulative deaths (494-5,308) between 2023-2050, which is an 8% relative reduction from those observed in SQ.

Notice, however, that all estimates have broad uncertainty intervals, all overlapping with SQ's (see section 8.2).

Table 7.4. Maternal deaths per tested strategy in 2030, 2040, 2050, and cumulative 2023-2050.

Strategy[1]	Maternal deaths (95% UI[2])			
	2030	2040	2050	Cumulative 2023-2050
5_0.75	68 (16-154)	61 (14-135)	58 (14-130)	1,850 (434-4,147)
5_0.5	76 (17-173)	71 (16-158)	68 (16-152)	2,084 (466-4,684)
2abc_0.75	84 (18-187)	80 (17-176)	77 (17-168)	2,290 (492-5,078)
3a_0.75	85 (18-195)	82 (17-185)	78 (17-178)	2,329 (494-5,308)
5_0.25	84 (18-191)	81 (17-181)	78 (17-174)	2,312 (497-5,206)
2abc_0.5	87 (18-195)	84 (18-185)	80 (17-178)	2,378 (503-5,305)
4_0.75	85 (18-194)	83 (18-186)	80 (18-179)	2,354 (514-5,321)
2a_0.75	86 (18-194)	84 (18-183)	80 (17-176)	2,370 (507-5,268)
3a_0.5	87 (18-199)	85 (18-190)	81 (17-184)	2,394 (501-5,437)
4_0.5	87 (18-199)	86 (19-191)	82 (18-185)	2,413 (521-5,448)
2a_0.5	88 (18-199)	86 (19-190)	83 (18-183)	2,429 (518-5,426)
2b_0.75	89 (18-203)	87 (19-194)	84 (18-188)	2,454 (518-5,524)
3a_0.25	90 (18-204)	88 (19-196)	84 (18-189)	2,463 (519-5,572)
2abc_0.25	89 (18-202)	88 (19-195)	84 (18-187)	2,459 (521-5,518)
4_0.25	90 (18-204)	88 (19-197)	85 (19-190)	2,475 (525-5,581)
2b_0.5	90 (18-205)	89 (19-197)	85 (18-190)	2,483 (523-5,590)
2a_0.25	90 (18-204)	89 (19-197)	85 (18-190)	2,484 (523-5,573)
1b_0.75	91 (19-207)	90 (19-201)	86 (19-194)	2,516 (527-5,669)
1ab_0.75	91 (19-206)	90 (19-199)	86 (19-192)	2,504 (526-5,624)
1ab_0.5	91 (19-207)	90 (19-200)	86 (19-193)	2,514 (527-5,651)
2b_0.25	91 (19-207)	90 (19-200)	86 (19-193)	2,510 (526-5,652)
1ab_0.25	92 (19-208)	91 (19-201)	87 (19-194)	2,525 (527-5,682)
2c_0.5	92 (19-209)	91 (19-203)	87 (19-195)	2,537 (529-5,716)
2c_0.25	92 (19-209)	91 (19-203)	87 (19-195)	2,536 (528-5,716)
1b_0.5	91 (19-207)	90 (19-201)	87 (19-194)	2,523 (527-5,682)
1b_0.25	92 (19-208)	91 (19-202)	87 (19-195)	2,529 (528-5,699)
1a_0.75	92 (19-208)	90 (19-201)	87 (19-194)	2,523 (527-5,667)
1a_0.5	92 (19-208)	91 (19-202)	87 (19-194)	2,527 (527-5,683)
1a_0.25	92 (19-208)	91 (19-202)	87 (19-195)	2,531 (528-5,697)
2c_0.75	92 (19-209)	91 (19-203)	87 (19-195)	2,538 (529-5,720)
SQ[3]	92 (19-209)	91 (19-203)	87 (19-195)	2,535 (528-5,715)

[1]Preffix (before underscore) indicates the strategy ID, whilst suffix (after underscore) indicates the tested improvement/reduction; [2]95% Uncertainty interval; [3]Status quo.

7.2 Cost-effectiveness analysis

The estimated average cost from 2023 to 2050 per unintended pregnancy was USD 1,448 (1,443.48-1,452.65) under the SQ strategy (Figure 7.3); the estimated costs in the majority of strategies (21 out of 31) were lower than this.

There seemed to be no statistically significant difference between the cost of SQ and reducing the change from behavioural to traditional contraception by 50% (strategy 1b_0.5; USD 1,445.55; 1,440.8-1,450.54) or reducing discontinuation of all forms of reversible contraception by 50% (strategy 2abc_0.5; USD 1,440.79; 1,436.09-1,445.49).

The least expensive strategies were 4_0.75 (USD 1,247.67; 1,243.51-1,251.61), 3a_0.75 (USD 1,200.13; 1,196.76-1,203.33), and 2b_0.25 (USD 1,194.52; 1,191.5-1,197.65). On the other hand, the most expensive strategies were 5_0.75 (USD 1,595.55; 1,590.3-1,600.45), 4_0. 5 (USD 1,610.62; 1,605.39-1,615.73) and 3a_0.25 (USD 1,873.94; 1,867.76-1,880.08). There is a USD 679.42 gap between the least (2b_0.25) and the most expensive (3a_0.25) strategy (Figure 7.3).

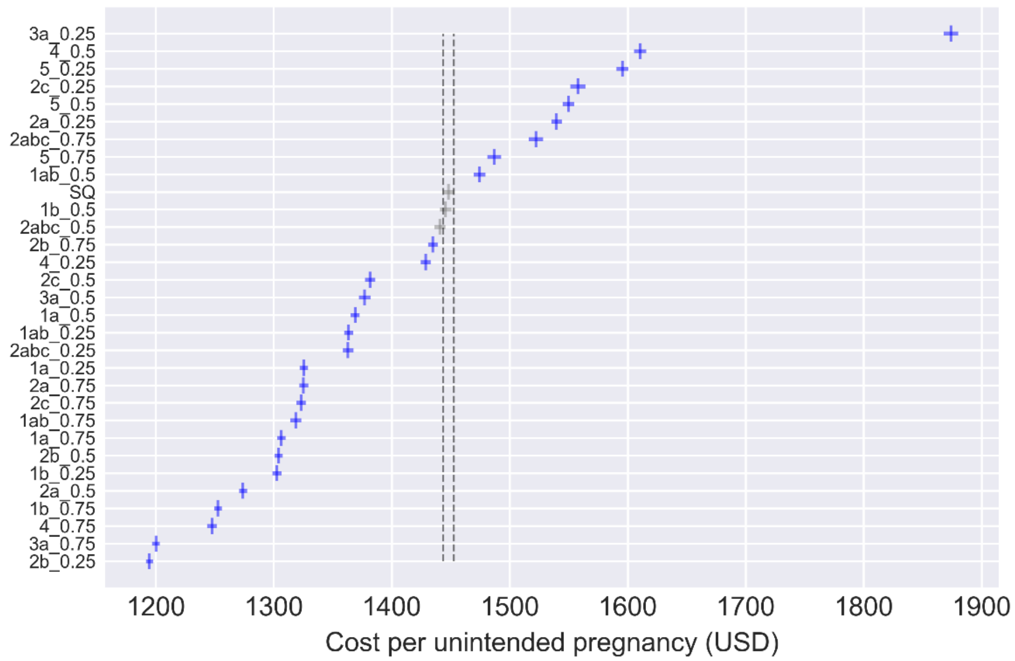


Figure 7.3. Average cost per unintended pregnancy under each strategy, 2023-2050.

Note: x-axis represents unit costs per unintended pregnancy; y-axis represents the tested strategy; dashed line indicates the 95% uncertainty interval of the Status quo strategy to compare against the rest of strategies.

Table 7.5 presents the discounted cumulative costs and unintended pregnancies (UP) from 2023 to 2050, together with avoided UP, cost difference, and incremental cost-effectiveness ratio (ICER) per strategy. Most of the tested strategies effectively reduce cumulative UP, excepting those aiming at reducing discontinuation of traditional contraception by 25, 50, or 75% (2c_0.25, 2c_0.5, 2c_0.75, respectively). Only 2c_0.25, however, resulted more expensive than SQ, and thus was ruled out as 'dominated' given it delivers worse health outcomes at a larger cost (Muening, 2008).

Strategies 5_0.75 (i.e., simultaneously improving modern reversible contraceptive adoption, reducing switching from more to less effective methods, and reducing contraceptive discontinuation by 75%), 5_0.5 (i.e., strategy five implemented at 50%), 2abc_0.75 (i.e., simultaneously reducing discontinuation of modern and traditional reversible methods by 75%), 4_0.75 (i.e., improving modern contraceptive adoption after pregnancy by 75%), and 5_0.25 (i.e., strategy five implemented at 25%) deliver the largest health benefits, as they avoid 2.6, 1.43, 0.78, 0.74, and 0.71 million UP when compared to SQ, respectively.

The strategies with the smallest cumulative cost, hence the largest cost difference relative to SQ were 3a_0.75 (i.e., improving adoption of modern reversible contraception by 75%), 4_0.75, 5_0.75, 2b_0.25 (i.e., preventing discontinuation of behavioural contraceptives by 25%), and 2a_0.5 (i.e., preventing discontinuation of long-acting reversible contraceptives by 50%). These strategies were estimated to cost USD 3.2 , 3 , 3, 2.7, and 2.5 billion less than SQ, respectively.

Despite strategies 1ab_0.25 (i.e., simultaneously preventing switching from more to less effective contraceptives by 25%), 5_0.25, 2a_0.25 (i.e., strategy two at 25%), 4_0.5 (i.e., strategy four at 50%), and 3a_0.25 (i.e., strategy three at 25%) were estimated to cost USD 165 million, USD 316 million, USD 678 million, USD 834 million, and USD 4 billion more than SQ, respectively, they were not dominated given they showed better health outcomes than SQ, reducing UP in 68k, 713k, 164k, 494k, and 183k, respectively.

ICERs are presented in the last column of the table, although optimality could be difficult to establish with this metric alone when multiple strategies are being compared (Barton et al., 2008; Fenwick et al., 2001; Fenwick & Byford, 2005): a strategy's ICER can take a positive value whenever it is more effective and more costly or less effective and less costly.

Table 7.5. Cumulative 2023-2050 unintended pregnancies, total programme costs, and incremental analysis per tested strategy.

Strategy	Unintended pregnancies (UP)[1]	UP avoided[1,2]	Total cost[3]	Cost difference[2, 3]	ICER[4]
3a_0.75	9,198 (9,146 , 9,248)	527 (521 , 534)	11,702 (11,663 , 11,743)	-3,225 (-3,244 , -3,206)	-6,120 (-6,199 , -6,037)
4_0.75	8,989 (8,937 , 9,042)	736 (730 , 741)	11,890 (11,848 , 11,933)	-3,038 (-3,067 , -3,012)	-4,130 (-4,181 , -4,082)
5_0.75	7,566 (7,515 , 7,613)	2,159 (2,142 , 2,177)	11,925 (11,881 , 11,969)	-3,002 (-3,032 , -2,975)	-1,390 (-1,403 , -1,377)
2b_0.25	9,642 (9,588 , 9,695)	83 (82 , 84)	12,210 (12,167 , 12,254)	-2,717 (-2,738 , -2,696)	-32,859 (-33,478 , -32,267)
2a_0.5	9,389 (9,336 , 9,441)	336 (331 , 340)	12,680 (12,636 , 12,727)	-2,248 (-2,264 , -2,230)	-6,711 (-6,810 , -6,608)
1b_0.75	9,659 (9,605 , 9,713)	65 (64 , 67)	12,828 (12,784 , 12,876)	-2,099 (-2,116 , -2,080)	-32,192 (-32,854 , -31,499)
2a_0.75	9,209 (9,156 , 9,260)	516 (509 , 523)	12,938 (12,894 , 12,983)	-1,989 (-2,012 , -1,968)	-3,862 (-3,924 , -3,801)
2b_0.5	9,555 (9,501 , 9,608)	170 (167 , 172)	13,212 (13,163 , 13,266)	-1,716 (-1,737 , -1,694)	-10,130 (-10,315 , -9,943)
1b_0.25	9,703 (9,649 , 9,756)	22 (21 , 22)	13,400 (13,358 , 13,444)	-1,528 (-1,547 , -1,508)	-71,276 (-72,950 , -69,622)
1a_0.75	9,687 (9,634 , 9,741)	37 (36 , 38)	13,417 (13,371 , 13,466)	-1,511 (-1,534 , -1,486)	-40,766 (-41,986 , -39,581)
1ab_0.75	9,622 (9,568 , 9,676)	103 (101 , 105)	13,450 (13,412 , 13,492)	-1,477 (-1,500 , -1,455)	-14,412 (-14,741 , -14,079)
5_0.5	8,293 (8,242 , 8,341)	1,432 (1,421 , 1,444)	13,625 (13,565 , 13,687)	-1,303 (-1,332 , -1,272)	-911 (-933 , -888)
1a_0.25	9,712 (9,659 , 9,766)	12 (12 , 13)	13,647 (13,602 , 13,697)	-1,280 (-1,299 , -1,260)	-104,556 (-108,154 , -101,165)
2c_0.75	9,731 (9,677 , 9,785)	-6 (-7 , -5)	13,650 (13,606 , 13,696)	-1,278 (-1,301 , -1,255)	731,151 (309,492 , 2,086,225)
3a_0.5	9,366 (9,314 , 9,418)	358 (354 , 363)	13,671 (13,632 , 13,717)	-1,256 (-1,277 , -1,237)	-3,513 (-3,584 , -3,447)
2abc_0.25	9,480 (9,426 , 9,532)	245 (242 , 248)	13,697 (13,657 , 13,740)	-1,231 (-1,251 , -1,212)	-5,032 (-5,131 , -4,942)
1ab_0.25	9,691 (9,637 , 9,745)	34 (33 , 34)	14,008 (13,960 , 14,058)	-919 (-942 , -898)	-27,244 (-28,063 , -26,457)
1a_0.5	9,700 (9,646 , 9,753)	25 (24 , 25)	14,078 (14,025 , 14,134)	-849 (-880 , -819)	-34,537 (-36,074 , -33,083)
2abc_0.5	9,223 (9,169 , 9,274)	502 (495 , 509)	14,087 (14,044 , 14,134)	-841 (-855 , -829)	-1,679 (-1,706 , -1,652)
2c_0.5	9,729 (9,675 , 9,782)	-4 (-5 , -3)	14,249 (14,207 , 14,295)	-678 (-699 , -658)	3,132,566 (287,921 , 16,964,682)
4_0.25	9,476 (9,422 , 9,529)	248 (247 , 250)	14,354 (14,309 , 14,403)	-574 (-595 , -553)	-2,315 (-2,407 , -2,225)
2b_0.75	9,464 (9,410 , 9,517)	261 (257 , 265)	14,394 (14,348 , 14,445)	-533 (-549 , -519)	-2,052 (-2,115 , -1,993)
2abc_0.75	8,953 (8,900 , 9,003)	772 (761 , 782)	14,447 (14,399 , 14,498)	-480 (-511 , -448)	-624 (-664 , -581)
1b_0.5	9,681 (9,627 , 9,736)	43 (43 , 44)	14,836 (14,792 , 14,885)	-92 (-113 , -73)	-2,159 (-2,694 , -1,718)

SQ[5]	9,725 (9,671 , 9,779)	-	14,928 (14,883 , 14,980)	-	-
1ab_0.5	9,657 (9,602 , 9,710)	68 (67 , 69)	15,093 (15,052 , 15,137)	165 (146 , 184)	2,424 (2,144 , 2,687)
5_0.25	9,012 (8,960 , 9,063)	713 (707 , 719)	15,243 (15,193 , 15,300)	316 (290 , 340)	443 (407 , 476)
2a_0.25	9,561 (9,507 , 9,613)	164 (162 , 166)	15,605 (15,551 , 15,664)	678 (652 , 704)	4,128 (3,969 , 4,283)
4_0.5	9,231 (9,178 , 9,284)	494 (490 , 497)	15,762 (15,712 , 15,817)	834 (812 , 858)	1,688 (1,644 , 1,739)
2c_0.25	9,727 (9,673 , 9,780)	-2 (-2 , -2)	16,062 (16,003 , 16,125)	1,135 (1,095 , 1,174)	Dominated
3a_0.25	9,542 (9,489 , 9,594)	183 (181 , 185)	18,956 (18,896 , 19,023)	4,028 (3,996 , 4,058)	22,048 (21,761 , 22,312)

[1]Figures are presented in thousands; [2]Compared to SQ; [3]Figures are presented in millions of USD of 2021; [4]Incremental cost-effectiveness ratio = cost difference/unintended pregnancies avoided; [5]Status quo.

Thus, to facilitate establishing the optimal strategy, cost-effectiveness acceptability curves (CEAC; blue-, red-, and black-coloured lines) and their efficiency frontier (CEAF; dashed gray-coloured line overlaid on top of 3a_0.75 and 5_0.75) are presented in Figure 7.4.

To build the curves, the net monetary benefit (NMB) of each strategy was estimated using fifty iterations over a range of willingness-to-pay (WTP) thresholds, representing the maximum sum a payor would be willing to pay in order to avoid an additional unintended pregnancy. For each WTP value, the strategy with the highest NMB at each iteration is selected, and a vector with the proportion of iterations (*N* iterations out of 50) in which the strategy had the highest NMB is created. This proportion is then interpreted as the probability of cost-effectiveness. For instance: with a WTP larger than USD 400, strategy 5_0.75 has the largest NMB among the whole set of strategies in each iteration (50/50), and thus a probability of one of being the most cost-effective. The CEAC is useful to account for budget constraints in the decision-making process, and for the dynamics between multiple alternative strategies in the WTP continuum.

With a WTP of zero, i.e., a severely constrained programme with no additional resources to allocate to avoiding unintended pregnancies, the most efficient way of using the available resources is adopting strategy 3a_0.75; i.e., improving adoption of modern reversible contraception (LARC, BEH) by 75%. This strategy has a 96% chance of being cost-effective when WTP is zero, compared to 2% for strategies 5_0.75 (i.e., simultaneously improving modern reversible contraceptive adoption, reducing switching from a more to a less effective method, and reducing contraceptive discontinuation by 75%) and 4_0.75 (i.e., improving modern contraceptive adoption after pregnancy by 75%), respectively.

The efficiency of employing strategy 3a_0.75 wanes as WTP increases, i.e., more resources are available to allocate to avoiding an additional unintended pregnancy. This allows the adoption of a more comprehensive strategy (5_0.75), which reaches a 50% chance of cost-effectiveness at a WTP value of roughly USD 120, improving further to 84% at USD 200 to avoid an unintended pregnancy. At WTP thresholds larger than USD 300, strategy 5_0.75 has a 100% chance of being cost-effective. Compared with 3a_0.75 and 5_0.75, strategy 4_0.75 has only a small chance of being cost-effective.

Notice, however, the three strategies presented in the CEACs are cost saving, i.e., are more effective and less costly than SQ (Table 7.5). The efficiency frontier indicates the strategy with maximum probability of being cost-effective at each WTP.

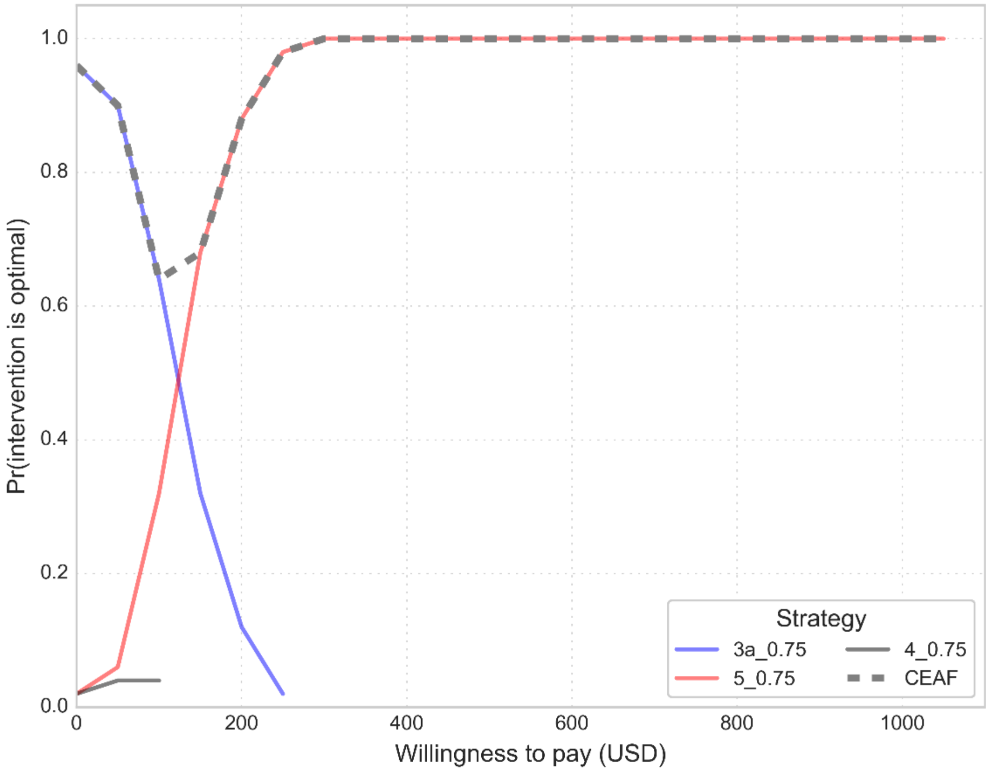


Figure 7.4. Cost-effectiveness acceptability curves and efficiency frontier.

Note: In the legend box, 3a_0.75: improving adoption of modern reversible contraception -LARC, BEH- by 75%; 5_0.75: simultaneously improving modern reversible contraceptive adoption, reducing switching from a more to a less effective method, and reducing contraceptive discontinuation by 75%; 4_0.75: improving modern contraceptive adoption after pregnancy by 75%; CEAF: cost-effectiveness acceptability (efficiency) frontier.

7.3 Chapter summary

The first section of Chapter seven reported the main outcomes of interest to this research: unintended pregnancies, unsafe abortions, and maternal deaths estimated with the 31 tested policies. The section also presented other important outcomes, i.e., proportion of pregnancies that are unintended out of total pregnancies, and their impact in the WoRA population development. The second and final section presented the economic impact and cost-effectiveness analysis of the tested policies.

Chapter 8 Discussion, conclusions, and further research

This final chapter is divided into three main sections. First, model features and results are contrasted against previously conducted research and are discussed in the light of the original research questions and objectives[3], as well as their contribution to policymaking. The section also specifies the limitations of this research, together with the procedures conducted to minimise their impact. The second section presents the conclusions reached, together with the original contributions of this research. Finally, future research streams are introduced.

8.1 Discussion

The present study investigated the health and economic impact of a set of contraceptive provision strategies to reduce unintended pregnancies (UP) in Mexico with a multistate, age-structured, time-varying, and stochastic system dynamics (SD) model. To the author's knowledge, it is the first time this dynamic simulation technique is used to conduct a full economic evaluation of different modes of contraceptive provision.

---

[3] Research questions (see section 1.3):

1. Can a system dynamics model accurately represent the reproductive life years of women, capturing the dynamics of contraceptive adoption, switching, and discontinuation?
2. Which contraceptive coverage policies are most cost-effective in reducing unintended pregnancy and other important reproductive/maternal health and economic outcomes over the longer term, given the dynamics of contraceptive adoption, switching, and discontinuation among Mexican women?

Research objectives (see section 1.3):

1. Develop a conceptual model to characterise the different stages in the reproductive life years of women aged 15 to 49, and depict their interrelations with contraceptive adoption, switching, and discontinuation.
2. Translate the conceptual model into an endogenously driven, multistate, age-structured, time-varying system dynamics simulation model which represents the evolving dynamics of contraceptive, sexual, and reproductive behaviours to estimate their impact on the following outcomes:
    a. Unintended pregnancies due to contraception failure and non-use of contraception.
    b. Live births, unsafe abortions, and maternal deaths attributable to unintended pregnancy.
    c. Economic impact of contraceptive provision and unintended pregnancy from the perspective of the health provider.
3. Use the devised model to compare the cost-effectiveness of different contraceptive provision policies aiming to reduce unintended pregnancy.

Approaching the contraceptive, sexual and reproductive dynamics via simulation modelling allowed us to explore the effectiveness and outcomes of different contraceptive provision strategies in a way that inferential statistics, often relying on observational or intervention data to estimate the effectiveness of the studied policies, could not: our simulation model integrates multiple factors (e.g., user behaviour, method failure rates, demographic birth cohorts) to simulate real-world dynamics. Thus, the model allowed us to assess the impact of different, hypothetical contraceptive provision strategies in a selection of outcomes without the need to conduct large-scale experiments.

The latter will appeal to stakeholders involved in the provision/study of sexual and reproductive health services, as they can use model results or the devised model structure to conduct additional analyses in response to their needs, data availability, and resources.

The model benefitted from the wealth of information available in public datasets to capture more than a decade of evolving contraceptive use intertwined with sexual and reproductive behaviours of Mexican women aged 15 to 49.

Such contraceptive, sexual, and reproductive behaviours were conceived and then represented as a variety of states that women of reproductive age (WoRA) might visit throughout their life. Some are absorbing, i.e., death; or can only be exited via ageing, e.g., permanent contraceptive users. Most of them, however, are transient and can be visited multiple times in response to the different circumstances WoRA undergo during their reproductive years.

Featuring recurrent spells in the model implied structuring the model in a multistate cohort framework and estimating the conditional probabilities of transitioning between the different states to represent the dynamics between the different behaviours (Ansah et al., 2017, 2021), e.g., moving from sexual inactivity to behavioural contraception use at the next timestep.

There are typically two methods to follow in such a task: 1) fitting hazard models under a regression framework (Andersen & Pohar Perme, 2008, 2014; Bijwaard, 2014; Hougaard, 1999; Schmoor et al., 2013), or producing multiple increment-decrement life tables from a longitudinal data source (Kuo et al., 2008; Schoen, 1988), e.g., panel data; and 2) estimating these transition probabilities from separate sources (M. F. Drummond et al., 2015c), including topic-specific literature (Babigumira et al., 2012; Hu et al., 2007; Zakiyah et al., 2019).

Whilst there is a longitudinal data source available in Mexico (Demographic Retrospective Survey) (Instituto Nacional de Estadística y Geografía, 2018) that also reports contraceptive behaviours (i.e., use/non-use), this biographical data source lacks data on sexual (e.g., sexual inactivity spells) and reproductive (e.g., trying to be pregnant spells) behaviours. Thus, the data source was deemed insufficient to fully parameterise the model after being put to use in estimating the transition probabilities. As it was expected, unsatisfactory validation results (not shown in this thesis) rendered it unusable for the matters of this research.

Therefore, an alternative approach was applied in this thesis, consisting in estimating the transition probabilities by solving an underdetermined system of equations with the Moore-Penrose pseudoinverse (Chen X, 2015; Erdmann et al., 2020; Feng Lin, 2013; Khosravi et al., 2016; Lin & Chen, 2010) using data from a cross-sectional survey (National Survey on the Demographic Dynamics, ENADID) (Instituto Nacional de Estadística y Geografía, 2019a). This procedure allowed to reduce uncertainty in the estimates as they came from a single source with a homogenous distribution of respondent biases (Boerma & Sommerfelt, 1993) and statistical representativity of Mexican WoRA.

Transition probabilities and the remaining model parameters were disaggregated in age classes since the modelled behaviours are age dependent. Babigumira et al (2012), and Zakiyah et al (2019) have previously used five-year age classes to parameterise dynamic simulation models and study the economic efficiency of scaling up contraceptive use. In this thesis, one-year age classes were implemented due to the granularity of the data sources available.

Moreover, and perhaps more importantly, single-year age classes were considered more appropriate to avoid averaging out behaviours at disparate ages within larger age groups. For instance, the sexual behaviour of a girl just starting her reproductive years at age 15 differs from what is observed in an adolescent about to turn 20: the estimated probability of becoming sexually inactive after a spell of sexual activity and non-use of contraception at age 19 (0.2) is nearly double that of age 15 (0.102) in 2006. This is also true for older women: the estimated probability of adopting long-acting, reversible contraception after a spell of sexual activity and non-use of contraception at age 49 (0.074) was 40% lower than that at age 45 (0.122) in 2006. Thus, having one-year stratified parameters allowed to produce more refined estimates.

Different annual transition probabilities are used during the period 2006-2018 to capture potential inter-cohort variations and to further refine the health and economic outcomes estimated. This, again, contrasts with studies of (Babigumira et al., 2012; Carvalho et al., 2013; Erim et al., 2012; Goldie et al., 2010; Hu et al., 2007; Zakiyah et al., 2019) who have assumed fixed parameters over time in their models, a contestable choice given previous discussions on the relatively fast-paced evolution of contraceptive, sexual, and reproductive behaviours (Alvergne & Stevens, 2021; Benagiano et al., 2007; Ortiz, 2009; van de Kaa, 2011). Two examples from the research in this thesis add to the likelihood of this assertion. Firstly, among girls aged 15, the probability of becoming a traditional contraceptive user after a spell of sexual activity and non-contraceptive use went from 0.14 in 2006 to 0.114 in 2018, a 19% reduction. Secondly, among women aged 49, the probability of discontinuing behavioural contraception to become a sexually active non-user increased from 0.206 in 2006 to 0.262 in 2018 (27%), peaking at 0.386 in 2009.

However, the health and economic consequences of the different strategies tested in this research could turn out to be conservative estimates of how the situation might develop over time, since the model parameters remain fixed for two decades after 2030. These estimates can be updated as new ENADID waves become available, helping also to update the conclusions and policy recommendations drawn from the model.

Uncertainty bounds surrounding the point estimates for health and economic consequences were obtained by performing fifty iterations of the model. Although this incurred a relatively high computational cost, the level of detail gained with this form of sensitivity analysis allowed us to present the results in a statistically intuitive manner (Leppink et al., 2016), and to introduce additional, robust cost-effectiveness analysis tools, i.e., cost-effectiveness acceptability curve (CEAC) and CEA frontier (CEAF). Both metrics exhaust the data produced at each iteration and evaluate the merits of each strategy simultaneously, helping decision-makers to have a more informed overview of what might constitute the best value for money (Barton et al., 2008; M. F. Drummond et al., 2015a; Fenwick et al., 2001; Fenwick & Byford, 2005).

However, although value for money is a highly sought-after and valuable prerequisite to the introduction of new medical technology in Mexico (Consejo de Salubridad General, 2023) and elsewhere (Jena & Philipson, 2013), additional considerations must be borne in mind when prioritising between interventions (M. F. Drummond et al., 2015d).

After almost half a century after its introduction as a population control policy (Quesada et al., 2001), contraception is now a staple in Mexican society. Its practice is extensively disseminated and for the most part it is a voluntary-use tool aimed at avoiding unintended pregnancy (Instituto Nacional de Estadística y Geografía, 2019c). Every institutional effort to reduce unintended pregnancy by implementing any new strategy, even one of the two strategies with the highest chance of being cost-effective according to this research (i.e., increasing adoption of modern reversible contraception, or a combined approach to tackle adoption, switching, and discontinuation of modern contraception), should not result in reversing past gains. Instead, the aim should be to strive to keep a philosophy of respect for the personal choices of potential and current contraceptive users (Marston & Tabot, 2023). The latter need not be a hurdle but a call to find innovative forms of affecting contraceptive behaviours by characterising the incentives at play when different methods are adopted, interrupted, or switched (Alvergne & Stevens, 2021; Anderson & Johnston, 2023).

In practice, sudden changes in both the contraceptive-sexual-reproductive dynamics and in resource availability are unrealistic. Therefore the effects of the interventions tested with the model were introduced incrementally rather than abruptly. The latter is customary practice when studying contraceptive provision (Babigumira et al., 2012; Black et al., 2015; Carvalho et al., 2013; Engstrand & Kopp Kallner, 2018; Erim et al., 2012; Goldie et al., 2010; Henry et al., 2015; Hu et al., 2007; Le et al., 2014; Moreau, Bohet, Trussell, et al., 2014; Trussell, 2007; Trussell et al., 2013; Zakiyah et al., 2019). It was concluded that our approach would increase the utility of the model as institutional efforts to expand contraceptive coverage in Mexico span several years and do not occur overnight (Secretaría de Salud, 2013).

The implementation period set in this research includes the last sprint of the United Nations' Sustainable Development Goals era (2023-2030) to show the required investment levels for Mexico to meet its health-related goals, specifically sexual health-related goals, e.g., secure contraceptive access to individuals. Given the model runs until 2050, the two-decade remaining period could be thought as a projection of the impact of sustaining financial (hence political) commitment to the goal of reducing UP. However, this does not account for economic downturns, losing political momentum, increasingly conservative attitudes towards contraception, or other disruptions.

Compared to the status quo (SQ), two strategies were found to be cost saving in avoiding unintended pregnancies at different WTP thresholds: 1) increasing the adoption of modern reversible contraception (LARC, behavioural) by 75% (3a_0.75); 2) and simultaneously increasing modern reversible contraceptive adoption, reducing switching from modern reversible contraception to traditional, and reducing contraceptive discontinuation, all by 75% (5_0.75). The first strategy allows cumulative savings of USD 5,784 per avoided UP and basically consists in expanding contraceptive coverage, whilst the second saves USD 1,313 per avoided UP with a multi-pronged approach to tackle the three defining components of contraceptive dynamics, i.e., adoption, switching, and discontinuation.

Both strategies result in fewer UP, which together with the associated cost savings imply dominance over the current situation. Their implementation is plausible given that the network of health clinics/hospitals is well developed in the country, there is a wide variety of contraceptives available at clinics, no major contraceptive shortages are reported (Quesada et al., 2001; Reproductive Health Supplies Coalition, 2021; Sarley et al., 2006), and there is interest at the health system level to increase adoption/reduce discontinuation of modern contraceptives, especially long-acting and reversible (Secretaría de Salud, 2021). Moreover, these two strategies do not appear to significantly impact the expected WoRA population development over time, as was also shown in this research. A possible implication of this finding, albeit outside the scope of this research, is the negligible impact these two strategies have in the development of the working-age population structure, and economic productivity over time, which further adds to the efficiency of their implementation.

In deciding which takes pre-eminence over the other, and according to the CEAC shown in Figure 7.4, strategy 3a_0.75 is optimal under budgetary constraints, giving way to strategy 5_0.75 as these relax. Having two strategies showing a high chance of cost-effectiveness at different WTP gives Mexican decision-makers flexibility in determining how to introduce them at different contexts in the country (Edlin, Hall, et al., 2015; Naveršnik, 2015). For instance, it would be sensible to apply strategy 5_0.75 in less resource-constrained settings, whilst reserving strategy 3a_0.75 for areas where the population demands contraceptives, however, the available resources and infrastructure does not allow applying an integral contraceptive provision policy (Ibáñez-Cuevas et al., 2021; Torres-Pereda et al., 2019). Although having separate policies for reaching the same goal -avoiding UP- could introduce fairness issues into the decision process, this approach could be useful in relieving competition for resources and pressure in the context of Mexico, where the population relies mainly on the public healthcare system to access contraceptives (Instituto Nacional de Estadística y Geografía, 2019c).

Furthermore, and although there is no official threshold to establish cost-effectiveness in the country, the WTP for strategy 3a_0.75 and 5_0.75 is well below the country's USD 11,091 per capita GDP estimated in 2022 (The World Bank, 2023). This adds to the argument in favour of their economic efficiency, according to the known rule of thumb of establishing cost-effectiveness in proportionality to per capita GDP, i.e., a strategy is highly cost-effective if below per capita GDP and cost-effective if below three times per capita GDP (Leech et al., 2018).

Natural units (unintended pregnancies avoided) were preferred over composite metrics such as quality-adjusted (QALYs) or disability-adjusted life years (DALYs) to study the effectiveness of the strategies tested. Transparency and ease of interpretation in the real world were the primary reasons for this choice, given natural units are more easily scrutable and programme planners/decision-makers are largely familiar with them, increasing their usability to inform contraceptive policies.

Furthermore, establishing the link between contraceptive use/non-use and unintended pregnancy is straightforward, which adds to the pertinence of conducting a CEA with such effectiveness units. To date, there are no sources available to draw QALYs, DALYs, or utility weights associated with contraceptive use that account for the impact of different contraceptive choices on various health outcomes of WoRA. Thus, the use of these composite metrics was discarded, acknowledging their convenience in comparing the economic efficiency of allocating resources between different treatments, not necessarily impacting the same natural units (Sanders et al., 2019).

In this research, unintended pregnancies were defined as those resulting from contraceptive failure amongst users or non-use of contraception by sexually active women who do not wish to become pregnant. Whilst the definition assumes an explicit intention to avoid pregnancy, different processes come at play within these groups. Firstly, women experiencing contraceptive failure have made an explicit decision to avoid pregnancy through method use, whereas those not using contraception may include individuals with varying degrees of intent or ambivalence (Frost et al., 2007), influenced by factors such as cultural norms, insufficient information on contraception, or barriers to accessing contraceptive methods (Gilliam et al., 2011; Nazar-Beutelspacher et al., 1999; Vázquez-Rodríguez et al., 2018). Moreover, some women may hold a strong and definitive desire to avoid pregnancy, while others may have less firm preferences, which could influence their likelihood of seeking contraceptive advice or using a method effectively (Harvey et al., 2006; K. L. White & Potter, 2013). Nuanced understanding of preferences should drive the design of interventions aimed at increasing contraceptive uptake and reducing unintended pregnancies.

After adjusting the total number of pregnancies with contraceptive failure rates, the proportion of unintended pregnancies obtained for 2009 (roughly 21.5%) differs substantially from the 55% reported for the same year by (Juárez et al., 2013). This latter estimate was obtained retrospectively by asking women whether their most recent pregnancy was mistimed (i.e., happened earlier than ideally desired) or unwanted (i.e., not desired at all), giving the estimate a strong element of subjectivity which was possibly influenced by other life events (e.g., dropping out of school, losing a job) associated with bringing a pregnancy to term. Thus, the two figures cannot be directly compared whatever the chance this thesis' estimates are contained into Juárez *et al*'s estimate.

Compared against official sources, the simulated demographic results show that the proposed SD model closely follows population development and produces reasonably accurate results regarding its age structure. It is expected that the population of WoRA will continue to increase, peak, then decrease in the years to come. This is mainly driven by the currently experienced and expected declines in fertility by Mexican WoRA, who are expected to exhibit below-replacement fertility levels by the middle of the 21st century (Consejo Nacional de Población, 2023).

With fewer live births and even with improving death rates, fewer women will mature to reach 15 years of age and start their reproductive life. It could also be argued that net migration, according to the available projections for the youngest reproductive age group, will play an important role since more women leave rather than enter the country (Consejo Nacional de Población, 2023).

However, and despite the negative correlation between migration and age, it is expected that net migration will remain stable for the 15-19 age group in the future. Naturally, the declining number of women entering the youngest reproductive ages will also be confirmed at subsequent stages as they age, reflecting the population's growth deceleration.

We can further verify the consequences of having fewer women of reproductive age by looking at the way the WoRA population pyramid evolves over time. In 2010, the pyramid had a broader and younger base where women aged 15-24 comprised nearly a quarter of the total population. If we also include girls before they enter their reproductive years, this figure grows to circa 60%. As time moves forward, the pyramid becomes narrower on its base, reaching a more uniform distribution in 2020, and inverts by 2050 (Figure 5.10). This raises interesting questions, given the differing contraceptive needs the Mexican health system has been required to meet in a short period of ten years (2010-2020).

It is expected that such needs will continue to evolve as women age (2020-2050). At this current pace, it could be argued, most women will demand permanent contraception services in the upcoming decades. At the very least, the makeup of the required contraceptive provisioning efforts will change, meaning that the response organised by the Mexican health system must update and revamp its approaches, to try to keep pace with a swiftly adjusting reproductive-age population structure within an ever-present context of resource scarcity.

8.2 Limitations

Firstly, the model is only capable of representing movement between stocks once a year, even though there is a chance that some transitions occur more frequently than this. Two attempts were made to change the transition probabilities to monthly, firstly using the original ENADID datasets consulted to obtain the model parameters, and then by following the matrix eigen decomposition approach suggested in (Chhatwal et al., 2016; Gidwani & Russell, 2020).

The first approach, deriving smaller (e.g., monthly) transition probabilities, was ruled out due to the survey design of ENADID. The population was sampled in single-year age groups (Instituto Nacional de Estadística y Geografía, 2019a). Any smaller time specification would have resulted in biased estimates.

The second approach consisted of obtaining the nth root of the estimated annual transition-probability matrices to modify their frequencies, i.e., taking the 12th root of the matrices to transform to monthly probabilities. Unfortunately, the algorithm resulted in imaginary or negative numbers, contradicting the notion of probability being bounded between zero and one, and hence these results were also discarded. Having single events per year could have resulted in underestimating health and economic outcomes as it is acknowledged that some transitions can occur more than once yearly (Upadhyay et al., 2012). However, after comparing our results against the selected benchmarks (see Chapter 5), these were overall in close agreement, which helps justifying the plausibility of the modelled results.

Being a first to Mexico, the estimated transition probabilities have no previous comparator; hence they possess a degree of uncertainty and require cautious interpretation. What is more, some of these probabilities had to be normalised, possibly increasing their uncertainty. It has been long known that to estimate transition probabilities to populate multistate, recurrent models, a longitudinal data source is used to calculate movement intensities within a competing risk framework (Steele et al., 2004). A longitudinal data source of the size and scope required to parameterise the model proposed in this thesis, however, does not exist for the country, nor it can be generated from the ENADID survey given it does not account for events in a contraceptive/reproductive calendar (The Demographic and Health Surveys Program, 2018), as in other demographic and health surveys (Leite & Gupta, 2007; Steele et al., 2004; Swiatlo et al., 2023).

To compensate for the lack of a longitudinal data source, transition probabilities representing the different contraceptive, sexual, and reproductive behaviours of Mexican WoRA were estimated from the National Survey of Demographic Dynamics (ENADID), a probabilistic, cross-sectional demographic survey that aims to *“[...] provide statistical information related to the level and* *behaviour of the components of demographic dynamics: fertility, mortality and migration (domestic and international); as well as reproductive preferences, sexuality, use of birth control methods, marriage and maternal and child health; as well as other topics related to the population, households and housing"* (Instituto Nacional de Estadística y Geografía, 2019a).

The ENADID data were collected for reasons that are a precise match to the needs of the model. Moreover, the ENADID dataset represents the same population, over time, which again precisely matches the requirements of the model, thereby avoiding some of the typical problems using secondary data such as inconsistencies in population representativeness, mismatches in temporal alignment, and challenges related to data completeness.

Given its scope, data collected through this survey was deemed highly relevant to parameterise the simulation model devised in this research, additionally being useful to represent the evolving nature of the C-S-R dynamics across different birth cohorts via its four different waves (2006, 2009, 2014, 2018). See Section 4.3.

Despite self-reporting in population surveys similar to ENADID introduces interpretation issues, these relatively low-cost data sources evenly distribute the likelihood of finding recall biases or misleading answers across age groups (Boerma & Sommerfelt, 1993). Thus, data from this survey were deemed useful to estimate population indicators.

Uncertainty also arises from the unaccounted impact of external shocks, e.g., the COVID-19 pandemic, that potentially modified the contraceptive, sexual, and reproductive dynamics of Mexican WoRA and of the health system's response to these changes (Castro, 2020; de Leon et al., 2022; Doubova et al., 2021; Mendez-Dominguez et al., 2021; Pilecco et al., 2021; Riley et al., 2020). It is unknown, however, whether these disruptions will pose long-term consequences or how they might evolve.

To conduct any cost-effectiveness analysis, credible unit cost estimates should be used to secure the quality of total cost estimates and ultimately of the conclusions raised. These unit costs could be reported by the different health providers or be estimated in a micro-costing exercise (M. F. Drummond et al., 2015b). About the first case, this research did not find any public source available, whilst in the second, and despite the fact that the author is experienced in conducting such exercises (MSP Ecuador et al., 2017), they require a level of detail that is too time-consuming and thus was deemed impractical in this case. Instead, a literature search restricted to studies conducted in Mexico allowed to find sufficient data points to account for unit costs of contraceptive provision and pregnancy/post-abortion care at different public health providers.

Uncertainty in the parameters described was accounted for by conducting a probabilistic sensitivity analysis, i.e., Monte Carlo simulation, assigning them probability distributions which after a number of model iterations allow to present uncertainty intervals surrounding average estimates. The low number of model iterations (fifty) could be increased after further optimising the simulation code to reduce its execution time, a task reserved for the short-term future.

The time step of 0.5 years was selected to balance the computational feasibility of the model and the resolution required to capture the system's key dynamics accurately. This choice is more aligned with the temporal specification of the ENADID data, reported in yearly age cohort intervals.

Formal convergence testing was not undertaken, and future versions of the model could benefit from conducting sensitivity analysis to explore the effects of alternative, perhaps smaller time steps. Nevertheless, the inclusion of stochastic parameters helps to improve robustness of the results over model iterations, partially addressing concerns about potential inaccuracies introduced by time step used in the current version of the model.

Care was taken to explicitly introduce the whole range of behaviours leading to unintended pregnancy and other important outcomes (i.e., unsafe abortions, maternal deaths) in the model devised. This level of detail was further expanded by stratifying behaviours per age classes to reduce homogeneity within stocks and allowing parameters to vary over time. Nevertheless, human behaviours are presented in a mechanistic manner, and condensed into explicit, single-method, compartmentalised states. In consequence, it was assumed that women can belong to a single state at a time, although it is recognised that women can clearly belong to two or more states at once in real life (Blanc & Rutenberg, 1991; Eisenberg et al., 2012; Woods et al., 2006), for instance: being a sexually inactive contraceptive user, or using two different types of contraception.

Furthermore, the model, as all mechanistic models, does not represent human decision-making in detail, and does not account for external factors that influence contraceptive use, such as social, institutional, cultural, or psychological factors (D'Souza et al., 2022; Frost et al., 2007; Gilliam et al., 2011; Harvey et al., 2006).

The cost-effectiveness analysis adopted the perspective of the health payer, i.e., Mexican public healthcare services, by including the direct costs related to the provision of contraceptives and pregnancy/abortion care. The positive externalities of contraception have been described profusely in the past, and these are not limited only to health gains (Bailey et al., 2013; Chadwick et al., 2012; Kavanaugh & Anderson, 2013).

The latter opens up the possibility of broadening the scope of this analysis in the future by including the perspectives of potential users and society to account, for instance, for the desirability of long-acting contraception or the impact of an integrated contraceptive provision policy in neonatal health. Nevertheless, the analysis conducted introduces valuable insights as it helps to prioritise interventions that remain within Mexican health system's financial constraints, and to project their long-term sustainability. It also helps the health system to explicitly prioritise between interventions based on their direct impact on the target population: Mexican WoRA.

Although the compared strategies were introduced at annual increments, thus relaxing the assumption of immediate availability of resources, the model could benefit from including an operational-level perspective to test them. This implies, for instance, evaluating whether a 50% increment in contraceptive provision is achievable in practice at the health clinic level, given the available human resources, infrastructure, or location. A hybrid modelling approach, e.g., combining system dynamics and discrete-event simulation, could help to further strengthen the conclusions reached with this research by capturing both the high-level policy impacts and the operational constraints within healthcare facilities. For example, while system dynamics can effectively model the long-term population-level effects of increased contraceptive adoption, discrete-event simulation could provide insights into clinic-level bottlenecks, such as staff availability, service times, and supply chain limitations, offering a more granular understanding of feasibility and efficiency. Data collection efforts could then be tailored to parameterise this new version of the model, ensuring that both strategic and operational aspects are adequately represented and aligned with real-world implementation challenges.

8.3 Conclusions

The following are the main conclusions of this research, arising from the different stages in model development and analysis of results:

1. A multistate, age-structured, time-varying, and stochastic system dynamics model is capable of accurately represent the reproductive life years of women, capturing the evolving dynamics of contraceptive adoption, switching, and discontinuation. The model can also be used to test a diversity of contraceptive provision strategies, making it highly adaptable to different contexts.
2. The population of women of reproductive age in Mexico is projected to grow until 2034 and then decline towards 2050, primarily driven by the ongoing decrease in fertility rates. The analysis of contraceptive provision strategies demonstrates that, while such interventions have an impact on unintended pregnancies, they do not alter the underlying demographic trend developing within this group.
3. The absolute number of unintended pregnancies (UP) can be reduced with all the strategies tested, excepting promoting women to remain traditional contraceptive users, which lead to more UP, unsafe abortions, and maternal deaths. Traditional methods, owing to their high likelihood of failure, should not be prioritised in any credible programme aimed at reducing UP. Nevertheless, it is important to consider the role of women's preferences and the distinction between mistimed and unwanted pregnancies. The former, which occur earlier than desired, often reflect a preference for short-term or less invasive contraceptives. On the other hand, unwanted pregnancies, where (further) childbearing is not desired, are more likely to reflect stronger preferences for avoiding pregnancy and thus drive demand for highly effective methods such as long-acting reversible contraceptives.
    a. Programmes aiming to reduce UP must strike a balance between increasing access to the full range of highly effective contraceptive options whilst respecting women's individual preferences and circumstances. Women currently using traditional methods should be supported with clear, accessible pathways to alternative, more effective methods while being empowered to make choices that align with their personal needs and reproductive intentions. By doing so, such programmes can address the risk of unintended pregnancy in a manner that is both effective and respectful of individual autonomy.
4. Promoting women to remain traditional contraceptive users is also an inefficient use of economic resources compared to the *status quo* (SQ), as it is a more costly and less effective option.

5. The majority of the tested strategies are potentially cost saving choices in avoiding UP compared to SQ. However, ambitiously improving adoption of modern reversible contraception (i.e., long-acting, behavioural); and simultaneously improving adoption of modern reversible contraceptives, reducing switching from modern reversible contraception to traditional, and reducing contraceptive discontinuation are the two most resource-efficient strategies at hand. These can even be applied in different contexts within the country without major modifications to the current landscape of health clinics.

8.4 Original contributions of this research

It is expected that both the methods and the results from the analyses conducted in this research will have relevance to the Sexual and Reproductive Health research field, and to the system dynamics simulation practice. What follows gives an account of these contributions:

1. Using different waves of a national demographic survey (ENADID) to estimate the transition probabilities that characterise the contraceptive, sexual, and reproductive behaviours of Mexican women of reproductive age from a single source. This is a first not only for the country and surpasses other techniques in its ease of implementation and data needs given no longitudinal source is required to its implementation.
2. A novel, stochastic model structure that captures the different contraceptive, sexual, and reproductive behaviours (multistate), across age groups (age-structured) and over time (time-varying) was used to study the impact of a variety of contraceptive provision strategies in unintended pregnancy, unsafe abortions, and maternal deaths. The model was also used to conduct a cost-effectiveness analysis of these strategies in avoiding unintended pregnancies.
    a. The model was coded in an open-source language (Python) and benefits from its large ecosystem of libraries which facilitated the preparation of the code. The model could be converted with relative ease to a specialised system dynamics library to be applied to problems of a related nature in public health research or other fields.
    b. Model boundaries are also extendible to study additional outcomes or to broaden the scope of the cost-effectiveness analysis.
3. The proposed model structure is the first of its kind to be applied to contraceptive provision research, offering a versatile framework for testing a range of policy arrangements. Whilst its data requirements are not trivial, the model could be adapted to and implemented in different contexts, given it is parameterised with widely available data sources: routine administrative datasets, cross-sectional demographic surveys, and the body of sexual and reproductive health literature, a substantially studied field. Its capacity to adjust to context-specific data inputs makes it applicable across a broad spectrum of settings, healthcare systems, cultural norms, and policy priorities. For instance, in low- and middle-income countries, where routine datasets may be less comprehensive, the model could be parameterised with data from demographic surveys or regional studies. Conversely, in high-income settings with well-developed electronic health records, it could leverage more detailed administrative data to enhance its precision. This flexibility positions the model as a valuable tool for policymakers and

researchers seeking to evaluate and optimise contraceptive provision strategies across diverse populations.

4. Informing the Mexican contraceptive provision policymaking cycle with a highly sought-after methodology (cost-effectiveness analysis), using data sources publicly available in the country, and applying the detailed model devised. The findings can be used to prioritise between different contraceptive provision arrangements and analyse their sustainability in the forthcoming decades. New strategies can also be tested given this is a flexible model, capable of simulating a broad range of contraceptive, sexual, and reproductive behaviours.

8.5 Further research

A variety of extensions and additional research objectives can be accomplished using the model devised in this thesis as main platform. The following are some possible new endeavours to explore with this model or versions of it.

1. Disaggregating the current the model stocks (age-use) to include school attainment levels (age-schooling-use), given this is a strong predictor of contraceptive behaviours during the reproductive life years of Mexican women and other contexts. Including them would certainly extend model execution times, however with the advantage of obtaining more nuanced estimates, refining human behaviour representation, and explicitly allowing to reflect on the widespread benefits that education introduces in society.
2. Including other important outcomes of contraceptive provision strategies, such as children's health, poverty mitigation, or school dropout adds new elements to analyse contraceptive policymaking.
3. A natural area of application of the model is calibrating it with parameters for different contexts to produce within-country or regional comparisons (e.g., Central American countries, middle-income countries in the American continent) whenever there is interest in determining which strategies are more efficient in reaching development goals set in global, common agendas, such as the Sustainable Development Goals.
4. Further evaluating the operational feasibility of the strategies found to be efficient by explicitly accounting for resources available to the Mexican health system (e.g., personnel, supplies, infrastructure) with a hybrid simulation model. Quality of care aspects, which are a regular concern in the country (Torres-Pereda et al., 2019), could also be embedded in this hybrid model to explore their impact in modelled outcomes.
5. Women's personal characteristics could also be more easily handled under a hybrid simulation framework by employing, for instance, a SD-state chart simulation model which captures contraceptive-sexual-reproductive behaviours as personal traits (e.g., double use of contraceptives, frequency of sexual encounters, use of emergency contraception, number of children, willingness to start permanent contraception after the nth child).

8.6 Chapter summary

This final chapter presented a discussion of the main research findings, emphasizing their contribution in the policymaking process. Model limitations were also presented, together with their implications and any procedures undertaken to attenuate their impact in the research results. The main conclusions of this research, original contributions, and further avenues of enquiry were also detailed in the last sections of the chapter.

Appendix A List of model parameters

The parameters used in the contraceptive, sexual, and reproductive dynamics model are listed in the table below. Their values are presented elsewhere in the different sections of this document.

Parameter	Category	Model symbol
Transition probability from any non-death stock[1] to all-cause death	Demographic	s9, s18, s27, s36, s38, s48, s50, s59, s69, s71, s79
Transition probability from NU to UP	Contraceptive, sexual, and reproductive (C-S-R) dynamics	s6
Transition probability from NU to INT	C-S-R dynamics	s7
Transition probability from NU to SI	C-S-R dynamics	s8
Transition probability from NU to NU	C-S-R dynamics	s1
Transition probability from NU to LARC	C-S-R dynamics	s2
Transition probability from NU to PERM	C-S-R dynamics	s5
Transition probability from NU to BEH	C-S-R dynamics	s3
Transition probability from NU to TRAD	C-S-R dynamics	s4
Transition probability from LARC to UP	C-S-R dynamics	s15
Transition probability from LARC to NU	C-S-R dynamics	s10
Transition probability from LARC to INT	C-S-R dynamics	s16
Transition probability from LARC to SI	C-S-R dynamics	s17
Transition probability from LARC to LARC	C-S-R dynamics	s11
Transition probability from LARC to BEH	C-S-R dynamics	s12
Transition probability from LARC to TRAD	C-S-R dynamics	s13
Transition probability from LARC to PERM	C-S-R dynamics	s14
Transition probability from BEH to UP	C-S-R dynamics	s24
Transition probability from BEH to NU	C-S-R dynamics	s19
Transition probability from BEH to INT	C-S-R dynamics	s25
Transition probability from BEH to SI	C-S-R dynamics	s26

Transition probability from BEH to BEH	C-S-R dynamics	s21
Transition probability from BEH to LARC	C-S-R dynamics	s20
Transition probability from BEH to TRAD	C-S-R dynamics	s22
Transition probability from BEH to PERM	C-S-R dynamics	s23
Transition probability from TRAD to UP	C-S-R dynamics	s33
Transition probability from TRAD to NU	C-S-R dynamics	s28
Transition probability from TRAD to INT	C-S-R dynamics	s34
Transition probability from TRAD to SI	C-S-R dynamics	s35
Transition probability from TRAD to TRAD	C-S-R dynamics	s31
Transition probability from TRAD to LARC	C-S-R dynamics	s29
Transition probability from TRAD to BEH	C-S-R dynamics	s30
Transition probability from TRAD to PERM	C-S-R dynamics	s32
Transition probability from UP to M_DTH_UPUP	C-S-R dynamics	s47
Transition probability from UP to INF_UP	C-S-R dynamics	s45
Transition probability from UP to NU	C-S-R dynamics	s39
Transition probability from UP to SI	C-S-R dynamics	s46
Transition probability from UP to UP^2	C-S-R dynamics	s44
Transition probability from UP to LARC	C-S-R dynamics	s40
Transition probability from UP to PERM	C-S-R dynamics	s43
Transition probability from UP to BEH	C-S-R dynamics	s41
Transition probability from UP to TRAD	C-S-R dynamics	s42
Fraction of UP-related maternal deaths due to abnormal product of conception	Clinical	α_1
Fraction of UP-related maternal deaths occurring at childbirth	Clinical	α_2
Fraction of UP-related maternal deaths due to miscarriage	Clinical	α_3
Fraction of UP-related maternal deaths occurring during the gestational period	Clinical	α_4

Fraction of UP-related maternal deaths due to unsafe abortion	Clinical	α_5
Fraction of UP-related maternal deaths due to other causes	Clinical	α_6
Fraction of UP-related maternal deaths during the puerperal period	Clinical	α_7
Fraction of UP-related maternal deaths due to stillbirth	Clinical	α_8
Fraction of UP ending in livebirth	Clinical	β_1
Fraction of UP ending in miscarriage	Clinical	β_2
Fraction of UP ending in unsafe abortion	Clinical	β_3
Fraction of UP ending in stillbirth	Clinical	β_4
Fraction of UP-related secondary infertility after livebirth	Clinical	χ_1
Fraction of UP-related secondary infertility after miscarriage	Clinical	χ_2
Fraction of UP-related secondary infertility after unsafe abortion	Clinical	χ_3
Fraction of UP-related secondary infertility after stillbirth	Clinical	χ_4
Transition probability from INT to IP	C-S-R dynamics	s57
Transition probability from INT to NU	C-S-R dynamics	s51
Transition probability from INT to SI	C-S-R dynamics	s58
Transition probability from INT to INT	C-S-R dynamics	s56
Transition probability from INT to LARC	C-S-R dynamics	s52
Transition probability from INT to PERM	C-S-R dynamics	s55
Transition probability from INT to BEH	C-S-R dynamics	s53
Transition probability from INT to TRAD	C-S-R dynamics	s54
Transition probability from IP to M_DTH_UPIP	C-S-R dynamics	s68
Transition probability from IP to INF_IP	C-S-R dynamics	s66
Transition probability from IP to NU	C-S-R dynamics	s60

Transition probability from IP to SI	C-S-R dynamics	s67
Transition probability from IP to IP[2]	C-S-R dynamics	s65
Transition probability from IP to LARC	C-S-R dynamics	s61
Transition probability from IP to PERM	C-S-R dynamics	s64
Transition probability from IP to BEH	C-S-R dynamics	s62
Transition probability from IP to TRAD	C-S-R dynamics	s63
Fraction of IP-related maternal deaths due to an abnormal product of conception	Clinical	δ_1
Fraction of IP-related maternal deaths occurring at childbirth	Clinical	δ_2
Fraction of IP-related maternal deaths due to miscarriage	Clinical	δ_3
Fraction of IP-related maternal deaths occurring during the gestational period	Clinical	δ_4
Fraction of IP-related maternal deaths due to other causes	Clinical	δ_5
Fraction of IP-related maternal death during puerperium	Clinical	δ_6
Fraction of IP-related maternal death due to stillbirth	Clinical	δ_7
Fraction of IP ending in livebirth	Clinical	ε_1
Fraction of IP ending in miscarriage	Clinical	ε_2
Fraction of IP ending in stillbirth	Clinical	ε_3
Fraction of IP-related secondary infertility after livebirth	Clinical	ϕ_1
Fraction of IP-related secondary infertility after miscarriage	Clinical	ϕ_2
Fraction of IP-related secondary infertility after stillbirth	Clinical	ϕ_3
Transition probability from SI to NU	C-S-R dynamics	s72
Transition probability from SI to INT	C-S-R dynamics	s77
Transition probability from SI to SI	C-S-R dynamics	s78
Transition probability from SI to LARC	C-S-R dynamics	s73
Transition probability from SI to PERM	C-S-R dynamics	s76
Transition probability from SI to BEH	C-S-R dynamics	s74

Transition probability from SI to TRAD	C-S-R dynamics	s75
Proportion of yearly females born	Demographic	γ
All-cause death rate of females aged 14 and younger	Demographic	η
Yearly maturation fraction, females aged 14 and younger[3]	Demographic	ι
Net migration rate, females aged 14 and younger	Demographic	φ
Net migration rate, WoRA	Demographic	κ
Fraction of under-fifteen females maturing into NU[3]	Demographic	λ_1
Fraction of under-fifteen females maturing into LARC[3]	Demographic	λ_2
Fraction of under-fifteen females maturing into BEH[3]	Demographic	λ_3
Fraction of under-fifteen females maturing into TRAD[3]	Demographic	λ_4
Fraction of under-fifteen females maturing into PERM[3]	Demographic	λ_5
Fraction of under-fifteen females maturing into UP[3]	Demographic	λ_6
Fraction of under-fifteen females maturing into INF_UP[3]	Demographic	λ_7
Fraction of under-fifteen females maturing into INT[3]	Demographic	λ_8
Fraction of under-fifteen females maturing into IP[3]	Demographic	λ_9
Fraction of under-fifteen females maturing into INF_IP[3]	Demographic	λ_{10}
Fraction of under-fifteen females maturing into SI[3]	Demographic	λ_{11}

[1]NU, LARC, BEH, TRAD, PERM, UP, INF_UP, INT, IP, INF_IP, SI; [2]Assumed to be zero given the one-year specification of age groups; [3]See section 4.1.1.

Note: ***NU*** are sexually active, not intending to be pregnant, contraceptive non-users; ***LARC*** are long-acting, reversible contraceptive users; ***BEH*** are behavioural contraception users; ***TRAD*** are traditional contraception users; ***PERM*** are permanent contraception users; ***UP*** are unintentionally pregnant females; ***INF_UP*** are infecund females, secondary to unintended pregnancy; ***INT*** are females trying to be pregnant ; ***IP*** are intentionally pregnant females; ***INF_IP*** are infecund females, secondary to intended pregnancy; ***SI*** are sexually inactive females; ***Gnrl_DTH*** are all-cause deaths; ***M_DTH_UPUP*** are deaths related to maternal causes during UP; ***M_DTH_UPIP*** are deaths related to maternal causes during IP.

Appendix B List of transition probabilities to produce the contraceptive, sexual, and reproductive dynamics in the model

Origin stock	Destination stock	Source	Transition variable
Non-use (NU)	All-cause death (Gnrl_DTH)[1]	Death registry, INEGI	s9
NU	Unintended pregnancy (UP)	(Bradley *et al.*, 2019)	s6
NU	Trying to be pregnant (INT)	Own estimation, M-P pseudoinverse	s7
NU	Sexually inactive (SI)	Own estimation, M-P pseudoinverse	s8
NU	NU	Own estimation, M-P pseudoinverse	s1
NU	Long-acting, reversible contraception (LARC)	Own estimation, M-P pseudoinverse	s2
NU	Permanent contraception (PERM)	Own estimation, M-P pseudoinverse	s5
NU	Behavioural contraception (BEH)	Own estimation, M-P pseudoinverse	s3
NU	Traditional contraception (TRAD)	Own estimation, M-P pseudoinverse	s4
LARC	Gnrl_DTH[1]	Death registry, INEGI	s18
LARC	UP	(Bradley *et al.*, 2019)	s15
LARC	NU	Own estimation, M-P pseudoinverse	s10
LARC	INT	Own estimation, M-P pseudoinverse	s16
LARC	SI	Own estimation, M-P pseudoinverse	s17
LARC	LARC	Own estimation, M-P pseudoinverse	s11
LARC	BEH	Own estimation, M-P pseudoinverse	s12
LARC	TRAD	Own estimation, M-P pseudoinverse	s13
LARC	PERM	Own estimation, M-P pseudoinverse	s14
BEH	Gnrl_DTH[1]	Death registry, INEGI	s27
BEH	UP	(Bradley *et al.*, 2019)	s24
BEH	NU	Own estimation, M-P pseudoinverse	s19
BEH	INT	Own estimation, M-P pseudoinverse	s25
BEH	SI	Own estimation, M-P pseudoinverse	s26

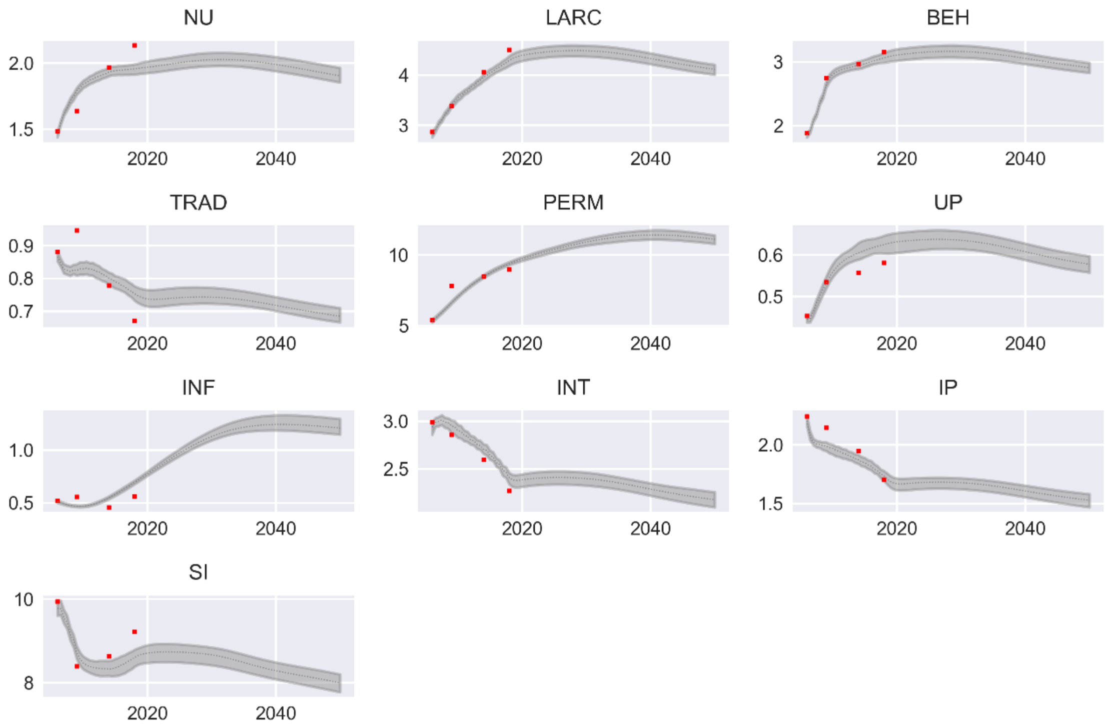
BEH	BEH	Own estimation, M-P pseudoinverse	s21
BEH	LARC	Own estimation, M-P pseudoinverse	s20
BEH	TRAD	Own estimation, M-P pseudoinverse	s22
BEH	PERM	Own estimation, M-P pseudoinverse	s23
TRAD	Gnrl_DTH[1]	Death registry, INEGI	s36
TRAD	UP	(Bradley *et al.*, 2019)	s33
TRAD	NU	Own estimation, M-P pseudoinverse	s28
TRAD	INT	Own estimation, M-P pseudoinverse	s34
TRAD	SI	Own estimation, M-P pseudoinverse	s35
TRAD	TRAD	Own estimation, M-P pseudoinverse	s31
TRAD	LARC	Own estimation, M-P pseudoinverse	s29
TRAD	BEH	Own estimation, M-P pseudoinverse	s30
TRAD	PERM	Own estimation, M-P pseudoinverse	s32
PERM	Gnrl_DTH[1]	Death registry, INEGI	s38
PERM	PERM	Own estimation[2]	s37
UP	Gnrl_DTH[1]	Own estimation, M-P pseudoinverse	s48
UP	Maternal deaths caused by UP (M_DTH_UP)	Death registry, INEGI	s47
UP	Infertility secondary to UP (INF_UP)	Own estimation, M-P pseudoinverse	s45
UP	NU	Own estimation, M-P pseudoinverse	s39
UP	SI	Own estimation, M-P pseudoinverse	s46
UP	UP	Assumed to be zero[3]	s44
UP	LARC	Own estimation, M-P pseudoinverse	s40
UP	PERM	Own estimation, M-P pseudoinverse	s43
UP	BEH	Own estimation, M-P pseudoinverse	s41
UP	TRAD	Own estimation, M-P pseudoinverse	s42
INF_UP	Gnrl_DTH[1]	Death registry, INEGI	s50
INF_UP	INF_UP	Own estimation[2]	s49
INT	Gnrl_DTH[1]	Death registry, INEGI	s59
INT	IP	Own estimation, M-P pseudoinverse	s57
INT	NU	Own estimation, M-P pseudoinverse	s51

INT	SI	Own estimation, M-P pseudoinverse	s58
INT	INT	Own estimation, M-P pseudoinverse	s56
INT	LARC	Own estimation, M-P pseudoinverse	s52
INT	PERM	Own estimation, M-P pseudoinverse	s55
INT	BEH	Own estimation, M-P pseudoinverse	s53
INT	TRAD	Own estimation, M-P pseudoinverse	s54
IP	Gnrl_DTH[1]	Death registry, INEGI	s69
IP	Maternal deaths caused by IP (M_DTH_IP)	Death registry, INEGI	s68
IP	Infertility caused by IP (INF_IP)	Own estimation, M-P pseudoinverse	s66
IP	NU	Own estimation, M-P pseudoinverse	s60
IP	SI	Own estimation, M-P pseudoinverse	s67
IP	IP	Assumed to be zero[3]	s65
IP	LARC	Own estimation, M-P pseudoinverse	s61
IP	PERM	Own estimation, M-P pseudoinverse	s64
IP	BEH	Own estimation, M-P pseudoinverse	s62
IP	TRAD	Own estimation, M-P pseudoinverse	s63
INF_IP	Gnrl_DTH[1]	Death registry, INEGI	s71,
INF_IP	INF_IP	Own estimation[2]	s70
SI	Gnrl_DTH[1]	Death registry, INEGI	s79
SI	NU	Own estimation, M-P pseudoinverse	s72
SI	INT	Own estimation, M-P pseudoinverse	s77
SI	SI	Own estimation, M-P pseudoinverse	s78
SI	LARC	Own estimation, M-P pseudoinverse	s73
SI	PERM	Own estimation, M-P pseudoinverse	s76
SI	BEH	Own estimation, M-P pseudoinverse	s74
SI	TRAD	Own estimation, M-P pseudoinverse	s75

[1]Women in these stocks were assigned an equal probability of dying from all causes after dividing the reported all-cause death rate in the registry by 11, the number of different stocks where such deaths might occur; [2]Estimated as 1- all-cause death rate; [3]Given the model uses yearly transition probabilities, the probability of being pregnant after one year was set to zero.

Appendix C Calibration. Visual agreement of model results against survey data

The hand calibration process ended once acceptable agreement was obtained between ENADID survey's (red dots in the figure) and simulated data (gray bands), as shown in the figure below. The full model was run each time an unknown parameter, i.e., secondary infertility after intended/unintended pregnancy was adjusted and a visual check was reattempted.



Note: 1) *x* axis represents simulated years, *y* axis represents population in each stock. 2) Stock names, from upper left to lower right, are: Non-user, sexually active (NU); long-acting user, sexually active (LARC); behavioural user, sexually active (BEH); traditional user, sexually active (TRAD); permanent user, sexually active (PERM); unintended pregnancy (UP); infertile (INF); trying to be pregnant, sexually active (INT); intended pregnancy (IP); sexually active (SI).

List of References

Alvergne, A., & Stevens, R. (2021). Cultural change beyond adoption dynamics: Evolutionary approaches to the discontinuation of contraception. *Evolutionary Human Sciences*, *3*. https://doi.org/10.1017/ehs.2021.8

American Pregnancy Association. (2015). *El Aborto Espontáneo: Los Signos, Los Síntomas, La Prevención y El Tratamiento*. American Pregnancy Association. http://americanpregnancy.org/es/pregnancy-complications/miscarriage/

Amonker, R. G., & Brinker, G. (2007). Reducing fertility in India. *International Journal of Sociology of the Family*, *33*(2), 327–348. https://www.jstor.org/stable/23070737

Andersen, P. K., & Pohar Perme, M. (2008). Inference for outcome probabilities in multi-state models. *Lifetime Data Analysis*, *14*(4 SPEC. ISS.), 405–431. https://doi.org/10.1007/s10985-008-9097-x

Andersen, P. K., & Pohar Perme, M. (2014). Multistate Models. In J. P. Klein, H. C. van Houwelingen, J. G. Ibrahim, & T. Scheike (Eds.), *Handbook of Survival Analysis* (pp. 417–439). CRC Press. https://statanaly.com/wp-content/uploads/2023/05/Handbook-of-Survival-Analysis.pdf#page=423

Anderson, D. J., & Johnston, D. S. (2023). A brief history and future prospects of contraception. *Science*, *380*(6641), 154–158. https://doi.org/10.1126/science.adf9341

Ansah, J. P., Chiu, C. T., Wei-Yan, A. C., Min, T. L. S., & Matchar, D. B. (2021). Trends in functional disability and cognitive impairment among the older adult in China up to 2060: estimates from a dynamic multi-state population model. *BMC Geriatrics*, *21*(1), 1–10. https://doi.org/10.1186/s12877-021-02309-4

Ansah, J. P., Koh, V., Chiu, C. T., Chei, C. L., Zeng, Y., Yin, Z. X., Shi, X. M., & Matchar, D. B. (2017). Projecting the Number of Elderly with Cognitive Impairment in China Using a Multi-State Dynamic Population Model. *System Dynamics Review*, *33*(2), 89–111. https://doi.org/10.1002/sdr.1581

Aracena-Genao, B., Leyva-Flores, R., & Gutiérrez-Reyes, J. P. (2022). Economic cost of pregnancy care attributable to the failure of Mexico's teenage pregnancy prevention policy. *Cadernos de Saude Publica*, *38*(6). https://doi.org/10.1590/0102-311XES109721

Arck, P. C., Rücke, M., Rose, M., Szekeres-Bartho, J., Douglas, A. J., Pritsch, M., Blois, S. M., Pincus, M. K., Bärenstrauch, N., Dudenhausen, J. W., Nakamura, K., Sheps, S., & Klapp, B.

F. (2008). Early risk factors for miscarriage: A prospective cohort study in pregnant women. *Reproductive BioMedicine Online*, *17*(1), 101–113. https://doi.org/10.1016/S1472-6483(10)60300-8

Avenir Health. (2012). *OHT-OneHealth Tool*. https://www.avenirhealth.org/software-onehealth

Babigumira, J. B., Stergachis, A., Veenstra, D. L., Gardner, J. S., Ngonzi, J., Mukasa-Kivunike, P., & Garrison, L. P. (2012). Potential cost-effectiveness of universal access to modern contraceptives in Uganda. *PLoS ONE*, *7*(2), 1–9. https://doi.org/10.1371/journal.pone.0030735

Bailey, M. J., Guldi, M., & Hershbein, B. J. (2013). Recent evidence on the road benefits of reproductive health policy. *Journal of Policy Analysis and Management*, *32*(4), 888–896. https://doi.org/https://doi.org/10.1002/pam.21710

Bancalari, A., Berlinski, S., Buitrago, G., García, F., De La Mata, D., & Vera-Hernández, M. (2023). *Sistema de salud e inequidades en salud en América Latina*. 1–47. https://scioteca.caf.com/handle/123456789/2188

Banks, J., & Carson, J. S. (1986). Introduction To Discrete-Event Simulation. *Winter Simulation Conference Proceedings*, 17–23. https://doi.org/10.1145/318242.318253

Barata, J. C. A., & Hussein, M. S. (2012). The Moore-Penrose Pseudoinverse: A Tutorial Review of the Theory. *Brazilian Journal of Physics*, *42*(1–2), 146–165. https://doi.org/10.1007/s13538-011-0052-z

Barton, G. R., Briggs, A. H., & Fenwick, E. A. L. (2008). Optimal cost-effectiveness decisions: The role of the cost-effectiveness acceptability curve (CEAC), the cost-effectiveness acceptability frontier (CEAF), and the expected value of perfection information (EVPI). *Value in Health*, *11*(5), 886–897. https://doi.org/10.1111/j.1524-4733.2008.00358.x

Báscolo, E., Houghton, N., & Del Riego, A. (2018). Types of health systems reforms in latin america and results in health access and coverage. *Revista Panamericana de Salud Publica/Pan American Journal of Public Health*, *42*, 1–9. https://doi.org/10.26633/RPSP.2018.126

Bearak, J., Popinchalk, A., Ganatra, B., Moller, A. B., Tunçalp, Ö., Beavin, C., Kwok, L., & Alkema, L. (2020). Unintended pregnancy and abortion by income, region, and the legal status of abortion: estimates from a comprehensive model for 1990–2019. *The Lancet Global Health*, *8*(9), e1152–e1161. https://doi.org/10.1016/S2214-109X(20)30315-6

Becerril-Montekio, V., Meneses-Navarro, S., Pelcastre-Villafuerte, B. E., & Serván-Mori, E.

(2024). Segmentation and fragmentation of health systems and the quest for universal health coverage: conceptual clarifications from the Mexican case. *Journal of Public Health Policy*, *45*(1), 164–174. https://doi.org/10.1057/s41271-024-00470-9

Bello-Chavolla, O. Y., Rojas-Martinez, R., Aguilar-Salinas, C. A., & Hernández-Avila, M. (2017). Epidemiology of diabetes mellitus in Mexico. *Nutrition Reviews*, *75*, 4–12. https://doi.org/10.1093/nutrit/nuw030

Benagiano, G., Bastianelli, C., & Farris, M. (2007). Contraception: A social revolution. *European Journal of Contraception and Reproductive Health Care*, *12*(1), 3–12. https://doi.org/10.1080/13625180601012311

Bianco, A., Stone, J., Lynch, L., Lapinski, R., Berkowitz, G., & Berkowitz, R. L. (1996). Pregnancy outcome at age 40 and older. *Obstetrics and Gynecology*, *87*(6), 917–922. https://doi.org/10.1016/0029-7844(96)00045-2

Bijwaard, G. E. (2014). Multistate event history analysis with frailty. *Demographic Research*, *30*(1), 1591–1620. https://doi.org/10.4054/DemRes.2014.30.58

Black, A. Y., Guilbert, E., Hassan, F., Chatziheofilou, I., Lowin, J., Jeddi, M., Filonenko, A., & Trussell, J. (2015). The Cost of Unintended Pregnancies in Canada: Estimating Direct Cost, Role of Imperfect Adherence, and the Potential Impact of Increased Use of Long-Acting Reversible Contraceptives. *Journal of Obstetrics and Gynaecology Canada*, *37*(12), 1086–1097. https://doi.org/10.1016/S1701-2163(16)30074-3

Blanc, A. K., & Rutenberg, N. (1991). Coitus and contraception: the utility of data on sexual intercourse for family planning programs. *Studies in Family Planning*, *22*(3), 162–176. https://doi.org/10.2307/1966643

Blümel, J. E., Chedraui, P., Calle, A., Bocanera, R., Depiano, E., Figueroa-Casas, P., Gonzalez, C., Martino, M., Royer, M., Zuñiga, C., Dulon, A., Espinoza, M. T., Futchner, C., Mostajo, D., Soto, E., Marco, A. A., Aravena, H., Busquets, M., Campodonico, I., … Castelo-Branco, C. (2006). Age at menopause in Latin America. *Menopause*, *13*(4), 706–712. https://doi.org/10.1097/01.gme.0000227338.73738.2d

Boerma, J. T., & Sommerfelt, A. E. (1993). Demographic and health surveys (DHS): Contributions and limitations. *World Health Statistics Quarterly*, *46*(4), 222–226.

Bradley, S. E. K., & Casterline, J. B. (2014). Understanding Unmet Need: History, Theory, and Measurement. *Studies in Family Planning*, *45*(2), 123–150. https://doi.org/10.1111/j.1728-4465.2014.00381.x

Bradley, S. E. K., Polis, C. B., Bankole, A., & Croft, T. (2019). Global Contraceptive Failure Rates: Who Is Most at Risk? *Studies in Family Planning*, *50*(1), 3–24. https://doi.org/10.1111/sifp.12085

Brailsford, S. C., Eldabi, T., Kunc, M., Mustafee, N., & Osorio, A. F. (2019). Hybrid simulation modelling in operational research: A state-of-the-art review. *European Journal of Operational Research*, *278*(3), 721–737. https://doi.org/10.1016/j.ejor.2018.10.025

Brailsford, S. C., Viana, J., Rossiter, S., Channon, A. A., & Lotery, A. J. (2013). Hybrid Simulation for Health and Social Care: the Way Forward, or More Trouble Than It 'S Worth? *Proceedings of the 2013 Winter Simulation Conference*, 258–269. https://doi.org/10.1109/WSC.2013.6721425

Brailsford, S., Desai, M., & Viana, J. (2010). Towards the holy grail: combining system dynamics and discrete-event simulation in healthcare. *Proceedings of the 2010 Winter Simulation Conference 2010*, 2293–2303. https://doi.org/10.1109/WSC.2010.5678927

Brugeilles, C., & Rojas, O. L. (2020). Análisis del comportamiento diferencial de la práctica anticonceptiva por sexo, origen social y educación en la población urbana de México. *Estudios Demográficos y Urbanos*, *35*(2), 293–332. https://doi.org/10.24201/edu.v35i2.1847

Burns, P. B., Rohrich, R. J., & Chung, K. C. (2011). The levels of evidence and their role in evidence-based medicine. *Plastic and Reconstructive Surgery*, *128*(1), 305–310. https://doi.org/10.1097/PRS.0b013e318219c171

Carvalho, N., Salehi, A. S., & Goldie, S. J. (2013). National and sub-national analysis of the health benefits and cost-effectiveness of strategies to reduce maternal mortality in Afghanistan. *Health Policy and Planning*, *28*(1), 62–74. https://doi.org/10.1093/heapol/czs026

Cassidy, R., Singh, N. S., Schiratti, P. R., Semwanga, A., Binyaruka, P., Sachingongu, N., Chama-Chiliba, C. M., Chalabi, Z., Borghi, J., & Blanchet, K. (2019). Mathematical modelling for health systems research: A systematic review of system dynamics and agent-based models. *BMC Health Services Research*, *19*(1), 15–17. https://doi.org/10.1186/s12913-019-4627-7

Castro, A. (2020). Challenges Posed by the COVID-19 Pandemic in the Health of Women, Children, and Adolescents in Latin America and the Caribbean. In *Policy Document Series*. https://doi.org/10.18356/9789210055390c013

Celhay, P., Martinez, S., Muñoz, M., Perez, M., & Perez-Cuevas, R. (2019). Long-term effects of public health insurance on the health of children in Mexico: a retrospective study. *The Lancet Global Health*, *7*(10), e1448–e1457. https://doi.org/10.1016/S2214-109X(19)30326-2

Centers for Disease Control and Prevention. (2024). *Contraception and Birth Control Methods*. https://www.cdc.gov/contraception/about/index.html

Cerrutti, M., & Massey, D. S. (2001). On the auspices of female migration from Mexico to the United states. *Demography*, *38*(2), 187–200. https://doi.org/10.2307/3088300

Chadwick, K. D., Burkman, R. T., Tornesi, B. M., & Mahadevan, B. (2012). Fifty years of "the pill": Risk reduction and discovery of benefits beyond contraception, reflections, and forecast. *Toxicological Sciences*, *125*(1), 2–9. https://doi.org/10.1093/toxsci/kfr242

Chang, A. Y., Ogbuoji, O., Atun, R., & Verguet, S. (2017). Dynamic modeling approaches to characterize the functioning of health systems: A systematic review of the literature. *Social Science and Medicine*, *194*, 160–167. https://doi.org/10.1016/j.socscimed.2017.09.005

Chen X, C. D. (2015). Systemize the Probabilistic Discrete Event Systems with Moore-penrose Generalized-inverse Matrix Theory for Cross-sectional Behavioral Data. *Journal of Biometrics & Biostatistics*, *06*(01), 1–6. https://www.researchgate.net/profile/Yuhlong-Lio/publication/281266318_Systemize_the_Probabilistic_Discrete_Event_Systems_with_Moorepenrose_Generalized-inverse_Matrix_Theory_for_Cross-sectional_Behavioral_Data/links/563f5cc108ae34e98c4e6f29/Systemize-the-

Chhatwal, J., Jayasuriya, S., & Elbasha, E. H. (2016). Changing Cycle Lengths in State-Transition Models. *Medical Decision Making*, *36*(8), 952–964. https://doi.org/10.1177/0272989x16656165

Coleman-Minahan, K., Boniface, E. R., Fuentes-Rivera, E., Saavedra-Avendaño, B., Riosmena, F., & Darney, B. G. (2022). Patterns in Contraceptive Use Among Women of Mexican Origin in the United States and in Mexico. *Obstetrics and Gynecology*, *140*(5), 784–792. https://doi.org/10.1097/AOG.0000000000004921

Consejo de Salubridad General. (2023). *Guía para la conducción de estudios de evaluación económica para la actualización del Compendio Nacional de Insumos para la Salud*. https://www.gob.mx/cms/uploads/attachment/file/920130/GCEEE_Enero_2023.pdf

Consejo Nacional de Población. (2019). *Necesidad Insatisfecha de métodos anticonceptivos (NIA) y Demanda satisfecha de métodos anticonceptivos 2014 y 2018*. Datos Abiertos.

https://datos.gob.mx/busca/dataset/salud-sexual-y-reproductiva/resource/15113a39-44c5-4489-abb4-369dc959c43d

Consejo Nacional de Población. (2023). *Conciliación Demográfica de 1950 a 2019 y Proyecciones de la población de México y de las entidades federativas 2020 a 2070*. https://www.gob.mx/conapo/acciones-y-programas/conciliacion-demografica-de-1950-a-2019-y-proyecciones-de-la-poblacion-de-mexico-y-de-las-entidades-federativas-2020-a-2070

Corsi, D. J., Neuman, M., Finlay, J. E., & Subramanian, S. V. (2012). Demographic and health surveys: A profile. *International Journal of Epidemiology*, *41*(6), 1602–1613. https://doi.org/10.1093/ije/dys184

Currie, C. S. M., & Cheng, R. C. H. (2013). A practical introduction to analysis of simulation output data. *Proceedings of the 2013 Winter Simulation Conference - Simulation: Making Decisions in a Complex World, WSC 2013*, 328–341. https://doi.org/10.1109/WSC.2013.6721431

D'Souza, P., Bailey, J. V., Stephenson, J., & Oliver, S. (2022). Factors influencing contraception choice and use globally: a synthesis of systematic reviews. *European Journal of Contraception and Reproductive Health Care*, *27*(5), 364–372. https://doi.org/10.1080/13625187.2022.2096215

Darabi, N., & Hosseinichimeh, N. (2020). System dynamics modeling in health and medicine: a systematic literature review. *System Dynamics Review*, *36*(1), 29–73. https://doi.org/10.1002/sdr.1646

Darney, B. G., Boniface, E., Jacobson, L. E., Fuentes-Rivera, E., Saavedra-Avendaño, B., Coleman-Minahan, K., & Riosmena, F. (2022). Adolescent Reproductive Health Outcomes Among Mexican-Origin Women on Both Sides of the U.S.-Mexico Border. *Journal of Adolescent Health*, *71*(6), 679–687. https://doi.org/10.1016/j.jadohealth.2022.06.021

de Leon, R. G. P., Bahamondes, M. V., Hellwig, F., Barros, A., Bahamondes, L., Tobar, F., da Silveira, M. F., Ali, M., Sánchez, P. I. G., Bremner, J., Smith, M., & Serruya, S. J. (2022). Potential of LARC to recover loss in satisfied demand for modern contraception after the COVID-19 pandemic: a case scenario analysis of Brazil and Mexico. *Revista Panamericana de Salud Publica/Pan American Journal of Public Health*, *46*, 1–8. https://doi.org/10.26633/RPSP.2022.41

Dewilde, S., & Anderson, R. (2004). The cost-effectiveness of screening programs using single and multiple birth cohort simulations: A comparison using a model of cervical cancer.

Medical Decision Making, *24*(5), 486–492. https://doi.org/10.1177/0272989X04268953

Diamond-Smith, N. G., Moreau, C., & Bishai, D. M. (2014). Reducing Unintended Pregnancies: A Microsimulation of Contraceptive Switching, Discontinuation, and Failure Patterns in France. *Studies in Family Planning*, *45*(4), 429–441. https://doi.org/10.1111/j.1728-4465.2014.00006.x

Doubova, S. V., Leslie, H. H., Kruk, M. E., Pérez-Cuevas, R., & Arsenault, C. (2021). Disruption in essential health services in Mexico during COVID-19: An interrupted time series analysis of health information system data. *BMJ Global Health*, *6*(9), 1–11. https://doi.org/10.1136/bmjgh-2021-006204

Drummond, M. F., Sculpher, M., Claxton, K., Stoddart, G. L., & Torrance, G. W. (2015a). Characterizing, reporting, and interpreting uncertainty. In *Methods for the Economic Evaluation of Health Care Programmes* (Fourth, pp. 389–425). Oxford University Press.

Drummond, M. F., Sculpher, M., Claxton, K., Stoddart, G. L., & Torrance, G. W. (2015b). Cost analysis. In *Methods for the Economic Evaluation of Health Care Programmes* (Fourth, pp. 218–265). Oxford University Press.

Drummond, M. F., Sculpher, M., Claxton, K., Stoddart, G. L., & Torrance, G. W. (2015c). Identifying, synthesizing, and analysing evidence for economic evaluation. In *Methods for the Economic Evaluation of Health Care Programmes* (Fourth, pp. 353–388). Oxford University Press.

Drummond, M. F., Sculpher, M., Claxton, K., Stoddart, G. L., & Torrance, G. W. (2015d). Making decisions in health care. In *Methods for the Economic Evaluation of Health Care Programmes* (Fourth, pp. 20–40). Oxford University Press.

Drummond, M., & McGuire, A. (2001). *Economic evaluation in health care: merging theory with practice* (First). Oxford University Press.

Edlin, R., Hall, P., McCabe, C., Wright, J., & Hulme, C. (2015). Outputs from Probabilistic Sensitivity Analysis. In *Cost Effectiveness Modelling for Health Technology Assessment. A Practical Course* (pp. 163–175).

Edlin, R., McCabe, C., Hulme, C., Hall, P., & Wright, J. (2015). Probability Distributions for Cost and Utility Parameters. In *Cost Effectiveness Modelling for Health Technology Assessment. A Practical Course* (pp. 105–109). Adis.

Egarter, C., Frey Tirri, B., Bitzer, J., Kaminskyy, V., Oddens, B. J., Prilepskaya, V., Yeshaya, A., Marintcheva-Petrova, M., & Weyers, S. (2013). Women's perceptions and reasons for choosing the pill, patch, or ring in the CHOICE study: A cross-sectional survey of contraceptive method selection after counseling. *BMC Women's Health*, *13*(1). https://doi.org/10.1186/1472-6874-13-9

Eisenberg, D. L., Allsworth, J. E., Zhao, Q., & Peipert, J. F. (2012). Correlates of dual-method contraceptive use: An analysis of the national survey of family growth (2006-2008). *Infectious Diseases in Obstetrics and Gynecology*, *2012*. https://doi.org/10.1155/2012/717163

Engstrand, S., & Kopp Kallner, H. (2018). Cost of unintended pregnancy in Sweden — a possibility to lower costs by increasing LARC usage. *Contraception*, *97*(5), 445–450. https://doi.org/10.1016/j.contraception.2018.01.009

Erdmann, S., Biddle, L., Kieser, M., & Bozorgmehr, K. (2020). Using independent cross-sectional survey data to predict post-migration health trajectories among refugees by estimating transition probabilities and their variances. *Biometrical Journal*, *64*(5), 964–983. https://doi.org/10.1002/bimj.202100045

Erim, D. O., Resch, S. C., & Goldie, S. J. (2012). Assessing health and economic outcomes of interventions to reduce pregnancy-related mortality in Nigeria. *BMC Public Health*, *12*(1), 1. https://doi.org/10.1186/1471-2458-12-786

Farland, L. V., Khan, S. M., Missmer, S. A., Stern, D., Lopez-Ridaura, R., Chavarro, J. E., Catzin-Kuhlmann, A., Sanchez-Serrano, A. P., Rice, M. S., & Lajous, M. (2023). Accessing medical care for infertility: a study of women in Mexico. *F and S Reports*, *4*(1), 112–120. https://doi.org/10.1016/j.xfre.2022.11.013

Feinberg, W. (1973). *Contraceptive protection provided individual couples and achievement of program goals: A computer simulation study of a marriage cohort under varying conditions associated with national family planning programs*. Brown University.

Feng Lin, X. C. (2013). Estimating Transitional Probabilities with Cross-Sectional Data to Assess Smoking Behavior Progression: A Validation Analysis. *Journal of Biometrics & Biostatistics*, 0–6. https://doi.org/10.4172/2155-6180.s1-004

Fenwick, E., & Byford, S. (2005). A guide to cost-effectiveness acceptability curves. *British Journal of Psichiatry*, *187*(2), 106–108. https://doi.org/10.1192/bjp.187.2.106

Fenwick, E., Claxton, K., & Sculpher, M. (2001). Representing uncertainty: The role of cost-effectiveness acceptability curves. *Health Economics*, *10*(8), 779–787. https://doi.org/10.1002/hec.635

Frenk, J., González-Pier, E., Gómez-Dantés, O., Lezana, M. A., & Knaul, F. M. (2006). Comprehensive reform to improve health system performance in Mexico. *Lancet*, *368*(9546), 1524–1534. https://doi.org/10.1016/S0140-6736(06)69564-0

Frost, J. J., Singh, S., & Finer, L. B. (2007). Factors Associated with Contraceptive Use and Nonuse, United States, 2004. *Perspectives on Sexual and Reproductive Health*, *39*(2), 90–99. https://doi.org/10.1363/3909007

Ganatra, B., Tunçalp, Ö., Johnston, H. B., Johnson, B. R., Gülmezoglu, A. M., & Temmerman, M. (2014). From concept to measurement: Operationalizing WHO's definition of unsafe abortion. *Bulletin of the World Health Organization*, *92*(3), 155. https://pmc.ncbi.nlm.nih.gov/articles/PMC3949603/

Garrido-Latorre, F., Lazcano-Ponce, E. C., López-Carrillo, L., & Hernández-Avila, M. (1996). Age of natural menopause among women in Mexico city. *International Journal of Gynecology and Obstetrics*, *53*(2), 159–166. https://doi.org/10.1016/0020-7292(96)02655-0

Gemmill, A., & Cowan, S. K. (2021). Low perceived susceptibility to pregnancy as a reason for contraceptive nonuse among women with unintended births. *Demographic Research*, *44*(April), 759–774. https://doi.org/10.4054/DEMRES.2021.44.31

Gidwani, R., & Russell, L. B. (2020). Estimating Transition Probabilities from Published Evidence: A Tutorial for Decision Modelers. *PharmacoEconomics*, *38*(11), 1153–1164. https://doi.org/10.1007/s40273-020-00937-z

Gilbert, N., & Terna, P. (2000). How to build and use agent-based models in social science. *Mind & Society*, *1*(1), 57–72. https://doi.org/10.1007/BF02512229

Gilliam, M. L., Neustadt, A., Whitaker, A., & Kozloski, M. (2011). Familial, Cultural and Psychosocial Influences of Use of Effective Methods of Contraception among Mexican-American Adolescents and Young Adults. *Journal of Pediatric and Adolescent Gynecology*, *24*(2), 79–84. https://doi.org/10.1016/j.jpag.2010.10.002

Goldie, S. J., Sweet, S., Carvalho, N., Natchu, U. C. M., & Hu, D. (2010). Alternative strategies to reduce maternal mortality in India: A cost-effectiveness analysis. *PLoS Medicine*, *7*(4). https://doi.org/10.1371/journal.pmed.1000264

Gómez Dantés, O., Sesma, S., Becerril, V. M., Knaul, F. M., Arreola, H., & Frenk, J. (2011). [The health system of Mexico]. *Salud publica de Mexico*, *53 Suppl 2*, s220-32.

Günal, M. M., & Pidd, M. (2010). Discrete event simulation for performance modelling in health care: A review of the literature. *Journal of Simulation*, *4*(1), 42–51.

https://doi.org/10.1057/jos.2009.25

Harris, C. R., Millman, K. J., van der Walt, S. J., Gommers, R., Virtanen, P., Cournapeau, D., Wieser, E., Taylor, J., Berg, S., Smith, N. J., Kern, R., Picus, M., Hoyer, S., van Kerkwijk, M. H., Brett, M., Haldane, A., del Río, J. F., Wiebe, M., Peterson, P., … Oliphant, T. E. (2020). Array programming with NumPy. *Nature*, *585*(7825), 357–362. https://doi.org/10.1038/s41586-020-2649-2

Harvey, S. M., Henderson, J. T., & Casillas, A. (2006). Factors associated with effective contraceptive use among a sample of Latina women. *Women and Health*, *43*(2), 1–16. https://doi.org/10.1300/J013v43n02_01

Henry, N., Schlueter, M., Lowin, J., Lekander, I., Filonenko, A., Trussell, J., & Skjeldestad, F. E. (2015). *Cost of unintended pregnancy in Norway : a role for long-acting reversible contraception*. 109–115. https://doi.org/10.1136/jfprhc-2014-100878

Hock-Long, L., Whittaker, P. G., & Herceg-Baron, R. (2010). Family planning service delivery research: a call to focus on the dynamics of contraceptive use. *Perspectives on Sexual and Reproductive Health*, *42*(1), 10. https://doi.org/10.1363/4201010

Hougaard, P. (1999). Multi-state Models: A Review. *Lifetime Data Analysis*, *5*(3), 239–264. https://doi.org/10.1023/A:1009672031531

Hoyt, J., Hamon, J. K., Krishnaratne, S., Houndekon, E., Curry, D., Mbembe, M., Marcus, S., Kambanje, M., Pryor, S., Barbra, A. A., Muhumuza, H., Spilotros, N., & Webster, J. (2022). "It was my own decision": the transformational shift that influences a woman's decision to use contraceptives covertly. *BMC Women's Health*, *22*(1), 1–13. https://doi.org/10.1186/s12905-022-01731-z

Hu, D., Bertozzi, S. M., Gakidou, E., Sweet, S., & Goldie, S. J. (2007). The costs, benefits, and cost-effectiveness of interventions to reduce maternal morbidity and mortality in Mexico. *PLoS ONE*, *2*(8). https://doi.org/10.1371/journal.pone.0000750

Hu, D., Grossman, D., Levin, C., Blanchard, K., & Goldie, S. J. (2009a). Cost-effectiveness analysis of alternative first-trimester pregnancy termination strategies in Mexico City. *BJOG: An International Journal of Obstetrics and Gynaecology*, *116*(6), 768–779. https://doi.org/10.1111/j.1471-0528.2009.02142.x

Hu, D., Grossman, D., Levin, C., Blanchard, K., & Goldie, S. J. (2009b). Cost-effectiveness analysis of alternative first-trimester pregnancy termination strategies in Mexico City. *BJOG: An International Journal of Obstetrics and Gynaecology*, *116*(6), 768–779.

https://doi.org/10.1111/j.1471-0528.2009.02142.x

Hubacher, D., Holtman, M., Fuentes, M., Perez-Palacios, G., & Janowitz, B. (1999). Increasing Efficiency to Meet Future Demand: Family Planning Services Provided by the Mexican Ministry of Health. *International Family Planning Perspectives*, *25*(3), 119–124. https://doi.org/10.2307/2991960

Humphreys, P. (2004a). 4.7. Deficiencies of Simulations. In *Extending Ourselves: Computational Science, empiricism, and scientific method* (1st ed., pp. 133–135). Oxford University Press.

Humphreys, P. (2004b). Further Issues. In *Extending Ourselves: Computational Science, empiricism, and scientific method* (1st ed., pp. 137–156). Oxford University Press.

Ibáñez-Cuevas, M., Torres-Pereda, P., Olvera-García, M., Pastrana-Sámano, R., & Heredia-Pi, I. B. (2021). Calidad de la atención en los Servicios de Salud Amigables para Adolescentes en Morelos, México: perspectiva de usuarios y prestadores. *Investigación y Ciencia de La Universidad Autónoma de Aguascalientes*, *29*(83). https://doi.org/10.33064/iycuaa2021833750

Instituto Nacional de Estadística y Geografía. (2018). *Encuesta Demográfica Retrospectiva (EDER)*. https://www.inegi.org.mx/programas/eder/2017/

Instituto Nacional de Estadística y Geografía. (2019a). *Encuesta Nacional de la Dinámica Demográfica (ENADID)*. https://www.inegi.org.mx/programas/enadid/2018/

Instituto Nacional de Estadística y Geografía. (2019b). *Mortalidad*. https://www.inegi.org.mx/programas/edr/#microdatos

Instituto Nacional de Estadística y Geografía. (2019c). *Tabulados. Encuesta Nacional de la Dinámica Demográfica (ENADID)*. https://www.inegi.org.mx/programas/enadid/2018/#Tabulados

Instituto Nacional de Estadística y Geografía. (2020). *Natalidad*. https://www.inegi.org.mx/programas/natalidad/default.html#Microdatos

Instituto Nacional de Estadística y Geografía. (2021). *Subsistema de Información Demográfica y Social*. Censo de Población y Vivienda 2020. https://www.inegi.org.mx/programas/ccpv/2020/

Instituto Nacional de Estadística y Geografía. (2024). *Mortalidad. Conjunto de datos: Defunciones registradas (mortalidad general) 1990-2022*.

https://www.inegi.org.mx/sistemas/olap/Proyectos/bd/continuas/mortalidad/MortalidadGeneral.asp#

Jena, A., & Philipson, T. (2013). Endogenous cost-effectiveness analysis in health care technology adoption. *Journal of Health Economics*, *32*(1), 172–180. https://www.nber.org/system/files/working_papers/w15032/w15032.pdf

Joseph, K. S., Boutin, A., Lisonkova, S., Muraca, G. M., Razaz, N., John, S., Mehrabadi, A., Sabr, Y., Ananth, C. V., & Schisterman, E. (2021). Maternal Mortality in the United States: Recent Trends, Current Status, and Future Considerations. *Obstetrics and Gynecology*, *137*(5), 763–771. https://doi.org/10.1097/AOG.0000000000004361

Juarez, B. F., & Singh, S. (2009). *Incidence of Induced Abortion by Age and State , Mexico , 2009 : New Estimates Using a Modified Methodology*. *2009*. https://doi.org/10.1363/3805812

Juarez, F., Gayet, C., & Mejia-Pailles, G. (2018). Factors associated with unmet need for contraception in Mexico: Evidence from the National Survey of Demographic Dynamics 2014. *BMC Public Health*, *18*(1), 1–8. https://doi.org/10.1186/s12889-018-5439-0

Juárez, F., Singh, S., Maddow-Zimet, I., & Wulf, D. (2013). Embarazo no planeado y aborto inducido en México. *Guttmacher Institute*, 48. http://www.guttmacher.org/pubs/Embarazo-no-deseado-Mexico.pdf

Jun, J. B., Jacobson, S. H., & Swisher, J. R. (1999). Application of Discrete-Event Simulation in Health Care Clinics: A Survey. *The Journal of the Operational Research Society*, *50*(2), 109. https://doi.org/10.2307/3010560

Kabagenyi, A., Kyaddondo, B., Nyachwo, E. B., Wasswa, R., Bwanika, J. M., Kabajungu, E., & Kiragga, A. (2022). Disruption in Essential Health Service Delivery: A Qualitative Study on Access to Family Planning Information and Service Utilization During the First Wave of COVID-19 Pandemic in Uganda. *Open Access Journal of Contraception*, *Volume 13*, 75–82. https://doi.org/10.2147/oajc.s360408

Kane, R., Irving, G., Brown, S., Parkes, N., Walling, M., & Killick, S. (2009). Long-acting, reversible and permanent methods of contraception: insight into women's choice of method. *Quality in Primary Care*, *17*, 107–114. https://pubmed.ncbi.nlm.nih.gov/19416603/

Kantorová, V., Wheldon, M. C., Ueffing, P., & Dasgupta, A. N. Z. (2020). Estimating progress towards meeting women's contraceptive needs in 185 countries: A Bayesian hierarchical modelling study. *PLoS Medicine*, *17*(2), 1–23. https://doi.org/10.1371/JOURNAL.PMED.1003026

Karpilow, Q. C., & Thomas, A. T. (2017). Reassessing the importance of long-acting contraception. *American Journal of Obstetrics and Gynecology*, *216*(2), 148.e1-148.e14. https://doi.org/10.1016/j.ajog.2016.10.012

Kavanaugh, M. L., & Anderson, R. M. (2013). Contraception and beyond: The health benefits of services provided at family planning centers. *Guttmacher Institute*, *July*, 1–39. https://www.guttmacher.org/sites/default/files/report_pdf/health-benefits.pdf

Keen, S., Begum, H., Friedman, H. S., & James, C. D. (2017). Scaling up family planning in Sierra Leone: A prospective cost–benefit analysis. *Women's Health*, *13*(3), 43–57. https://doi.org/10.1177/1745505717724617

Kennedy, E. C., Mackesy-Buckley, S., Subramaniam, S., Demmke, A., Latu, R., Robertson, A. S., Tiban, K., Tokon, A., & Luchters, S. (2013). The case for investing in family planning in the Pacific: Costs and benefits of reducing unmet need for contraception in Vanuatu and the Solomon Islands. *Reproductive Health*, *10*(1). https://doi.org/10.1186/1742-4755-10-30

Khosravi, A., Mansournia, M., Mahmoodi, M., Pouyan, A., & Holakouie-Naieni, K. (2016). Estimating the transitional probabilities of smoking stages with cross-sectional data and 10-year projection for smoking behavior in Iranian adolescents. *International Journal of Preventive Medicine*, *7*(1), 101. https://doi.org/10.4103/2008-7802.188602

Kim, K. W., & Kim, O. S. (2020). Super Aging in South Korea Unstoppable but Mitigatable: A Sub-National Scale Population Projection for Best Policy Planning. *Spatial Demography*, *8*(2), 155–173. https://doi.org/10.1007/s40980-020-00061-8

Koch, E., Gatica, S., Huerta-zepeda, A., & Calhoun, B. C. (2015). *Fundamental discrepancies in abortion estimates and abortion-related mortality : A reevaluation of recent studies in Mexico with special reference to the International Classification of Diseases*. 613–623. https://pdfs.semanticscholar.org/0413/f9147ed28d9200b8932f4ee2180b71385375.pdf

Kuo, T. M., Suchindran, C. M., & Koo, H. P. (2008). The multistate life table method: An application to contraceptive switching behavior. *Demography*, *45*(1), 157–171. https://doi.org/10.1353/dem.2008.0013

Küppers, G., Lenhard, J., & Shinn, T. (2006). Computer Simulation: Practice, Epistemology, and Social Dynamics. In G. Kuppers, J. Lenhard, & T. Shinn (Eds.), *Simulation: Pragmatic Constructions of Reality* (1st ed., pp. 3–24). Springer.

Kuri-Morales, P. A., Guevara-Guzmán, R., Phillips-Gutiérrez, V., Mota-Sánchez, A., & Díaz-Olavarrieta, C. A. (2020). Panorama nacional del embarazo precoz en México: lecciones aprendidas en un sexenio. *Gaceta Medica de Mexico*, *156*(2), 151–156. https://doi.org/10.24875/gmm.20005588

Lachenbruch, P., Sheps, M., & Sorant, A. (1974). Applications of POPREP, a modification of POPSIM. In *Computer Simulation in Human Population Studies* (pp. 305–328). Elsevier. https://doi.org/10.1016/B978-0-12-785185-3.50024-6

Lara, D., García, S. G., Ellertson, C., Camlin, C., & Suárez, J. (2006). The measure of induced abortion levels in Mexico using random response technique. *Sociological Methods and Research*, *35*(2), 279–301. https://doi.org/10.1177/0049124106290442

Le, H. H., Connolly, M. P., Bahamondes, L., Cecatti, J. G., Yu, J., & Hu, H. X. (2014). The burden of unintended pregnancies in Brazil: A social and public health system cost analysis. *International Journal of Women's Health*, *6*(1), 663–670. https://doi.org/10.2147/IJWH.S61543

Ledberg, A. (2020). Exponential increase in mortality with age is a generic property of a simple model system of damage accumulation and death. *PLoS ONE*, *15*(6 June), 1–17. https://doi.org/10.1371/journal.pone.0233384

Leech, A. A., Kim, D. D., Cohen, J. T., & Neumann, P. J. (2018). Use and Misuse of Cost-Effectiveness Analysis Thresholds in Low- and Middle-Income Countries: Trends in Cost-per-DALY Studies. *Value in Health*, *21*(7), 759–761. https://doi.org/10.1016/j.jval.2017.12.016

Legorreta, D., Montaño, J. A., Hernández, I., Salinas, C., & Hernández-Bueno, J. A. (2013). Age at menopause, motives for consultation and symptoms reported by 40-59-year-old Mexican women. *Climacteric*, *16*(4), 417–425. https://doi.org/10.3109/13697137.2012.696288

Leite, I. C., & Gupta, N. (2007). Assessing regional differences in contraceptive discontinuation, failure and switching in Brazil. *Reproductive Health*, *4*, 1–10. https://doi.org/10.1186/1742-4755-4-6

Leppink, J., O'Sullivan, P., & Winston, K. (2016). On variation and uncertainty. *Perspectives on Medical Education*, *5*(4), 231–234. https://doi.org/10.1007/s40037-016-0281-5

Levin, C., Grossman, D., Berdichevsky, K., Diaz, C., Aracena, B., Garcia, S. G., & Goodyear, L. (2009). Exploring the costs and economic consequences of unsafe abortion in Mexico City before legalisation. *Reproductive Health Matters*, *17*(33), 120–132. https://doi.org/10.1016/S0968-8080(09)33432-1

Li, Y., Lawley, M. A., Siscovick, D. S., Zhang, D., & Pagán, J. A. (2016). Agent-Based Modeling of

Chronic Diseases: A Narrative Review and Future Research Directions. *Prev Chronic Dis*, *13*(69). https://doi.org/https://doi.org/10.5888/pcd13.150561

Lin, F., & Chen, X. (2010). Estimation of transitional probabilities of discrete event systems from cross-sectional survey and its application in tobacco control. *Information Sciences*, *180*(3), 432–440. https://doi.org/10.1016/j.ins.2009.09.018

Lunenfeld, B., & Van Steirteghem, A. (2004). Infertility in the third millenium: Implications for the individual, family and society: Condensed meeting report from the Bertarelli Foundation's Second Global Conference. *Human Reproduction Update*, *10*(4), 317–326. https://doi.org/10.1093/humupd/dmh028

Lyneis, J. M., & Pugh, A. L. (1996). Automated vs. "Hand" Calibration of System Dynamics Models: An Experiment With a Simple Project Model. *Proceedings of the 1996 International System Dynamics Conference*, *42*. https://proceedings.systemdynamics.org/1996/proceed/papers/lynei317.pdf

Macal, C. M., & North, M. J. (2008). Agent-based modeling and simulation: ABMS examples. *Proceedings - Winter Simulation Conference*, 101–112. https://doi.org/10.1109/WSC.2008.4736060

MacAusland, R. (2014). The Moore-Penrose Inverse and Least Squares. *Advanced Topics in Linear Algebra*, 11. http://buzzard.ups.edu/courses/2014spring/420projects/math420-UPS-spring-2014-macausland-pseudo-inverse.pdf

Manlove, J., Cook, E., Karpilow, Q., Thomas, A., & Fish, H. (2014). *Male involvement in family planning: the estimated influence of improvements in condom use and efficacy on nonmarital births among teens and young adults*. https://www.researchgate.net/profile/Elizabeth-L-Cook/publication/293816865_Male_Involvement_in_Family_Planning_The_Estimated_Influence_of_Improvements_in_Condom_Use_and_Efficacy_on_Nonmarital_Births_among_Teens_and_Young_Adults/links/56bbaae808ae47fa3956

Manlove, J., Karpilow, Q., Welti, K., & Thomas, A. (2015). Linking Changes in Contraceptive Use to Declines in Teen Pregnancy Rates. *Societies*, *6*(1), 1. https://doi.org/10.3390/soc6010001

Marshall, C., Kandahari, N., & Raine-Bennett, T. (2018). Exploring young women's decisional needs for contraceptive method choice: a qualitative study. *Contraception*, *97*(3), 243–248. https://doi.org/10.1016/j.contraception.2017.10.004

Marshall, D. A., Burgos-Liz, L., Ijzerman, M. J., Crown, W., Padula, W. V., Wong, P. K., Pasupathy, K. S., Higashi, M. K., & Osgood, N. D. (2015). Selecting a dynamic simulation modeling method for health care delivery research - Part 2: Report of the ISPOR dynamic simulation modeling emerging good practices task force. *Value in Health*, *18*(2), 147–160. https://doi.org/10.1016/j.jval.2015.01.006

Marston, C., & Tabot, M. (2023). How can we put rights at the core of global family planning? *The Lancet*, *401*(10394), 2096–2098. https://doi.org/10.1016/S0140-6736(23)00523-8

Mavranezouli, I. (2008). The cost-effectiveness of long-acting reversible contraceptive methods in the UK: Analysis based on a decision-analytic model developed for a National Institute for Health and Clinical Excellence (NICE) clinical practice guideline. *Human Reproduction*, *23*(6), 1338–1345. https://doi.org/10.1093/humrep/den091

Mavranezouli, I. (2009). Health economics of contraception. *Best Practice and Research: Clinical Obstetrics and Gynaecology*, *23*(2), 187–198. https://doi.org/10.1016/j.bpobgyn.2008.11.007

Mendez-Dominguez, N., Santos-Zaldívar, K., Gomez-Carro, S., Datta-Banik, S., & Carrillo, G. (2021). Maternal mortality during the COVID-19 pandemic in Mexico: a preliminary analysis during the first year. *BMC Public Health*, *21*(1), 1–9. https://doi.org/10.1186/s12889-021-11325-3

Meneses Navarro, S., Pelcastre-Villafuerte, B. E., Becerril-Montekio, V., & Serván-Mori, E. (2022). Overcoming the health systems' segmentation to achieve universal health coverage in Mexico. *International Journal of Health Planning and Management*, *37*(6), 3357–3364. https://doi.org/10.1002/hpm.3538

Mitchell, A., Gutmann-Gonzalez, A., Brindis, C. D., & Decker, M. J. (2023). Contraceptive access experiences and perspectives of Mexican-origin youth: a binational qualitative study. *Sexual and Reproductive Health Matters*, *31*(1). https://doi.org/10.1080/26410397.2023.2216527

Moreau, C., Bohet, A., Le Guen, M., Loilier, A. R., & Bajos, N. (2014). Unplanned or unwanted? A randomized study of national estimates of pregnancy intentions. *Fertility and Sterility*, *102*(6), 1663–1670. https://doi.org/10.1016/j.fertnstert.2014.08.011

Moreau, C., Bohet, A., Trussell, J., & Bajos, N. (2014). Estimates of unintended pregnancy rates over the last decade in France as a function of contraceptive behaviors. *Contraception*, *89*(4), 314–321. https://doi.org/10.1016/j.contraception.2013.11.004

Morgan, S. L., & Winship, C. (2015). Introduction. In *Counterfactuals and Causal Inference: Methods and Principles for Social Research* (Second, pp. 3–29). Cambridge University Press.

MSP Ecuador, Senplades, UNFPA, & SENDAS. (2017). *Costos de Omisión en Salud Sexual y Reproductiva en Ecuador*. https://ecuador.unfpa.org/sites/default/files/pub-pdf/Resumen001.pdf

Muening, P. (2008). Chapter 2. Principles of cost-efffectiveness analysis. In *Cost-effectiveness Analyses in Health. A practical approach* (Second, pp. 19–35). Jossey-Bass.

National Institute for Health and Care Excellence. (2016). *Contraception* (p. 8). https://www.nice.org.uk/guidance/qs129/resources/contraception-pdf-75545366974405

Naveršnik, K. (2015). Output correlations in probabilistic models with multiple alternatives. *European Journal of Health Economics*, *16*(2), 133–139. https://doi.org/10.1007/s10198-013-0558-0

Nazar-Beutelspacher, A., Molina-Rosales, D., Salvatierra-Izaba, B., Zapata-Martelo, E., & Halperin, D. (1999). Education and Nonuse of Contraceptives among Poor Women in Chiapas, Mexico. *International Family Planning Perspectives*, *25*(3), 132–138. https://doi.org/10.2307/2991962

Oosthuizen, M., & Magero, J. (2021). *Modelling the Demographic Dividend: A Review of Methodologies*. https://esaro.unfpa.org/sites/default/files/pub-pdf/modelling_the_demographic_dividend-_a_review_of_methodologies_v5_1.pdf

Ortiz, P. (2009). Does Sex Education Influence Sexual and Reproductive Behaviour of Women?: Evidence from Mexico. *Instituto Valenciano de Investigaciones Económicas*. https://www.ivie.es/downloads/docs/wpasad/wpasad-2009-01.pdf

Pariani, S., Heer, D. M., & Arsdol, M. D. Van. (1991). Does Choice Make a Difference to Contraceptive Use? Evidence from East Java. *Studies in Family Planning*, *22*(6), 384. https://doi.org/10.2307/1966452

Patil, M., Janahanial, P., & Ghista, D. (1983). Mathematical simulation of impact of birth control policies on Indian population system. *Simulation*, *41*(3), 103–117.

Paulden, M. (2020). Calculating and Interpreting ICERs and Net Benefit. *PharmacoEconomics*, *38*(8), 785–807. https://doi.org/10.1007/s40273-020-00914-6

Phipps, M. G., Rosengard, C., Weitzen, S., Meers, A., & Billinkoff, Z. (2008). Age Group

Differences among Pregnant Adolescents: Sexual Behavior, Health Habits and Contraceptive Use. *Journal of Pediatric and Adolescent Gynecology*, *21*(1), 9–15. https://doi.org/10.1016/j.jpag.2007.07.009

Pilecco, F. B., McCallum, C. A., da Conceição Chagas de Almeida, M., Alves, F. J. O., dos Santos Rocha, A., Ortelan, N., Gabrielli, L., & de Souza Menezes, G. M. (2021). Abortion and the COVID-19 pandemic: Insights for Latin America. *Cadernos de Saude Publica*, *37*(6). https://doi.org/10.1590/0102-311X00322320

Ponce de Leon, R. G., Ewerling, F., Serruya, S. J., Silveira, M. F., Sanhueza, A., Moazzam, A., Becerra-Posada, F., Coll, C. V. N., Hellwig, F., Victora, C. G., & Barros, A. J. D. (2019). Contraceptive use in Latin America and the Caribbean with a focus on long-acting reversible contraceptives: prevalence and inequalities in 23 countries. *The Lancet Global Health*, *7*(2), e227–e235. https://doi.org/10.1016/S2214-109X(18)30481-9

Quesada, N., Rao, S., & Kinzett, S. (2001). *Mexico. Contraceptive Logistics System (DGSR): Review of Accomplishments and Lessons Learned*. https://www.rhsupplies.org/uploads/tx_rhscpublications/DOC109.pdf

Rao, A., Lindsey, Q., Bhavsar, R., Shah, B., Horvitz, D., & Batts, J. (1973). The evaluation of four alternative family planning programs for POPLAND, a less developed country. In *Computer Simulation in Human Population Studies* (pp. 261–304). Academic Press.

Ravindran, T. K. S., & Govender, V. (2020). Sexual and reproductive health services in universal health coverage: a review of recent evidence from low- and middle-income countries. *Sexual and Reproductive Health Matters*, *28*(2). https://doi.org/10.1080/26410397.2020.1779632

Reproductive Health Supplies Coalition. (2021). *Hoja Informativa Sobre Indicadores de Seguridad Anticonceptiva*. Reproductive Health Supplies Coalition. https://www.rhsupplies.org/uploads/tx_rhscpublications/FS-Mexico-FINAL-May2021.pdf

Reyes, H., Dreser, A., Arredondo, A., Bautista, S., & Ávila, L. (2019). Análisis y reflexiones sobre la iniciativa de reforma a la Ley General de Salud de México 2019. *Salud Pública de México*, *61*(5), 685. https://doi.org/10.21149/10894

Richiardi, M., van de Ven, J., & Bronka, P. (2023). Back to the future: Agent-based modelling and dynamic microsimulation. *CeMPA Working Paper Series*, *8*(23). https://hdl.handle.net/10419/306903

Riley, T., Elizabeth, S., Zara, A., & Ann, B. (2020). Estimates of the Potential Impact of the COVID-

19 Pandemic on Sexual and Reproductive Health In Low-and Middle-Income Countries Impacts of the Pandemic on SRH Outcomes. *International Perspectives on Sexual and Reproductive Health*, *46*, 73–76. https://doi.org/10.1363/46e9020

Roberts, M. S. (2015). Dynamic simulation in health care comes of age. *Value in Health*, *18*(2), 143–144. https://doi.org/10.1016/j.jval.2015.02.006

Saavedra-Avendano, B., Andrade-Romo, Z., Rodriguez, M. I., & Darney, B. G. (2017). Adolescents and Long-Acting Reversible Contraception: Lessons from Mexico. *Maternal and Child Health Journal*, *21*(9), 1724–1733. https://doi.org/10.1007/s10995-016-2013-1

Samari, G., Foster, D. G., Ralph, L. J., & Rocca, C. H. (2020). Pregnancy preferences and contraceptive use among US women. *Contraception*, *101*(2), 79–85. https://doi.org/10.1016/j.contraception.2019.10.007

Sanchez-Morales, J. E., Rodriguez-Contreras, J. L., Ruiz-Lara, L., Ochoa-Torres, B., Zaragoza, M., & Padilla-Zuniga, K. (2022). Cost Analysis of Surgical and Medical Uterine Evacuation Methods for First-Trimester Abortion Used in Public Hospitals in Mexico. *Health Services Insights*, *15*. https://doi.org/10.1177/11786329221126347

Sanders, G. D., Maciejewski, M. L., & Basu, A. (2019). Overview of cost-effectiveness analysis. *JAMA - Journal of the American Medical Association*, *321*(14), 1400–1401. https://doi.org/10.1001/jama.2018.6072

Santelli, J., Rochat, R., Hatfield-Timajchy, K., Gilbert, B. C., Curtis, K., Cabral, R., Hirsch, J. S., & Schieve, L. (2003). The Measurement and Meaning of Unintended Pregnancy. *Perspectives on Sexual and Reproductive Health*, *35*(2), 94–101. https://doi.org/10.1363/3509403

Santelli, J., Rochat, R., Hatfield, K., Gilbert, C., Curtis, K., Cabral, R., Hirsch, J. S., Gilbert, B. C., Curtis, K., & Hirsch, J. S. (2003). The Measurement and Meaning of Unintended Pregnancy. *Perspectives on Sexual and Reproductive Health*, *35*(2), 94–101. https://www.guttmacher.org/sites/default/files/article_files/3509403.pdf

Sarley, D., Dayaratna, V., Abramson, W., Gribble, J., Quesada, N., Olson, N., & Siman-Betancourt, V. (2006). *Options for contraceptive procurement. Lessons learned from Latin America and the Caribbean*. https://pdf.usaid.gov/pdf_docs/PNADI194.pdf

Sarma, R. S. S. (1970). *Alternative Family Planning Strategies for India: A simulation experiment* [North Carolina University]. https://repository.lib.ncsu.edu/server/api/core/bitstreams/8cc0235a-59cb-40fe-8411-a47f9a8edce5/content

Schmoor, C., Schumacher, M., Finke, J., & Beyersmann, J. (2013). Competing risks and multistate models. *Clinical Cancer Research*, *19*(1), 12–21. https://doi.org/10.1158/1078-0432.CCR-12-1619

Schoen, R. (1988). The Multistate Life Table. In *Modeling Multigroup Populations* (pp. 63–105). Springer. https://doi.org/10.1007/978-1-4899-2055-3_4

Secretaría de Salud. (2013). *Programa de Acción Específico. Planificación Familiar y Anticoncepción 2013-2018*. https://www.gob.mx/salud/acciones-y-programas/programa-de-accion-especifico-planificacion-familiar-y-anticoncepcion-2013-2018-10070

Secretaría de Salud. (2021). *Programa de Acción Específico. Salud Sexual y Reproductiva 2020-2024*. https://www.gob.mx/cms/uploads/attachment/file/644374/PAE_SSR_24_5_21.pdf

Secretaría de Salud. (2022). *Mortalidad Materna. Datos y Recursos*. https://www.datos.gob.mx/busca/dataset/mortalidad-materna

Serván-Mori, E., Cerecero-García, D., Morales-Vazquez, M., Sosa-Rubí, S., Heredia-Pi, I., & Hernández-Serrato, M. (2022). The Role of Effective Knowledge on Contraceptive Methods Use in the Replication of Mother-Daughter Adolescent Pregnancy in Mexico. *Archives of Sexual Behavior*, *51*(8), 4035–4046. https://doi.org/10.1007/s10508-021-02272-6

Severens, J. L., Milne, R. J., & Severens, H. (2004). Discounting health outcomes in economic evaluation: The ongoing debate. *Value in Health*, *7*(4), 397–401. https://doi.org/10.1111/j.1524-4733.2004.74002.x

Sharma, P. (2015). Discrete-event simulation. *International Journal of Scientific & Technology Research*, *4*(4), 136–140. https://ieeexplore.ieee.org/document/6371174/

Shattuck, D., Kerner, B., Gilles, K., Hartmann, M., Ng'ombe, T., & Guest, G. (2011). Encouraging contraceptive uptake by motivating men to communicate about family planning: The Malawi Male Motivator project. *American Journal of Public Health*, *101*(6), 1089–1095. https://doi.org/10.2105/AJPH.2010.300091

Shearer, J. C., Walker, D. G., & Vlassoff, M. (2016). Costs of post-abortion care in low- and middle-income countries. *International Journal of Gynecology and Obstetrics*, *108*(2), 165–169. https://doi.org/10.1016/j.ijgo.2009.08.037

Sievert, L. L., & Hautaniemi, S. I. (2003). Age at Menopause in Puebla, Mexico. *Human Biology*, *75*(2), 205–226.

Singh, S., Darroch, J., Ashford, L., & Vlassoff, M. (2009). Adding it up: the costs and benefits of investing in family planning and maternal and newborn health.. *Popline.Org*, 44. https://doi.org/978-1-934387-04-7

Singh, S., & Darroch, J. E. (2012). Adding It Up: Costs and Benefits of Contraceptive Services Estimates for 2012. *Guttmacher Institute and United Nations Population Fund (UNFPA), 201*, *June*.

Singh, S., Sedgh, G., & Hussain, R. (2010). Unintended Pregnancy: Worldwide Levels, Trends, and Outcomes. *Studies in Family Planning*, *41*(4), 241–250. https://doi.org/10.1111/j.1728-4465.2010.00250.x

Sobolev, B., Sanchez, V., & Kuramoto, L. (2012). Design of a Simulation Study. In *Health Care Evaluation Using Computer Simulation* (1st ed., pp. 97–108). Springer.

Sosa-Rubi, S. G., Dainelli, L., Silva-Zolezzi, I., Detzel, P., Espino y Sosa, S., Reyes-Muñoz, E., Chivardi, C., Ortiz-Panozo, E., & Lopez-Ridaura, R. (2019). Short-term health and economic burden of gestational diabetes mellitus in Mexico: A modeling study. *Diabetes Research and Clinical Practice*, *153*, 114–124. https://doi.org/10.1016/j.diabres.2019.05.014

Srivastava, T., Latimer, N. R., & Tappenden, P. (2021). Estimation of Transition Probabilities for State-Transition Models: A Review of NICE Appraisals. *PharmacoEconomics*, *39*(8), 869–878. https://doi.org/10.1007/s40273-021-01034-5

Statistics Finland. (n.d.). *Crude fertility rate*. https://stat.fi/meta/kas/hedelmallisyys_en.html

Steele, F., Goldstein, H., & Browne, W. (2004). A general multilevel multistate competing risks model for event history data, with an application to a study of contraceptive use dynamics. *Statistical Modeling*, *4*(2), 145–159. https://doi.org/10.1191/1471082X04st069oa

Sterman, J. D. (2000a). 2.3.4. The Modeling Process. In *Business Dynamics: Systems Thinking and Modeling for a Complex World* (1st ed., pp. 61–64). Irwin/McGraw-Hill.

Sterman, J. D. (2000b). *Business Dynamics: Systems Thinking and Modeling for a Complex World*. Irwin/McGraw-Hill.

Sterman, J. D. (2006). Learning from evidence in a complex world. *American Journal of Public Health*, *96*(3), 505–514. https://doi.org/10.2105/AJPH.2005.066043

Subbayyan, R., Surendran, K., & Nataranjan, A. (1982). Modeling of a rural health system. In *Proceedings of the IFAC Symposium* (p. 704). Pergamon.

Sully, E. A., Biddlecom, A., Darroch, J. E., Riley, T., Ashford, L. S., Lince-Deroche, N., Firestein, L., & Murro, R. (2020). *Adding it up: Investing in Sexual and Reproductive Health 2019*.

https://www.guttmacher.org/sites/default/files/report_pdf/adding-it-up-investing-in-sexual-reproductive-health-2019.pdf

Swiatlo, A., Curtis, S., Gottfredson, N., Halpern, C., Tumlinson, K., & Lich, K. H. (2023). Contraceptive Behavior Dynamics and Unintended Pregnancy: A Latent Transition Analysis. *Demography*, *60*(4), 1089–1113. https://doi.org/10.1215/00703370-10877862

Taylor & Francis. (2024). *Underdetermined*. Knowledge and References. https://taylorandfrancis.com/knowledge/Engineering_and_technology/Engineering_support_and_special_topics/Underdetermined/

Teel, J. H., & Ragade, R. K. (1984). Simulation modeling perspectives of the Bangladesh family planning and female education system. *Behavioral Science*, *29*(3), 145–161. https://doi.org/10.1002/bs.3830290303

The Demographic and Health Surveys Program. (2018). *DHS Contraceptive Calendar Tutorial*. https://www.dhsprogram.com/data/calendar-tutorial/upload/DHS-Contraceptive-Calendar-Tutorial.pdf

The World Bank. (2023). *GDP per capita (current US$) - Mexico*. https://data.worldbank.org/indicator/NY.GDP.PCAP.CD?locations=MX

Thomas, A. (2011). *Estimating the effects and costs of three pregnancy-prevention programs*. https://www.brookings.edu/wp-content/uploads/2016/06/03_pregnancy_prevention_thomas.pdf

Thomas, A. (2012). Three strategies to prevent unintended pregnancy. *Journal of Policy Analysis and Management*, *31*(2), 280–311. https://doi.org/10.1002/pam.21614

Thomas, A. (2014). The role of mass media campaigns in preventing unintended pregnancy. *Journal of Media and Communication Studies*, *6*(1), 23–27. https://doi.org/10.5897/jmcs2013.0376

Thomas, A., & Karpilow, Q. (2015). *FamilyScape 3.0: Architectural Overview*. https://www.brookings.edu/research/familyscape-3-0-architectural-overview/

Thomas, A., & Karpilow, Q. (2016). The intensive and extensive margins of contraceptive use: comparing the effects of method choice and method initiation. *Contraception*, *94*(2), 160–167. https://doi.org/10.1016/j.contraception.2016.03.014

Torres-Pereda, P., Heredia-Pi, I. B., Ibáñez-Cuevas, M., & Ávila-Burgos, L. (2019). Quality of family planning services in Mexico: The perspective of demand. *PLOS ONE*, *14*(1), 1–22.

https://doi.org/10.1371/journal.pone.0210319

Tracy, M., Cerdá, M., & Keyes, K. M. (2018). Agent-Based Modeling in Public Health: Current Applications and Future Directions. *Annual Review of Public Health*, *39*, 77–94. https://doi.org/10.1146/annurev-publhealth-040617-014317

Treadway, R. C. (1978). Experience in Using Popsim in a Family Planning Simulation Experiment. *Simulation & Games*, *9*(2), 159–172. https://doi.org/10.1177/104687817800900202

Trussell, J. (2007). *The cost of unintended pregnancy in the United States*. *75*, 168–170. https://doi.org/10.1016/j.contraception.2006.11.009

Trussell, J., Henry, N., Hassan, F., Prezioso, A., Law, A., & Filonenko, A. (2013). Burden of unintended pregnancy in the United States: Potential savings with increased use of long-Acting reversible contraception. *Contraception*, *87*(2), 154–161. https://doi.org/10.1016/j.contraception.2012.07.016

Twenge, J. M., Sherman, R. A., & Wells, B. E. (2017). Sexual Inactivity During Young Adulthood Is More Common Among U.S. Millennials and iGen: Age, Period, and Cohort Effects on Having No Sexual Partners After Age 18. *Archives of Sexual Behavior*, *46*(2), 433–440. https://doi.org/10.1007/s10508-016-0798-z

United Nations. (2015). *The Millennium Development Goals Report*. https://www.un.org/millenniumgoals/2015_MDG_Report/pdf/MDG 2015 rev (July 1).pdf

United Nations. (2019). *Family Planning and the 2030 Agenda for Sustainable Development*. United Nations. https://digitallibrary.un.org/record/3832669?v=pdf

United Nations. (2020a). *Goal 3: Ensure healthy lives and promote well-being for all at all ages*. https://www.un.org/sustainabledevelopment/health/

United Nations. (2020b). *Indicator 3.7.1: Proportion of women of reproductive age (aged 15–49 years) who have their need for family planning satisfied with modern methods* (p. 7). United Nations. https://unstats.un.org/sdgs/metadata/files/Metadata-03-07-01.pdf

Upadhyay, U. D., Brown, B. A., Sokoloff, A., & Raine, T. R. (2012). Contraceptive discontinuation and repeat unintended pregnancy within 1 year after an abortion. *Contraception*, *85*(1), 56–62. https://doi.org/10.1016/j.contraception.2011.05.009

van de Kaa, D. J. (2011). On the Societal Impact of Modern Contraception. In *The Future of Motherhood in Western Societies* (pp. 49–60). Springer. http://ndl.ethernet.edu.et/bitstream/123456789/50943/1/111.pdf#page=57

Vázquez-Rodríguez, C. F., Vazquez-Nava, F., Vazquez-Rodriguez, E. M., Castillo-Ruiz, O., Correa, J. B. V., & Betancourt, N. V. O. (2018). Family, personal, and social factors associated with the non-use of contraceptive methods during the first sexual experience in adolescent women. *Journal of Public Health Policy*, *39*(1), 100–110. https://doi.org/10.1057/s41271-017-0094-8

Vertinsky, I., Buckingham, S. L., Walters, C. J., & Zaltman, G. (1972). Family planning computer simulation: the Costa Rica population control model. *Simulation & Games*, *3*(2), 123–145. https://doi.org/10.1177/003755007200300

Virtanen, P., Gommers, R., Oliphant, T. E., Haberland, M., Reddy, T., Cournapeau, D., Burovski, E., Peterson, P., Weckesser, W., Bright, J., van der Walt, S. J., Brett, M., Wilson, J., Millman, K. J., Mayorov, N., Nelson, A. R. J., Jones, E., Kern, R., Larson, E., … Vázquez-Baeza, Y. (2020). SciPy 1.0: fundamental algorithms for scientific computing in Python. *Nature Methods*, *17*(3), 261–272. https://doi.org/10.1038/s41592-019-0686-2

Welti, K., Manlove, J., Washington, C. I., Jamshidi, R., Thung, S. F., Nayeri, U. A., Trussell, J., Hassan, F., Lowin, J., Law, A., Filonenko, A., Engla, N. E. W., Monea, E., Thomas, A., Tavernise, S., Sonfield, A., Gold, R. B., Ricketts, S., Klingler, G., … Brindis, C. D. (2011). How increasing the use of effective contraception could reduce unintended pregnancy and public health care costs Acknowledgments. *Perspectives on Sexual and Reproductive Health*, *43*(1), 88–93. https://doi.org/10.1016/j.ajog.2014.03.015

White, H. (2006). *Impact evaluation: The experience of the Independent Evaluation Group of the World Bank*. https://mpra.ub.uni-muenchen.de/1111/

White, K. L., & Potter, J. E. (2013). Patterns of contraceptive use among Mexican-origin women. *Demographic Research*, *28*(June), 1199–1212. https://doi.org/10.4054/DemRes.2013.28.41

Woods, J. L., Shew, M. L., Tu, W., Ofner, S., Ott, M. A., & Fortenberry, J. D. (2006). Patterns of Oral Contraceptive Pill-taking and Condom Use among Adolescent Contraceptive Pill Users. *Journal of Adolescent Health*, *39*(3), 381–387. https://doi.org/10.1016/j.jadohealth.2005.12.014

World Health Organization. (2006). *Reproductive health indicators: guidelines for their generation, interpretation and analysis for global monitoring*. http://apps.who.int/iris/bitstream/10665/43185/1/924156315X_eng.pdf

World Health Organization. (2012). *World Health Organization. The WHO application of ICD-10 to deaths during pregnancy, childbirth and puerperium: ICD-MM*.

https://apps.who.int/iris/bitstream/handle/10665/70929/9789241548458_eng.pdf;sequence=1

World Health Organization. (2016). *ICD-10 Version:2016*. https://icd.who.int/browse10/2016/en#/O00-O08

World Health Organization. (2019). *Contraception* (p. 4). World Health Organization. https://apps.who.int/iris/bitstream/handle/10665/329884/WHO-RHR-19.18-eng.pdf

World Health Organization. (2023a). *Maternal mortality*. WHO. https://data.who.int/indicators/i/C071DCB/AC597B1

World Health Organization. (2023b). *Women of reproductive age (15-49 years) population (thousands)*. The Global Health Observatory. https://www.who.int/data/gho/indicator-metadata-registry/imr-details/women-of-reproductive-age-(15-49-years)-population-(thousands)

World Health Organization. (2024a). *International Statistical Classification of Diseases and Related Health Problems (ICD)*. International Classification of Diseases 11th Revision. https://www.who.int/standards/classifications/classification-of-diseases

World Health Organization. (2024b). *Maternal deaths*. https://www.who.int/data/gho/indicator-metadata-registry/imr-details/4622

World Health Organization. (2024c). *Maternal mortality ratio (per 100 000 live births)*. https://www.who.int/data/gho/indicator-metadata-registry/imr-details/26

Zakiyah, N., van Asselt, A. D. I., Setiawan, D., Cao, Q., Roijmans, F., & Postma, M. J. (2019). Cost-Effectiveness of Scaling Up Modern Family Planning Interventions in Low- and Middle-Income Countries: An Economic Modeling Analysis in Indonesia and Uganda. *Applied Health Economics and Health Policy*, *17*(1), 65–76. https://doi.org/10.1007/s40258-018-0430-6

Zeger, S. L., & Diggle, P. J. (1994). Semiparametric Models for Longitudinal Data with Application to CD4 Cell Numbers in HIV Seroconverters. *Biometrics*, *50*(3), 689–699. https://doi.org/10.2307/2532783

Zhang, X. (2018). Application of discrete event simulation in health care: A systematic review. *BMC Health Services Research*, *18*(1), 1–11. https://doi.org/10.1186/s12913-018-3456-4