On Modelling the Transmission of the Human Immunodeficiency Virus (HIV) in a Closed Mixed Society

by

Edinah Mudimu

submitted in accordance with the requirements for the degree of

Doctor of Philosophy

in the subject

Operations Research

at the

UNIVERSITY OF SOUTH AFRICA

SUPERVISOR : Dr. Gerhard N. Engelbrecht
CO-SUPERVISOR: Prof. Christiaan J. Swanepoel

2016

This thesis is dedicated to my parents who taught me that even the largest task can be accomplished if it is done one step at a time. It is also dedicated to my lovely husband, Brian and children – Pardon, Tariro, Tania and Marlon.

Declaration of Authorship

I declare that 'On Modelling the Transmission of the Human Immunodeficiency Virus (HIV) in a Closed Mixed Society' is my own work and that all the sources that I have used or quoted have been indicated and acknowledged by means of complete references.

I further declare that I have not previously submitted this work, or part of it, for examination at Unisa for another qualification or at any other higher education institution.

Name: Edinah Mudimu

Student Number: 47278846

Signature: EMudimu

Date: 20 June 2016

Acknowledgments

I would like to thank many people who have helped me through the completion of this thesis. The first to mention is my supervisor, Dr. G.N. Engelbrecht (deceased October 2014). He never got to read the final draft of this thesis. Second on the list is Prof C.J. Swanepoel my co-supervisor. Prof Swanepoel devoted an enormous amount of his valuable time supervising my research before and after the passing on of my supervisor. His comments have consistently helped to improve and clarify this thesis. His patience, flexibility, concern, genuine caring and faith in me during the thesis process enabled me to earn my PHD while at the same time attending to other commitments of life. He never pushed nor judged me when I needed to juggle priorities. He provided insight, support and direction-right up to the end. For this, I cannot thank him enough. I will forever be grateful. Thank you, Prof Swanepoel.

Besides my supervisors, I would like to thank Prof. Enrico Lombardi, Mr Martin Prinsloo and Mr Jacques A. Auret in the Research and Academic Computing Department at the University of South Africa (UNISA) for their technical support throughout my studies. Many thanks also go to the AnyLogic Support team for their expert advice in agent-based modelling during the development of my simulation model. Email conversation with Dr. D.J. Klein and Dr. A. Bershyten experts in the field of agent-based simulation went a long way in facilitating the completion of this thesis. Thank you for insightfully replying to my emails.

Without financial support this thesis would not have been achievable. I would like to extend my sincerest thanks and appreciation to UNISA for financial support to attend conferences, workshops and pay my study fees. Colleagues in the Department of Decision Sciences at UNISA, I thank you for your unfailing support, encouragement and interest in my work.

Lastly, special recognition goes out to my family, for their encouragement, support and patience during the pursuit of my doctorate. I especially thank my mom and my late dad for providing unconditional love and care. I would not have made it this far without them. To my lovely husband Brian, who inspired me, provided valuable comments, suggestions and emotional support during the entire process. To my eldest son Pardon, my two little girls Tariro and Tania, and my darling little son Marlon, who missed out a lot of Mommy time while I sought intellectual enlightment. Marlon you are such a good little boy that you made it possible for me to complete what I started. I love you all more than you will ever know.

Executive abstract

This thesis sought to develop an agent-based model that replicates the formation of social and sexual partnerships in real-world settings with an eventual aim of revealing the main drivers of the HIV pandemic in a closed mixed society. Agent-based modelling is a computational modelling approach that allows for the simulation of the actions and interactions of autonomous agents, with the eventual objective of discovering global effects on the system. This modelling technique is less dependent on generalisations and does not average out the behaviour of individuals. Sexual partnerships formed in the model goes through the process of dating, courting and has a chance of developing into marriage as well as the possibility of breaking up or undergo divorce. Sexual partnership formation is based on a likeability index calculated using aspiration, attractiveness and age. Over and above the the sexual relationships we include commercial sex work. Commercial sex work depends mainly on the availability of female sex workers and their clients. We superimpose the spread of HIV on the social and sexual network model. Results from the model reveal that saturation of HIV prevalence is driven by the social and sexual network structure, behaviour change as well as biologic factors. Excluding commercial sex work in the model resulted in a decrease in HIV prevalence and incidence. Dense social networks resulted in a dense sexual network which consequently increased HIV incidence. A change in the infection probability per coital act contributed significantly to a change in incidence and prevalence levels. Model results also show that enrolling all HIV positive agents on antiretroviral therapy (ART) as from 2016 simulation year will help in curbing HIV transmission if zero dropout rate from ART is assumed. Therefore, concomitant action to avoid dropouts from ART is necessary if full benefits of introducing ART to all HIV positive individuals are to be realised.

Key terms: HIV, agent-based model, partnership formation, social networks, sexual networks, antiretroviral therapy, antiretroviral drugs, commercial sex workers, drop out, social simulation

Abstract

This thesis sought to develop an agent-based model that replicates the formation of social and sexual partnerships in real-world settings with an eventual aim of revealing the main drivers of the HIV pandemic in a closed mixed society. Parameters used in the development of the model were derived from literature. Unvalidated assumptions were made where data were unavailable or unreliable. To benchmark our model, we used data collected through South African Demographic and Health Surveys (SADHS). This is the only available data that we could use to evaluate our model since in real life a closed mixed society does not exist. The social and sexual network model developed in this thesis builds on existing models allowing for marriage, divorce, widowhood, aging of agents, remarriage, concurrent sexual relationships at all levels of romantic relationships and commercial sex work.

The social and sexual network model has contributed to the understanding of the evolution of mate search models in a dynamically changing agent population. Agents are assigned attributes such as attractiveness, aspiration, courtship duration and sexual drive. Partnership formation is based on a likeability index which is calculated using age, aspiration and attractiveness. Results from the social and sexual network model suggest that a change in sexual behaviour in a society results in a change in the pattern of a sexual network. For example, decreasing the likeability threshold in our model resulted in an increase in concurrency levels as well as the percentage of agents involved in sexual relationships outside marriage. They also suggest that dense social networks result in formation of more sexual relationships as compared to sparse network structures. There was significant statistical variation in model results obtained when we intialised our model with friendship connections only for a few selected agents as compared to when we allowed all agents to have more than one connection at model initialisation.

We implemented the HIV transmission process in the social and sexual network model using parameters derived from literature. HIV/AIDS affects the well-being of an individual and has long-term effects on the economic development of a society. Implementing the HIV transmission process in the model contributed to understanding of the progression of HIV/AIDS in a society represented by agent behaviour rules in our model. Results obtained after implementing the HIV infection process into our social and sexual network model suggest that HIV prevalence decreases and is finally eradicated without any intervention if sexual partnerships are formed based on the behaviour rules set in our social and sexual network model. The drivers of HIV in our social and sexual network model are HIV positive agents with concurrent partners and vertical transmission. Introduction of a population at high risk for contracting HIV (commercial sex workers (CSWs), opportunistic sex workers (OPSWs) and their clients) allows the virus to keep in pace with the aging of infected agents through finding new younger victims at a faster rate than the rate at which the infected agents die. CSWs, OPSWs and their clients facilitate the sexual mixing required by the virus to survive even with interventions in place. HIV incidence is on average 1% throughout the 50 simulation years. Prevalence stabilises above 10%. Results obtained from our HIV general simulation model are quite comparable to data in literature.

We also investigated the effect of introducing antiretroviral therapy for all HIV positive agents. Model results show that enroling all HIV positive agents on antiretroviral therapy (ART) as from 2016 simulation year will help in curbing HIV transmission if zero dropout rate from ART is assumed. Therefore, concomitant action to avoid dropouts from ART is necessary if full benefits of introducing ART to all HIV positive individuals are to be realised. Model results also suggest that the infection probability for agents who dropout from treatment (if zero dropout rate is not achieved) has to be quite low (less than the asymptomatic HIV stage infection probability) for HIV incidence to decrease after introducing ART for all HIV infected individuals. Simulation results reported in this thesis show that agent-based simulation is a potential tool that can enhance understanding of the complex process in social-sexual partnership formation and HIV progression in a closed mixed society.

Key terms: HIV, agent-based model, partnership formation, social networks, sexual networks, antiretroviral therapy, antiretroviral drugs, commercial sex workers, drop out, social simulation

Contents

List of Figures

List of Tables

Acronyms

AIDS	Acquired Immunodeficiency Syndrome
ABM	Agent-based model
ABSS	Agent-based social simulation
ADI	Age difference index
ADR	Age difference range
AI	Attractiveness index
ALI	Aspiration level index
ANOVA	Analysis of variance
ART	Antiretroviral therapy
ARV	Antiretroviral
ASSA	Actuarial Society of South Africa
BBC	British Broadcasting Corporation
CB	Child Birth
CD4	Cluster of differentiation 4
CDC	Centres for Disease Control and Prevention
CRFs	Circulating Recombinant Forms
CSW	Commercial sex worker
DOT	Directly observed treatment
EMOD	Epidemiological Modelling
EPP	Estimation and Projection Package
GCIS	Government Communication and Information System
GDP	Gross domestic product
GERMS	Geographic-Environmental Reinfection Modelling Simulator
GIS	Geographic information system
GSM	General simulation model
HCT	Human Immunodeficiency Virus Counselling and Testing
HIV	Human Immunodeficiency Virus
HSRC	Human Sciences Research Council
HSV-2	Herpes simplex virus type 2
KISS	Keep it simple, stupid
MABS	Multi-agent-based simulation
MARPs	Most-at-risk populations
MTCT	Mother-to-child transmission
NACOSA	Networking HIV/AIDS Community of South Africa
NAPHSIS	National Association for Public Health Statistics and Information Systems
NHI	National Health Insurance
NSP	National Strategic Plan
OPSW	Opportunistic sex workers

PEPFAR	President's Emergency Plan for AIDS Relief
PMTCT	Prevention of Mother-to-Child Transmission
SAAS	Social aspects of agent systems
SADC	Southern African Development Community
SADHS	South African Demographic and Health Survey
SANAC	South African National AIDS Council
SARS	Severe acute respiratory syndrome
SEIR	Susceptible-Exposed-Infected-Removed
SIR	Susceptible-Infected-Removed
SocSim	Social simulation
StatsSA	Statistics South Africa
STD	Sexually transmitted disease
STDSIM	Sexually transmitted diseases simulation model
TB	Tuberculosis
THO	Traditional Healers Organization
UNAIDS	United Nations & AIDS
USDHHS	United States Department of Health and Human Services
VCT	Voluntary Counselling and Testing
VLSI	Very large scale integration
VMMC	Voluntary medical male circumcision
WHO	World Health Organization
XDR-TB	Extensively drug-resistant tuberculosis

"...when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely in your thoughts advanced to the state of Science, whatever the matter may be."

Baron William Thomson Kelvin,
Popular Lectures and Addresses
1889

"Do not go where the path may lead; go instead where there is no path and leave a trail"

Ralph Waldo Emerson

Chapter 1

Problem Statement and Research Questions

1.1 Background

Globally, the number of people living with the Human Immunodeficiency Virus (HIV) increased from approximately 29,8 million in 2001 to 35,0 million in 2013 (WHO, 2014). Of the 35,0 million people living with HIV in 2013, 24,7 million were in sub-Saharan Africa (WHO, 2014). HIV is a virus that gradually attacks the human immune system making the body more vulnerable to infections. The gradual damage of the immune system may last up to 10 years before a person is diagnosed with Acquired Immune Deficiency Syndrome (AIDS). HIV/AIDS control has been a major concern all over the world as the number of people living with HIV worldwide continues to increase since its recognition in the early 1980s (Centres for Disease Control and Prevention (CDC), 1982).

Up to now, the origins of HIV still puzzle scientists. According to Worobey et al. (2008) HIV is thought to have originated in non-human primates in sub-Saharan Africa. It was then transferred to humans in the 19th or early in the 20th century. AIDS was first clinically observed towards the end of 1980 and early 1981 (CDC, 1982). The first cases of AIDS were among homosexual men. Initially, it was believed that the virus is only associated with homosexual men, but late in 1981 the virus was discovered among heterosexuals. Since then, the virus has been spreading among humans all over the world irrespective of race, sex, age or income.

HIV is found in varying quantities in the blood, saliva, tears, semen, breast milk and in vaginal fluid of an infected person. Infection occurs when a sufficient amount of these fluids get into someone else's bloodstream. However, the quantities of HIV present in saliva, sweat, urine and tears is too small to facilitate transmission from one person to another (CDC, 2011). There is also a difference in concentration levels of HIV in different people, depending, in part on their stage of HIV disease (CDC, 2011). There are a number of ways in which HIV can be transmitted, and these are:

1. Unprotected sexual intercourse with an infected person: Most of the HIV transmission cases are through vaginal and anal sex since the virus from the infected person's sexual fluids can pass directly into the body of the partner. HIV transmission can also occur through oral sex if a condom is not used, but the risk is lower than vaginal and anal sex.

2. Contact with an infected person's blood: If sufficient blood from an infected person enters someone else's body, then it can pass on the virus.

3. Vertical transmission: HIV can be transmitted from an infected mother to her baby during pregnancy, delivery and breastfeeding. This is also referred to as mother-to-child transmission.

4. Use of infected blood products: One can be infected with HIV during blood transfusions and use of blood products which are contaminated with the virus.

5. Injecting illegal drugs: Injecting equipment are shared which makes individuals using injected illegal drugs to be at risk to HIV infection.

A study carried out by Iliff, Piwoz, Tavengwa, Zunguza, Marinda, Nathoo, Moulton, Ward and the ZVITAMBO study group; Humphrey (2005) found that exclusive breastfeeding during the first six months substantially reduces vertical transmission. Another study by Becquet et al. (2008) concluded that mixed feeding during the first month of life and breastfeeding beyond six months increases the risk of HIV transmission. This message must be correctly conveyed to the public. Exclusive breastfeeding for the first six months protects infants from morbidity and mortality whether or not HIV related (Iliff et al., 2005). In settings where replacement feeding is not feasible and affordable, exclusive breastfeeding must be recommended.

There are no other ways besides those stated above in which HIV can be transmitted (Rees, 1997, p. 3). Studies by CDC have shown that drying of infected human blood or other body fluids reduces the amount of infectious virus by 90 to 99 percent within several hours (CDC, 2003). In other words, we can say that HIV cannot reproduce outside its living host.

CDC (2003) confirmed that insect bites do not transmit HIV. When an insect bites a person, it injects its saliva, not the previously bitten person's blood. Furthermore, CDC studies have also shown that HIV does not survive in insects, neither is it found in insects. This means that an insect does not become infected by sucking blood from an infected person, hence does not transmit HIV to the next human it feeds on.

HIV survives and multiplies in body fluids (CDC, 2003). In the human body, HIV attacks CD4 cells which play a major role in protecting the body from infections. CD4 cells circulate in the blood, but most of them are stored in lymph glands (HIV/AIDS, 2014). As the virus multiplies, the infected lymph glands deteriorate and eventually die, releasing more viruses which also infect new CD4 cells (HIV/AIDS, 2014). HIV has a very rapid mutation, to such an extent that once it is in a human body the immune system can never fully get rid of it (CDC, 1982). The immune system of an HIV positive person becomes weaker and weaker as the virus replicates, destroying more CD4 cells. As the immune system deteriorates, the body will not have the strength to fight off infections that it would have before HIV infection (CDC, 2008). This leads to the infected person becoming ill more and more often.

WHO (2005) defined four stages of HIV infection - the primary infection stage (also referred to as the acute infection stage), the clinical asymptomatic stage, the symptomatic stage and the AIDS stage. The first stage of HIV infection is the acute infection stage which lasts for approximately 10 weeks. During the acute infection stage the viral load of the infected person is extremely high. The risk of transmitting HIV to other people via unprotected sex (Waver, Gray, Sewankambo and et. al., 2005, p. 5), or through any other means that involve the blood of the newly infected person is high during this time because of the high levels of the HIV virus in the blood stream (CDC, 2011).

The acute infection stage is followed by the clinical asymptomatic stage which lasts for an average of eight years (Morgan, Mahe, Mayanja and Whitworth, 2002). During this stage the viral load of the infected person is quite low and the risk of transmitting HIV to other people during unprotected sex is also low (Waver et al., 2005, p. 5). Research has shown that HIV is not dormant during this stage, but is very active in the lymph nodes (WHO, 2005). This weakens the immune system over time. As the immune system deteriorates the infected person progresses to the symptomatic stage. At this stage an HIV positive person will start to have bacterial and fungal diseases that the immune system would normally prevent (Holmes, Wood, Badri, Zilber, Wang, Maartens, Zheng, Lu, Freedberg and Losina, 2006, p. 466).

As time elapses an HIV positive person will become ill from opportunistic infections such as toxoplasmosis and cryptococcosis. This is the point in the stage of HIV infection that a person is said to have full-blown AIDS. In most cases, an HIV positive person will become very ill if the CD4 cells count drops below 200 cells per cubic millimeter (CDC, 1994).

The main stumbling block in the HIV/AIDS pandemic is that there is no cure for the virus at the moment. Significant progress has been made in trying to suppress HIV in HIV positive individuals through the use of antiretroviral (ARV) medication. ARV's reduce the viral load of the virus in the blood stream of an infected person (WHO, 2005). HIV-infected individuals on ARV treatment usually remain in the clinically asymptomatic stage. The final step to eradicate the virus has not been achieved. The development of a vaccine for HIV is proving to be difficult since it is affected by the range of virus subtypes, variety of human population who differ in their genetic make up and their routes of exposure. Research on vaccines has recently given promising results in Thailand (Corey, 2009). The promising vaccine had an efficacy of 30%, which is too low to eradicate or control the pandemic and possible associated changes in behaviour may even increase the pandemic.

Studies by researchers such as Longini and Halloran (1996), Smith and Blower (2004) and Anderson and Hanson (2005) predicted that a vaccine alone is unlikely to bring HIV to extinction without a combined effort of reducing risk behaviour. The main course of HIV transmission is through sexual interactions. These sexual interactions are influenced by human behaviour. As indicated by DiClemente, Wingood, Blank and Metzger (2008), behaviour is at the core of the HIV/AIDS pandemic. They argue that:

> ... *it is people's behaviour, or rather the lack of appropriate preventative behaviour that propels the pandemic.*

Researchers have exerted themselves in developing models that resemble the spread of the pandemic and how the virus attacks the immune system (Blower, Ma, Farmer and Koenig, 2003; Ueda, Iwaya, Abe and Kinoshita, 2004). Despite the continuous research in HIV/AIDS modelling, a gap still exists in fully understanding how the virus propagates in a population. The latest addition of experts involved in HIV/AIDS research are microsimulation modelers. Microsimulation models seem to have great potential in exploring some of the gaps that exist in trying to understand the propagation of the virus. They are able to model a global outcome using the smallest possible element of the system, like an individual human being (Bracher, Santow and Watkins, 2003, p. 210).

A model that clearly explains the influence of intervention programmes on human behaviour can be a helpful tool in understanding the dispersion patterns and spreading mechanisms of HIV. Agent-based modelling techniques, as described by Axelrod (1997), form the basis of this research. Agent-based modelling is a microsimulation technique. It simulates large representative populations of low-level entities in order to obtain global results for a population such as an entire country. Even though there are general observations that can be made from aggregate models, microsimulation models give a closer insight into the propagation of infectious diseases (Heuveline, Sallach and Howe, 2004). They are able to capture the interactions of individual entities which mainly influence the propagation of a disease in a population.

In order to use microsimulation, individual base elements of the system must be specified in great detail. This allows simulation of stochastic events using simple rules of behaviour to represent complex interactions. The overall dynamics of the system result from the different events that interest an individual. Ideally, the model should allow the modeller to view the complexity and non-linearity of a complex system.

Microsimulation models typically consist of an environment in which interactions of individuals occur. Individuals are defined in terms of their behaviours and characteristic parameters as opposed to aggregate models which have a higher level of aggregation. It is fully possible to trace the evolution of an individual behaviour as intervention programmes are introduced. Therefore, a microsimulation model is a good start in addressing the gaps that exist in understanding the propagation of the HIV pandemic.

This thesis is primarily concerned with capturing the non-linear interactions at individual level that drive the HIV/AIDS pandemic. Once these interactions are established, guidelines for intervention programmes that can be implemented to stop the spread of the virus can be designed. In the following section, we review the models that have been used in modelling the transmission of HIV.

1.2 Modelling of infectious diseases

Since 1766, when Bernoulli expressed the proportion of susceptible individuals of an endemic infection in terms of the force of infection and life expectancy (Dietz and Heesterbeek, 2000), epidemiological models have been and still are essential to the theory and practice of infectious disease control. Further concepts of modelling infectious diseases were developed by Ross (1911) and his students McKendrick (1926) and Kermack and Mckendrick (1927). Over the years, epidemiological models have been extended by the same authors and by other researchers such as Hethcote and Ark (1980), Hethcote et al. (1981), Hethcote (2000), Dietz and Hadeler (1988), Blower and Mclean (1995), Blower, Aschenbach, Gershengorn and Kahn (2001), Blower et al. (2003), Blower, Bodine and K (2005), Anderson et al. (1991), Anderson and Hanson (2005) Mukandavire et al. (2009) and Mukandavire, Malunguza and Chiyaka (2010). A simple framework for the models that are discussed in this thesis is given in Figure 1.1.

	Deterministic	Stochastic
Dynamic	*Determinstic compartmental models (SIR and its derivatives)*	*Microsimulation models* *Stochastic compartmental models*
Static	*Projection models that makes use of the workbook approach*	*Statistical models*

Figure 1.1: **Modelling Techniques**

The *SIR* model is the point of reference for most models in infectious diseases (epidemic) modelling. The model divides the population into three fundamental groups: S represents subjects susceptible to contracting the infection, I the subjects that have already contracted the infection and R the removed or recovered subjects. The removed or recovered subjects are those who may have gained temporary or permanent immunity, have died or have been isolated (quarantined).

Using the *SIR* model as a point of departure, researchers in epidemic modelling have proposed various models that are basically derivatives of the SIR model. The derived models depend on the characteristic of the viral agent causing the disease. For example, if individuals do not recover once infected, then the model is an SI model and if recovery does not give immunity, then the model is called an SIS model. A class or compartment can also be added to the SIR model to obtain the *SEIR* models where E is the exposed class, which is a class of infected individuals who are not yet infectious. The major drawback of using the SIR models and its derivatives in modelling the spread of infectious diseases is that they fail to effectively model the effects of individual behaviours, the spatial aspects of the epidemic and individual contact processes (Teweldemedhin, Marwala and Mueller, 2004).

Static models are rarely used in modelling infectious diseases since the transmission and propagation of such diseases in a population is quite complex. Most models for infectious diseases are dynamic. Over time, the dynamics for an infectious disease can be represented in a deterministic or stochastic form. These deterministic or stochastic models use a set of difference, differential or integral equations to model the dynamics and the biology of the virus. The major difference between the two is that with deterministic models, variables are deterministic functions of time that completely ignore randomness. In stochastic models, variables are random and variable states are not described by unique values, but rather by probability density functions.

Statistical models are those which are constructed from observed data from the system. These models have contributed significantly to the HIV/AIDS knowledge base. In the statistical community, the most commonly used method by researchers such as Rosenberg (2006), Rao and Kakehashi (2005) and Nishiura et al. (2004) is the back-calculation method. The back-calculation method has been used to estimate HIV infection prevalence and to develop short-term incidence projections.

The major limitation of statistical models in modelling epidemics is their use of collected data. In most cases, data quality suffers from under and inaccurate reporting. Another limitation of statistical models is that they ignore the mechanism of the system, that is, important clinical, epidemiological and biological features of the HIV pandemic as well as other prior information about the system (Tan, 2000).

Researchers have combined the strengths from statistical models with those from stochastic models to come up with state space models. A well known state space model is the Kalman filter model. Kalman (1960) originally proposed the model in the 1960s for communication and engineering control.

The Kalman filter model was first used in AIDS research in 1995 by Wu and Tan (2000). Basically, state space models consist of two complimentary or sub-models – a stochastic model that takes into account the dynamic aspect of the HIV pandemic and a statistical model which makes full use of AIDS epidemiological data. Estimates of the state variables in state space models can be updated whenever new data becomes available.

Epidemiological models can be used to provide an in-depth understanding of some basic features and principles of the HIV/AIDS pandemic and HIV pathogenesis. Most of the deterministic and stochastic models that have been developed for the HIV/AIDS pandemic use an aggregate approach. An aggregate approach uses a top-down technique which is essentially the decomposition of a system to gain insight into its underlying subsystems.

In most cases, an aggregate model is built using mathematical or statistical equations. If all sub-populations, corresponding infection rates and removal rates are considered in an aggregate model, the number of equations needed grows exponentially. This makes it very difficult, or even impossible, to find the analytical form of the equations. When real life situations are to be modelled using such models, there is a need to use assumptions and simplifications in order to be able to write the model in a set of equations.

To overcome this analytical intractability of top-down models, researchers categorise individuals in terms of populations and use average contact rates and average transmission risk between the various categories. See for example Mukandavire et al. (2010) and Blower et al. (2005). They assume that in each category, individuals are homogeneous and well mixed. This categorisation helps modelers to obtain analytical solutions, but the models fail to accurately describe the phenomena observed by the macroscopic behaviours which emerge resulting from the local interaction between entities.

In the spread of infectious diseases, there is heterogeneity in individual attributes and in the network structure of their interactions. Researchers have identified such heterogeneity in contacts and network position as having a disproportionate impact on risk. There is a need to emphasise these microscopic entities explicitly in order to estimate their behaviour at a macroscopic level. Both spatiality and topology impact on individual interactions. Both of them cannot be ignored when attempting to come up with an accurate model to represent a system.

We have to keep in mind that certain types of modelling problems are best dealt with using an aggregate approach whereas for others an individual-based approach is more appropriate. In particular, HIV has complex patterns of transmission as well as a complex genetic make-up. This makes it very difficult to use an aggregate approach in predicting its propagation in a population or replication in a human host.

The limitations of aggregate models have led to the adoption of microsimulation or computational stochastic methods. A bottom-up technique is used in microsimulation methods. Using the bottom-up approach allows the modeller to specify characteristics and behaviours at the lowest individual level possible.

Some researchers started to apply microsimulation approaches to the epidemiological field in the early 1990s (Leslie and Brunham, 1990; Rhodes and Anderson, 1996; Rhodes and Anderson, 1997; Benyoussef et al., 2003). At the moment, two fundamentally different types of microsimulation approaches are being used with regards to the HIV pandemic, namely, cellular automaton and agent-based approaches. With the invention of relational databases, microsimulation has become one of the most practical developments in modelling infectious diseases. This approach will be considered in depth in the next section.

1.3 Simulation and microsimulation modelling

Microsimulation is a modelling technique that attempts to model a system by means of interactions between the most elemental units in a system. Microsimulation modelling can be traced back to the Von Neumann machine, which is a theoretical machine capable of reproduction (Pesavento, 1995). Stanislaw Ulam improved the concept by building the machine on paper using a collection of cells on a grid. Since then mathematicians, physicists and computer scientists have put their ideas together to develop these modelling ideas further. This lead to the development of the current agent-based modelling tradition which is a meshing of influences from a microsimulation tradition and traditions from computer science and physics (Eckhardt, 1987).

Microsimulation models have numerous advantages over aggregate models. They allow simulation of stochastic events using relatively simple rules of behaviour to represent complex interactions. This is possible because the models are able to specify agents at an individual level (Teweldemedhin et al., 2004). The overall dynamics of the system result from the different events that are of interest to an individual.

From microsimulation models we can observe the interactions between entities specifically and study how the local interactions contribute to the emergence of a global property. Microsimulation models are flexible, that is, they allow refinement of the analysis and offer modelling possibilities close to biologic reality. They allow the modeller to view the complexity and non-linearity of a system under investigation. Microsimulation models enable researchers to simulate events and evaluate the effect of interventions in cases where laboratory experiments cannot be conducted easily.

The major problems that are encountered when using microsimulation has to do with the amount of programming, computing power and data required by these models. Using expert opinion and relational databases partly solve the problem of the large amounts of data required by simulation models. The computing power of computers and related devices is improving over time. This will be helpful in realising the full potential of microsimulation models.

Despite the shortfalls we have in microsimulation modelling, there is potential for this modelling technique to shed considerable light on the propagation of infectious diseases in a population. Orcutt (1957) introduced microsimulation five decades ago and since then there have been major advances made with microsimulation in the social sciences and in epidemic modelling. Cellular automaton and agent-based approaches are the most recently developed microsimulation models.

The distinction between cellular automaton and agent-based approaches is not sharp. These two terms are often used interchangeably. The first generation of examples to demonstrate the potential of microsimulation in social simulation were done by Schelling (1978), Maynard (1982) and Axelrod (1984). Ideas used by these researchers were drawn from complex adaptive systems and evolutionary game theory. In Chapter 2 we review the work that has been done on cellular automaton and agent-based modelling.

1.4 Problem statement

Despite progress that has been achieved in preventing new infections, HIV/AIDS still threatens lives of individuals susceptible to the infection and the social structure of the community. The spread of the disease in a population is complex and is influenced by many interacting factors. Until now, researchers are still trying to understand the differences we have in HIV prevalence and trends among populations. The basic routes of HIV transmission between persons are well understood. One of the most predominant transmission mode being heterosexual coitus. If heterosexual coitus is the predominant mode of HIV transmission, why do we have high HIV prevalence in sub-Saharan Africa compared to other regions and why are there large differences in prevalence between different regions are two important questions that still need to be answered (Cassels, Clark and Morris, 2008).

The most common approach to study and understand the spread of infectious diseases involves the use of differential equations (Kermack and Mckendrick, 1927; Edelstein-Keshet, 1988) or stochastic processes to build simulation models. These models use a top-down modelling approach which specifies the global characteristics and behaviours at the system level. Unfortunately, in these models, individuals are categorised in terms of populations and use average contact rates and average transmission risk between various categories. Consequently, they often fail to take into consideration social phenomena associated with human interactions. Moreover, the complex nature of HIV transmission makes it hard to design a top-down model that effectively explain the interactions involved in its transmission.

Researchers like Halperin and Epstein (2004; 2007) and Mah and Halperin (2010a) have cited concurrency in Southern Africa as the major driver of HIV in the region. Concurrency alone cannot explain the high prevalence levels observed in the region, since the type of concurrency and sexual relationships observed in this region are not markedly different from those observed in other regions with low HIV prevalence levels (Wellings et al., 2006). Therefore, this suggests that there are other factors unique to the region driving the HIV pandemic over and above sexual behaviour. A systematic review by Sawers and Stillwaggon (2010) reveals that the models used by Mah and Halperin (2010a) and Halperin and Epstein (2007) to support the notion that concurrency is the major driver of HIV in Africa fail to prove the notion since the researchers did not establish that concurrency is unusually prevalent in Africa. As a result, it is important to find other possible explanations that explain the extraordinary HIV pandemics observed in some African countries.

To ensure a comprehensive response that can explain the high HIV prevalence levels in some African countries, there is a need to have a model that takes into consideration the heterogeneity in individuals and the environment in which they live. More research still needs to be done to understand more about the role of basic biological parameters such as: transmission probability per coital act, circumcision and the occurrence of viral blips in a person on antiretroviral therapy (ART) to HIV transmission. Behavioural aspects like multiple concurrent partners including commercial sex work and condom usage also remain largely uncertain.

Modelling the transmission system taking into account the different bio-behavioural characteristics of individuals with different rates of contact within and between groups and other environmental factors that may contribute to HIV transmission may help in finding ways towards slowing the pandemic. Using such a model, one must be able to determine the time to reach the pandemic "saturation" level of HIV infections in a given population. Since intervention programmes such as ART and sexual behavioural changes contribute immensely to the transmission system of HIV, the model must incorporate these factors to fully explain the transmission dynamics of the virus.

It is important to remark that microsimulation models, in particular agent-based models, have a potential to effectively model the propagation of HIV (Macal and North, 2006, pp. 76-77). Microsimulation has been used to model the HIV/AIDS pandemic for at least a decade now. The major drawback we have in the microsimulation models developed so far is that most of the models do not use a holistic approach. It is often more feasible to separate the population into parts; for example, homosexuals, heterosexuals, sex workers *et cetera* and mobility of the population is often ignored.

In this thesis a microsimulation model is developed to estimate the prevalence of infection for a *closed mixed* society. A *closed mixed* society in this context means a heterosexual population that contains individuals who can engage in monogamous, concurrent, commercial and opportunistic sexual relationships without in or out migration. Because of the non-linearity of the individual interactions and change of behaviour in such a population, there is a need to have an innovative use of the agent-based techniques to facilitate the development of a state-of-the-art model.

Studying and modelling of the disease can be useful in gaining an understanding of these interacting factors. The construction of a model that represents the pandemic dynamics in a holistic approach would constitute a valid tool for designing intervention policies. The model will enable intervention policy designers to uncover the best combination of control and eradication techniques.

1.5 Research questions

Major advances have been made in developing compartmental and stochastic simulation models for HIV propagation in human populations. Microsimulation models which can represent most social mechanisms that have been shown and believed to contribute to the propagation of HIV are still in their foundation stage. This research aims to use agent-based modelling, a relatively new class of microsimulation models, to model the propagation of HIV in a community.

Results from most research on HIV transmission indicate that strong interactions between agents have a significant effect on the spread of HIV in a population. These strong interactions are hypothesised to be the major cause of the substantial variations in the degree of spread of the virus between and within countries (Anderson et al., 1991). The interactions also give rise to dynamic sexual networks where sexual partnership links change during the simulation.

The social structure in which individuals interact, sexual interactions between individuals and the social norms that control individual sexual behaviour can be represented in an agent-based model. Using agent-based modelling will aid to the understanding of emergent patterns that result from agent interaction. For example, a change in courtship duration affects the divorce rate observed in a population (see model results on page 147). This is a result of using basic rules that depend on the state of the system at a given time (Gordon, 2003, p. 399). With this relatively new approach to HIV modelling we attempt to answer the following questions;

1. How well can such an approach be used to model the spread of HIV/AIDS in a closed mixed population?
2. How can the "saturation" prevalence level of HIV infections in the same population be found for the HIV pandemic?
3. How does the sexual behaviour impact on the spread of HIV in a closed mixed population?

4. How does the use of antiretroviral therapy (ART) by HIV infected individuals impact on the spread of HIV/AIDS in the stated population?

To answer the above mentioned questions, the following objectives were set to guide this research:

1. To develop an agent-based model for social and sexual partnership formation, including marriage, divorce, widowhood, aging of agents, remarriage, concurrent sexual relationships at all levels of romantic relationships and commercial sex work in a context of a specific culture and in South Africa, based on available evidence;
2. To validate the agent based model by comparing model results with available statistics; and
3. To implement HIV transmission process in the agent-based model and evaluate how the network structure generated, facilitate or limit HIV transmission.

We are unaware of any effective vaccines to prevent new HIV infections at the moment. Therefore, the main focus in the fight against the virus is to prevent new infections through behavioural change. Studying and modelling of the disease using agent-based models can be useful in gaining an understanding of human interactions, as well as uncovering possible methods for controlling new infections.

1.6 Structure of the thesis

Chapter 1, of which this is a subsection, introduces the background against which the thesis is set. The problem statement is laid out, followed by the research questions that this study is going to address. The introductory chapter is concluded with a description of the thesis structure. Chapter 2 presents an overview of the models that have been used in modelling HIV/AIDS and the gaps that are in the models.

Chapter 3 begins with a bird's eye view on the demographic and socio-economic characteristics of the population of South Africa. This is followed by a discussion of HIV/AIDS prevalence in South Africa and the government response to the pandemic. The chapter concludes with an examination of specific HIV risk factors in South Africa.

We present a detailed description of agent-based modelling and social simulation in Chapter 4. The structure of the model developed in this thesis with the eventual aim of answering the research questions is described in Chapter 5. Results of the simulation model are discussed in Chapter 6. Model description for the social and sexual network model (part of Chapter 5) and results obtained from the social and sexual network model (part of Chapter 6) appears in the Adaptive Behavior journal volume 23(1) pages 34 to 49 published in February 2015. In our last chapter, Chapter 7, we present our model implications, limitations and areas that need further research in modelling the HIV pandemic.

Chapter 2

Literature Review

There are a variety of HIV models ranging from simple one-year-ahead predictions, for example, the spectrum projection package (Stover, 2004), deterministic ordinary differential equations models (McKendrick, 1926; Blower et al., 2003), to agent-based computer simulations sometimes referred to as microsimulation models. Agent-based computer simulations explicitly represent each person, relationships between individuals and infection from one person to the next. The purpose of this chapter is to review literature relevant to the modelling of the transmission of HIV using microsimulation models. The chapter consists of two parts. The first part looks at cellular automata and the second part looks at agent-based approaches. In both sections, we present the applications of each modelling approach to the transmission of HIV in a population. Cellular automaton and agent-based approaches are the most recently developed microsimulation models.

2.1 Cellular automata

A typical cellular automaton model is made up of a regular two-dimension grid with boundary conditions and a group of agents living in the cells within the grid. The neighbourhood of each agent is defined based on some or all of the adjacent cells.

Agents inhabiting neighbouring cells are called neighbours. Agents cannot communicate globally since they are restricted to local neighbourhood interaction. Cellular automata are more suitable in describing proliferation phenomena such as particle percolation, innovation propagation, rumour spreading and disease spreading (Xuan, Xu and Li, 2009).

In the 1950s, Neumann and Ulam were the pioneers in using cellular automata in modelling (Neumann, 1966). Their ideas have since driven research on cellular automata, and researchers have developed simpler and practical architectures of cellular automata that can be used in different application areas. Wolfram (1984) classified the qualitative characterization of cellular automata into four basic groups, *viz* cellular automata which evolve to:

(i) a homogeneous state;

(ii) a set of separated simple stable periodic structures;

(iii) a chaotic pattern; and

(iv) complex localised structures that are sometimes long-lived.

Wolfram's classification has been used as a base for categorising cellular automata by a number of researchers (Kurka, 1997; Wuensche, 1999).

A concise up-to-date survey on cellular automata and its applications was done by Ganguly, Sikdar, Deutsch, Canright and Chaudhuri (2003). In the survey, they divided cellular automaton methodologies into two categories, namely; additive linear cellular automata and non-linear cellular automata. Additive linear cellular automata are amenable to algebraic analytic treatments while non linear cellular automata are based upon configuration of the rules of cellular automaton cells. Cellular automaton models use a discrete time framework to model variables that evolve over time.

Fields of applications of cellular automata as presented by Ganguly et al. (2003) include parallel computing machines, games, physical and biological systems, applications in social sciences, very-large-scale integration (VLSI) applications and pattern recognition. In biological systems, early work by Boer and Hogeweg (1992), and Celada and Seiden (1992) used cellular automata to model the immune system. Cellular automaton models have been developed to model infectious diseases, and contributions in this field date back to 1993 when Boccara and Cheong (1993) used a probabilistic automaton network SIS model for the spread of an infectious disease in a population of moving individuals.

More recent work on modelling the spread of infectious diseases was done by White, del Rey and Sanchez (2007), Venkatachalam and Mikler (2005) and Fu and Milne (2003). They used theoretical models to simulate epidemic spreading of an infectious disease without specifying the disease. The outbreak of Severe Acute Respiratory Syndrome (SARS) in 2002 led to the development of cellular automaton models for SARS. Huang et al. (2004) and Gao et al. (2006) proposed cellular automata models to simulate the dynamics of SARS transmission taking into account social influences. Following the identification of AIDS as a uniquely defined infectious disease (CDC, 1982), researchers have applied the cellular automata paradigm in modelling the spread of HIV, its biology and how it interacts with the human immune system.

2.1.1 Cellular automata applied to HIV/AIDS

To be able to successfully cure HIV, there is a need to fully understand the development of the disease and the reason why there are different time scales in the course of infection. There has been commendable work on developing cellular automaton models that model the immune response to HIV infection (see Ueda et al. (2004) and Santos and Coutinho (2001)). In both papers, the authors use cellular automaton models to model the interactions at cell level, between the immune system and HIV. Their findings were similar, since they all concluded that cellular automaton models describe emergent properties of complex biological systems better than mathematical models.

Some progress has been made by researchers in using cellular automata to model the spread of HIV. Xuan et al. (2009) proposed an extended cellular automaton simulation model to study the dynamic behaviours of HIV/AIDS transmission. They incorporated heterogeneity into agents' behaviours, latent period, infectivity and susceptibility, and different degrees of influence and mobility on their neighbours. They borrowed ideas from discrete event and agent-based simulation techniques to improve a typical cellular automaton model to accommodate state transition events. In their findings, they concluded that agent mobility, initial infection ratio, population density, and the extent of neighbourhood affect the model's HIV infection levels. If there is an increase in any of these factors, there will be an increase in HIV infection levels.

Some researchers like Dabbaghian et al. (2006) and Alimadad et al. (2009) developed cellular automaton models for people with risky behaviours for contracting HIV. Alimadad et al. (2009) developed a model for a population with risky sexual behaviour. In the model, they included sex workers and also introduced influences that promote or discourage unsafe sex. Dabbaghian et al. (2006) developed a cellular automaton model for a community of drug users where the main transmission route of HIV is through sharing of contaminated needles.

In these two models, the impact of social influences on the spread of HIV were taken into consideration. The models developed use social counters to track positive and negative social influences with respect to risky behaviour among groups of individuals.

2.1.2 Drawbacks of cellular automata

The major drawbacks encountered with the cellular automaton modelling approach are that the structure of the grid, the neighbourhood definition and state transition rules are simple and unchanged over time. All cells in the grid use the same rules to update their states based on the state values of the neighbouring cells. A new generation is created each time the rules are applied to the grid. Thus, there is no autonomy (Xiang, Zheng and Xiang, 2009). Also, there is no cell diffusion, since one site represents one cell.

The patterns in cellular automaton modelling are not strictly aligned with the real world. It makes the modelling of complicated dynamics using cellular automata problematic. For instance, partnership formation and social networking cannot be well represented since agents are restricted to move only into an adjacent empty cell and influence of an agent is only on those agents in its neighbourhood.

Due to these drawbacks, Xuan et al. (2009) borrowed ideas from discrete-event simulation techniques and some features from agent-based modelling to improve a typical cellular automaton model. Their model is one of the best cellular automata models for HIV/AIDS, but it still has a number of things that need to be modified for it to adequately characterise the progression of HIV/AIDS in a population. For example, their model does not take into consideration the various levels of infectivity at the different stages of infection and the effect of various control policies.

Because of these limitations, researchers have recently started using agent-based modelling in various fields to solve problems, including the HIV/AIDS pandemic. Agent-based modelling is also a bottom-up approach similar to the cellular automaton approach. The major difference between the two is that in agent-based modelling both the network structure and the spatial dynamics are much more flexible and potentially dynamic (Bagni, Berchi and Cariello, 2002). In the next section, we explore the applications of agent-based modelling to model the HIV/AIDS pandemic.

2.2 Agent-based modelling

An agent-based model is a computational model that simulates actions and interactions of autonomous individuals in a network to assess their global effect on the system. There are different names such as individual-based modelling, bottom-up modelling and multi-agent modelling that are being used to refer to the concept of modelling autonomous individuals.

Agent-based approaches have the ability to model the social structure in which individuals meet, social norms that control sexual behaviour, and the sexual interactions between individuals (Heuveline et al., 2004, pp 2-3). In agent-based models, an agent is considered to be autonomous, able to make decisions based on its internal state, situated in an environment, able to take initiative and react to changes, exhibit goal directed-behaviour and is able to interact with other agents and cooperate.

Agent-based simulation modelling is a relatively new modelling technique in the class of microsimulation models. It is one of the practical developments in modelling since the introduction of relational databases (North and Macal, 2007). Agent-based modelling can be applied in a variety of fields from human geography (Alam, Meyer and Ziervogel, 2006; Kohler, Gumerman and Reynolds, 2005), economic geography (Fang et al., 2002), epidemiology (Rhee, 2006) and the complexities of the human immune system (Castiglione et al., 2007; Folcik and Orosz, 2006). Mechanisms that contribute to the spread of HIV can be studied in detail using agent-based models (Heuveline et al., 2004) since it uses a bottom-up approach which is able to capture the emergence of new behaviours during a simulation run.

One of the early agent-based models is the Sugarscape model, developed by Epstein and Robert (1996). In this model, agents are assigned attributes and behaviour rules to simulate genetic inheritance, disease epidemics, trade, search for food and other societal activities. Furthermore, Axelrod (1997) and Young (1998) illustrated how agent-based simulation can be used to simulate a range of interactive social processes. By using agent-based simulation based on simple agent rules, one can gain some insight into the development of social institutions and the structure of agent interaction.

Based upon such foundations, more specialised types of research started to emerge. Agents are modelled as being in one of a finite number of discrete states. State transitions among the agents are usually stochastic, with constant probabilities or probabilities dependent on the states of other agents (Xuan et al., 2009; Ueda et al., 2004; Lomi and Larsen, 2001).

In epidemic modelling, early work by Adams, Koopman, Chick and Yu (1999) was concerned with a basic approach to understanding the use of discrete-event stochastic simulations of individuals based on sexual transmission of a non-specific infectious disease. Four important issues addressed in their study are as follows:

1. Heterogenous populations of individuals with varying social and geographic characteristics;
2. Complex interaction among individuals to characterise opportunities for transmission;
3. Infection characteristics such as transmission probabilities (transmission depends on the gender of the infector and infected person) and infection duration; and
4. Contact and infection histories.

A Geographic-Environmental Reinfection Modelling Simulator called GERMS, developed at the University of Michigan, is classified under microsimulation models. It had several innovative ways that improved many microsimulation models which studied individual phenomena (Ghani et al., 1997; Adams et al., 1998).

Connell et al. (2009), Perez and Dragicevic (2009) as well as Gordon (2003) also developed general purpose agent-based models to demonstrate the propagation of an epidemic in a given society. These general models give a good understanding of the propagation of epidemics and provide a base for experimentation with infectious diseases. Perez and Dragicevic (2009) implemented his general purpose model using a measles outbreak in an urban environment as a case study.

The major limitation of general purpose models is that they do not take into account the progression of a specific disease. Diseases differ in the way they are transmitted, their incubation period and infectious periods, as well as the duration and stages of infection in the human system. Epidemics are also affected by the behaviour and interactions of individuals who differ with respect to culture, beliefs, environment, *et cetera*. These general purpose models only give a base for epidemic modelling but do not model a specific disease adequately.

2.2.1 Agent-based modelling applied to HIV/AIDS

To our knowledge, a few agent-based models have been developed for the HIV/AIDS pandemic. The models attempt to explain the patterns of the spread of HIV/AIDS in a population, aspects of the immune response to HIV, and the impact of the pandemic on society and economic development. Authors like Mei et al. (2010), Tawfik and Farag (2008), Alam, Meyer and Norling (2008), Rhee (2006), Sumodhee, Hsieh, Sun and Huang (2005), Heuveline et al. (2004) and Teweldemedhin et al. (2004) have demonstrated that using agent-based modelling can result in a considerable understanding about the behaviours and interactions of different individuals in the transmission of HIV.

The use of agent-based approach to model the immune system started in 2004 (Xiang et al., 2009, p. 80). Researchers like Guo, Han and Tay (2005), Tay and Jhavar (2005) and Perrin, Ruskin and Crane (2008) attempted to model the immune system response to HIV using agent-based simulations. Their models displayed the dynamics of HIV infection at a micro level more accurately. The models helped to further understand the underlying mechanisms of the reaction of the complex immune system to HIV.

In this thesis, we are interested in understanding how the virus spreads in a population. Most of the parameter values used in the model are derived from the South African population. Africa is the hardest hit continent by the HIV pandemic (UNAIDS/WHO, 2009). A number of agent-based models for HIV have been developed to model the pandemic in Africa. Here we review some of the agent-based models developed mostly for the Southern Africa population and also highlight a few models developed for populations outside Africa.

One model mostly used by researchers to model HIV progression in Southern Africa (Hontelez et al., 2011; Orroth et al., 2007; van Vliet et al., 2001) is the sexually transmitted diseases simulation model (STDSIM) (see background paper by Van der Ploeg et al. (1998)). The model can be used to simulate the spread and public health consequences of HIV and four other sexually transmitted diseases (STDs) (gonorrhea, chlamydia, syphilis and chancroid) under different intervention scenarios. The

STDSIM model contains modules on demography, sexual behaviour, transmission, including co-factor effects of STDs on HIV transmission, disease aspects and health care. The model, however, does not take into consideration the differential characteristics of different stages of HIV. Partner selection in the model takes place on the basis of age and the processes of searching for a partner and being available depend on chance processes. Researchers like Hontelez et al. (2011) modified the STDSIM model to the HIV pandemic with parameters derived from a specific population.

Another individual based stochastic simulation for HIV transmission called EMOD-HIV (developed in 2008 and revised in 2012) was developed by Bershteyn, Klein, Wenger and Eckhoff (2012). The model simulates sexual and vertical transmission of HIV and is parameterized for the setting of South Africa. However, the model does not take into consideration the geographic distribution of the population and the variable viral loads during the disease duration, although its results are quite comparable to the models that use STDSIM model as a base. HIV transmission in the model is not gender biased. The only bias introduced in the model for the transmission rate is when the male agent is circumcised. ART intervention and condom usage are also considered in the model.

Bendavid, Brandeau, Wood and Owens (2010) developed a similar model to the EMOD-HIV. The model takes into consideration ART, CD4 cell count decline and viral load increase in infected agents, condom usage and circumcision. It is parameterised using South African data and data from Southern African studies. However, the model does not keep track of the sexual network structure.

Teweldemedhin et al. (2004), Alam et al. (2008) and Tawfik and Farag (2008) also developed agent-based models for infectious diseases using the South African population as a case study. Tawfik and Farag (2008) provided a multi-agent simulation model to examine the effect of various awareness interventions on the spread of HIV/AIDS, malaria and tuberculosis in the Limpopo Province, while Teweldemedhin et al. (2004) worked on the different biological, social and environmental factors that are responsible for transmitting HIV from an infected person to a healthy person.

Teweldemedhin et al. (2004) defined an agent in their model as a computing entity that can perform information processing to achieve a specific task. The entities in the model developed by Teweldemedhin et al. (2004) communicate among themselves and with the environment. In this model, person agents interact with one another and randomly choose partners. No rules were set for partner selection and space was not explicitly represented. Random choice of a partner ignores cultural and social context of a respective society; hence the mixing behaviour which has significant implications on the spread of the disease is not well represented in the model.

Notable contributions on the impact of HIV/AIDS on society and economic development are by Alam (2008) and Alam and Meyer (2006). The authors used a rural community in South Africa to model the influence of HIV/AIDS on livelihoods and household structure. These models demonstrate how a social simulation model can help in understanding the impact of changing policies in a community. In the model developed by Alam et al. (2008), partnership selection has several mixing processes, that is, a scheme based on simple aspiration and each relationship had a courtship duration. Only 5-10% chance was assigned to an agent for picking a partner randomly. Alam et al. incorporated mother-to-child transmission (vertical transmission) and the different transmission probabilities for the stages of HIV which were not considered by Teweldemedhin et al. (2004).

In their research, Heuveline et al. (2004) considered four mechanisms which they assume to be contributing more to HIV transmission patterns in Southern and Eastern Africa. The four mechanisms are disease mortality, networking and interaction, marriage and divorce, and work-related migration. In their model, marriage and divorce is modelled using simple behaviour rules and agents interaction to determine the observed distribution. The other three mechanisms are modelled using aggregate statistical distributions as in any other microsimulation model.

The full potential of their simulation model will only be realised when all the mechanisms are replaced by the corresponding rules of behaviour and interactions of individuals. The model they developed has produced a number of qualitative structures that characterise the pandemic for Eastern and Southern Africa. The major limitation with their model is that the other three mechanisms are using aggregate statistical distributions and hence fails to capture social and demographic complexities into the model.

Alam et al. (2008), Heuveline et al. (2004) and Teweldemedhin et al. (2004) used data from Southern Africa to validate their models. Heuveline et al. (2004) argue that for reasons that are still poorly understood, the time to reach a plateau ("saturation") as well as the prevalence level reached vary across epidemics, while the overall shape of incidence over time appears similar across epidemics.

Another contribution in the use of agent-based in modelling the HIV pandemic is by Rhee (2006). Rhee developed an HIV spread and policy interventions agent-based model based on a community in Papua New Guinea. In the model, the idea of condom use spreads through agent sexual and friendship links. Rhee uses a fixed transmission probability. Different HIV infection stages are included in the model. A fixed population size is maintained in the model and HIV is spread through a stochastic sexual mixing scheme developed by Kretzschmar and Morris (1996). Rhee (2006) selected Papua New Guinea as a case study area since it is characterised by geographic isolation of ethnic groups with different cultural practices and beliefs that may amplify the rate at which HIV is spread.

Agent-based modelling is also being used in studying the spread of HIV among groups of people who practice risky behaviours like homosexual men and intravenous drug users. Mei et al. (2010) and Sumodhee et al. (2005) used the agent-based paradigm in a community of homosexual men. Sumodhee et al. (2005) used a multi-agent system to model the spread of HIV in a homosexual community in Taiwan. Their model assesses the influence of different policies on social behaviour of individuals and the impact the behaviour has on the spread of HIV.

Mei et al. (2010) used a complex agent network to study the HIV epidemic among homosexual men in Amsterdam. In their model, agents contain specified personal information whilst the complex network emphasize the relationship dynamics among the agents. The relationship contacts are modelled using an undirected, scale-free complex network. To propagate the virus in the population, they developed formulae for the transmission probability, treatments, risk behaviour, steady or casual partnerships and transmissibility at different infection stages.

This section reports a survey of the various agent-based models developed in epidemiological modelling, paying particular attention to, HIV/AIDS pandemic. The survey provides a sketch of the different theoretical developments which have taken place over the years. These developments have established an immense potential for agent-based modelling of pandemics and epidemics.

Agent-based models represent real life situations in a superior way to cellular automata since an agent is considered to be autonomous, able to make decisions, able to react to changes and situated in an environment where making and breaking of ties can be well represented. These features are not easy to include in cellular automaton models, hence agent-based models may provide better insight into how the HIV/AIDS pandemic propagates in a population (Macal and North, 2006, p. 73).

2.2.2 Strengths and weaknesses of agent-based modelling

The spread of HIV mainly depends on the interaction of individuals in a population. In order to model human interactions accurately, there is a need to use a technique that captures the characteristics of individuals and see how they contribute to the emergence of a global property, for example, HIV prevalence. One method that has proved to closely model the interactions at a micro level is the agent-based modelling technique. This modelling technique is able to exploit the emergence of the complex deterministic macroscopic functions from stochastic microscopic interactions (Xiang et al., 2009). Agent-based modelling also has the capability to model the networks in which individuals interact. Understanding the network structure in which infectious diseases spread, makes it easier to estimate the behaviour of the disease at a macroscopic level.

Since agent-based models are able to capture individual characteristics, it is possible to model a population of individuals with different beliefs and cultures and see how the epidemic progresses in such a population. Most models developed so far fail to capture all key aspects that contribute to the spread of HIV/AIDS in one model. Another advantage of agent-based models is that many such packages have an “open” structure that allow integration with other tools such as statistical packages and geographic information system (GIS) packages. Because of these benefits, there is a notion that agent-based models will give a better understanding to the progression of HIV in a population (Teweldemedhin et al., 2004).

Though the agent-based modelling approach gives a better understanding of the interactions at a micro level it requires greater computational power. The computational complexity tend to rise super-linearly with the number of entities in the model (Xiang et al., 2009). We can get an accurate representation from agent-based model but at the cost of high computational complexity. Given the advances we have in computational power, we hope that we will be able to capture most drivers of the pandemic in one microsimulation model.

2.3 Conclusion

From the literature presented in this chapter, we can conclude that there is still room to improve results obtained from HIV/AIDS agent-based models. More data about human behaviour must be collected to improve the accuracy of the models. We also need to keep in mind that besides the microsimulation models discussed here, there are a number of mathematical models (ordinary differential equations and difference equation models) that have been developed to describe and evaluate the HIV pandemic in Southern Africa. Earliest models were developed by Doyle and Millar (1990) and Groeneveld and Padayachee (1992). Widely used and publicly available models in South Africa are the Spectrum/EPP model by Stover, Brown and Marston (2012) and Actuarial Society of South Africa (ASSA) models which originated from the Doyle-Metropolitan model proposed by Doyle and Millar (1990). Regular updates are done on these two models as new HIV prevalence and behavioural data become available.

UNAIDS estimates for the global distribution of HIV are produced using the Spectrum/EPP model. The major limitation of this model is its failure to use age-specific data in model calibration due to the separation of the modelling of HIV incidence and the demographic impact. It has also limited ability to evaluate the impact of HIV prevention strategies.

ASSA is behind the development of a series of the ASSA models. The first ASSA model was developed in 1996 and was called ASSA500 (Dorrington and Schneider, 2001). The most recent version was released in 2011 and is called ASSA2008 (ASSA, 2011). The ASSA model is a fully-integrated demographic and epidemiological model. However, the model has a number of assumptions that deviate from reality; for example, the assumption that ART initiation can only occur at the first AIDS-defining illness. In South Africa, ART initiation guidelines have changed and there is a need to update the model assumptions. The model also assumes that there is no movement between risk groups over time. This is problematic since human behaviour changes. For example, a commercial sex worker may stop his or her career and have a stable relationship over time.

The ASSA model does not take this into account. As all the other mathematical models, these two mathematical models suffer from the inability to effectively model the spatial aspects of the spread of the pandemic, the individual contact process and the effects of individual behaviours. Therefore, in this thesis, we aim to develop a model that will close this gap in science using agent-based simulation. Before we present our model, we present an overview of the South African population, where we derive most of the parameters used in the model development phase.

Chapter 3

South African Demographics

3.1 Introduction

South Africa is a middle-income country. It has an abundant supply of natural resources, and well developed financial, legal, communications, energy, and transport sectors. Despite being among the top five largest economies in Africa, the country has the highest number of people living with HIV (UNAIDS, 2013). This may be attributed to the combined effect of high incidence rate and an expansion in the ART programme (HSRC, 2014). The most recent survey done by the Human Sciences Research Council (HRSC) in 2012 (HSRC, 2014) revealed that there was an increase in the number of new infections among females aged 15 to 24 years and an increase in the number of people living with HIV on ART.

The spread of HIV in the country depends on a number of factors. These include: poverty, high levels of sexually transmitted infections, sexual violence and a history of limited attention to the pandemic (Simelela and Venter, 2014). Surveys carried out in the country indicate a high level of understanding by the public about the means of transmission of HIV and methods of prevention. Unfortunately this is not reflected in the sexual behaviour. For example, some individuals report to have multiple sexual partners within a 12 month period (HSRC, 2014). To have a better understanding of the HIV/AIDS situation in South Africa, in the following section, we present the demographic and socio-economic characteristics of the South African society that contribute to the HIV pandemic. HIV/AIDS prevalence is presented in Section 3.3, followed by an overview of the government's response to HIV. We close this chapter by discussing HIV risk factors in South Africa.

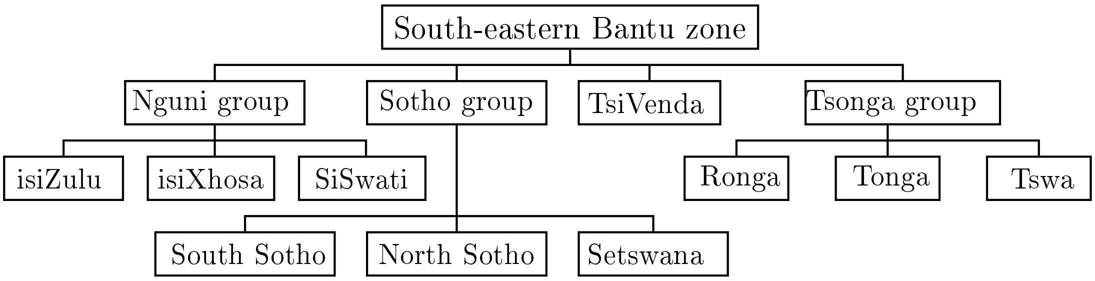
3.2 Demographic and socio-economic characteristics

The World Bank classifies South Africa as a middle-income country, but not everyone in the country falls within that bracket. Compared to other developing countries of similar status, there is a big gap between the rich and the poor in South Africa. These differences in income affect living standards as well as access to amenities in the country.

In terms of population density, South Africa is ranked number five in Africa with approximately 49,9 million people (Statistics South Africa (StatsSA), 2010, p. 3). The country is a nation of diversity, with people of diverse origins, a variety of cultures, languages and religious beliefs. According to the 2010 mid-year population estimates from StatsSA, the largest group, which takes up 79,4% of the population, is made up of the nine officially recognised Bantu-speaking groups. Bantu people originally came from the region of Central Africa.

One would expect little variation in culture and language since the Bantu-speaking group take more than three quarters of the population. However, this is not the case, as within the group itself there is no homogeneity in language or culture. Figure 3.2 shows the major four groups of the Bantu-speaking people and their subdivisions.

English speaking descendants from Britain, and Afrikaans speaking descendants from the Netherlands, France and Germany who are estimated to be 9,2% of the population are second to the Bantu-speaking group in terms of population numbers. Approximately 8,8% of the population is made up of a mixed-race population which speaks



Source: English-Zulu, Zulu-English Dictionary: Doke, Malcolm, Sikakana & Vilakazi

Figure 3.1: **Bantu-speaking groups**

both Afrikaans and English. The smallest group, which takes up only 2,6% of the population, consists of descendants of the Tamil and Urdu speaking Indian population (StatsSA, 2010b).

In 2009, approximately 57% of the South African population were living in urban areas (Kaiser family foundation, 2009). In Gauteng Province, there are several cities, which include Johannesburg, the largest and financial capital city, as well as Pretoria, the administrative capital of the country. The province is the most densely populated, with 22,4% of the total population, despite the fact that it is the smallest in terms of land area. This province is almost entirely urban. Following Gauteng is Kwazulu Natal, with 21,3% of the population. This province also has one of the major urban centres, Durban, with the busiest port on the central east coast. These two provinces take up to 43,7% of the total population in South Africa and yet have less than one-tenth of the total land area (StatsSA, 2010b).

Other major centres with high urban concentration include Cape Town in the Western Cape, called the “Mother City”, as it was the first established town in South Africa, Port Elizabeth, an industrial and manufacturing city, East London in the Eastern Cape Province, and Bloemfontein in the Free State. Limpopo Province is the most rural province in South Africa, though it also has small urban centres like city of Polokwane. Northern Cape Province, with the largest total area, is the most sparsely populated province, with only 2,2% of the total population. Demographic and socio-economic characteristics of South African society are discussed in detail in the following sections.

3.2.1 Cultural aspects and religion in South Africa

The San were the earliest people to live in Southern Africa before the arrival of Khoikhoi about 2 000 years ago, followed by Bantu-speaking communities who migrated from east and central Africa (South African History Online (SAHO), 2010). The San cultural activities slowly declined as the Khoikhoi settled in the land formerly occupied by the San. As the Bantu and Tswana-Sotho speaking communities moved in, they had their ways of life which differed across the different groups and this further diluted the San culture as well as the Khoikhoi culture (SAHO, 2010a). Europeans and people from Asian countries came down to South Africa from the mid seventeenth century to the early eighteenth century (Ramerini, 2010). They also had their own ways of life. The mixing of these different cultures led to a multilingual and ethnically diverse country where to date there is no single "Culture of South Africa" (SAHO, 2010a).

In Bantu speaking communities, women were assigned to light agricultural tasks, domestic work and child care while men tendered livestock, did heavy agricultural labour and ran local political affairs (Coplan, 2000). As the country started to develop urban centres, most of the males in the African villages became migrant labourers in distant employment centres. The old ways of life slowly faded as urbanisation climaxed, but in the countryside some of the traditional cultures are still strong (SAHO, 2010b, p. 1).

For instance, education of the young around the rites of initiation into adulthood is stll practiced as part of tradition. This was a common cultural feature in the Bantu speaking communities. During the ceremonies, boys and girls were taught the disciplines of manhood and womanhood respectively. Circumcision was one of the major activities of the ceremonies. Nowadays, these ceremonies are still done but at a lower rate as urbanisation and the western culture is now preferred by many South Africans.

Research by Coplan (2000) on South African culture provides interesting facts about the country. One of the facts is about marriage. In Bantu-speaking communities, marriage was based on polygamy before Christianity was introduced by the Europeans. Nowadays, most men regardless of the ethnic group, prefer to have one wife, although polygamy is still legal. Most South Africans prefer to cohabit without marriage (Coplan, 2000). Those who marry have fragile marital bonds, to such an extent that divorce rates in South Africa are above 50%.

At present, South Africa is among the most urbanised countries in Africa but male dominance is still evident in domestic and working life of all the ethnic groups in the country. Although men are customarily the heads of the households, the new democratic constitution has fostered gender equality. This gender equality policy is mainly practiced in the legal and official spheres. However, this policy is not widely practiced in the community at large. Hence women remain the most affected by unemployment, poverty, lack of education and lack of access to amenities (Robin and Alessandra, 2007, p. 19).

A common feature to all population groups in South Africa is the recognition of lengthy family lines and extended family relationships (Coplan, 2000). Adults in the extended families are expected to be role models and caregivers for the children within the kinship network. However, poverty has damaged most of these family structures amongst the poor, and a high incidence of early teenage pregnancy is a result of social problems affecting these communities.

When it comes to religion, South Africa is a home to a variety of religious traditions, and the constitution of the country respects the right to freedom of religion. In schools, there is a Religion Education programme which aims to teach religion in its broadest sense, that is, about religious diversity and different religions in the country and the world. This enables pupils to be aware of a variety of religious traditions, encouraging them to grow their moral and spiritual dimensions (Asmal, 2003).

3.2.2 Urbanisation in South Africa

Before Europeans came into South Africa, Africans used to live in multiple dwelling homesteads sometimes referred to as villages. In these villages, division of labour between sexes was well defined. Women and girls did most of the light agricultural labour, while men and boys attended to the livestock. The introduction of the plow and the European way of agriculture in the nineteenth century changed the division of labour. That period saw the growth of small towns and urban centres around mines, farming areas, commercial and industrial centres where male labour was required.

Men who were residing in the rural African communities started to migrate towards the mines, farms, commercial and industrial centres. This meant that manpower in the rural communities disappeared and was compensated by the flow of wages. Migration destroyed the political and organisational life of rural African communities (Coplan, 2000). New types of settlements started to grow in the small towns and urban areas.

As the small towns and urban centres continued to grow, labour was permanently drawn away from rural communities to the growing centres. Today there is an accelerated rate of movement from the rural areas to the urban centres. The main factors attracting people to urban centres are opportunities for employment, education and access to healthcare services.

Women have also joined the migration in search of employment or as partners of male migrants employed in the urban areas (Peberdy, Crush and Msibi, 2004, p. 14). Migration has resulted in an increase in the number of urban settlements and a dramatic expansion of existing centres. The type and pattern of human settlement in contemporary South Africa is now comprised of varying sizes in different geographic locations; places that are urban and rural, planned and unplanned.

Settlements in South Africa are socially and economically divided. Research carried out by Kilian, Fiehn, Ball and Howells (2005) on human settlements in South Africa emphasised these differences in the settlements. The major differences are found under the planned settlements in urban areas where there are two major categories – the upmarket suburbs and the poorer surbubs. The upmarket suburbs are mainly occupied by the rich and some of the middle class earners. These suburbs are characterised by well planned provision of services, infrastructure and high security. Most people who live in these suburbs have good living standards and are employed.

The poorer planned suburbs, normally referred to as townships, have basic services and infrastructure. These suburbs are densely populated, as most of the migrants from the rural areas settle there first with the hope of securing housing in the future. This has fueled the growth of what are called informal settlements[1], which normally develop at the margins of townships. These areas are mostly occupied by unemployed people who have moved from rural areas in search of employment in the cities.

Some of these informal settlements are well established, but they are plagued by high unemployment, crime and insecurity (Coplan, 2000). Drug dealing, alcoholism, rape, domestic violence and child abuse are common behaviours of individuals residing in such settlements. Young girls residing in such communities end up practising prostitution in order to earn a living (Coplan, 2000). This places them at a higher risk of contacting HIV and other sexually transmitted diseases.

3.2.3 Education

School life in South Africa takes up to 13 years, that is, from grade 0, sometimes referred to as grade R or "reception year" to grade 12 or "matric". South African Schools Act of 1996 expects everyone in South Africa to have at least had general education and training – grade 0 to grade 9. To achieve this, the South African government allocates on average 6% of its gross domestic product (GDP) towards education (National Treasury, 2014). Despite the effort undertaken by the government, there are still inequalities that exist in facilities and resources among poor, rich, urban and rural schools (Kilian et al., 2005, p. 16) which affect the quality of education. The most affected provinces are the poorer provinces (KwaZulu Natal, Eastern Cape, Limpopo and North West).

Education plays a significant role in determining one's access to formal labour in any country. Though South Africa provides basic education to all, this may not be sufficient, since development of the economy and the society requires more than basic

[1] Informal settlements are often referred to as "squatter settlements" or "shanty towns".

education (SADC Secretariat, 2008, p. 15). The labour market of South Africa, which is growing at a faster rate than the economy, is mainly composed of low and unskilled labour (Burger and Woolard, 2005, p. 4). Less skilled labour is not attractive to employers. This is one of the reasons why the country is faced with high unemployment rates (Kingdon and Knight, 2007, p. 14).

3.2.4 Income sources

There are a number of sources of income in South Africa. Nationally, the major source of income is a formal salary or wage earned by an employed individual. Besides a formal salary, South Africa has also grant schemes for children, orphans, disabled people and pensioners as part of poverty alleviation programmes (StatsSA, 2010b). These grants provide the main source of income in households where no-one has formal employment. The 2012 General Household survey carried out by StatsSA provides an insight of the different sources of income in the country. Table 3.1 summarises the findings from this survey (StatsSA, 2013). Note that a specific household can have more than one source of income. Therefore percentages do not add up to 100%.

Table 3.1: **Percentage of Households Receiving different sources of income**

Source of Income	**South Africa** (%)
Salary and Wages	64,9
Grants	43,9
Remmitances	14,9
Income from business	13,0
Pension	3,1

Source: StatsSA General Household Survey 2012

3.2.5 South Africa's health system

Health care services in South Africa range from basic primary health care offered free by the government to first class modern health care services in the private sector.

The first class modern health facilities are quite expensive and are mostly utilised by those with medical aid schemes or the money to pay for the treatment. The private sector is largely run on commercial basis and it attracts most of the country's health professionals. This sector is small as compared to the public sector but it is growing at a faster rate.

The South African government spends approximately 8,5% of the GDP on health (Department of Health Republic of South Africa, 2011, p. 9). WHO recommends that at least 5% of a country's GDP be allocated towards health. South Africa is substantially above what WHO recommends but health services in the country remain poor (Department of Health Republic of South Africa, 2011, p. 13). This is mainly caused by the inequalities between private and public sector healthcare services. The private sector healthcare is utilised by approximately 16% of the total population in the country and spends at least 4% of the GDP. The rest of the population (84%) rely on the public sector which is allocated the remainder of the GDP (approximately 4,5%) (see Department of Health Republic of South Africa (2011, p. 9)).

Public hospitals and clinics are mostly understaffed, have fewer resources in relation to the number of people they service, and are struggling to deal with the needs of the majority of the population (Benatar, 2013). There are huge disparities between the public and private health sectors with respect to funding, health services delivery and accessibility. In 2012, private sector annual per capita expenditure on health was approximately R12 000 whereas in the public sector the annual expenditure per capita was approximately R1 200 (Benatar, 2013).

Since 1928, the government of South Africa has been trying to remove the disparities between the private and public sector healthcare services (Department of Health Republic of South Africa, 2011, p. 13). The most recent policy to address this issue is the National Health Insurance (NHI) scheme (HSRC, 2008). The main aim of NHI scheme is to redistribute healthcare resources between the public and private sectors. Under this scheme, all clinics, hospitals, specialised and tertiary hospitals would be organised under one roof. Those who need to seek additional care can subscribe to a medical scheme only after paying the basic package services (HSRC, 2008, p. 5).

Besides the service delivery differences between the sectors, access to health facilities also varies across the country. Rural settlements and informal settlements have low access to health facilities as compared to urban formal settlements (Kilian et al., 2005, p15). An imbalance in distribution of healthcare also exists across and within provinces.

Another medical sector which seem to be growing in South Africa is the traditional herbalists and diviners. They provide treatment for physical and psycho-spiritual illnesses to millions, including those who receive treatment from modern health professionals and facilities (Coplan, 2000). There are a number of organisations that formally recognise traditional healers and diviners. One of the biggest and earliest of such organisations is called "Traditional Healers Organisation (THO)", which was established in 1970 (Morris, 2001).

Another example is the "South African Traditional Healers Health Care Group" which has a number of branches across South Africa. This organisation's focus is specifically on home-based care, Direct Observation Treatment (DOT) support for people with tuberculosis (TB), Voluntary Counselling and Testing, education on HIV/AIDS and "street counselling" (Richter, 2003, p. 12). These specialists are often utilised when western medicine fails to provide a cure. Given the current situation in the health sector in South Africa, it is evident that the health system is under pressure. This pressure is further increased by the high prevalence of HIV in the country.

3.3 HIV/AIDS prevalence in South Africa

The first official report of AIDS in South Africa was in 1982, when two cases of AIDS were reported. These two cases were identified in men who have sex with men (Karim et al., 2009, p. 923). In 1985, the first AIDS-related death was reported. Since then, the figures in AIDS-related deaths and HIV prevalence have been on the increase for both homosexuals and heterosexuals (StatsSA, 2010b, p. 6). In 2012, South Africa was ranked number two in terms of the number of children orphaned by AIDS-related deaths and number one on the estimated number of people needing ART (AVERT, 2012).

The first cases of AIDS were identified among homosexuals in South Africa, but from 1990 heterosexual transmission became the main mode of HIV transmission (Karim et al., 2009, p. 922). Though to this day the main transmission mode is heterosexual, we cannot completely ignore HIV transmission among homosexuals. A study carried out in Soweto 2008 by Lane et al. (2011) confirms that HIV prevalence is still high among those who are involved in same sex sexual relationships. Hence, lesbians, bisexuals, gay and transgender people still contribute to the transmission of HIV in South Africa. It is important to note that sharing of needles for injecting drugs is a potent vector for HIV transmission. In South Africa, intravenous drug use is not that prevalent. Smoking is the most common way used by drug addicts in the country although a steady increase in people injecting heroin has been noted in a research carried out in 2013 by the South African Community Epidemiology Network on Drug Use (SACENDU).

South Africa is ranked number five in Africa and number 26 worldwide in terms of total population, but it has the highest number of people living with HIV (UNAIDS, 2013). It is estimated that 5,7 million people in South Africa, approximately 12,2% of the population, were living with HIV in 2012 (UNAIDS, 2013). The HIV pandemic in South Africa has been mainly driven by a limited attention by the government for almost a decade after the first AIDS-related death in 1985 (Simelela and Venter, 2014, p. 249).

Before the national population-based surveys on HIV/AIDS, estimates of HIV prevalence in South Africa were initially based on surveys of women attending antenatal clinics (Shisana and Simbayi, 2002). These surveys do not give adequate information to estimate national prevalence level in the general population for several reasons which include:

1. Only sexually active women who are pregnant are included in the survey. This effectively limits the survey to the 15 to 49 year age group only; and

2. It excludes people who have adopted key HIV prevention practices such as condom use.

As from 2002, the country started to carry out national level surveys. To date, there are four national surveys that have been carried out. The first survey was done in 2002 followed by 2005, 2008 and the most recent one was done in 2012. These surveys attempt to investigate in depth the social, economic and cultural determinants which drive the pandemic. The four surveys targeted people who were two years and older residing in homes and hostels in the country.

It is evident from the three surveys that there is great variation in HIV prevalence within the country. Out of the nine provinces, the second most densely populated province, Kwazulu Natal, is the most affected province with an HIV prevalence of about 16,9%, followed by Mpumalanga (14,1%). Northern Cape, which is the most sparsely populated province, has an HIV prevalence of about 7,4%. Western Cape is at the lower end of the scale with an HIV prevalence of 5,0%. The densely populated Gauteng Province is ranked number five in the provincial HIV prevalence levels with an HIV prevalence of 12,4% (HSRC, 2014), which is just more than the national average of approximately 12%.

In addition to the high HIV prevalence figures in South Africa, there is a high proportion of people co-infected with TB (WHO, 2010). Though TB is curable, the inconsistent and partial treatment may cause multi-drug resistant TB (MDR-TB) and extensively drug-resistant TB (XDR-TB). These two resistant strains are more fatal to people living with HIV/AIDS, since they are more difficult to treat (CDC, 2008). In the next sections, we highlight the positive and negative policies of the South African government on the pandemic.

3.4 Government response to the HIV pandemic

Between 1982, when the first AIDS cases were reported in South Africa and 1990, the government of South Africa did very little to contain the pandemic (Karim et al., 2009,

p. 923). The history of HIV in South Africa started in the gay community, just like in most countries. This led to the belief that AIDS was a problem for the gay community only, hence the government excused itself from making plans to curb the disease (AVERT, 2010a). The inaction by the government fueled the spread of HIV affecting people from all walks of life. The number of AIDS cases continued to increase in both gay and non-gay communities. Approximately eight years after the first AIDS cases, the number of homosexual and heterosexual cases were approximately the same[2].

An exponential increase in HIV infection was observed between 1990 and 1994 (Karim et al., 2009, p. 923). During this time, HIV prevention was publicly acknowledged (Simelela and Venter, 2014, p. 249). This led to the creation of the National AIDS Convention of South Africa (NACOSA) in 1992 (AVERT, 2010a). The establishment of NACOSA brought together political parties, academics, trade unions, civic groups and business organisations to collaborate towards HIV prevention, research, counselling and welfare. A number of intervention programmes were started since then, but did not have a significant impact on the pandemic because of lack of high profile political support (Karim et al., 2009, p. 923).

A trial carried out in Thailand in 1998 found that Zidovudine, an effective ARV drug, had reduced vertical transmission by half (Overy, 2011). This was followed by another trial in Uganda (November 1997 to April 1999), which proved that a single dose of nevirapine (another ARV drug) also substantially reduced vertical transmission (Guay et al., 1999). Despite the positive news of using these two ARV drugs to reduce vertical transmission, the South African government rejected their use in the country, arguing that the treatment plan was unaffordable (Overy, 2011, p. 2).

Instead, the government of South Africa preferred to focus on prevention rather than treatment, though using these two drugs was also a preventative measure (Van Der Vliet, 2004). The debate about using Zidovudine and Nevirapine to prevent vertical transmission led to what was labelled HIV and AIDS pandemic denialism (AVERT, 2010a). The South African Department of Health argued that good nutrition was the

[2] Information released by the Department of National Health and Population Development based on anonymous data supplied by the South African Institute of Medical Research.

answer to the pandemic (AVERT, 2010a).

In the midst of government HIV pandemic denialism, a group of 15 people protested in Cape Town demanding medical treatment for people living with HIV (Treatment Action Campaign (TAC), 2001). This happened on 10 December 1998, International Human Rights day. Members in the group were aware that treatment for HIV was available (Treatment Action Campaign (TAC), 2001), but the government of South Africa did not want to consider treatment of HIV, since the drugs were judged too expensive (Overy, 2011, p. 2). The group managed to gather support from the public and TAC was launched. TAC managed to spread the message that people with HIV/AIDS can be treated and everyone has right to healthcare regardless of their economic status.

The country faced national and international criticism about its HIV/AIDS pandemic denialism. At the same time, countries in Southern Africa adopted ART programmes. This to some extent made the government of South Africa to change its denialism attitude towards HIV and AIDS (Simelela and Venter, 2014, p. 250). HIV prevention programmes started to gain momentum from 2001 (Karim et al., 2009). In April 2002, the Cabinet of South Africa released a statement about the government's commitment to the first HIV/AIDS and STI (sexually transmitted infections) strategic plan for South Africa, designed in 2000 for the 2000 to 2005 period. This was the first time that the Cabinet of South Africa accepted the premise that HIV causes AIDS (Cabinet of South Africa, 2002).

The announcement by Cabinet led to the development of a roll-out plan of prevention of mother-to-child transmission (PMTCT) and protocols for HIV treatment using ART for both adults and children (Simelela and Venter, 2014, p. 250). The United States (U.S.) President's Emergency Plan for AIDS relief (PEPFAR) and other donors assisted South Africa to initiate HIV/AIDS prevention care and treatment services by providing financial and technical support for HIV/AIDS prevention and treatment plans (Simelela and Venter, 2014, p. 250). An operational plan for Comprehensive HIV/AIDS Care, Management and Treatment was approved, by the Cabinet of South Africa in November 2003 (Cabinet of South Africa, 2003). In 2004, the government of South Africa finally officialised the use of ART in South Africa (Simelela and Venter, 2014).

In March 2007, a new HIV and AIDS STI 2007 to 2011 strategic plan for South Africa was released, with key objectives of providing ARV drugs to 80% of people in need of the drug, and reducing new infections by 50% by 2011 (Government of South Africa, 2007). The national strategic plan of 2000 to 2005 and the operational plan for comprehensive HIV and AIDS care, management and treatment released in November 2003 were used as guiding frameworks for the 2007 to 2011 strategic plan. The strategic plan was reinforced by the approval of another plan to scale up the HIV and AIDS prevention programme by the Cabinet in March 2010 (Government Communications-(GCIS), 2010). This was followed by the introduction of the HIV Counselling and Testing Campaign (HCT) in April 2010. Other campaigns being run in the country are discussed in the following section.

3.4.1 AIDS awareness campaigns

There are a number of programmes, national and subnational, that are running in South Africa to raise AIDS awareness. Under the national programmes, there are four large scale programmes – Khomanani, Soul City, Soul Buddyz and loveLife (HSRC, 2009, p. 58) among others. Soul City, the oldest of the four, was initiated in the early 1990s. This was followed by loveLife, which has run since 1999; Soul Buddyz and Khomanani were intiated in the early 2000s. Khomanani, meaning "caring together", was the Department of Health's first AIDS awareness campaign launched in 2001 (AVERT, 2010b, p. 3). The Department of Education also introduced HIV and sex education in schools as from 2002 in an effort to enhance HIV/AIDS awareness (IRINPlusNews, 2008).

The government of South Africa is investing in HIV/AIDS campaigns, but there is a report of limited success faced by the campaigns (Swanepoel, 2005, p. 63). One of the major reasons why the campaigns are not successful is because of the heterogeneity in the target audiences and the range of complex behavioural determinants within the South African population, as pointed out by Shisana and Simbayi (2002). The general efficacy of most of the HIV/AIDS campaigns in South Africa is difficult to judge. Swanepoel (2005) argues that there are no studies that have been done to systematically and comprehensively evaluate the impact of the campaigns. A survey carried out by HSRC (2009) only established that most of the awareness campaigns penetrate more into the young age groups (15 to 24 year age group) of the population, than into the older population. Lower knowledge as well as lower levels of adoption of prevention measures contribute to the low penetration of campaigns into the population, especially the older age groups (HSRC, 2009).

WHO (2003a) pointed out that unsafe sexual practices play a big role in the transmission of HIV in sub-Saharan Africa. They argued that there is a need to have campaigns that promote safer sex practices. In South Africa, about 87% of the population is aware that a condom can be used as a prevention method for HIV transmission (South African Government Information, 2009, p. 2). Abstinence, faithfullness and partner reduction are other possible ways of reducing HIV transmision, but this is understood by very few individuals (Shelton et al., 2004). Initially, most of the HIV/AIDS campaigns emphasised more on prevention, that is, lowering sexual risks, than on non-sexual aspects, such as abstinence and voluntary counselling and testing (Parker, Makhubele, Ntlabati and Connolly, 2007, p. 22). This might be one of the reasons why abstinence is rarely one of the most popular ways of reducing HIV transmission in South Africa.

The Life Orientation curriculum has its own drawbacks. In South Africa, there is a high drop-out rate from grade 10 to 12 (Chuenyane, 2010). Children remain in school until 16 years, the compulsory school age – which is in most cases the year they complete their basic education, grade 0 to 9. Most children then drop out from school at this age before acquiring enough knowledge from the Life Orientation curriculum. As a result, the whole aim of learning Life Orientation as a subject is defeated. It is again around this age that teenagers become increasingly sexually active.

A shortage of teachers as well as teachers who are not comfortable to teach the curriculum since it contradicts their values and beliefs contribute towards the failure of the Life Orientation curriculum (AVERT, 2010b). Most teachers view Life Orientation as an extra workload to their "normal" working load; hence, there is limited passion for the subject from the educators. Teachers are also not trained to teach the subject, and it is not compulsory in studying to become a teacher (IRINPlusNews, 2008).

Knowledge about HIV transmission through breastfeeding is quite high in South Africa (South African Government Information, 2009, p. 2), but the correct practice regarding HIV and breastfeeding is not well known. International guidelines recommend HIV positive mothers to avoid breastfeeding when replacement feeding is feasible and affordable. The problem in many African countries is that replacement feeding is not feasible and affordable to all; hence, many women choose to breastfeed regardless of their HIV status (Kiarie et al., 2004). The challenge is that women who choose to breastfeed do not practice exclusive breastfeeding (Iliff et al., 2005, p. 700). In the next sections, we examine the specific risk factors that drive the HIV pandemic in South Africa.

3.5 HIV risk factors in South Africa

3.5.1 Behavioural determinants

As mentioned earlier, heterosexual sex is the most common mode of HIV transmission in South Africa. The 2007 to 2011 National Strategic Plan of South Africa identified key indicators related to sexual behaviour for HIV infection. Some of these factors are sexual debut age, multiple sexual partnerships, condom use and intergenerational sex. In the following section, we discuss the factors that were identified as key indicators related to sexual behaviour for HIV infection.

Sexual debut

The age at which sexual debut occurs is important, as it increases vulnerability to HIV infection. Early sexual debut increases vulnerability to HIV infection mainly because there is a higher probability of having multiple sexual partners, high biological susceptibility to infection, as well as a low probability of condom use at first encounter (Harrison, Cleland, Gouws and Frohlich, 2005, p. 259).

In a study carried out by Harrison et al. (2005) in Kwazulu Natal Province in South Africa, they found that 13,1% of men aged between 15 to 24 reported having sex before the age of 15 years. Statistics from the 2003 South African Demographic and Health Survey (SADHS) show that boys become sexually active earlier than girls. The survey also showed that 42% of women and 63% of men had become sexually active by the end of their childhood, that is, 18 years. The median age at time of first sex was found to be approximately 18 years (Bakilana, 2005). Though the age at time of first sex is quite early in South Africa, marriage occurs at a relatively older age (Parker et al., 2007, p. 13). This may explain the high rate of multiple sexual partners and hence high incidence and prevalence rates of HIV in South Africa.

Some of the Acts passed by the government of South Africa partially promote early sexual debut. For example the Children's Act, 2005 which states that:

> *No person may refuse*
>
> *(a) to sell condoms to a child over the age of 12 years; or*
>
> *(b) to provide a child over the age of 12 years with condoms on request where condoms are provided or distributed free of charge.*

This also applies to other contraceptives other than condoms. This act suggests that children under the age of 15 have access to contraceptives, which promotes an early sexual debut.

Other laws or acts that to some extent support early sexual debut are the National Education Policy Act of 1996 and the Termination of Pregnancy Act, Act 92 of

1996. These laws do have positive impact on the society but at the same time may promote unsafe sexual practices among teenagers. The National Education Policy Act allows pregnant pupils to attend school as well as to return to school after birth. The Termination of Pregnancy Act allows any woman of any age less than 13 weeks pregnant to abort without stating any reasons why the pregnancy must be terminated. These policies may encourage teenagers to think that falling pregnant is not a serious issue since they can still go to school or terminate the pregnancy.

Multiple sexual partners

The National Communication Survey on HIV/AIDS 2009 found that 3% of men and 15% of women aged 20 to 24 are in stable relationships. The South African youth, especially young men, have multiple sexual partners and usually not committed to have stable relationships. There is a situation whereby an individual claims to have a "main" sexual partner and one or more "other" sexual partners. The main sexual partner is considered to be a long-term partner with which one shares love. The other sexual partners are not part of a long term plan but can fulfill the needs for intimacy (Parker et al., 2007, p. 22). This shows that South Africans are not yet convinced that abstinence, faithfulness and partner reduction reduces HIV infection risk.

Besides the need to fulfill intimacy, there are other reasons why people engage in multiple sex relationships in the country. These include intergenerational relationships motivated by financial exchange, sexual exploration, peer pressure, acquisition of status as a product of being sexually desirable and a de-emphasis of long-term relationships (HSRC, 2009, p. 65).

Models developed by Morris and Kretzschmar (1995) prove the concept that concurrent sexual partners stimulate the spread of HIV. Concurrent sexual relationships in South Africa range from long-term "closed" polygamous marriages, to one off encounters. Mah and Halperin (2010b) points out that, if all the members involved in a long closed polygamous marriage are HIV negative, we can expect the relationship to be protective to some extent. The problem is that it is now rare to have such relationships in most of the African countries, and South Africa is no exception. The causes of such relationship involve socio-economic, cultural contexts and psychological factors related to self-esteem and fatalism (Parker et al., 2007, p. 46).

Age disparate and intergenerational sex

Age disparate sex is normally defined as a sexual relationship with an age gap of more than five years but less than ten years between partners. Intergenerational sex usually refers to sexual relationships with an age gap of ten years or more. Studies that have been carried out in South Africa reveal that these types of sex do occur. The population based survey of 2005 revealed that teenage males and females have sex with partners five or more years older. This is consistent with studies carried out by Pettifor et al. (2004) and Jewkes et al. (2001). Jewkes et al. (2001) conducted a study about the relationship dynamics and teenage pregnancy in South Africa. They found that most of the pregnant teenagers had boyfriends who were older by five or more years.

Leclerc-Madlala (2008) presented a paper which reviewed literature on age disparate and intergenerational sex in Southern Africa. Most of the studies conducted revealed that age disparate and intergenerational sex were relatively common in Southern Africa. The researchers found that young women in these relationships did not have the power to negotiate for safer sex practices, since doing so would jeopardise their economic goals in the relationship.

Economic benefits or material gain nurture age disparate and intergenerational sex in Southern Africa (Leclerc-Madlala, 2008). The author also points out that cultural practices also contribute to the formation of age disparate relationships. Under cultural practices, it is believed that an adult rich man is best positioned to help young women to meet their various material needs and desires.

The 2005 population-based survey in South Africa revealed that HIV infection rate of girls between 15 to 19 years in sexual relationships with an age disparity of five or more years was very high. Leclerc-Madlala (2008) argues that risk perception in such relationships is often low. Men involved in these relationship believe that their young partners do not have STIs and HIV. Similarly, young women also think that older man are less involved in risk taking and more stable, hence less concern is put on the probability of contracting HIV or STIs.

Condom use and distribution

Consistent and correct use of the male latex condom reduces HIV incidence by about 80% (Weller and Davis-Beaty, 2002, p. 2). The South African government has played a major role in the distribution of condoms. The use of condoms during sexual intercourse is a key part of the government's HIV prevention strategy. In South Africa, the female condom was introduced in 1996. According to Council (2010), 3,6 million female condoms were distributed by 2006. Although the government of South Africa is trying to have both male and female condoms accessible, the male condom is far more widely available. This may be attributed to cost and other logistical concerns (HSRC, 2009).

Most of the campaigns in South Africa promote the use of condoms as one of the most effective ways of protecting against contracting HIV (Parker et al., 2007, p. 22). An increase in the number of males and females using condoms during sex was observed in the 2008 population-based survey. Unfortunately, the 2012 population-based survey indicated a drop in use of condoms during sexual encounters (HSRC, 2014). Pettifor et al. (2004, p. 2002) reported inconsistent use of condoms in transactional sex, early sexual encounters and in age disparate sexual relationships. Inconsistent use and non-use of condoms during sexual encounters is also noted to occur among primary partners (spouses or steady partners) and people with multiple sexual partners (Lichtenstein et al., 2008; Kalichman et al., 2007).

3.5.2 HIV testing and counselling

Voluntary testing and counselling is one of the strategies used to curb the spread of HIV/AIDS. In South Africa, voluntary testing and counselling was never the main topic in mass media intervention, hence did not play a large role in intervention programmes until 2004. According to the National Communications Survey, HIV testing levels in South Africa have improved from 60% in 2009 to approximately 65,5% in 2012 based on the sample collected for the surveys (HSRC, 2014, p. 126). Those staying in the rural areas have a lower testing rate than those in urban areas (AVERT, 2010b).

In South Africa, voluntary counselling and testing coverage has been on an increase since 2006. By 2009, 96% of public health facilities in the country were offering voluntary counselling and testing. Though there has been an increase in voluntary counselling and testing, there is still a need to have more people tested for South Africa to effectively reduce the HIV prevalence levels.

In February 2010, the policy on voluntary testing and counselling was revised. In the revised policy, HIV testing and counselling remain voluntary but health workers are obliged to encourage patients to be tested as part of a normal health seeking behaviour. Most importantly, the health workers must explain to patients the importance of knowing one's HIV status. Once the HIV status is known, individuals can start medication early if HIV positive and practice safety precautions so as not to spread the virus (Council, 2010).

HIV counselling and testing (HCT) campaigns are known to have positive results. Similar campaigns were carried out in Kenya, Uganda, Tanzania and Malawi and had positive results (Council, 2010). These positive experiences have led to the choice of HCT campaigns by the government of South Africa. The campaign has been designed in such a way that information easily penetrates into communities and villages through national media; for example, a newspaper written in five major languages, secondary school campaigns, door-to-door campaigns and during large gatherings of people in the community.

Stigmatisation and discrimination faced by people living with HIV in South Africa may undermine the efforts of the HCT campaign. There is a strong social stigma attached to HIV/AIDS in South Africa. According to Groenewald et al. (2005, p. 199), many people who are HIV positive are reluctant to disclose their status and some may request their doctors not to do so. One of the reasons which fuels this attitude is that many funeral services and life insurance policies in the country do not cover for death from HIV/AIDS. Non-disclosure hinders the efforts being made to reduce the incidence rate.

3.5.3 Antiretroviral therapy

The official distribution of free ARVs to ordinary South Africans was delayed until 2004 (Simelela and Venter, 2014, p. 250). This contributed to the fast increase in HIV prevalence in the country. Since 2004, the government has been trying to control the pandemic through providing free health care to HIV positive children and pregnant women. The only challenge being faced is that very few of the target groups are receiving the medication (Kilian et al., 2005, p. 15). This has partially led to the designing of a new National Strategic plan on AIDS and STI's in 2007. Two of the strategic plan targets were to have a 50% reduction in new infections by 2011 and to expand access to appropriate treatment, care and support to 80% of people infected with HIV (Council, 2010).

A review of the 2007 to 2011 National Strategic Plan showed some positive results for the two targets, although the targets were not fully achieved (Colvin, 2011, p. 15). HIV incidence in 2007 was estimated at 1,3%. To achieve a 50% reduction in new infections by 2011, the incidence rate was supposed to decrease to approximately 0,65% (Colvin, 2011). In 2012, a year after the end of the 2007 to 2011 Strategic Plan, incidence was estimated at 1,07% (HSRC, 2014). The target for reduction of new infections by 50% by 2011 was not met, although there was a drop in new cases of HIV infection (Colvin, 2011, p. 9).

Progress was observed in expanding access to appropriate treatment, care and support to people infected with HIV. This was achieved through engaging high-level political leadership in HIV response, development of strong policies to support HIV/AIDS response, revision of the ART treatment guidelines and the launch of the HCT Campaign in April 2010 (Colvin, 2011, p. 15). According to Colvin (2011, p. 12), approximately 24,7% of adults have been tested between 2008 and 2009. This exceeded a target of 11% which was set for the same period.

The roll-out of ART has greatly improved in South Africa since its inception in 2003. This was one of the major targets that were set in the National Strategic Plan in 2007. An estimated 40% of adults and 10% of children were receiving free ART by the end of June 2009 (Council, 2010). The 2012 South African National HIV Prevalence, Incidence and Behaviour Survey revealed that 31,2% of people living with HIV are on ART (HSRC, 2014, p. 56).

As from 2006, an HIV positive person in South Africa was given ARVs when their CD4 cell count is less than 200 cells per microliter (cells/μL). On World AIDS Day, 1 December 2009, the President of South Africa announced that patients with TB and HIV infection and all pregnant HIV positive women will start receiving ARVs when their CD4 count is 350 cells/μL or less. He also announced that individuals with AIDS symptoms will also receive ARVs regardless of the level of their CD4 count (Council, 2010).

3.5.4 HIV and TB

TB is one of the opportunistic infections with a high fatality rate among HIV/AIDS patients (WHO, 2007). In countries with a high HIV/AIDS prevalence, TB incidence is also very high. This positive correlation between HIV/AIDS and TB demands for continual effort to prevent and treat those infected with HIV. In South Africa, 75% of TB patients are co-infected with HIV (Erasmus, 2010). The Former President of South Africa, Nelson Mandela, said that “We cannot fight AIDS unless we do much more to fight TB as well” (Hogg, 2004).

TB in South Africa was first identified in the 17^{th} century (Karim et al., 2009, p. 923). TB started to spread at an alarming rate from late 1800s when the mining industry started to grow. The poor working conditions, overcrowding, silica dust exposure and poor nutrition in the mining industry facilitated the spread of the disease (Edginton, 2000). In a bid to control the HIV/AIDS pandemic, President Jacob Zuma announced that patients with both TB and HIV would receive treatment for both at the same time (Erasmus, 2010).

3.5.5 Gender-based violence and inequality

In 1992, the United Nations Entity for Gender Equality and Empowerment of Women defined gender-based violence as "a form of discrimination that seriously inhibits women's ability to enjoy rights and freedoms on a basis of equality with men". The violence includes acts that cause sexual, physical or mental harm or suffering, threats of such acts, coercion and other deprivations of liberty[3]. Studies that have been carried out in sub-Saharan Africa indicate that gender-based violence is a risk factor for HIV seropositivity (Robin and Alessandra, 2007; Dunkle et al., 2004a).

According to the study carried out by HSRC (2014), HIV prevalence data for South Africa is higher for females in the 15 to 49 year age group (23,2%) as compared to the male prevalence in the same age group (14,5%). The differences in HIV prevalence is even greater if we compare younger age groups. Young women in the 20 to 24 year age group have an HIV prevalence that is approximately three and a half times higher – 11,4% compared with 2,9% – than among men of the same age group HSRC (2014, p. 42).

Women are biologically more vulnerable to HIV infection (Waver et al., 2005). A recent study carried out by the Centre for the AIDS Programme of Research in South Africa revealed that women in KwaZulu Natal Province had more immune cells in their vaginas which are "friendly" to HIV transmission. This increases the risk for

[3] U.N. Convention for the Elimination of All Forms of Discrimination against Women (1992). General Recommendation No. 19 (llth session, 1992)

women to contract HIV regardless of the number of sexual partners or encounters (Child, 2015). Forced sex further increases their HIV infection risk; hence the differences in HIV prevalence levels between men and women within the same age group.

The patriarchy system common in some of the cultures in the country makes women quite vulnerable to domestic and sexual violence. Sexual violence and rape are quite common in South Africa (AVERT, 2010b) especially towards economically deprived women (Robin and Alessandra, 2007). The economic imbalance between men and women in South Africa exposes women to agree to unsafe sex practices which in turn increases their risk of contracting HIV (Robin and Alessandra, 2007, p. 24). Research conducted by Dunkle et al. (2004a) in South Africa proved that women with violent or controlling male partners had a higher risk of HIV infection.

Generally, people in South Africa accept male dominance. A study carried out by Anderson et al. (2004) observed that 28% of males and 27% of females believed that a woman does not have the right to refuse sex with her boyfriend. Over 50% of both males and females in the same study did not consider forced sex with someone you know to be sexual violence. Furthermore, it is common for women in sub-Saharan Africa to have older intimate partners.

The unequal power in relationships makes it difficult for women to negotiate for safe sex or to refuse sex (Anderson et al., 2004). Most interventions to contain the HIV pandemic focus on condom use, ART, and treatment for STIs. However, these strategies may not work for women who suffer from gender-based violence, since it is not easy for the women to negotiate for safe sex, go for HIV testing and to seek treatment after infection (Jewkes, Dunkle, Nduna and Shai, 2010). This makes the fight against HIV/AIDS difficult, particularly for women. Therefore, gender-based violence must be taken into consideration when developing policies to fight against HIV/AIDS.

3.5.6 Migration

Migration is another factor that is believed to contribute to HIV transmission just like any other infectious disease (Quinn, 1994, p. 2407). The first AIDS cases in South Africa were flight stewards who visited United States (AVERT, 2010a, p. 1). This provides evidence that mobility contribute to fast progression of diseases. Though migration has its own disadvantages, it also has some advantages. For example, the urbanisation process in South Africa did depend on transboundary migration, particularly in the mining and agricultural sectors (Crush, Jeeves and Yudelman, 1993, p. 283).

Labour migration into South Africa has been on the increase ever since 1990, when the country started to have economic and political stability. Most of the migrants are from countries within the Southern African Development Community (SADC) which are experiencing political and economic instability. Given the size of South Africa's economy, most migrants in the region believe that the country provides more opportunities for unskilled, skilled and professional labour (Crush and Williams, 2002, pp. 2-3).

National migration accounts for rural to urban, inter-city, intra-city and intra-provincial migration. These migration patterns are often "circular"[4] and non-permanent (Collinson et al., 2003). South African men often work far away from their families and only return home two or three times each year. This increases the chances of both the male and the female partner to be involved in unsafe sex practices outside their marriages (Cichocki, 2007). This was confirmed by a study carried out by Lurie et al. (2003b) which established that migration is a risk factor not only from the male partner returning home to infect the rural partner, but the rural women also have a risk of becoming HIV infected during the absence of the male partner. Migration also contributes to formation of concurrent relationships.

Migration facilitates the mixing of HIV subtypes, and hence the introduction of new

[4] This is when men leave their rural partners to work in urban areas and only return home periodically (Lurie et al., 2003a, p. 149)

hybrid viruses known as "circulating recombinant forms" (CRFs) (Robertson et al., 2000, p. IV-55). This may render the development of a vaccine very difficult. Although migration has a negative effect on the progression of a disease, it also has a positive effect if it is used as a mode to spread awareness messages as well as intervention programmes (Lurie et al., 2003b, p. 156).

3.5.7 Cultural practices

As mentioned earlier on, traditional values in South Africa are still being observed. Some of the cultural social structures, such as concurrent relationships, continue to exist despite the health risks associated with them (Mah and Halperin, 2010a, p. 14). A study carried out by Selikow, Zulu and Cedras (2004) in South Africa revealed that male sexuality is measured by the number of sexual partners one has.

Circumcision is among cultural practices that are still observed in South Africa. Before the launch of voluntary medical male circumcision (VMMC) programme in 2010 (Colvin, 2011, p. 57), circumcision was done mostly in initiation schools (Peltzer et al., 2008). Traditional circumcision does not adhere to some of the health precautions needed during the circumcision process. Failure to adhere to health precautions may lead to serious adverse events, including death (Peltzer et al., 2008, p. 3).

Several studies have been carried out to establish the degree to which male circumcision prevents HIV transmission. Firm evidence have been produced by a number of studies showing that circumcision can reduce the risk of sexual transmission of HIV from women to men by 60% (Bailey et al., 2007; Gray et al., 2007). Researchers (Weiss et al., 2006; Tobian et al., 2009) have also reported a lower risk for some STDs (syphilis and chancroid) in circumcised men. Other research studies have shown that female partners of circumcised men have a low risk of developing female genital ulceration, bacterial vaginosis and trichomoniasis (Gray et al., 2009). Therefore, the government of South Africa decided to increase the rate at which males are circumcised in the country. A national VMMC programme was rolled out in April 2010

(Colvin, 2011, p. 58). By April 2011, aproximately 150 000 circumcisions were conducted (Colvin, 2011, p. 58).

Same sex sexual relations have a long history in South Africa. As from 1994, homosexuality was legalised in the country. By 2002, South Africa was considered to be the country with the most permissive gay rights legislation worldwide (BBC News, 2002). In 2006, same sex marriages were made official. Despite the progress in legal protection of same sex sexual relationships, most South Africans do not accept such practices (Rule and Mncwango, 2006). A quote from BBC news about "Taking Gay Pride to SA's townships" clearly supports that some communities do not support homosexual relationships:

> *Tradition, ritual, family is paramount in any African culture out there, so as a young black man I would need to be looking for a wife, making babies, and because I am not fulfilling those roles, society does not know how to deal with me. You risk not being part of the community, not being part of the family, not being part of society.*

This was quoted from Africa Melane, a presenter on the radio station Cape Talk. The same applies to prostitution. Prostitution is not culturally accepted but it may be acceptable for a young unmarried man or woman to have a number of pre-marital relationships (Leclerc-Madlala, 2008).

3.5.8 Vertical transmission

As in any other country, HIV/AIDS in South Africa targets younger adults who are most active sexually. Younger adults are economically and biologically productive. The 2012 South African National HIV Prevalence, Incidence and Behaviour Survey considered African females aged 20 to 34, African males aged 25 to 49, people living together (not married), high-risk drinkers, drug users and people with disabilities 15 years and older to be the most-at-risk populations (MARPs) in the country. Out of these groups, females aged 20 to 34 years had the highest HIV prevalence, followed by people living together, not married (15 to 49 years) (HSRC, 2014, p. 53). The high incidence rate in this age group results in premature deaths, which have been on the increase since 1999 (AVERT, 2010b); hence a decrease in life expectancy, which in 2010 stands at 53,3 years for males and 57,2 years for females (StatsSA, 2010b, p. 3).

High incidence and prevalence within the sexually active age group also increases vertical transmission rates of HIV. Vertical transmission is the second dominant mode of HIV transmission in South Africa. The national transmission rate of HIV from mother to child in 2010 was approximately 11% of all infants born to HIV-positive mothers (AVERT, 2010b). This greatly affected the infant mortality rate, which increased between 1990 – 44 deaths per 1000 infants and 2008 – 48 deaths per 1000 (WHO, 2009).

3.5.9 Sexually transmitted infections (STIs)

The presence of STIs increases the chances of HIV transmission (Vernazza et al., 1999, p. 156). A study carried out in four cities in Africa from four different countries, that is, Kenya, Zambia, Benin and Cameroon, between June 1997 and March 1998 confirmed that there is a strong positive and consistent association between Herpes Simplex Virus type II (HSV-2) and HIV infection (Weiss, Buve, Robinson, Dyck, Kahindo and et al., 2001).

HSV-2 is one of the STIs that is common in South Africa. The prevalence of HSV-2 was found to increase very rapidly with age in a study carried out in August 1996 to March 1997 in the KwaZulu-Natal midlands of South Africa (Ramjee, Gouws, Dyke, Williams and Karim, 2002). It is also thought that the presence of STIs may also increase viral load, which in turn increases the probability of infection per coital act (Vernazza et al., 1999, p. 160).

Auvert et al. (2001) found that the presence of biological factors result in greater variability in efficiency of transmission of HIV than does differences in sexual behaviours. Therefore, including biological factors in models to explain the spread of

HIV may better explain the variations observed in the rate at which HIV propagates in a population and the observed differences in prevalence levels.

3.6 Conclusion

This chapter has presented an overview of the HIV pandemic in South Africa. From the overview, we can conclude that there is still a need to come up with a comprehensive model to understand the HIV pandemic in South Africa. It will also be worthwhile to embed the new HIV prevention policies, such as the HCT campaign and the use of ART as a prevention measure, in the model and to systematically evaluate the effectiveness of such interventions. In the next chapter, we discuss agent-based and social simulation modelling, the two modelling techniques behind the model developed in this thesis.

Chapter 4

Agent-Based Modelling and Social Simulation

4.1 Introduction

This chapter introduces agent-based social simulation modelling as the methodology used to answer the research questions presented in Chapter 1. As a tool, simulation modelling provides the means to describe a systems' behaviour when it is not feasible to apply analytical techniques, and is normally used to study complex systems. In this research, we are interested in understanding the progression of HIV in a human society. Human societies are usually complex adaptive systems. The interactions among the members of most human societies are mostly non-linear and cannot be easily represented by traditional computational and mathematical models. Individual based models like agent-based models can give a better understanding of complex systems since they use a bottom-up approach.

In agent-based modelling, a system (social or nonsocial) is modelled as a collection of autonomous agents capable of making decisions (Bonabeau, 2002, p. 7280). Social simulation is a research field that makes use of computational methods to study human behaviour and society. A combination of agent-based modelling and social simulation results in agent-based social simulation (ABSS). In the following section, we discuss agent-based modelling and social simulation. We conclude by giving an overview of ABSS.

4.2 Social simulation

By definition, social science is an academic field which deals with society and human behaviour (Williams, 1999). On the other hand, simulation is a tool used to study complex systems. Therefore, social simulation aims to use simulation tools to understand the dynamics in societies and human behaviour by exploring complex non-linear systems that exist in societies. Such complex non-linear systems cannot be studied using the classical mathematical equation-based models. Social science lays the theoretical foundation for social simulation and modelling.

Gilbert and Troitzsch (2005) defined social simulation as a computer program developed to model the behaviour of some social system. Social simulation models are usually developed to test new social theories or to have a deeper understanding of interactions among members of the society. Hence, the basic idea behind social simulation is to develop a simulation model that is very close to social reality. When developing a simulation model, the following steps outlined by Maria (1997) are normally used:

1. Problem formulation – this is the statement of the problem.
2. Setting of objectives and overall project plan. At this stage, the modeller is able to determine if simulation is the appropriate methodology to solve the problem at hand;
3. Model conceptualization – this is the stage when a model is developed. It is better to start with a simple model and build toward greater complexity;
4. Data collection – there is a constant interplay between model construction and collection of model input data. Data requirements may change as the model

develops. Required data elements may also change, hence more data may need to be collected;

5. Model translation – this is when a model is translated into a computer program. Some problems may not require actual coding;

6. Verification – this is when the computer program is tested to check if it is performing properly, that is, to check if it really represents the model intended for development;

7. Validation is when the developed model is evaluated against the real system;

8. Experimental design – the number of replications for each simulation run and alternatives to be simulated must be laid out; and

9. Analysis and documentation of the results.

Simulation models are classified into static and dynamic models. A static simulation model represents a system at a particular point in time. Static simulation models are usually known as Monte Carlo simulations. On the other hand, a dynamic simulation model represents a system as it evolves over time.

Deterministic simulation models do not contain random variables. Such models have a known set of inputs which gives a unique set of outputs. If a simulation model contains one or more random variables as inputs, it is classified under stochastic simulation models. Random inputs usually lead to random outputs. A simulation model can evolve continuously (variable(s) change continuously over time) or at discrete time steps (variable(s) change only at a discrete points in time).

In order to model a system, one must understand the concept of a system. According to Maria (1997), a system is defined as a collection of entities that acts and interacts toward the accomplishment of some logical end. A system is often affected by changes occurring in its environment (Gordon, 1978). Since there is an interaction between the system and the environment, it is very important to clearly define the boundary between the system and its environment. Systems generally tend to be dynamic and to describe this status, the concept of the state of a system is used. The following are definitions of terms used in a system as outlined by Maria (1997):

1. The state of a system is the collection of variables necessary to describe the status of the system at any given time;
2. An entity is an object of interest in the system;
3. An attribute is a property of an entity;
4. An activity represents a time period of specified length;
5. An event is defined as an instantaneous occurrence that may change the state of the system;
6. Endogenous is a term used to describe activities and events occurring within a system; and
7. Exogenous is used to describe activities and events in the environment that affect the system.

There are four major types of social simulation, namely; (*i*) System level simulation, (*ii*) System level modelling, (*iii*) Agent-based modelling and (*iv*)Agent-based social simulation. The system level approach is an analytical approach that uses large mathematical equations and computer programming to determine the impact of global conditions on a society and its members if certain variables change. In this research, we focus on agent-based simulation. In the following section, we introduce the agent-based modelling approach. We then present an overview of an agent-based social system.

4.3 Agent-based modelling

By definition, an agent-based model, sometimes related to the term multi-agent system, is a computational model used to simulate the actions and interactions of autonomous decision entities called agents, with the aim of understanding their effects on the global system. Agent-based modelling uses elements of complex systems, evolutionary programming, computational sociology and game theory.

Agent-based models normally have a hierarchical model structure, with the higher level representing system environment where agents stay and the lower level representing individual agents, their attributes, states, behaviours and their interaction with each other and with their environment (Gilbert and Terna, 2000). DeLoach and Valenzuela (2007, p. 1) argue that, to design, analyse and understand the operation of a system, it is important to first understand the environment in which an agent is situated.

According to Odell, Parunak, Fleischer and Brueckner (2003, p. 17), the environment provides the platform for agent interaction. It defines the properties of the world in which an agent functions. Odell et al. (2003) further classifies the environment in which an agent can exist, namely; physical and communication environment. Physical environment provides the principles and processes that govern and support the agents.

The communication environment, which embeds the social environment, provides the principles, processes and structures that enable agents to convey information. The social environment is an environment where agents interact in a coordinated manner. Kesaniemi and Terziyan (2011) state that the social environment is composed of 1) groups in which agents participate, 2) roles of the agent and 3) all the members who play roles in the social group.

The main objective of agent-based models is to simulate the simultaneous actions and interactions of multiple autonomous agents, individual or collective, in an attempt to recreate the appearance of a complex real life situation. Agent-based models use simple behavioural rules to generate complex behaviour. This principle is known as the KISS (Keep It Simple, Stupid) modelling approach.

According to Ferber (1999), most agent-based models are composed of the following:

1. an environment;

2. a set of objects which can be active or non-active. Active objects are agents which can be specified at various scales;
3. decision-making heuristics that agents can use;
4. learning rules or adaptive processes; and
5. an interaction topology.

In agent-based modelling, an agent is a representation of an entity, for example, an individual, household or firm in the real world. Bonabeau (2002) argues that each agent individually assesses its situation and makes decisions using heuristics or simple decision-making rules. An agent has a choice of making decisions using either the bounded rationality concept or an omniscient point of view. Omniscience is when an agent has the capability to know everything that is there to know. In reality, an agent may not have complete knowledge of the outcome of its actions. This then implies that decision making mainly depends on past experiences and partial knowledge of the system; hence the concept of bounded rationality which was first proposed by Simon (1957).

Under the bounded rationality concept, Edmonds (1998) states that an agent

1. does not have perfect information about the dynamically changing environment. The information that an agent has is only acquired through its interaction with the environment.
2. does not have a perfect model of its environment.
3. has limited computational power, which limits the agent's ability to make optimal decisions.
4. has other resource limitations; for example, memory, hence perfectly rational decisions are not feasible in practice.

There are different definitions for the word "agent" depending on the context. Wooldridge (2002) defines an agent as "*an encapsulated computer system that is situated in some environment and is capable of having flexible, autonomous actions in the environment in order to meet its design objectives*". Wooldridge's definition is aligned more to computer science systems; for example, designing software systems.

In this research, we are more interested in defining an agent as an entity representing social reality. Here we present a definition for an agent as described by Macal and North (2006). According to Macal and North (2006), an agent is a physical entity that possess the following characteristics: an agent

1. is an identifiable, discrete individual with a set of characteristics and rules governing the individual's behaviour and decision making capability.

2. is situated, living in an environment with which it interacts along with other agents.

3. may be goal-directed, having goals to achieve with respect to its behaviour.

4. is autonomous and self directed.

5. is flexible, having the ability to learn and adapt its behaviour based on experience.

The most important feature of an agent is its ability to make independent decisions (Samuelson and Macal, 2006). Though agent-based modelling is a technique that can be used to model complex systems, it is not all complex systems that can be modelled using agent-based models. Bonabeau (2002) states that agent-based modelling can be used when

1. individual behaviour is nonlinear and can be characterized by thresholds, if-then rules, or nonlinear coupling.

2. individual behaviour exhibits memory, path-dependence, and hysteresis, non-markovian behaviour, or temporal correlations, including learning and adaptation.

3. agent interactions are heterogeneous and can generate network effects.

4. averages will not work.

In other words, in systems where the differentiated behaviour of individuals determine the dynamics of the system, agent-based models are appropriate. In each of the cases stated by Bonabeau (2002), it is difficult to use differential equations. Differential equations tend to smooth out fluctuations. With agent-based modelling, one is able to capture the natural description of the system and observe the emergent phenomena with its fluctuations. In the next section, we discuss agent-based social simulation, which is a hybrid of social simulation and agent-based modelling.

4.4 Agent-based social simulation (ABSS)

Social simulation aims to use simulation to model behaviour of autonomous individuals. To achieve this, agent-based modelling has been found to be an appropriate tool to use. With agent-based models, one can create “artificial” societies in which individuals can be directly represented and the effect of their interactions observed. The individual interactions normally lead to an emergence of social structures (Epstein and Robert, 1996) that are inherently complex.

Combining the three techniques, agent-based computing, social sciences and computer simulation led to the emergence of ABSS in the mid 1980s. Hence, ABSS is a cross disciplinary research and application field. Davidsson (2002) defines ABSS as an intersection of the three scientific fields, namely; agent-based computing, computer simulation and social sciences (see Figure 4.1).

ABSS represents an intersection of all the three academic fields. Davidsson (2002) also defines and differentiates the research areas that are a combination of two of

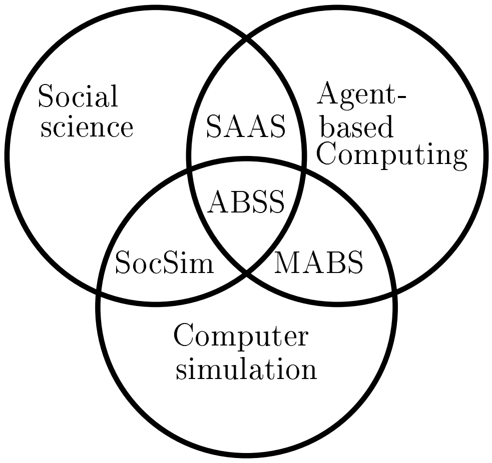


Figure 4.1: **Agent-based social simulation: an intersection of three areas defining it (source: Davidsson 2002)**

the three research areas. Social Aspects of Agent Systems (SAAS) consists of social science and agent-based computing. SAAS is mainly the study of norms, institutions, organisations, co-operation, competition, *et cetera*. Social simulation (SocSim) which is the simulation of social phenomena on a computer using any simulation techniques, lies on the intersection of social sciences and computer simulation. Finally, on the intersection of computer simulation and agent-based computing, lies Multi Agent-Based Simulation (MABS). This is when agent technology is used to simulate any phenomenon on a computer.

The main objective of ABSS approach was to close the gap that exists between the descriptive approach used in social sciences and the formal approach used in the hard sciences (Axelrod, 1984). ABSS models simulate the social behaviour of autonomous individuals and the interaction amongst them. This means that the emergent structure of the system is derived from the interactions among individual agents without using a top down and centralised control.

Agents in ABSS models possess a set of attributes and behaviour rules. Flow charts are used to represent the process through which agents experience events and change of status. The behaviour rules defined through flow charts allow agents to interact with other agents and the environment. Interactions with other agents may transform the state of an agent or the environment through the use of real or hypothetical probability distributions.

ABSS can also be classified as an experimental technique. Electronic theoretical laboratories can be developed using ABSS and explored via a computer simulation with detailed assumptions about individual agents, their behaviours and interactions (Samuelson and Macal, 2006). Experiments done on such artificial societies are sometimes quite impossible, time consuming, expensive or unethical to perform on actual human populations. Hence, construction of agent-based models that can simulate aspects of social behaviour can add to the understanding of social processes.

In this thesis, we use ABSS to explore the various scenarios of sexual relationships formed in a mixed society and their effect on HIV transmission. Our aim is to replicate the complexity of the behavioural and epidemiological processes that underline the transmission of HIV in a society which mainly depends on the interactions and decisions made by individual human beings. The corresponding system environment is the real world where agents live. Agents in the model correspond to individual human beings.

We used AnyLogic to develop our agent-based simulation model. AnyLogic is a Java-based modelling platform that supports agent-based, system dynamics and discrete event simulation methodologies. It allows the user to extend simulation models with Java code. Models developed in AnyLogic can be exported as standalone Java applications or applets. These applets make AnyLogic models very easy to share or place on websites. AnyLogic has tools, library objects and a graphical interface that allow the user to quickly model diverse areas such as consumer and patient behaviour even without an extensive coding background. It also supports the incorporation of geographical information system (GIS) in simulation models (for future development of our model).

Chapter 5

Agent-based Model Description

5.1 Introduction

Analytical models for STDs, including HIV, have shown that the progression of STDs in a society is very sensitive to human behaviour which include: the amount of risky sexual behaviour (for example, multiple concurrent sexual partners), the distribution of the risk behaviour in the society and the social network structures within which people practice the risky behaviours (Anderson and Hanson, 2005; Blower et al., 2003). In order to have effective intervention programmes to curb the spread of HIV, there is a need for researchers to understand how the three factors contribute to the non-linear behaviour of the HIV pandemic. Researchers have to take into consideration the underlying social networks since networks structured differently lead to different types of pandemics (Heuveline et al., 2004).

A number of approaches have been used to simulate social issues. The different approaches can be classified into two major classes: analytical and network based simulations. Though analytical models have successfully proved that human behaviour contributes significantly to HIV progression, their major drawback is that the models assume random interactions among people. Random mixing, for example, can be assumed if the disease is spread in an airborne manner within a smaller region.

However, with STDs, randomness seem to fail since sex does not happen randomly. This automatically means that analytical models do not account for social network patterns which do contribute to the rate at which the virus is spread (Rothenberg et al., 2000).

In this chapter, we present a network agent-based social simulation model which will add to the understanding of how HIV spreads in a society. We keep in mind that no model will perfectly represent the real world situation but we aim to develop a model in a manner that reflects available data. The main assumption of our model is that the population in which the virus is active is composed of different subgroups of individuals. We examine the temporal dynamics of the spread of the virus in such a population. In the model, we rely heavily on the use of random numbers generated from probability distributions to simulate events such as partnership formation, number of coital acts and transmission of the virus. In the context of HIV transmission modelling, agents are considered to be human beings.

Our model is a discrete time model in which each step represents one week. We decided to use discrete time, since some actions and events we pay attention to in our model appear to be discrete. In addition, some parameters used in our model are derived from real data. Real data mostly comes in discrete form hence using a discrete time step in our model makes it easier to calibrate using real data points. This chapter begins by describing the model structure, followed by the description of agent attributes required in the model. We then present the approach adopted in modelling the personal network formed by agents and the three key aspects of the model, namely: sexual networking, child birth and the modelling of HIV progression in a society.

5.2 Model structure

The agent-based microsimulation model simulates individuals in a dynamic social and sexual network overlaid by HIV transmission. The only type of agent considered in this model is a human individual. At model initialisation, all agents are assigned several characteristics that are required in the model. We want to acknowledge that parameters and attributes used in this model are derived from literature.

Decision making by the agents in the model depends on the interactions an agent undergoes with other agents and the environment. The number of agents in the model changes as new agents are introduced through birth and existing agents exit the model through death. Death of agents is either through AIDS-related illnesses or non-AIDS causes and illnesses. In the model, there are global rules that may cause a change in an agent's attributes as the model runs. Occurrence of some events can generate new events that either occur immediately (for example, marriage of a non-promiscuous individual stops all other romantic relationships with that individual). At each time step, each agent's states are updated.

In this model, three types of human interaction networks are presented. We consider these interaction networks to have a hierarchical structure. At the bottom of the hierarchy, we have the personal network, which we also refer to as the friendship network. The friendship network forms the foundation of all other networks in this model. Agents search for sexual partners from the friendship network. Sexual relationship ties form the second level of the interaction networks. At the highest level of the hierarchy, we have marriage network ties.

The basic assumption behind this structuring is that friendship links are naturally more than sexual links, hence the sexual network is smaller compared to the friendship network. Links created represent the connection between agents. In this model, we take into consideration multiple concurrent sexual partners but we restrict ourselves to monogamous marriages (each agent has only one spouse). So, for marriage, there is a maximum of only one tie per agent. This then makes the marriage network much smaller compared to the other two networks already mentioned.

New friendship, sexual and marriage links are formed and existing links are broken during the simulation run. Creation and deletion of links in the sexual network is one of the key factors that contribute to HIV propagation. The rules for the formation and breaking of links in our personal network were developed based on rules described by Jin, Girvan and Newman (2001). Since our model has sexual and marriage links, additional rules were added to those described by Jin et al. (2001). The additional rules do not allow a friendship link between two agents in a romantic relationship (dating, courting or married) to be broken. A romantic relationship link is broken if one of the partners decides to drop the current partner in favour of another partner. The model incorporates divorce for married agents.

Over and above the sexual and marriage network, we introduce sexual relationships for commercial and opportunistic sex workers. Opportunistic sex is when agents are in a sexual relationship either for financial or non-financial benefits; for example, a sexual relationship that will afford one to be promoted in an organisation. This may happen not because there is love but because there is something one needs and an opportunity arises where sex can facilitate its acquisition. It is different from commercial sex in the sense that in commercial sex one is after financial gain (commercial sex can be seen as a job).

Transmission of HIV in the model is through sexual transmission and vertical transmission. The model incorporates the effect that ART has on the transmission of HIV. Not all agents will have access to ART at the right time. Some agents may initiate treatment earlier than the standardised national eligibility criteria for starting ART whereas others may initiate it well after.

The model has been developed using the AnyLogic simulation toolkit, which uses Java as the programming language. Most of the parameters used in the model are derived from available literature. Where parameters could not be found in available literature, unvalidated assumptions were made. In some instances sensitivity analysis was used to evaluate the assumptions made. However these assumptions may need to be validated in future. A full list of model parameters is available in Appendix A. In the following section, we explore the basic attributes that an agent in our model must possess at creation. We also present the states and behaviour rules that alter the states of an agent as the simulation runs.

5.3 Agent characteristics

Each agent created in the model possesses basic attributes represented by continuous or discrete state variables. Each agent has static and dynamic attributes. Static attributes do not change throughout the lifetime of an agent. Among the static attributes are gender, maximum number of date and sexual partners and desire for sexual variety. Dynamic attributes change in response to simulation events and aging. These attributes include number of sexual partners at any given point in time, marital status, HIV status and age among others. Attributes attached to the agents define the structure of the population at any given time during the simulation run.

Data collected in South Africa through South African Demographic and Health Surveys (SADHS); for example SADHS (2003), is used in our model to assign agents' characteristics such as gender, age and marital status at model initialisation. South Africa is a nation of diversity with people of diverse origins, a variety of cultures, languages and religious beliefs. Four racial groups are recognised in South Africa: Black African, White, Coloured and Indian/Asian (see Chapter 3, Section 3.2). Out of the four population groups, Black Africans constitute 79,4% of the total population (StatsSA, 2010b, p. 4). The remainder 20,6% is divided among the other three ethnic groups. Given such a scenario, we can conclude that data collected through SADHS reflects characteristics of the major group more than that of the other three ethnic groups.

To reduce the complexity of our model, we consider only the largest population group in South Africa: Black Africans. The main aim of our model is to model HIV progression in the population and the efficient route of HIV transmission is through sexual contact. In South Africa, inter-racial intimate relationships are not so common (Sherman and Steyn, 2009; Jacobson et al., 2004; Heaton and Jacobson, 2004); hence we assume that restricting our model to one racial group does not significantly affect the results of the model.

5.3.1 Agent basic attributes

Each agent in this model is assigned several characteristics upon creation. Our agents will have gender and age among the basic attributes. Age is assigned to agents using the age/sex structure of the 2001 population census (StatsSA, 2004). As the simulation runs, the age of an agent is updated each year. Death of agents in the model occurs either at the time of non-AIDS mortality or at the time of AIDS/ART-related mortality, whichever comes first. Non-AIDS death age is determined using the death probability table published by Actuarial Society of South Africa (ASSA) (2007). We assume that the death probability table takes into consideration all other possible ways a person can die, excluding death due to HIV/AIDS-related causes.

Each agent has an attractiveness level (a measure of how attractive an agent is to other agents), and aspiration level (the quality that an agent looks for in a partner). The idea of using attractiveness level and aspiration in the partnering mechanism is adopted from research done by Simao and Todd (2003). Alam (2008, pp. 116-117) and Knittel, Riolo and Snow (2011, p. 5) adopted the same approach to model their partnering algorithm.

We do admit that what makes one individual more attractive than the other is quite a subjective issue. A range of characteristics, which include appearance, wealth, age, fertility, and familiarity may be used to judge the attractiveness of an individual. Research results obtained by French and Kus (2008) and Hills and Todd (2008) using a range of characteristics to estimate attractiveness did not show a marked difference from those obtained using a one-dimensional measure for attractiveness (Simao and Todd, 2003).

Therefore, in this model we use a one dimensional measure of attractiveness. Default parameters for attractiveness and aspiration are adopted from Knittel et al. (2011). A normal distribution with mean 50 and standard deviation 25 with lower and upper limits of 0 and 100 respectively is used to assign attractiveness level and aspiration level randomly to each agent (Knittel et al., 2011, p. 9). In our model attractiveness and aspiration do not change over time. The dynamic aspect on attractiveness and aspiration is dealt with in the likeability index.

The maximum number of friendship connections an agent can have in the personal network is assigned at model intialisation. Knittel et al. (2011) fixed the maximum number of connections to 10. Research (Allan, 2006) has shown that the number of friendship connections can be more than 10, with one researcher arguing that the maximum number of social network connections can be as high as 150 (Dunbar, 1992). An individual's social network, which can have a maximum of 150 connections in real world settings, is composed of family members, spouses, coworkers, society fellows, *et cetera*. The maximum number of close confidants excluding family members is approximately 15 (Allan, 2006).

The number of close confidants that a person can have is highly dependent on one's social behaviour and the behaviour of the people one encounters in life. To model the heterogeneity in the number of close confidants an individual can have, we use a Weibull distribution with scale parameter β set to 10 and a shape parameter α set to 5. Weibull distribution is used due to its versatility in modelling a variety of life behaviours (Wayne, 1982, p.36). In section 5.4.1 on page 86, we give a detailed explanation about the formation of a friendship network.

Collecting and interpreting data about human sexual behaviour is a daunting task. The problem is even more acute in South Africa, where there are diverse marriage forms, cultures, religions and languages. For the purpose of our model, we rely on parameters available in literature and on probability distributions that fit the data found in literature.

To model the diverse mating strategies experienced in real life, three static parameters are assigned to our agents, namely: the maximum number of dating partners an agent can have concurrently; desire for sexual variety; and the maximum number of sexual partners an agent can have concurrently. Studies have shown that these three parameters vary from one individual to the next (Helleringer and Kohler, 2007; Baumeister et al., 2001), with desire for sexual variety contributing significantly to the number of sexual partners one may have in a lifetime (Baumeister et al., 2001, p. 244, 247).

Desire for sexual variety has been proved to vary across gender and to decrease with age (Bradford and Meston, 2007; DeLamater and Sill, 2005). Studies have shown that generally men have stronger sex desire than females (Baumeister et al., 2001). In this model, sexual drive, SD, parameter values are randomly assigned to agents using a Beta distribution with minimum and maximum values equal to zero and one respectively . The parameters of the Beta distribution, alpha (α) and beta (β) are defined differently to suite the differences in gender specific sexual desire.

Besides gender differences in sexual drive, research has shown that aging decreases sex drive. Menopause, which occurs in women at an average age of 50, and factors associated with being older, such as onset of several health-related and sexual problems, have been shown to decrease sexual drive of older people (Bradford and Meston, 2007; DeLamater and Sill, 2005). The age at which the drive starts to decrease is not very specific due to the difficulty associated with collecting sex-related data. To reduce complexity of our model, we do not decrease the sexual drive of the agents. We only assume that male sex worker visitors and agents who engage in opportunistic sex activities as defined in this thesis are removed from these categories at age 55 and 60 for females and males, respectively. Female sex workers are removed from the sex worker group at 45 years. This is done to cater for the decrease in sexual drive (DeLamater and Sill, 2005, p. 147) and in perceived attractiveness in the eyes of potential partners with age.

The maximum number of dating and sexual partners represent the maximum number of partners an agent can have simultaneously at any given time. Parameter values for the maximum number of sexual partners used in this model are adopted from Alam (2008, p. 124). Alam (2008, p. 124) used data collected by Helleringer and Kohler (2007) which follows a lognormal distribution. This model uses the same distribution and parameters used by Alam (2008). The parameters used to model the maximum number of date and sexual partners for male and female agents are shown in Table 5.1 on page 83.

The model incorporates a courtship time period. We define the courtship time period as the time agents in a romantic relationship spend before deciding to marry. This time starts when two agents begin dating until the two decide to marry. From anecdotal records collected by Alam (2008, p. 119), it takes about one to two years for a courting couple to marry. Research done by Huston, Niehuis and Smith (2000) established that couples that tend to enjoy their marriage usually have an average courtship duration of 18 months. In our model, we use a truncated normal distribution with a mean of 78 weeks (approximately 18 months) and a standard deviation of 10, a minimum of 26 weeks and a maximum of 156 weeks. More information about formation of romantic relationships is in Section 5.4.2 on page 89.

Table 5.1: **Agent attributes**

Attribute	**Possible value or distribution with parameters**
Age (years)	Any value between 0 and 100
Attractiveness level	Normal(50;25)
Aspiration level	Normal(50;25)
Maximum number of connections	Weibull(6;10)
Maximum number of dating partners	female:Lognormal(0,2;0,3) male:Lognormal(0,4;0,7)
Maximum number of sexual partners	female:Lognormal(0,2;0,3) male:Lognormal(0,4;0,7)
Dating time period (without sex) (weeks)	Normal(10;2)
Courtship duration (weeks)	Normal(78;10)

The courtship time period contains a dating time period which is divided into two: dating without and with sexual activities. The maximum dating time period is fixed at 60 weeks (see page 97 for the justification of 60 weeks). During the first few weeks of the 60 weeks of dating time, agents do not have sex. This time period is called the non-sexual dating period. Buss (2006, p. 250) tried to estimate the non-sexual dating time period. From the study, Buss (2006) concluded that males tend to let little time elapse before seeking sexual intercourse as compared to females. We model this time using parameters adopted from Knittel et al. (2011) (see Table 5.1 for the parameter values). Agents will engage in sexual activities once the non-sexual dating period lapses and they are both sexually active.

5.3.2 Agent states and behaviour rules for agents

States

Each statement in the following list shows mutually exclusive states that can be assumed by an agent. For example, an agent can either be a child or an adult but not both at the same time. In this model, an agent may be simultaneously involved in any of the four listed mutually exclusive states:

1. a child, under 15 years or an adult, older than 15 years;
2. sexually active or not sexually active;
3. marital status which can be single, married, divorced or widowed; and
4. health status which can be HIV negative or positive. The HIV positive state include sub-states outlined in Figure 5.7 on page 123.

Behaviour rules

Behaviour rules are rules that change agent states from one state to another. The change depends on the focal agent and other agent attributes and states as well as the environment around the focal agent. When a change of an agent state is caused by other agent attributes and states or the environment, we have interaction between agents or interaction between the agent and the environment, respectively.

For the purpose of this model, main behaviour rules at each time step include the following:

1. Formation and breaking of friendship links: there is a higher probability of a friendship link formation if an agent is of the same age. A link is only formed if the maximum number of connections is not yet reached for each of the two agents to be connected. A friendship link is removed between two friends if there is no romantic relationship;

2. Dating relationship formation: if the asking agent has potential partners, the agent sends a date request to one of the potential partners. For all agents receiving a date request, a decision must be made to accept or decline the date request based on the characteristics of the agents involved. Asking or receiving agents can send or accept only one message at each time step;

3. Sexual relationship formation: a dating couple makes a decision to initiate sexual activities once the non-sexual dating period has elapsed. A sexual relationship can stop if a better partner is encountered or if the relationship develops into marriage;

4. Marriage rules: if an agent is not married, he or she must evaluate his current state and make a decision to marry or not to marry. If an agent is married and a better partner becomes available, a decision to or not to divorce has to be made; and

5. HIV infection rules regulates how a susceptible (HIV negative) agent is infected with HIV.

Detailed information about the behaviour rules used in the formation of the friendship network and the sexual network outlined above are presented in the following section.

5.4 Dynamic interaction networks

This section presents a detailed description of the rules used in the formation of the three network layers considered in our model. At the base of the networks in the model, there is the agent friendship network, followed by the dating and sexual network. At the highest level, there is the marriage network. As the model runs, new links between agents are formed and existing links may be lost, hence all the networks in the model are dynamic.

The three network layers take into consideration both assortative and disassortative interaction of agents. Assortative interaction takes place within a subgroup, for example a friendship link formed between agents of the same age group. Disassortative interaction is when agents of different subgroups interact. An example is when a friendship link is formed between agents with an age difference of 10 years or more. Assortative and disassortative interactions are always evident in societies, though the former is the most common phenomenon. The rate at which an infectious disease spreads in a population also depends on the degree of assortative and disassortative interactions in the population (Gupta, Anderson and May, 1989). The following three sections give detailed information about the rules governing the three network layers.

5.4.1 Dynamic friendship network

Rules outlined by Jin et al. (2001) are used as a basis for developing the friendship network. Jin et al. (2001) used the following three general rules to illustrate the growth of human social networks:

1. Meetings take place between pairs of individuals at a rate which is high if a pair has one or more mutual friends and low otherwise;
2. Acquaintances between pairs of individuals who rarely meet decay over time; and
3. There is an upper limit on the number of friendships an individual can maintain.

Three assumptions have been added over and above the rules outlined by Jin et al. (2001) based on the available literature of social networks. According to Allan (2006), social networks are classified into different kinds distinguished by the relationships they include. Allan (2006) defines the global network or "social network" as the network that consists of all existing social relationships of a person. The social network includes family members, spouses, friends, coworkers, society fellows, neighbours *et cetera*.

Dunbar (1992) argues that there is a direct correlation between the neocortex volume of the human brain and the number of social relationships a human can monitor simultaneously. This cognitive ceiling of relationships, now known as Dunbar's number is approximately 150 (Dunbar, 2010). Though some researchers (Goncalves, Perra and Vespignani (2011)) tend to support Dunbar's number, some researchers remain skeptical about this cognitive ceiling (de Ruiter, Weston and Lyon (2011)).

A social network has a number of subnetworks. Among them are the personal network (support network), family network, friendship network and work-related network (Wrzus et al., 2012). The personal network consists of close confidants, family members and close friends (Allan, 2006). Most of the subnetworks intersect; for example, the personal network which includes family members does intersect with the family network.

In our model, we do not include interactions with family members. The main aim of our model is to model romantic relationships. Most romantic relationships, if not all, are formed between non-family members (incest is a taboo). Therefore, first assumption that is added to our friendship network, which also reduces the complexity of the model, is that there are no family links and any link created in the model is a friendship link. The second assumption is that the number of very well connected friends an agent can have follows a Weibull distribution with shape and scale parameter β set to ten and a shape parameter α equal to five (Allan, 2006).

The third assumption is that friendship links start when an agent turns 15 years. In this model, we use the friendship network to develop the sexual network; hence we have used 15 years as a starting point for joining the friendship network since most individuals start to be sexually active around that age (StatsSA, 2010a). This is done to simplify matters and to reduce the number of computations done during the simulation by avoiding unnecessary link formations which will not necessarily contribute to the main objective of this research.

During the formation of friendship links, we do not take into consideration physical proximity of agents. To model physical proximity, we need to include geographical coordinates for the agents. This will increase the complexity of the model. We will leave the implementation of physical proximity as an area for further research.

An agent can have a friend of any age but there is a higher probability of connecting to agents with an absolute age difference of at most five years. This is supported by the fact that homophily limits people's social networks. McPherson et al. (2001, p. 424) argue that race and ethnicity creates the strongest divides, followed by age, religion, education, occupation and gender. The author further states that homophily on age has been found to create stronger division in close friendship relationships than any other dimension. Hargreaves (2005) also supports the assumption, stating that the age difference between friends is usually between zero and five years.

In our model, we consider age as the only divide since we assume that our agents are from one population group. The likelihood of connection decreases as the age difference between agents increases (Louch, 2000, p. 58). Therefore, in this model friendship links are created probabilistically based on the age difference between agents. The following is the pseudocode implemented in the model:

```
FOR all agents with links less than the maximum number of
personal connections
Run through list of potential friends
IF (absolute age difference is less or equal to 5)
    agent connects to friend;
IF (absolute age difference is between 5 and 10 years)
    agent connects to friend with α_1 probability;
IF (absolute age difference is between 10 and 15 years)
    agent connects to friend with α_2 probability;
IF (absolute age difference is greater than 15)
    agent connects to friend with α_3 probability;
```

Friendship links created will break up based on rule number 2 stated by Jin et al. (2001). In our model spatiality is not explicitly modelled, hence we apply rule number 2 stated by Jin et al. (2001) using probabilities. The social network created by Jin et al. (2001) does not take into consideration couple formation. Since our model takes into consideration couple formation, a social link between any two agents involved in a romantic relationship (dating, sexual or marriage) is not allowed to break up. This fits well into Jin et al. (2001) rule 2, since agents in a romantic relationship meet regularly. Their friendship does not decay over time; hence they remain connected. Parameters used to develop the social and sexual network are shown in Table 5.2.

5.4.2 Dynamic sexual and marriage network

The main source of HIV transmission is when two agents have sexual intercourse (Schmid et al., 2004). Sexual intercourse between a male and a female agent may result in pregnancy. If the female agent is HIV positive, there is a possibility of infecting the new born either at birth or during breastfeeding (Rauner, 2005). This is called mother-to-child transmission or vertical transmission.

For us to be able to model the progression of HIV in a society, there is a need to develop a comprehensive sexual mixing scheme. Modelling sexual relationships is quite difficult since it is not easy to obtain information on how people select their sexual partners. In our model, we consider five types of sexual relationships: short-term relationships, long-term relationships, spousal (marriage) relationships, commercial sex worker (CSW) contacts and opportunistic sexual relationships. This section describes how short-term relationships, long-term relationships and spousal (marriage) relationships are formed in our model. CSW contacts and opportunistic sexual relationships are discussed in Section 5.5.

During dating and courting, an agent may have numerous encounters with other agents of the opposite sex and must select agents that are potentially compatible. Encounters with other agents may lead to formation of new romantic relationships and breaking of existing ones until a stable romantic relationship is formed, which may finally lead to marriage. In this model, marriage does not stop an agent from continuing to search for agents with which to have romantic relationships. Our model accommodates changes in marital status over the life span of an individual.

We allow concurrency at all levels of agent romantic relationships for both males and females. This is supported by research carried out by Parker et al. (2007) which has shown that in Southern Africa, multiple concurrent partnerships occur at all levels of romantic relationships. This section of our model builds up on ideas proposed by Knittel et al. (2011) and Alam (2008). In this section, we first present the dynamic processes in dating and courtship of agents, which then lead to marriage.

Dating and courtship scheme

Agents in this model use the likeability index to search for potential love mates from their friendship network. In his paper entitled "Triangular Theory of Love" Sternberg (1986) argues that love is made up of three components, namely; intimacy, passion and decision or commitment. The author defines liking as when one experiences only the intimacy component of love in the absence of passion and commitment. Therefore, liking is the set of feelings one experiences in emotionally close friendship relationships which are not necessarily romantic relationships (Sternberg, 1986).

This set of feelings, which we call the likeability index, is used in this model to select potential candidates an agent can date. Because of the subjective nature of attractiveness ("beauty lies in the eyes of the beholder"), we assume that perceived likeability index is not uniform across an agent's friends, even friends of the same age. The index depends on the traits of the proposer and the known traits of the friend. A friend with a likeability index greater than an agent's likeability threshold is considered to be a potential candidate to date.

Table 5.2: **Social and sexual network agent attributes**

Parameter/Variable	**Default value**	Description	**Source**
		Social and sexual network	
Environmental parameters			
intialSexualRelationships	0,5	Proportion of agents in a sexual relationship at model initialisation	Assumed
initialPregnancy	0,019	Proportion of pregnant female agents married at model initialisation	Myatt (2012)
r_0	0,00002	Proportion of agents chosen to make random friendship connections	Based on Jin et al. (2001)
r_1	2	Multiplier to determine number of agents chosen to make neighbour meetings	Based on Jin et al. (2001)
Gamma	0,05	Probability of removing a friendship connection	Assumed
beta1F	0,2	Female multiplier used to calculate the upper acceptable age limit for a male potential date	Assumed
beta2F	0,8	Female multiplier used to calculate the lower acceptable age limit for a male potential date	Assumed
beta1M	0,5	Male multiplier used to calculate the lower acceptable age limit for a female potential date	Assumed
beta2M	0	Male multiplier used to calculate the upper acceptable age limit for a female potential date	Assumed
α_1	0,4	Probability of creating a friendship connection for agents with 5 to 10 years age difference	Assumed
α_2	0,01	Probability of creating a friendship connection for agents with 10 to 15 years age difference	Assumed
α_3	0,001	Probability of creating a friendship connection for agents with age difference greater than 15 years	Assumed

The likeability threshold for agents below the median age at first marriage (26 for female agents and 30 for male agents (see Budlender et al. (2004, pp. 18-19)) lies between 0,55 and 0,9. The likeability threshold starts to decrease as soon as an agent reaches the age at first marriage without a partner. Research about the perceptions of single adults has shown that they feel social pressure because of their status when older than the age at first marriage (DePaulo and Morris, 2005). Women are subjected to more pressure than men due to an increasing risk of infertility with age. Also, as a women ages, the pool of eligible single men decreases (Sharp and Ganong, 2011).

To model the perception of being single with increasing age, we assume that agents below the age at first marriage have a higher potential of getting a romantic partner, hence the likeabilty threshold is set high, between 0,55 and 0,9. As soon as an agent's age is above the age at first marriage, the likeability threshold starts to decrease with every discrete time step (one week) that passes without a date partner. The minimum value that can be attained by the likeability threshold in this model is 0,1. Single female and male agents reduce their likeability threshold until it reaches a minimum of 0,1 approximately at age 45 and 50 years, respectively. This assumption is weakly supported by the fact that as an agent ages without having a romantic partner, they become better adjusted to being single (Morris et al., 2008; Ferguson, 2000; Lewis and Moon, 1997); hence no need to continue decreasing the likeability threshold to values below 0,1.

Since potential dates are selected from the friendship network, it is highly likely that the focal agent know basic traits, such as age, marital status, and attractiveness of the individuals they choose to be potential mates. Therefore, the likeability index is calculated using age, attractiveness and aspiration level of the agent. If the likeability index is greater than or equal to the agent likeability threshold, the opposite sex friend is added into the set of potential partners. The set of potential partners contains all opposite sex friends to whom an agent can send a dating message.

Research has shown that average age differences of individuals in romantic relationships depends on age and marital status prior to the focal marriage. The mean age difference tends to increase with age and marital status, excluding the single marital status (Wilson and Smallwood, 2008; StatsSA, 2010b). To calculate the likeability index, we have assumed that male agents prefer female agents of the same age or younger and female agents prefer male agents of the same age or older (cf. Buss (2006, pp. 245-247)). This gives rise to distributions skewed towards younger females for males and towards older males for females. Gender differences in preferences of age of the partner is further supported by the mean age at first marriage for males and females. Male median age at first marriage is usually higher than that for females (Budlender et al., 2004, pp. 18-19).

To reduce the complexity of our model, age differences in romantic relationships depend on age and gender only. We model age differences by assigning an upper and lower limit to what we call the "standard" relationship age range for both male and female agents. In real life the "standard" age range increases linearly with age. This assumption is weakly supported by the fact that the mean difference in age and the standard deviation of couples increase with age (Wilson and Smallwood, 2008). More research needs to be done to support the linear increase in the age range. In this model, we maintain clear cut off points for the standard age range. We assume a constant "standard" age range across all ages. A male agent has a higher chance of marrying a female agent up to eight years younger. Out of this age range, a higher penalty is assigned when calculating age difference index (ADI).

The ADI is calculated using an age difference ratio (ADR) and a probabilistic term to avoid having the same index being used for females of the same age. This is done to try and model the differences in perceived attractiveness. ADR is calculated by dividing male agent age into absolute age difference between the male and female agent. If the absolute age difference is within the "standard" relationship age difference range, then

$$\mathrm{ADI} = 0{,}25 \times \mathrm{ADR} \times \mathrm{uniform}(1 - \mathrm{ADR}, 1).$$

If the absolute age difference is outside the "standard" relationship age range and the female is younger, we multiply ADR by four. If the female is older than the male agent, we add a constant 0,5 and multiply ADR by four.

The pseudo-code for the process handling the calculation of the ADI for a male agent is as follows:

```
IF (male agent has opposite sex friends
    AND the  friend ∉ potential friends collection)
    Calculate absolute age difference;
      IF (absolute age difference is within the ‘‘standard’’
          age difference range)
          ADI = 0,25 × ADR × uniform(1 − ADR,1)
      IF (absolute age difference is outside the ‘‘standard’’
       age difference range AND female is younger)
          ADI = 4 × ADR × uniform(1 − ADR,1)
      IF (absolute age difference is outside the ‘‘standard’’
       age difference range AND female is older)
          ADI = 0,5 + 4 × ADR × uniform(1 − ADR,1)
```

The pseudo-code for the process handling the calculation of the ADI for a female agent is similar to that of a male agent. The major difference is that we choose the values of the multipliers in such a way that the “standard” range is skewed towards older male agents. This is done to model the distribution observed in the age differences between older males and young females and between older females and young males (Wilson and Smallwood, 2008). Generally, females prefer older male partners; therefore, we have skewed the distribution by having a small multiplier between older man and younger females and a large multiplier between older females and younger males.

If the absolute age difference is within the “standard” relationship age difference range, for both males and females, then

$$\text{ADI} = \text{ADR} \times \text{uniform}(1 - \text{ADR}, 1).$$

If the absolute age difference is outside the “standard” relationship age range and female is younger, we double ADR. If the female is older, we multiply ADR by 20.

The attractiveness index (AI) and the aspiration level index (ALI) are calculated by first finding the absolute difference in the male agent and female agent attractiveness and aspiration levels, respectively. The absolute difference is then divided by 100 to obtain the two indices (100 being the maximum cut off point for attractiveness and aspiration). The larger the difference in aspiration or attractiveness, the larger the weight. The likeability index is therefore calculated as follows:

```
Likeability Index = 1− ADI −AI − ALI
IF (likeability index ≥ likeability threshold)
     add friend into potential partners OR accept date message
```

In this model, if a romantic relationship breaks up, there is a possibility of reconciliation as indicated by Dailey et al. (2009). According to the study by Dailey et al. (2009), 61,6% of the participants experienced an on-off relationship, with some relationships breaking up and reconciling more than once. We assume that the likeability index of an ex-partner is calculated the same way as that for a new potential partner.

At each discrete time step, the asking agents get a list of potential dates by calculating the likeability index of all opposite sex friends. After getting the list of potential dates, the asking agent sends a date message to one of the potential dates if not currently involved in any romantic relationship. If an agent is currently involved in a romantic relationship, a decision to send a date message has to be made. The decision making depends on a number of factors. Figure 5.1[1] shows the logical flow of activities involved in making the decision of sending and accepting a dating message.

The first thing to be considered in the decision making process is the sexual desire value. Sending a date message happens with probability less or equal to the asking agents' sexual desire value. The lower the sexual desire value, the less the chance of sending or receiving a date message if an agent is already dating.

The second condition to be checked is the attractiveness of the potential partner compared to the current dates or partners. The evaluation of the attractiveness of the potential date depends on the duration of current relationships. To model the effect of relationship duration on the attractiveness of a potential partner, we assume that

[1]SD in the flow diagram represents sexual drive with parameter values randomly assigned to agents using a Beta distribution with minimum and maximum values equal to zero and one respectively

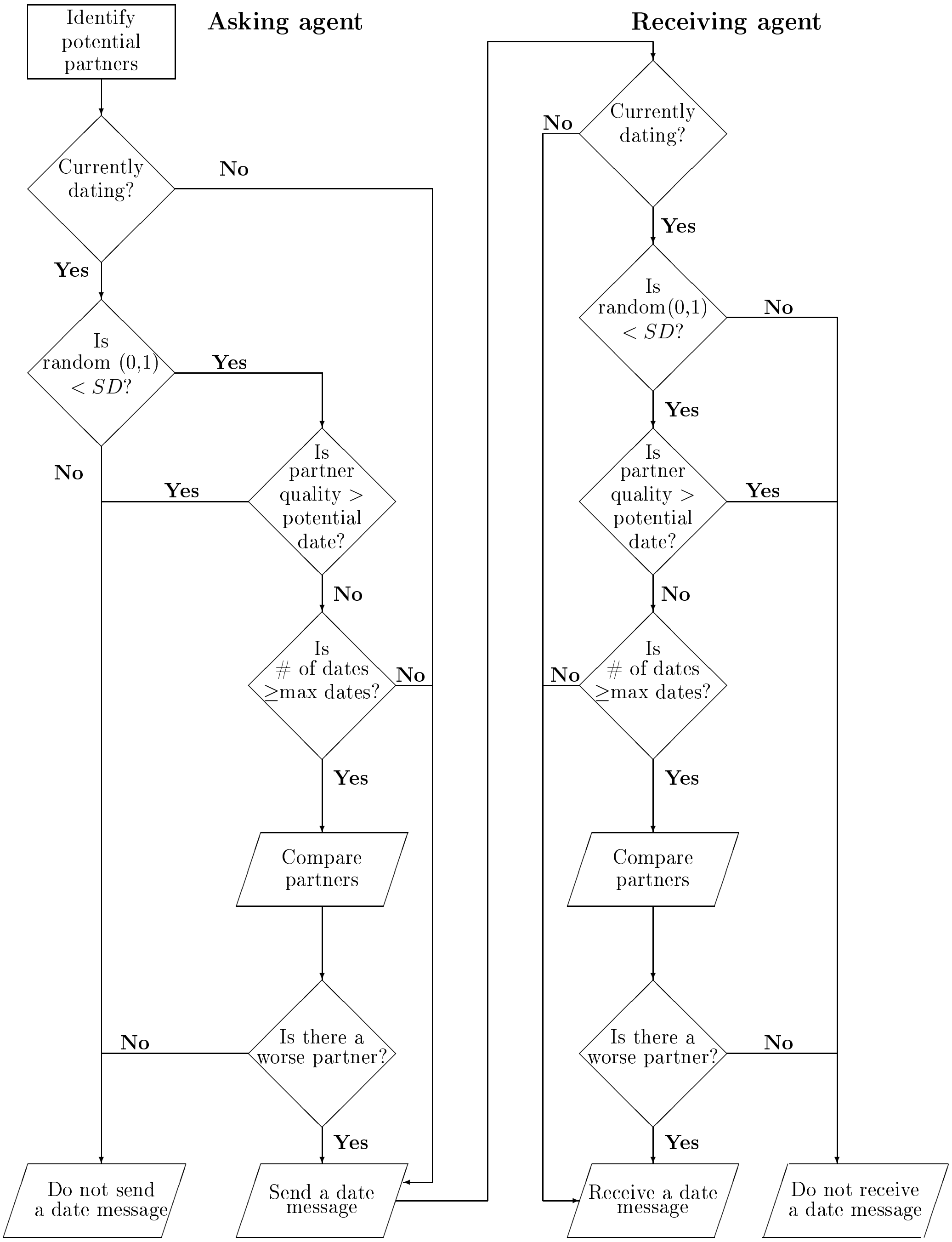


Figure 5.1: **Partnering algorithm**

dating couples go through two types of love: passionate and companionate (Haidt, 2006, Chapter 6). Sternberg (1986) states that the three components of love, namely; intimacy, passion and commitment interact with each other in any type of romantic relationships, and the kind of love one experiences depends on the strength of each of the components.

For free mate choice romantic relationships, passionate love develops almost immediately, approaching a peak fairly rapidly at the beginning of a relationship compared to the other two components (Haidt, 2006; Sternberg, 1986). During this time, when the passion between the two is high, it is very difficult for dating couples to fall in love with another agent. We assume that within the first weeks of falling in love interaction with individuals of the opposite sex is significantly reduced, mainly because of the need to invest "quality" time with the new date (Simao and Todd, 2002, p.6).

After reaching a peak, passionate love starts to decrease. At this stage, we assume that interaction with opposite sex friends starts to increase but will not be 100% since there is still need to invest time in the current relationship. Intimacy and commitment, which generally develop at a slower rate and usually last for a lifetime, normally supersedes the passion component of love as time progresses. These two components, namely; intimacy and commitment, create the pair bond required in a long lasting love relationship in which the physical attraction has died down (Sternberg, 1986, p. 124). If the bond is not created, or if the relationship starts to flag, as Sternberg (1986, p. 127) puts it, the relationship fails.

In this model, passionate love reaches its peak in 24 weeks (approximately 6 months). This idea is weakly supported by Garcia (1998). Thereafter, the opponent process of passion begins to decrease the experienced level of passion (Sternberg, 1986, p. 127) from about 24 to 60 weeks (approximately 15 months). Companionate love then takes over after about 60 weeks from the beginning of the relationship. Therefore, we fix the dating time period to 60 weeks. During the first 24 weeks in a new relationship, it is very difficult for one to propose to a new agent since passionate love towards the new partner will be very strong. Figure 5.2 illustrates the course of passionate and companionate love as a function of time for a romantic relationship.

We consider a date with a relationship duration of less or equal to 60 weeks, approximately 15 months, as a new date. To model the changes of the love components, during the first 60 weeks of dating, attractiveness of a potential partner is weighed against the attractiveness of the new date partner(s). If there are multiple partners an average is taken. During the first 24 weeks of a new date, the attractiveness of a date

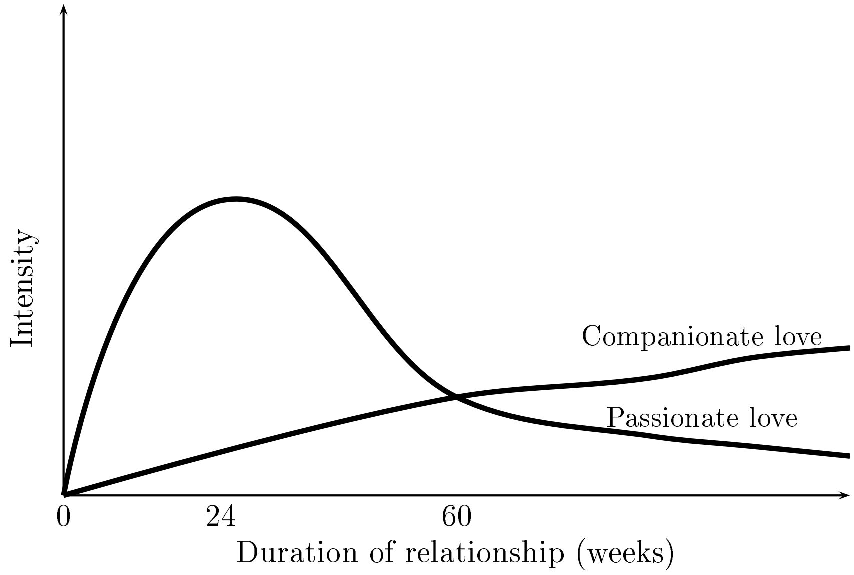


Figure 5.2: **The course of passionate and companionate love as a function of time of a relationship** (see Robert Sternberg and Jonathan Haidt: Chapter 6)

partner is assumed to increase. This is done to take into consideration the increase in passionate love during the first few weeks of dating. This makes it difficult for a person just falling in love to propose or to accept a date message. The pseudo-code used to model the first 24 weeks is as follows:

```
IF (average relationship duration of date partners ≤ 24 weeks)
    current date Partner(s) quality = min(datingPartnerQuality*
    (1+avgWeeksNewDating/24),100)
IF (current date Partner(s) quality < potentialDate
     attractiveness))
    send or receive a date message;
```

Between 24 and 60 weeks, the attractiveness of the new date decreases to its original value. We assume that this is the time when the opponent process of passion begins to act. This increases the chance of a potential partner to be proposed to. The pseudo-code used in the model is as follows:

```
IF (average relationship duration of date partners is
    between 24 and 60 weeks )
    current date Partner(s) quality = datingPartnerQuality
                                     *(2-avgWeeksNewDating/60)
IF (current date Partner(s) quality < potentialDate.attractiveness)
    send or receive a date message;
```

After 60 weeks, we assume that passionate love plays no role in making a decision of sending or receiving a date message. Companionate love takes over, hence the attractiveness of the selected new potential date is weighed against the duration of current relationships (Knittel et al., 2011). The longer a partnered couple is in a relationship, the more difficult it is to break up the relationship. The pseudo-code is as follows:

```
IF (average relationship duration > 60 AND
    there are no new date partners)
    potential date quality = potentialDate.attractiveness*A
IF (totalPartnerQuality<potential date quality)
    send or receive a date message;
```

where $A = 1 - \min\left(\frac{\text{avgWeeksDating}}{\text{courtshipDuration}}, 1\right)$.

The last condition to be checked is the maximum number of dating partners for the agent. If the maximum number of dating partners is reached, then the agent evaluates the potential date against the current date partners. If the potential partner has a higher attractiveness and if the maximum number of date partners is not yet reached, or there is a current date partner that can be dropped, then the agent makes a decision to send a date request. A date relationship is discontinued one a dating is dropped.

The receiving agent basically follows the same steps as the asking agent. The only difference is that the receiving agent calculates the likeability index for all agents sending a dating message. If the likeability index is less than the receiving agent's likeability threshold, the dating message is rejected immediately. A date message is accepted immediately if the receiving agent is not currently in any romantic relationship and the asking agent has a likeability index greater than the receiving agent likeability threshold. If the receiving agent is currently involved in a relationship, then a decision to receive the message depends on the sexual desire value and dating partner quality, as explained above for the asking agent.

Once the receiving agent accepts the dating message, a dating couple is formed. A dating relationship develops into a sexual relationship if both agents, non-sexual dating period is exceeded and both agents are sexually active. We assume that sexual activity depends on the sexual maturity distribution table adapted from the

2003 South African Demographic and Health survey (SADHS, 2003, p. 98). From the sexual maturity distribution table, there is no chance for sexual activities earlier than 15 years of age.

Two ways of ending romantic relationships before marriage as proposed by Knittel et al. (2011, p. 8) are used in this model. The first one is probabilistic, with a higher probability between 24 and 60 weeks when passionate love starts to decrease. Second, a break-up can happen if an agent meets a new agent with a weighted attractiveness level higher than the current date(s). To weigh the attractiveness of the new date we multiply the attractiveness of the new date by $1 - \min\left(\frac{\text{avgWeeksDating}}{\text{courtshipDuration}}, 1\right)$ (Knittel et al. (2011, p. 8)). The longer the average dating time, the lower the weighted attractiveness level, the lower the chance of a break-up. Figure 5.3 on page 101 presents the couple update process described in this thesis.

If length of relationship between a courting couple exceeds both courtship durations assigned to each of the agents in a couple, the couple may decide to marry. We use a truncated normal distribution with a mean of 78 weeks and standard deviation of 10 weeks with a minimum of 26 weeks and a maximum of 156 weeks to model courtship duration (Alam, 2008). Since not all couples that exceed courtship duration end up in marriage (Buss, 2006, p. 242), a marriage probability parameter, which depends on age and current marital status, is used in the model. There are a number of factors that may cause courting couples not to marry; for example, the availability of the bride price (lobola), the marital status of the partners, *et cetera*.

In some cultures in Southern Africa, lobola has to be paid for a couple to be declared as married. Most young adults may not have the required amount to pay the bride price since they will be just leaving school and may not be employed. Wealth does increase with age; hence, the marriage probability of young adults is lower than that for middle and older aged adults. To model this, we assign different marriage probability dependent on age of both agents. We use the mean age at first marriage as our cutoff point. Single agents below the mean age at first marriage (male and female) have a marriage probability lower than that of single agents above the mean age at first marriage. If a random number is greater than the marriage probability

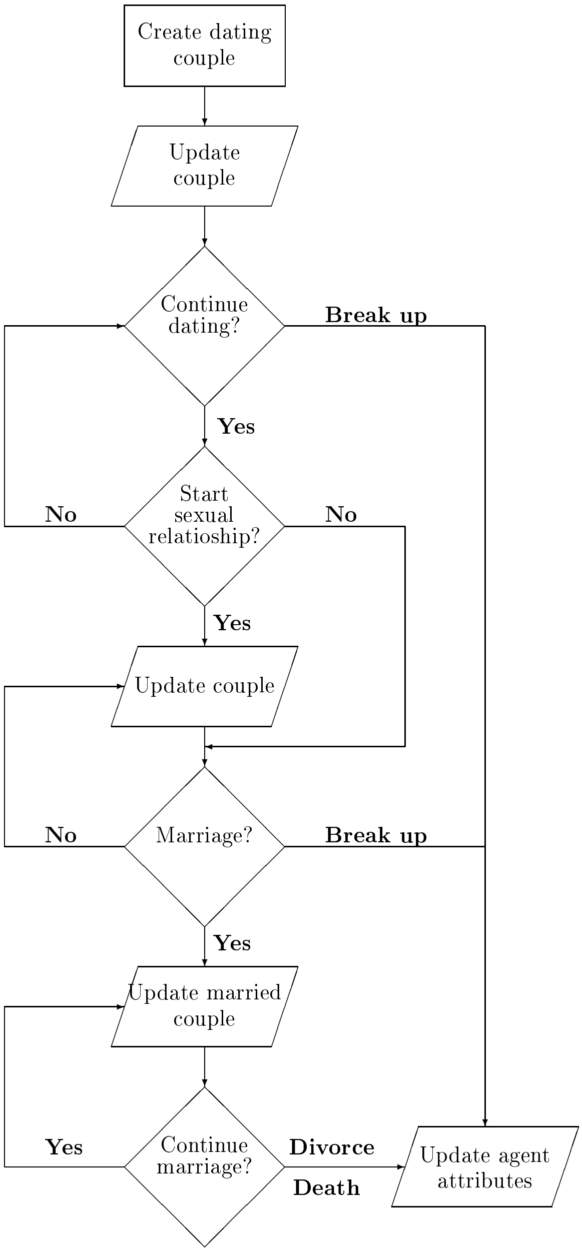


Figure 5.3: **Couple update**

and none of the dating couples is married, then the dating couple becomes a married couple. Divorced and widowed agents have a lower marriage probability compared to never married agents, with female agents having the lowest marriage probability.

Married agents continue to encounter both married and single agents. If a better potential partner is encountered by a married agent, a decision to divorce the current married partner in favour of the new potential partner has to be made. We found it necessary to incorporate divorce and remarriage in the model since divorce and remarriage happens in real-life settings (Budlender et al., 2004, p. 19).

To facilitate divorce in our model, we use the attractiveness of the potential partner to be married. The attractiveness of the potential partner is weighed by the duration of the current marriage as a proportion of the average duration of marriage relationship and the attractiveness of the current partner. According to StatsSA (2010a, p. 40), the duration of marriage of divorcing couples is between five and nine years. In our model, we use nine years, which is approximately equivalent to 468 weeks for the maximum duration of divorcing couples. After nine years, we have assigned a 10% probability of divorce based on the statistics collected by StatsSA (2010a, p. 40), which indicates a significant decrease in the number of divorces after nine years in marriage. The divorce decision is based on the following rule:

```
shouldDivorce = minimum(Marriage duration in weeks/468,1)
     IF (shouldDivorce is equal to 1)
         THEN shouldDivorce = uniform (0.9,1)
     IF (potentialPartner.attractiveness*
        (1-shouldDivorce) > partner.attractiveness)
         drop current married partner;
```

Divorced agents re-enter the mate search pool again. In this model, married agents, both male and female can have extramarital affairs which may lead to divorce as described above or may remain as a long-term sexual relationship. If the person is already married and another person decides to have a sexual relationship with that person, Buss (2006, p. 253) describes that as mate poaching. According to Sternberg (1986), married individuals may meet another person with whom they may fall in love and be intimate with the person but do not have full commitment to the relationship. This allows the relationship to survive, but it may never lead to marriage since there is lack of full commitment to the relationship. In the next section, we present sexual relationships that are not governed by behaviour rules discussed in this section.

5.5 Commercial and opportunistic sex work

Over and above the social and sexual network, we introduce a network for commercial and opportunistic sex work. In any society, there are sexual relationships that are not bounded by what we have presented in the previous section. Such sexual relationships are mainly for money or its equivalent and are normally classified under sex work. The boundaries for sex work are quite vague. Sex work can range from erotic displays without physical contact with clients to unprotected sexual intercourse with numerous clients (Harcourt and Donovan, 2005).

We are not aware of any research done to establish how the "normal" dynamics of sexual mixing presented in the previous section can be altered by the presence of sex work in a society. What is well documented is the fact that sex work does exist (Harcourt and Donovan, 2005) and is known to contribute quite significantly to the pattern of HIV incidence and prevalence in a society (Suiming, William and Huang, 2011). Therefore, we include sex work in our model and analyse the effects that sex work has on the progression of HIV in a society. We assume that it does not have any impact on the social and sexual network presented in the previous section. In this thesis, we only consider sex work which involves sexual intercourse with numerous clients. We classify it into commercial and opportunistic sex work.

We define commercial sex work as a service offered solely in exchange for money and ends there (see UNAIDS (2001, p. 13) for a full definition). Commercial sex workers (CSWs) earn all or most of their income by selling sex. Commercial sex work is sometimes referred to as "direct" sex work (Harcourt and Donovan, 2005). We only consider female CSWs in our model since it is the most prominent type of sex work in South Africa (South African National AIDS Council (SANAC), 2013, p. 3). However, male and transgender CSWs also exist in some societies (South African National AIDS Council (SANAC), 2013; Harcourt and Donovan, 2005).

In contrast, opportunistic sex work is a service offered occasionally for money and in most instances for gifts or favours. Opportunistic sex is also known as "indirect"

(Harcourt and Donovan, 2005) or transactional sex work (Johnson, 2014). People who engage in opportunistic sex activities do not perceive themselves as sex workers. In sub-Saharan Africa and Southern Africa, opportunistic sex workers (OPSWs) are sometimes engaged as an "outside wife" (Harcourt and Donovan, 2005, p. 204). In South Africa, women involved in a sexual relationship hidden from the primary relationship are referred to as "roll-ons" (isiZulu: *makwapeni; seSotho: nyatsi*) (Jewkes, Nduna, Jama, Dunkle and Levin, 2002).

It is not easy to estimate the number of CSWs and OPSWs in a society, let alone the number of their clients. But it is known for a fact that services of that nature are available in most societies, since there are a number of studies that have been carried out to try and get statistics from individuals involved in sexual work (see studies by Konstant, Rangasami, Stacey, Stewart and Nogoduka (2015) and Harcourt and Donovan (2005)). In South Africa, only one study by Konstant et al. (2015) tried to estimate the national population size of sex workers in the country. The study found that the sex worker population is between 0,76 and 1% of the adult female population in the country.

Konstant et al. (2015) define sex work as "the regular professional exchange of sex for cash". The target group in their study was defined as females who identified themselves as sex workers. Sex workers who are home-based, who did not self-identify themselves as sex workers (hidden) were not included in this study. In this thesis, we classify all the sex workers who do not self-identify themselves as sex workers under OPSWs. This represents the sex worker population not included in the study carried out by Konstant et al. (2015, p. S13).

It is believed that there is even a larger percentage of females who are involved in opportunistic sex work as compared to those involved in commercial sex work (Konstant et al., 2015; Jewkes et al., 2002). The biggest challenge in trying to estimate the number of females and males involved in such sexual relationships is that this part of the population is not easy to identify. Up to now, there are no studies that we are aware of that have been carried out specifically to have statistics on opportunistic sex work.

OPSWs are also reported to be involved in once-off transactional sex acts (Dunkle et al., 2004b) and may have more than one partner regarding them as a 'roll-on' (Hunter, 2002). This shows that there are significant overlaps in the different sexual behaviours for males and females which makes it difficult to come up with a proper definition for sex work.

Konstant et al. (2015, p. S13) stated that the group of males or females who do not identify themselves as sex workers (OPSWs in this thesis) is assumed to represent an additional 5% of the overall population of adult females, to the overall sex worker estimate. This shows that females who engage in opportunistic sex work are much more as compared to those who self-identify themselves as sex workers. Research done by Jewkes et al. (2002) in South Africa, also found that offering sex for material gain is a common practice and women who engage in such sexual acts rarely identify themselves as sex workers.

Clients for CSWs and OPSWs are married or single males who also have one or more other sexual relationships: stable or a short-term sexual partner (Suiming et al., 2011). A study by Carael et al. (2006) found that the largest proportion of CSWs clients are married or have regular girlfriends. Estimating the number of CSWs and OPSWs clients is a daunting task since they are not easily accessible. They do not have sex work venues where one can find them. Also most men who visit sex workers do not self-identify themselves as sex worker clients. For instance, in South Africa, a national survey carried out by HRSC in 2008 found that only 0,4% of men aged 15 and older had sex with a CSW in the previous year (Fraser-Hurt et al., 2011).

Ijsselmuiden et al. (1990) and Williams et al. (2000) tried to measure the rate at which male miners visit CSWs. These two studies found a low reported frequency of commercial sex visits. Statistics obtained in these studies cited here are most likely to be under estimates since men tend to under-report contact with CSWs in face-to-face interviews (see Morison et al. (2001)). However, an analysis of 78 national household surveys and nine city based surveys done by Carael et al. (2006) deduced that around 9 to 10% of men in the surveys had exchanged sex for money in the past 12 months. Central Africa and Southern Africa ranged from 10 to 15%. However it is not clear how the cited surveys overcomed the underreporting challenges faced in South African surveys. A study carried out by Suiming et al. (2011) in China found that 25% of the 18 to 49 year old men in their study visited sex workers once a year, 26% had two to three visits, 27% had four to six visits and 21% had 7 to 60 visits per year.

The number of men who visit CSWs can also be estimated using the average number of clients per week reported by CSWs. The only challenge is that some men visit the same CSW more than once a week (Carael et al., 2006, p. iii26). Men who visit the same CSW more than once a week are called regulars by the CSWs (Wojcicki and Malala, 2001). Some CSWs reported more than seven regulars per month (Baral et al., 2014).

A cross-sectional study for female CSWs carried out in South Africa by Richter et al. (2012), showed that the number of clients per week for a CSW has an interquartile range which lies between 5 and 23 clients with an average between 11 and 13 clients per week. What is not clear about the statistics obtained is whether the calculated values include repeat visitors or they are unique visits per week.

The length of time that CSWs and OPSWs spend in the career and reasons for entering and remaining in the career varies from one person to the next (Abel, Fitzgerald and Brunton, 2007, pp. 74-108). Studies carried out in South Africa have indicated that CSWs remain in their career for an average 5,5 years (Fazito et al., 2012, p. i26). A study carried out by Richter et al. (2013) found that 43,9% of the female CSWs have been in the profession for more than 5 years, 39,7% between one and five years and 16,4% had less than one year.

Given what is available in literature as discussed in this section, we assume that one percent of the adult females in our model are CSWs. We define a CSW as a single female agent older than 15 years with or without children. We assign duration in sex work using a Weibull distribution with shape and scale parameters equal to three and 10 respectively. All CSWs cease to be sex workers at 45 years. It is difficult to obtain the age at which the sexual drive for men and women starts to decrease but Bradford and Meston (2007) and DeLamater and Sill (2005) found that sex drive decreases with age. Perceived attractiveness of sex workers also decreases with age. To accommodate this in our model, we put an age upper bound for an agent involved in sex work (CSWs, OPSWs and their clients).

Marriage is possible once a CSW has stopped her career either because of aging (age > 45 years) or end of career duration assigned using the Weibull distribution. The number of CSWs is maintained at one percent of the adult females throughout the simulation run. At each time step, the number is checked. If it is less than one percent, CSWs are selected from available females who meet sex worker characteristics described here.

We maintain that three percent of the adult females in our model are involved in opportunistic sex activities. Due to lack of data about the duration of their career, we maintain the same Weibull distribution as for CSWs but we increase the cut-off age of being in the career to 55 years. We also assume that OPSWs maintain the same clients for six months. The number of coital acts per six month period is sampled from a normal distribution with mean four and standard deviation one. The normal distribution has minimum and maximum cut-off points of two and eight respectively. The normal distribution used here does not depend on data. It is an assumption that requires further research. OPSWs can marry and at the same time be involved in sex work. Both CSWs and OPSWs can fall pregnant.

The proportion of men who visit CSWs and OPSWs is not easy to estimate. Therefore, in our model, we assume that 0,9 of the adult male population below 60 years of age have the potential to visit a CSW or OPSW. The remaining 10% will not visit CSW or OPSW in their lifetime due to reasons like physical disability, religious zeal *et cetera*. Males who visit CSWs or OPSWs can date, court and marry other females using the rules stated in our dating and courting network algorithm (Section 5.4.2). Married male agents who are concurrent but not flagged as sexual worker visitors do not visit sexual workers but they can have concurrent relationships bounded by the rules described by our social and sexual network behaviour rules. At each time step, 10% of the males flagged as CSW visitors are selected to have one coital act with a

CSW. However, we do not consider repeat visits in our simulation model. We assume that each visit to a CSW is independent of the existing of an earlier visit.

Clients for CSWs will visit CSWs for as long as the duration of the period assigned using a Weibull distribution with 3 and 25 as the shape and scale parameters respectively. Please note that parameters used here are not from literature, since it was difficult for us to obtain data for CSWs clients. However, it is documented that clients of CSWs may stop visiting CSWs for a short or long period and may return after the break (Fazito et al., 2012).

Once a sexual relationship is formed, there is a possibility of the female agent falling pregnant; hence adding a new agent to the population. The following section presents how childbirth is implemented in our model. It is necessary to explicitly track birth from the relationships formed in the model as this will help us to evaluate our sexual network model by comparing observed fertility levels with our model fertility level results.

5.6 Child birth

A change in the total population is through childbirth which is dependent on the social and sexual partnering of agents. Birth is possible for a female agent within the child-bearing age group involved in a sexual relationship(s) or married. We consider the child-bearing age group to range from 15 years to 49 years, which is the age range used to calculate the general fertility rate (NAPHSIS, 2012). There is a very small proportion of births that may occur outside the 15 to 49 years age range (NAPHSIS, 2012) which we do not take into account in our model, and we assume that the exclusion does not affect the model results significantly.

Female fertility declines with age, typically after age 30, and the actual age at which a female becomes infertile varies (Balasch, 2010). Therefore, we assign a fertility upper age limit at agent creation for each female. The fertility upper limit is sampled from a normal distribution with mean 39 years and standard deviation of five years (Alam, 2008) with maximum and minimum cut-offs of 35 and 49 years respectively. For simplicity, we assume that during the fertile period, a female agent's fertility is uniform. To facilitate pregnancy, the female agent must have at least one sexual male partner.

A female agent may fall pregnant anytime after initiating a sexual relationship. The duration between the beginning of a sexual relationship and first pregnancy (first birth interval) differs from one women to the next. There are a number of factors that contribute to the time variation, which among them include the type of sexual relationship, availability and knowledge of family planning methods, personal life planning, age at the time of initiating a sexual relationship, societal norms and at times biological elements (Amin and Bajracharya, 2011).

A study by Lofstedt et al. (2005) for Chinese women aged between 15 and 64 established that the first birth interval can vary from 11 months to over 30 months depending on the cohort being studied. Cohorts that marry early seem to have longer first birth intervals than those that marry late (Amin and Bajracharya, 2011; Lofstedt et al., 2005). Amin and Bajracharya (2011) studied the variation in first birth intervals for over 60 developing countries. They found that the first birth interval varied mostly between 12 and 63 months, with extreme cases where pregnancy was immediately after marriage.

We would like to note that differences in condom use and other birth control measures in different countries may lead to differences in the first birth intervals. We therefore model the time variation before the first pregnancy for married or unmarried female agents in a sexual relationship by assuming that there is a one percent chance to fall pregnant at each time step. Not all females in sexual relationships fall pregnant; hence we assume that 20% of females in a sexual relationship will fall pregnant during the course of the sexual relationship.

The time between births (birth interval) also differ from one female to the next. In South Africa, the median birth interval is between 27 and 33 months (Moultrie, Sayi and Timaeus, 2012). Some women have short or long birth intervals of 12 months or more than six years respectively. Women who have shorter birth intervals usually have their planned number of children within a restricted part of their reproductive lifespan (Timaeus and Moultrie, 2008, p. 7).

Availability of contraceptives has been found to be one of the major factors that impact on the length of birth intervals. Women in countries with reliable contraceptives may lengthen birth intervals or use contraceptives before or after a short period of their reproductive lifespan (Moultrie et al., 2012; Timaeus and Moultrie, 2008). According to the CATALYST Consortium (2002), the optimal birth spacing recommended is between 36 and 60 months. Most women will not fall pregnant within the first six weeks after child birth.

In our model, we model birth interval time using a waiting period modelled by a normal distribution and a one percent chance of falling pregnant after the waiting period. The normal distribution waiting period is truncated at six weeks (minimum) and 52 weeks (maximum) with a mean of 26 weeks and a standard deviation of four weeks. After the waiting period, there is a one percent chance of failing pregnant at each time step (weekly).

The birth date of the new baby depends on the day the female became pregnant and the duration of the pregnancy. If there are no health complications, pregnancy duration usually varies between 38 and 40 weeks (Kieler, Axelsson, Nilsson and Waldenstrom, 1995). For simplicity, we assume a pregnancy duration with a mean of 40, standard deviation of one, truncated at 34 and 42. A new agent is introduced into the model once the pregnancy duration lapses. The new agent is assigned static and dynamic characteristics that define an agent upon birth. Figure 5.4 outlines the states a woman can be in as the model runs.

A female agent can decide to stop having more children after each birth. Data collected by StatsSA (2003, p. 49) shows that approximately 40% of women in the 45 to 49 year age group had two or three children. About 0,9% of females in the same age group had 10 plus children. We try to model the decision to stop having children by using a probability of 0,025 after each birth. No female will fall pregnant once they are above the fertility age limit that is assigned at female agent creation.

5.7 Modelling infection transmission

The main objective of our model is to model the spread of HIV in a closed mixed society. This section describes the process of HIV transmission considered in this thesis. The main route of HIV transmission in our model is through heterosexual contact. Previous research has proved that the transmission of HIV is high if a population contains a highly active sexual group (Kretzschmar and Morris, 1996). In our model we consider high risk group to be anyone who can have multiple sex partners simultaneously including female CSWs, OPSWs and their clients. The rate at which HIV spreads in a population depends on a complex interplay between sexual behaviour and biological factors. The other transmission method which heavily depends on heterosexual contact is vertical transmission. We model vertical transmission by explicitly tracking the HIV status of the mother giving birth. We give a detailed description of how we model child birth and vertical transmission in Section 5.7.3 on page 132.

HIV transmission in our model depends on the dynamics of the sexual network discussed in Section 5.4.2. The sexual network presented in Section 5.4.2 is dynamic in the sense that new links are created and existing links are broken throughout a simulation. Creation of new links is important in HIV transmission modelling, as it facilitates the spreading of the virus to a new portion of the sexual network. For prevalence to remain high in a population, HIV must find new victims faster than the rate at which existing victims age and die. In this model, we use a set of assumptions in order to identify the possible drivers of the HIV pandemic. The drivers can be either behavioural, biological or a combination of both.

To date, there is no known cure for HIV. This means that if a person is infected by the virus, there is no full recovery. Hence, when modelling HIV, agents only have two possible states: susceptible and infected. The infected state is further divided

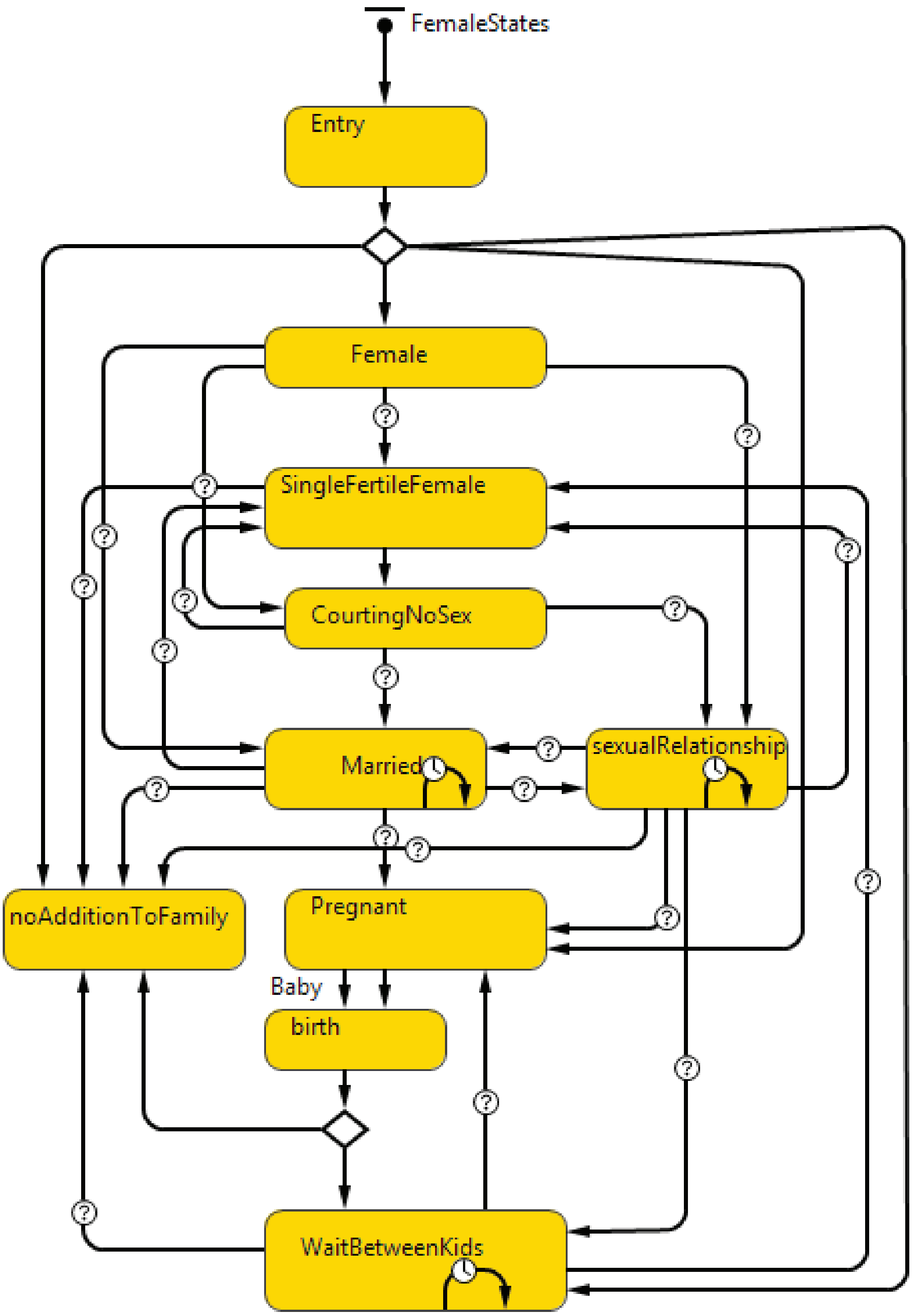


Figure 5.4: Female states during her lifetime

into substates. In our model, we use clinical staging of HIV infection defined by the World Health Organisation (WHO, 2005).

Susceptible individuals have a chance of becoming infected if they have one or more HIV infected sexual partners. Concurrency in this model is determined by agent attributes, agent preferences, availability of potential partners, and parameters governing the dynamics of the social network (see Section 5.4.1). In the following subsections, we discuss the infection dynamics and the factors that drive the infection process in our model.

5.7.1 Stages of HIV infection

All agents that are HIV negative are classified as susceptible. A susceptible agent may exit the model in the same state (HIV negative state). The CD4 cell count for a susceptible agent is drawn from a truncated normal distribution with minimum and maximum cut-off values of 845 and 1 341 cells/μL, mean of 1 179 cells/μL and standard deviation of 36 cells/μL (Williams et al., 2006, p. 1452).

The infected status is composed of a number of sub-states. An infected person can be on ART, which in most cases depends on the stage of infection as well as a personal decision about taking the therapy. In the following subsections, we present the stages of HIV infection without and with treatment and how this contributes to the rate of transmission of HIV. Parameters used in the model are derived from literature.

HIV stages of infection without ART

Stages of HIV infection can be defined using either the clinical or immunological approach. The clinical staging approach is mostly used if laboratory services to obtain CD4 cell counts are limited or are not available (WHO, 2005, p. 5). In the case where laboratory services are available, the immunological staging of HIV which relies on CD4 cell count levels must be used to support the clinical staging decision (WHO, 2005).

Four consecutive stages of HIV infection defined by WHO (2005, p. 5) are the primary infection stage, the clinical asymptomatic stage, the symptomatic stage and the AIDS stage. The primary infection stage, also known as the acute stage, is the period immediately after infection and lasts for approximately 10 weeks (Waver et al., 2005). During this time, the viral load of the newly-infected person is very high. No HIV infection symptoms will be evident except for acute mononucleosis-like illness (Lavreys et al., 2002). According to Williams et al. (2006), the CD4 cell count drops approximately by 25% during this stage.

The average lifetime from HIV infection until death varies significantly with age (Todd et al., 2007; Babiker et al., 2001). Children less than 15 years and adults above 60 years have a shorter survival time after seroconversion as compared to adults between 15 and 45 years old (Morgan et al., 2002). On average, survival time after seroconversion is approximately 10 years for adults greater than 15 years (Morgan et al., 2002). Using this as a reference point and removing the acute and AIDS stage duration, it follows that the clinical asymptomatic stage and symptomatic stage lasts for approximately eight years on average. Researchers like Williams et al. (2006), Holmes et al. (2006) and Kaleebu et al. (2001) have shown that during these two periods, the CD4 count decreases by approximately 75 cells/μL per year.

No major symptoms are evident during the clinical asymptomatic stage and the viral load is quite low. Symptoms start to develop during the symptomatic stage and worsen as time progresses (Holmes et al., 2006, p. 466). During the symptomatic stage, the viral load increases as the CD4 cell count decreases. This then leads to the final stage, the AIDS stage, which lasts for approximately two years (Waver et al., 2005). During this stage, the immune system is severely compromised. Usually, the CD4 count will be less than 200 cells/μL. Eventually, the person dies of AIDS-related illnesses (Waver et al., 2005).

The model developed in this thesis makes use of the immunological approach since in South Africa HIV testing is being promoted through the HCT campaign (see page 47). Facilities to do CD4 cell counts are available in most parts of the country (Colvin, 2011). In our model, we use the stages defined by WHO (2005) and use CD4 cell count decline combined with the approximate time period spend in each stage to move agents from one state to the next. The duration from infection to death without ART in our model depends on the age of the agent at infection.

The time that an agent remains in the primary infection stage is drawn from a truncated normal distribution (mean of 10 weeks and standard deviation of two weeks) with maximum and minimum cut-off values of four weeks and 12 weeks, respectively. CD4 cell count drops by 25% during the primary infection stage. From the primary infection stage, the agent moves to the clinical asymptomatic stage. The rate at which CD4 cell count declines after the primary infection stage is modelled using a formula developed by Bershteyn et al. (2012, p. 7). The formula is as follows:

$$\text{CD4 decrease } = (24{,}363 - 16{,}672f)^2 \text{ cells}/\mu\text{L}.$$

Where f is a fraction of the total survival time since infection obtained by dividing the time since infection by the total survival time sampled once from a Weibull distribution. Since survival time of HIV positive people is age dependent, the Weibull distribution parameters used by Bershteyn et al. (2012) have shape and scale parameters that are age dependent. The parameters used by Bershteyn et al. (2012) are classified into three categories: adult survival time parameters (15 years or older), child survival time parameters (five to fifteen year olds) and infant survival time parameters (less than five years). The parameters are based on studies carried out by Todd et al. (2007), Marston et al. (2005) and Babiker et al. (2001). The parameters for the Weibull distribution were calculated using empirical data, hence the resulting prognosis for infants (less than 5 years) and children (between 5 and 15 years) is shorter compared to that of people 15 years and older. Table 5.3 summarises the parameters used in our model, where a represents the age of the agent:

Table 5.3: **Weibull distribution parameters (see Bershteyn et al. 2012)**

Age (years)	λ (scale parameter)	κ (shape parameter)
$a \geq 15$	2	$21{,}182 - 0{,}2717a$
$5 < a < 15$	$10{,}0 + 0{,}474a$	$5{,}39 - 0{,}226a$
$a \leq 5$	$1{,}515 + 1{,}039a$	$0{,}97 + 0{,}0687a$

An agent moves to the symptomatic stage once the CD4 cell count is between 200 and 350 cells/μL (WHO, 2005). Once the CD4 count goes below 200 cells/μL, the agent moves to the AIDS stage (WHO, 2005). An agent dies as soon as the CD4 cell count is below 59 cells/μL (Bershteyn et al., 2012). The stages of HIV infection are presented diagrammatically in Figure 5.5.

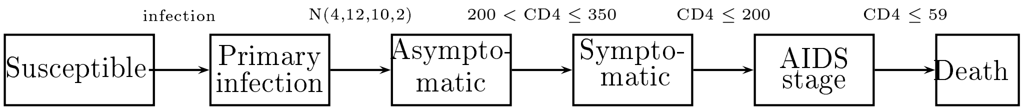


Figure 5.5: **State transition diagram without antiretroviral therapy**

An HIV positive person may take ARVs, which help in reducing the rate at which HIV multiplies within the human body. This reduces morbidity and mortality of infected individuals (Palella et al., 1998). In the next subsection, we present how we model an HIV positive agent on ART. We assume that same medication is used for all agents under treatment.

HIV stages of infection with ART

The official use of ART in South Africa began in April 2004 (Simelela and Venter, 2014). Since then, the number of people who enrol for ART has been on the increase. This has been done through developing National Strategic Plans (NSPs) that guide South Africa's response to HIV/AIDS and STIs control and HIV campaigns. One example is the HCT campaign launched in April 2010 (Government Communications-(GCIS), 2010). The first strategic plan was developed for the 2000 to 2005 period. This was followed by the 2007 to 2011 NSP, with the most recent one being the 2012 to 2016 NSP.

The primary aims of the last two NSPs were to reduce the rate of new HIV infections by 50% and to expand access to appropriate treatment, care and support to 80% of all people living with HIV. In a review of the 2007 to 2011 plan, an increase in the number of people testing for HIV and of those initiating ART was observed (Colvin, 2011).

The launching of the HCT campaign in April 2010 also resulted into an increase in the number of people testing for HIV and of those initiating ART (Colvin, 2011).

Guidelines for initiating ART differ from country to country. Usually, ART initiation is determined by the CD4 cell count or clinical symptoms of the HIV positive person (WHO, 2005). From 2004, ART initiation was guided by one of the three WHO conditions, namely; WHO clinical Stage IV regardless of the CD4 cell count; CD4 cell count below 350 cells/μL accompanied by symptoms classified under clinical stage III; or CD4 cell count below 200 cells/μL and in WHO clinical Stage I or II (see WHO (2005)).

South Africa used the guidelines issued by WHO (2005) from April 2004 to 31 March 2010. From 1 April 2010, the South African government changed the guidelines (Council, 2010). The new guidelines for initiating ART as published by Council (2010, p. 6) are as follows:

1. HIV positive pregnant women with CD4 cell count below 350 cells/μL;
2. HIV positive individuals coinfected with TB with CD4 cell count below 350 cells/μL;
3. HIV positive individuals with AIDS symptoms irregardless of their CD4 count; and
4. HIV positive individuals with CD4 cell count below 200 cells/μL and who do not fall into the first three categories described.

In July 2015 Minister of Health announced that antiretoviral medication will for the first time be available to HIV positive people with a CD4 count of 500 cells/μL as from January 2016. This announcement was made to align the South African government policy with the WHO recommendations (WHO, May 2015). Figure 5.6 contains an extract from the Times newspaper of 24 July 2015 showing a clip of part of the story about the earlier start of antiretoviral medication therapy.

.

Government to start treatment earlier

HLENGIWE NHLABATHI and KATHARINE CHILD

HIV-POSITIVE people with a CD4 count of 500, likely to be still relatively healthy, will for the first time qualify for government-supplied antiretroviral medication from next year.

Minister of Health Aaron Motsoaledi announced yesterday that an additional 2 million people with HIV would be put on treatment in the next three years.

About 2.5 million South Africans are already being treated with antiretrovirals.

The inclusion of those with a higher CD4 count — the count is a measure of the extent to which their immunity has been compromised — is in line with World Health Organisation recommendations.

The director of the Centre for Aids Programme Research in South Africa, Professor Salim Karim, welcomed Motsoaledi's announcement, saying: "The whole world is moving in this direction."

The move was a good idea because "the risk of HIV transmission to partners is substantially lower if the patient is on ARVs, regardless of CD4 count", he said.

Currently, only HIV-positive people with a CD4 count of below 350 qualify for government ARVs.

Motsoaledi announced that pregnant women who were HIV-positive would be put on treatment for life.

But doctors and activists warned that the new measures would work only if the government sorted out drug shortages around the country.

Professor Francois Venter, deputy director of the Wits Reproductive Health and HIV Institute, said: "Though the minister's intentions are excellent, the fact is that we continue to have province-wide stock-outs of ARVs, TB drugs, vaccines and other medicines.

"I would have preferred a commitment to ensuring that not a single clinic in South Africa runs out of

I'd have preferred a commitment to no clinic running out of drugs

● Continued on Page 2

Figure 5.6: **ART to start earlier**

Research done by HSRC (2014) shows that there has been a constant increase in ART uptake in South Africa since its official launching in April 2004 (Simelela and Venter, 2014). In 2008, approximately 16,6% of people with HIV were on ART. This percentage increased to 31,2% (confidence interval: 28,1 to 34,5) in 2012. The increase in ART uptake maybe attributed to the NSPs designed by government of South Africa and the HIV/AIDS campaigns. Though a successive increase in ART has been observed, there are still people living with HIV who need ART and have not received it.

In our model, we use probabilities to select HIV infected agents to enrol for ART at each time step. We include the effect of HIV campaigns, increased commitment by government of South Africa and changes in treatment guidelines on HIV progression in our model. We do this by allowing only agents in the AIDS and symptomatic stage of infection to enrol for ART from the beginning (January 2002) of the simulation to April 2010. CD4 cell count of agents in these two stages of infection is less or equal to 350 cells/μL. This aligns with the treatment guidelines used in South Africa as from 2004 to April 2010 (see WHO (2005)).

We increase the enrolment probabilities in 2004, 2007, 2010 and 2012 simulation years (see Table 5.4). This is done to take into account the main events initiated by the government of South Africa to fight the HIV/AIDS pandemic through the NSPs and HIV/AIDS campaign. We assume that the probability remains at the 2012 enrolment probability from 2012 simulation year to the end of the simulation in our HIV general simulation model. We also assume that the probability for ART enrolment is higher for agents in the HIV stage of infection. The probabilities stated here were chosen so as to achieve an approximately 16,6% and 31,2% ART uptake by 2008 and 2012 simulation years respectively.

Table 5.4: **Probabilities for initiating ART (per week)**

Simulation year	**AIDS**	**Symptomatic**
2002 $-$ $<$ 2004	0,0010	0,0005
2004 $-$ $<$ 2007	0,0020	0,0015
2007 $-$ $<$ 2010	0,0025	0,0020
2010 $-$ $<$ 2012	0,0030	0,0025
$\geq$ 2012	0,0035	0,0030

From 428 simulation weeks (April 2010), we update ART initiation conditions based on the announcement made by the President of South Africa in 2009 published by Council (2010, p. 6). Using these guidelines, we assign a probability of 0,01 per time step for pregnant females to initiate ART and a probability of 0,0001 per time step for agents with CD4 cell count above 350 cells/μL. In our model, these agents are in the clinical asymptomatic stage. A probability of 0,6 is also assigned to all pregnant females not on ART to receive HIV treatment at child birth so as to reduce vertical transmission. No ART treatment is considered for agents in the primary HIV infection stage in our model.

Once ART is initiated and the patient does not experience medication related toxicity, the CD4 cell count starts to increase. The rate at which CD4 cells increase depends on a number of factors. One primary factor is the CD4 cell count at ART initiation (Lawn, Myer, Bekker and Wood, 2006). To reduce the complexity of our model, we assume that the rate of CD4 cell count increase is the same across all HIV positive agents on ART.

According to Lawn et al. (2006) and Frater et al. (2002), CD4 cell count of agents on ART increases by 7,2 cells/μL per week for the first 12 weeks after ART initiation. Thereafter it increases by 1,3 cells/μL per week and reaches a plateau in approximately three years' time (Moore and Keruly, 2007). In this model, we use the quadratic formula developed by Bershteyn et al. (2012) to model the increase in CD4 cell count after ART initiation. The formula closely represents the increases observed by Lawn et al. (2006) and Frater et al. (2002). The quadratic formula is as follows:

$$\text{CD4 increase} = 15{,}584t - 0{,}2113t^2 \text{ cells}/\mu\text{L}$$

where t represents time in months since ART initiation. The increase in CD4 cell count reaches a plateau in three years time. The other restriction imposed on CD4 cell increase is the pre-infection CD4 count. The maximum value for CD4 count after ART initiation is either the CD4 count at the end of the three year period on ART or the pre-infection CD4 count, whichever comes first (Bershteyn et al., 2012).

We estimate remaining life expectancy for agents on ART using a prognostic formula developed by May et al. (2010) and also used by Bershteyn et al. (2012). The prognostic formula is as follows:

$$s = \left(\frac{123{,}83}{m^{2{,}9}}\right) \log\left(\frac{1}{r}\right)^{2{,}9} \quad \text{weeks}$$

where r is a uniformly distributed random number between 0 and 1 and m is a multiplier assigned to an individual based on one of the four conditions listed by Bershteyn et al. (2012). The use of the term multiplier is adopted from Bershteyn et al. (2012) though in the given formula m is an inverse multiplier. The four conditions that can be used to determine the multiplier are: WHO stage, age, CD4 cell count at ART initiation and gender. In our model, we only use multipliers that are based on CD4 cell count at ART initiation. We use CD4 cell count since in our model CD4 cell count is the major descriptive factor for the health of an HIV positive agent. Table 5.5 lists the multipliers (Bershteyn et al., 2012) used in our model. Life expectancy

Table 5.5: **List of Multipliers (m) (see Bershteyn et al. 2012)**

CD4 at ART initiation	Multiplier
25-49	0,7497
50-99	0,4258
100-199	0,3068
200+	0,2563

on ART is calculated as soon as an agent initiates therapy. Agents die as soon as the life expectancy on ART or life expectancy assigned at creation lapses (whichever comes first). Agents that initiate ART may drop out from treatment or suffer from treatment failure.

There are a number of factors that contribute to the dropping out of ART and treatment failure for individuals on ART. A study by Miller et al. (2010) revealed that transport costs, time needed for transport and logistical challenges are the major reasons why ART patients drop out of treatment. Drop out patients indicated that long queues, difficulty in booking appointments, poor record keeping, medication stock outs and limited time spent with health workers are among some of the logistical reasons why they had to stop medication (Miller et al., 2010).

Studies that have been carried out to establish ART patient retention have shown that patient retention rate varies from cohort to cohort, with some cohorts having a very low patient retention of approximately 46% at the end of a two-year period (see systematic review by Rosen, Fox and Gill (2007)). According to the systematic review, the maximum patient retention rate observed in studies carried out before 2008 is approximately 85% at the end of a two-year period. Rosen et al. (2007) state that one of the major causes of attrition is loss to follow-up (which we call drop out in this thesis), followed by death.

In South Africa, a number of studies have been carried out to establish patient drop out rate from ART (Rosen et al., 2007). From these studies, the lowest drop out rate was 0,3% with a median follow-up period of 13,9 months. The highest drop out rate was 25,4% with a median follow-up period of 19,5 months. In 2014, Dr. Gottfried Hirnschall, Director of WHO, noted that despite the efforts being taken by the South African government to fight the HIV pandemic, it is concerning that 40% of patients on ART are lost in a three-year period (Child, 2014). Some of the agents in the 40% stated by Dr. Gottfried Hirnschall may have been lost due to death.

From the systematic review by Rosen et al. (2007) we deduce that in the worst case scenario, the probability of dropping out of ART is approximately 0,016 in four weeks' time. In the best case scenario, the probability is approximately 0,0034 for the same time period. Most of the studies from South Africa considered in the systematic review indicate that the drop out rate in the country is below half the range of drop out rate obtained using the best and worst case scenarios. Therefore, we use 0,007 as the probability of dropping out of ART in a 4 week period in our HIV general simulation model. We note that there is a need to vary this probability and study its effect on model results. We will leave this as an area that needs further research.

When an agent drops out of ART, we compute prognosis after dropping out using the age-dependent Weibull distribution we used to calculate prognosis after HIV infection. However, the prognosis parameters for an agent will change due to an increase in age. The CD4 cell count decrease rate is identical to the decrease rate before ART initiation (see page 115). We determine the infection probability after dropping out using CD4 cell count. According to an email conversation with an expert in HIV modelling, the infection probability for agents that drop out of ART returns to the latent stage level and may then transition to the AIDS stage infection probability if they progress to the AIDS stage (Klein, (personal communication, June 09, 2015)).

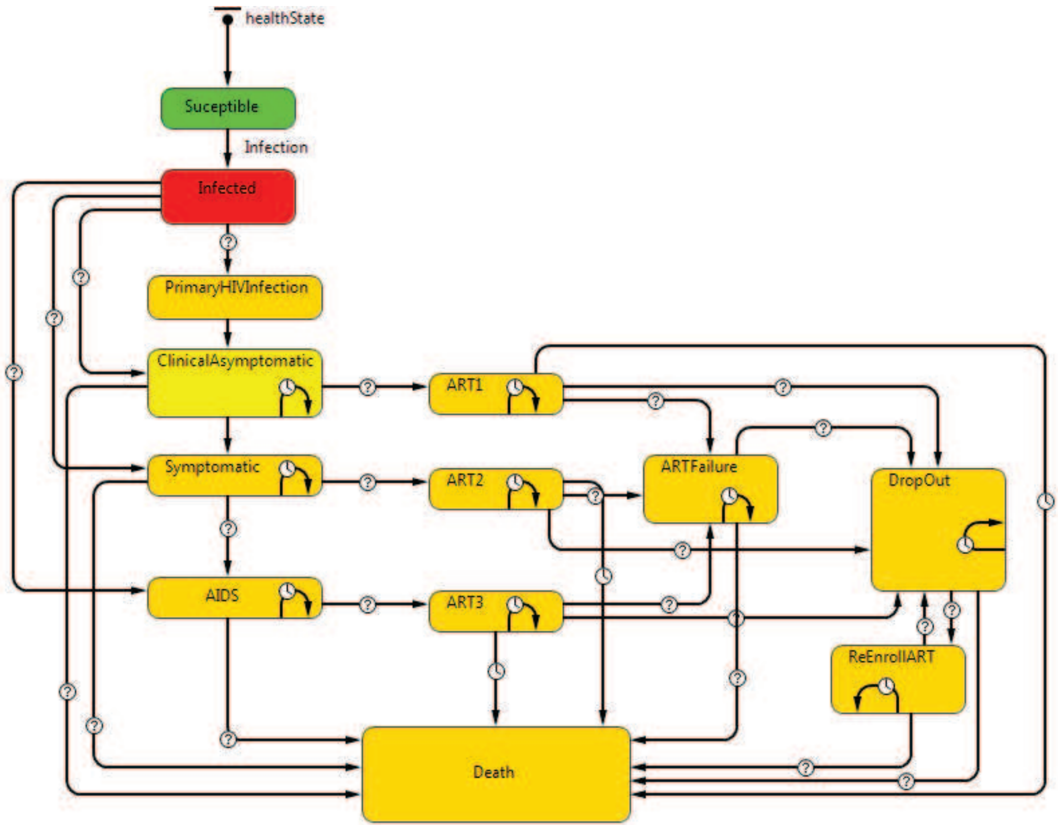


Figure 5.7: **Complete state transition diagram**

ART failure is defined using virological criteria, CD4 cell count response or clinical disease progression (Black et al., 2014, p. 127). Lack of adherence to ART treatment and a lower CD4 count at ART initiation are among some of the factors that contribute to treatment failure and may also lead to the development of drug resistant HIV strains (Black et al., 2014; Kwobah et al., 2012). A systematic review study carried out by Renaud-Thery et al. (2010) to establish first-line drug failure and attrition rates in HIV positive adults on ART found that the failure rate per 100 patient years of follow-up in Africa was 2,64 (with a 95% confidence interval between 1,73 and 3,56) using the clinical disease progression definition and 7,10 (with a 95% confidence interval between 5,11 and 9,09) using the virological criteria definition.

Based on the results from the systematic review, we use probabilities equal to 0,001, 0,002 and 0,003 at each time step to model final ART failure or drug resistance for the asymptomatic, symptomatic and AIDS stage of infection, respectively. Our aim was to achieve an average failure rate within the virological failure limit stated in the systematic review done by Renaud-Thery et al. (2010). Our model does not explicitly model drug resistance and we assume that agents who suffer from first-line drug failure will enrol for alternative therapy. This means that treatment failure in our model is once after all options are exhausted. The CD4 cell count of an agent experiencing treatment failure decreases at each time step. Once it is below 50cells/μL the agent dies.

5.7.2 Transmission of the virus

The probability of HIV transmission per coital act depends on the viral load in the blood of the infected person. The higher the viral load, the higher the probability of transmission per coital act (Attiaa et al., 2009). Though there is no cure for HIV, ARV drugs suppress the multiplication of HIV in the human body if used correctly and consistently (WHO, 2003b). Using ART correctly and consistently is known as medication adherence. Medication adherence is one of the biggest challenges for people taking ARVs (Frater et al., 2002; Vergne et al., 2002). If there is poor adherence, it usually leads to the development of a resistant strain or treatment failure (Vergne et al., 2002). The adherence rate per person must be greater than 95% to have the maximum benefit of ART (WHO, 2003b, p. 34).

There are a number of factors that may affect the consistent uptake of ARVs, including availability and cost of the drugs. In South Africa, cost of drugs may not contribute to low adherence rates since ARVs are issued for free in public hospitals and clinics. The South African government has been working hard to ensure that all infected people who need treatment receive it (AVERT, 2010b).

Availability is the major stumbling block since, to some extent, the management and the supply chain of the drugs is not very efficient (AVERT, 2010b). Drug shortages are reported in some public outlets (Kimberley, 2012; Ndlovu, 2009), while other public outlets report overstocking, which sometimes leads to expiry of the drugs

(Kimberley, 2012). There is a need for such issues to be resolved since a combination of high levels of drug access and adherence have been shown to reduce the HIV pandemic (Eaton et al., 2012). Though the government aims to have everyone eligible to initiate ART, some eligible infected individuals may not initiate ART due to cultural and practical reasons.

Guidelines to initiate ART differ from country to country and may cause differences in the course of the HIV pandemic. Auvert et al. (2004) used guidelines outlined by WHO and those outlined by the United States Department of Health and Human Services (USDHHS) to see if there are significant differences in the rate at which HIV is transmitted. The study concluded that different guidelines result in different rates of HIV transmission in a population. In our model, we change ART eligibility criteria to reflect the changes made to the guidelines by the South African government (see Section 5.7.1).

If a person is not on ART, the probability of transmission per coital act is high, with very high probabilities during the primary, symptomatic and AIDS stage (Hollingsworth, Anderson and Fraser, 2008). Lower probability of transmission is experienced during the asymptomatic period (Waver et al., 2005), but the duration of the stage may contribute significantly to the transmission of HIV (Hollingsworth et al., 2008, p. 690). The rate of HIV transmission is very low if a person is under ART and adheres to therapy (Cohen et al., 2011).

Other factors which increase the probability of transmission of HIV are: presence of STDs in either of the two individuals having sexual intercourse (Waver et al., 2005; Rottingen et al., 2001) and the frequency of sexual contacts with an infected partner (Waver et al., 2005). It is not easy to get data about the number of coital acts a person can have in a week. Researchers like Waver et al. (2005) and Bracher et al. (2003) among others, have tried to establish the number of coital acts for a person in a given time interval and have shown that number of coital acts per week varies with the type of sexual relationship and the stage of infection.

Married individuals are reported to have a higher number of coital acts in a week compared to dating couples (Bracher et al., 2003). In the study by Bracher et al. (2003, p. 214), some married couples reported having sex every day. Coital acts are also reported to decrease during the AIDS stage of HIV infection (Waver et al., 2005) and during late years of one's lifetime (Bracher et al., 2003, p. 214). In this model, we assume that the number of coital acts per couple follows a normal distribution where the mean depends on the type of relationship and the concurrency status of the agent (see Table 5.6).

A decrease in the number of coital acts during the last few months (approximately 10 months before death) of the AIDS stage has been noted by Waver et al. (2005). The infection probabilities in Table 5.6 were derived from data based on study populations. Infection probability calculated using such data is based on reduced coital acts observed during the study. It is difficult to translate the lifetime HIV stage infection probabilities of an individual at any particular point due to variation in sexual risk behaviour and population pandemic dynamics (Hollingsworth et al., 2008). Therefore, for simplicity, in our model we do not decrease the number of coital acts during the AIDS stage of infection. We assume that the effect of reduced coital acts during the AIDS stage is inbuilt in infection probabilities in Table 5.6 since the probabilities were derived from emprical data. An improvement in modelling this phenomenon is called for in future.

Transmission of HIV from a person co-infected with STDs is reported to be higher than in the absence of STDs (Corey et al., 2004; Gray et al., 2001). Also, the presence of bacterial, viral and parasitic infections increases the chances of both infecting and being infected per coital act (Boily et al., 2009; Gray et al., 2001). Infection by malaria raises viral load in an HIV infected person (Abu-Raddad, Patnaik and Kublin, 2006) which, in turn, increases the probability of HIV transmission per coital act (Waver et al., 2005). Unfortunately, we are not aware of any study that has quantified the increase in infection probability caused by malaria. In our general simulation model settings, we use the infection rates for each stage of infection without ART as proposed by Orroth et al. (2007, p. i6) for all female agents that are not CSWs, OPSWs and male agents that are not clients of CSWs and OPSWs.

Table 5.6: **Model input parameters related to HIV infection stage transmission probabilities and number of coital acts per relationship type.**

Stage	Probability	
	Male to Female	Female to Male
Primary Infection	0,028	0,014
Clinical asymptomatic	0,002	0,001
Symptomatic	0,006	0,003
AIDS	0,014	0,007
Coital acts per week per relationship type		
Courting (no concurrency for both partners)		normal(1,5,3,1)
Courting (concurrency for both or one of the partners)		normal(1,3,2,1)
Married (no extra-marital affairs for both partners)		normal(1,7,4,1)
Married (extra-marital affairs for both or one of the partners)		normal(1,3,2,1)

Men who visit CSWs facilitate the spread of the virus from the small CSW community into the general population. Research done by Suiming et al. (2011) found that countries with a high percentage of CSWs have higher HIV prevalence and incidence levels among the CSWs themselves and the general population. CSWs and their clients are believed to have higher transmission probability of HIV due to higher rates of STIs incidence (Cowan et al., 2005).

Dunkle et al. (2005) assumed that if 1% of the adult female population are sex workers and if each sex worker has an average of eight different clients in a week assuming no repeat visits, it means that 8% of the adult male population will have contact with a CSW in just one week. If CSWs and their clients consistently and correctly use condoms for all sexual encounters, given also the low HIV infection probabilities, not all 8% of the adult male population will get infected in one week, even in a year with 52 weeks (Dunkle et al., 2005).

But, the reality is that CSWs and their clients do not always use condoms and the HIV infection probability is higher within CSWs due to higher rates of STIs incidence (Cowan et al., 2005). A number of studies (Luchters et al., 2008; Adu-Oppong et al., 2007) have documented resistance to using condoms by CSW clients by offering to pay more for unprotected sex. Alcohol and drug use by CSWs and their clients also contribute to the chances of having unprotected sex (Chersich, Rees, Scorgie and

Martin, 2009). Sex workers also engage in anal sex since it has a higher fee than other sexual acts but it is associated with a higher HIV transmission probability (Scorgie et al., 2012).

Also surprising is the fact that HIV positive CSWs do not decrease the number of sexual partners nor consistently use condoms during sexual encounters (Baral et al., 2014, p. 6). CSWs seldom use condoms with regular clients since they perceive sex with a regular client to be less risky and classify them as "clean" (Wojcicki and Malala, 2001). Studies carried out in the KwaZulu Natal Province in South Africa and other parts of the country have shown that, in general, women in the country have more immune cells in their vaginas that increases the risk of contracting HIV (Child, 2015).

In our general simulation model, we therefore multiply the infection probability by five for all stages of infection for CSWs, OPSWs and their clients to accommodate higher transmission probability of HIV due to higher rates of STIs incidence (Cowan et al., 2005) and the practice of risky sexual behaviour in this group of the population. Note that the infection probability for women not OPSWs or CSWs in our model is not multiplied by five although Child (2015) stated that women in South Africa, in general, have an increased risk to contracting HIV due to the presence of immune cells that favour HIV transmission. Modelling this phenomenon is an area that requires further research.

Researchers have established that circumcision reduces HIV transmission by 60% (Bailey et al., 2007; Gray et al., 2007). Results from a model – Decision Makers' Program Planning Tool (DMPPT) developed by Njeuhmeli et al. (2011) suggest that male circumcision should reach 80% of men 15 to 49 years old in countries with high HIV prevalence between 2011 and 2015. The 80% coverage should be maintained between 2016 and 2025. Doing this will avert 3,36 million (Njeuhmeli et al., 2011) new infections through 2025. South Africa is one of the countries in the list of countries that should have an 80% coverage of male circumcision by end of 2015.

To achieve this target, South Africa must circumcise 4,3 million men by 2016. Approximately 1,3 million circumcisions have been performed by the end of 2013. This represents 31% of the set target (Medical male circumcision media and information hub, 2015). Three million more men must be circumcised for the country to achieve the 80% coverage by 2016. The government of South Africa aims to scale-up voluntary medical male circumcision (VMMC) but there are problems being encountered that reduce the rate at which circumcisions are done. A major funding shortfall has been cited as one of the major problems that will affect the rate at which VMMC is performed in the country (Medical male circumcision media and information hub, 2015). There are also concerns about a decline in the quality of services offered at VMMC sites (Rech et al., 2014). This may negatively affect the efforts undertaken by the government of South Africa to scale-up VMMC.

In our model, we do not explicitly model condom use and circumcision. We use a probability distribution to represent the chance of protection against HIV transmission using a condom and from circumcision. Condom usage is not 100% for all coital acts and circumcision reduces infection probability by 60%. To benefit from circumcision, South Africa should achieve an 80% coverage by 2016, which, according to the current statistics might not be achieved (Medical male circumcision media and information hub, 2015). According to the study by HSRC (2014), percentages of individuals using a condom in their last sexual encounter decreases with age, with the highest percentage of condom use for individuals below 24 years. This may be attributed to the fact that there are few married individuals below 24 years, hence the use of condoms is more prevalent in this age group.

Using these facts, we assume that chance of protection against HIV transmission per coital act follows a probability distribution. We increase the probability of protection per coital act from 2002 (0,471) to 2008 (0,852) – when the country experienced a high condom usage during sexual acts. From 2008, we decrease the probability due to a decrease in condom usage experienced from 2008 to 2012 (HSRC, 2014). But within the same time period, there was an increase in the number of male circumcisions. To include the effect of male circumcision in the model, the decrease in the chance of protection from 2008 to 2012 is done in such a way that by 2012 the protection chance is 10% higher compared to 2002 chance of protection. We also assume that married agents do not use condoms during sexual encounters. All other sexual encounters outside marriage, condoms are used and depends on the chance of protection discussed here. The chance of protection probability distribution used in our model is shown in Table 5.7.

Table 5.7: **Probabilities for condom use per coital act**

End of year	Probability
2003	0,471
2004	0,6495
2005	0,728
2006	0,7693
2007	0,8106
2008	0,852
2009	0,7077
2010	0,6634
2011	0,6191
2012	0,571

Since there is no data about condom use from 2012 onwards, we assume that chance of protection per coital act remains at 0,571 up to the end of the simulation in our HIV general simulation model. This may need to be adjusted if new data on condom usage and male circumcision is obtained.

According to Cohen et al. (2011), if ART is taken correctly and consistently and there is no treatment failure, transmission probability is drastically reduced. The transmission probability will be equal to 96% of that in the clinical asymptomatic stage. This translates to a transmission probability of approximately 0,00008 and 0,00004 per coital act for male to female and female to male, respectively.

In our model, we assume that the infection probability of agents who drop out with a CD4 cell count greater than 350 cells/μL is equal to the asymptomatic stage infection probability. If the CD4 cell count is between 200 cells/μL and 350 cells/μL, the infection probability is equal to the symptomatic stage infection probability. The infection probability will be the same as the AIDS stage infection probability if the

CD4 cell count is below 200 cells/μL. The infection probability of agents that drop out of ART is updated as their CD4 cell count decreases.

Agents who drop out of ART may re-enrol. In some instances people who re-enrol for ART suffer from drug resistance (Cohen et al., 2011) but in our model we do not consider drug resistance. We leave this as an area for future research. It is not easy to get statistics about the number of people who drop out of ART treatment. No study has, to our knowledge, quantified the number of dropouts who re-enrol. In their research, Klein, Bershteyn and Eckhoff (2014) analysed three drop out scenarios, 0%, 50% and 100% to try and see the effect of ART drop out and re-enrolment on HIV/AIDS epidemiological projections. As a starting point, in our model we assume that the probabilties used to intially enrol agents for ART applies to agents who wish to re-enrol. This assumption requires further investigation.

Infection probability per coital act of an agent who re-enrols for ART is assumed to be equal to that of a person on ART. We are aware of the fact that the infection probability does not decrease immediately after re-enroling for ART; instead, it decreases linearly over a six month period (Klein, personal communication, June 09, 2015). To reduce the complexity of our model, we do not take into consideration a linear decrease in infection after re-enroling for ART and in all other HIV state changes.

The prognosis after re-enroling is calculated based on CD4 cell count at re-enrolment. We compute prognosis after re-enroling using the same formula as when the agents initially enrol for ART. We do not have a cut off point for the number of dropouts and re-enrolments for agents in the model. The only event that can stop agents from dropping out of ART and re-enroling for ART is death that may be due to natural causes or HIV/AIDS.

People living with HIV on ART may suffer from treatment failure (Kwobah et al., 2012). Low ART adherence and low CD4 cell count at ART initiation have been shown to contribute to ART failure (Kwobah et al., 2012). Usually, a second line regimen is recommended to HIV patients who experience treatment failure (WHO, 2003b). Some HIV positive people may still experience virological failure even after changing the regimen(s) (Deeks et al., 2009). During ART failure, the viral load of the HIV infected person is reported to increase (WHO, 2003b; Deeks et al., 2009).

In our model, we assume ART failure is after all possible options are considered. Hence once an agent is selected to experience treatment failure, there is no reversal. Furthermore, we assume that the infection probability of agents experiencing ART failure is equal to the AIDS stage infection probability per coital act. We use the AIDS stage infection probability per coital act since HIV patients experiencing treatment failure have a high viral load (Deeks et al., 2009). High HIV viral load increases the infection probability per coital act (Baeten et al., 2011).

The final cut-off point for an HIV positive agent experiencing treatment failure is death. A study by Deeks et al. (2009) found a cumulative mortality of 5% at 1 year and 26% at 5 years for HIV positive people suffering from ART failure. To reduce complexity of our model, we assume that survival of agents suffering from ART failure is derived from a Weibull distribution used to calculate prognosis at HIV infection. The agent's prognosis parameters may change because of aging.

5.7.3 Child birth and vertical transmission

A child born to an HIV positive mother may become HIV positive at birth or during the postpartum period. In this model, we only consider HIV infection at birth. We assume that for each child born to an HIV positive mother not on ART, there is an infection probability of 0,30 (Rauner, 2005). If the mother is on ART, the probability of infection is 0,02 (Torpey et al., 2012; Cooper et al., 2002). A child infected at birth will follow the stages of HIV infection as described in Section 5.7.1 on page 113. The prognosis of the baby is calculated using the Weibull parameters shown in Table 5.3 on page 115. The parameters for the Weibull distribution were calculated using empirical data. The resulting prognosis for infants (less than 5 years) and children (between 5 and 15 years) is shorter compared to that of people 15 years and older.

The fertility of HIV positive mothers not on ART decreases during the incubation period. Researchers like Alam (2008) included decrease in fertility for HIV positive female, in their model. In our model, we do not explicitly model decrease in fertility for HIV positive mothers. We leave this as an area that needs further investigation.

5.8 Model initialisation

At model intialisation, 52% of agents are females. The ASSA life tables are used to assign age to each agent. Agents are also assigned dynamic and static attributes listed in Appendix A. We initialise the model with married agents, agents in sexual relationships and some in dating relationships. We use marriage data published by StatsSA (2011, p. 6) to select males that must be married at model initialisation. It is very difficult to obtain accurate data about individuals in sexual or dating relationships at any given time. Therefore, we assume that 20% of males above 15 years are in a sexual relationship at model initialisation and 10% from the same age group are in a dating relationship.

According to Myatt (2012), we can estimate the number of pregnant women in a given time period if we have the yearly birth rate, population size and the mean gestation period. In South Africa, yearly crude birth rate has been decreasing from 2002 at 24,5 to 20,5 in 2013. To calculate the number of pregnant women at any given time, we use the crude birth rate (24,5) and the total population for 2002 (43 647 660) as our baseline. Data used are from StatsSA (2002) and StatsSA (2013). We maintain a mean gestation period of 40 weeks (Kieler et al., 1995). The initial number of pregnant women is therefore calculated as follows (see Myatt (2012) for more detail):

$$\begin{aligned}\text{Births per year} &= \text{Birth rate} \times \text{Total population}\\ &= \frac{24{,}5}{1\,000} \times 43\,647\,660 \approx 1\,069\,368.\end{aligned}$$

The number of births per day translates to

$$\begin{aligned}\text{Births per day} &= \frac{\text{Birth per year}}{\text{Number of days in a year}} \\ &= \frac{1\,069\,367{,}670}{365{,}25} \approx 2\,928.\end{aligned}$$

Given that the gestation period is approximately 280 days, the number of pregnant women at any given time point can be estimated to be

$$\begin{aligned}\text{Number of pregnant women} &= \text{Birth per day} \times \text{mean gestation period} \\ &= 2\,927{,}76912 \times 280 \approx 819775.\end{aligned}$$

which is approximately 1,9% of the total female population. Therefore, we assume that at model initialisation, 0,019 of the females are pregnant.

We initialise the model with females that already have children. It is not easy to get data that explicitly state the number of females with children in a population, let alone the number of single females with children. Females become single mothers if the husband dies or is divorced or if she is never married but had a child during a sexual relationship. Some females end up getting married after being a single mother for a certain period of time. Hence during data collection, it becomes very difficult to come up with correct statistics on single motherhood and mothers that are living with the fathers of their children. According to StatsSA (2003, p. 14), approximately 33,7% of children in South Africa in 2003 were living with both parents.

We assume that 53% of females above 15 years have at least one offspring. Out of the 53%, 40% are single females. The younger a female is, the lower the number of children she has under normal circumstances (see data for number of children ever born against age published by StatsSA (2003, p. 49)). Therefore, we use age to allocate the number of children. We use a uniform distribution with an interval [0,3] for female agents between 15 and 25 years and a truncated normal distribution with a mean of 4, a standard deviation 1, minimum of 1 and a maximum of 10 for females above 25 years. We assume that of the single females with children, 38% are within the 15 to 25 year age group. To cater for teenage pregnancy, we made the percentage for single females with children in the 15 to 25 years age group higher than that for partnered females.

We also have agents that are widows, widowers, divorcees at the start of the simulation. Being a widow or widower is highly age dependent with older people much likely to be in such marital status (Carr and Bodnar-Deren, 2009, p. 705). To simplify our model initialisation conditions, we assume that there are approximately 5,7% of widows and also 5,7% widowers and approximately 1,9% of agents above 15 years are divorcees for each gender (StatsSA, 2003, p. 24).

5.8.1 HIV/AIDS initialisation in the model

We use HIV prevalence data for year 2002 published by O.Shisana and Simbayi (2002, p. 52) to initialise HIV in the model. The prevalence data is given per age group and for each gender. The CD4 count for infected agents who are not on ART is drawn from a normal distribution with mean 564 cells/μL and standard deviation of 82 cells/μL (Williams et al., 2006). We assume that the percentage of agents on ART is zero at model initialisation. ART started to be publicly available in April 2004 in South Africa (Karim et al., 2009, p. 924) but before the official launch in 2004, there were several projects providing ART in the country (see Boulle et al. (2008) and Bekker et al. (2006)). Therefore, we allow agents to start enroling for ART just after model initialisation.

Chapter 6

Simulation Results

6.1 Introduction

Simulation results allow us to examine the patterns of social, sexual and marriage networks that can develop given different behaviour rules and agent parameters. Instead of examining the patterns of existing couples and sexual relationships using historical data, social simulation is used in this thesis to match people. We examine the patterns that emerge from the matching process. In this thesis, we develop a simulation model for a matching process that is close to reality as much as possible using individualised interactions. We expect that the individualised interactions will give a realistic presentation of heterogeneity in the spread of infectious diseases, with a specific focus on HIV.

The previous chapter presented a detailed description of an agent-based simulation model to simulate the life course of individuals in a dynamic social and sexual network. We further described how we implement the HIV/AIDS transmission process in the dynamic social and sexual network. Partnership formation is based on a dynamic social network and also on a very low chance of random selection. This chapter presents the results obtained from the simulation model.

Model results are presented as aggregates (mostly median and averages), histograms and also as time series charts of key performance measures. The average results are obtained from 10 simulation runs, with each run lasting for 50 simulation years (2 600 model time steps). Our model is a discrete time model in which each time step represents one week. The occurrence of most events in the model is determined by probability distributions, hence model results are subject to stochastic variation. To obtain good results from such a model, multiple runs must be performed to diminish the stochasticity in predictions. It is important to note that due to time and resource constraints, we managed to have a maximum of 10 simulation runs for each scenario and for parameter variations explored. Model results from the 10 simulation runs still show some stochastic variation which could have been minimised if more runs were performed.

Results for social and sexual network, are classified into two categories, namely; general simulation model and parameter variation model results. We selected eight parameters for variation. Our model has a wide variety of parameters and a vast range of scenarios that can be explored but, due to time constraints, we only selected eight parameters. Five of the eight parameters, namely; likeability index, concurrency levels for married agents, sexual drive, probability to initiate sexual activities and population growth rate have never been used in the development of social and sexual network from the literature of which we are aware. We are interested in finding out the effect of varying these parameters on model results. The other three parameters: probability of random partner search, courtship duration and divorce criterion have been used in the development of social and sexual networks in literature (see Simao and Todd (2002), Hills and Todd (2008), Alam (2008) and Knittel et al. (2011)). We would like to see if varying these parameters under the new model settings will produce results close to what is in literature. We explore the characteristics of the social, sexual and marriage networks that emerge from agent interaction when we vary the eight parameters under two different scenario settings.

General simulation model results are compared with census and household survey data collected in South Africa from 2001 to 2011. It is important to acknowledge that data from census and household survey is not from a closed mixed society.

Our model represents a closed mixed society. To benchmark our model, we need to compare model results to observed data. In real life settings, a closed mixed society does not exist. We therefore use census and household survey data as a proxy, and have to keep this in mind when interpreting model results.

Also, our model does not include all the aspects encountered in social and sexual relationship formation in real life settings; for example, gay and bisexual relationships, yet data collected include this sub-population. To reduce the complexity of our model, we exclude these sub-populations in the model developed for this thesis (Department of Health, Republic of South Africa, 2015, p. 3). The model developed in this thesis can be expanded in the future to include human social and sexual behaviours as well as HIV transmission routes not considered in this thesis.

Another major challenge in comparing model results and data in literature is the reliability of data related to romantic relationships. For example, when collecting data about marriage, some individuals confuse marriage which in South Africa is in two major categories (civil and customary marriage), with cohabitation. Using marriage registration data is also not very reliable since more than 85% of customary marriages in South Africa are registered more than a year after the marriage (StatsSA, 2012, p. P0307). An increase in cohabiting couples in South Africa has been observed as from 1995 (Posel and Rudwick, 2013, p. 172). This results in under-or over-reporting on marriage statistics and other romantic relationship statistics. Given the challenges encountered in collecting marriage and romantic data model, results obtained here may not fit exactly to what is in literature but are sufficiently close to what is recorded in literature.

The main objective of our model is to understand the factors that contribute to the progression of HIV in a society but we first present results for the social and sexual network in this chapter. Understanding how the social and sexual network evolve may help in understanding how HIV progresses in a society, since the structure of the social and sexual network contributes to the progression of HIV in a society (Heuveline et al., 2004). We present results and aspects related to the spread of HIV/AIDS including the use of ART to try and curb the progression of HIV in Section 6.5.

6.2 General simulation run

In this section, we present basic results of the model obtained using a general simulation model scenario explained in the previous chapter. The social network structure for the general scenario is initialised by assigning n randomly selected agents a number of friendship connections between one and the maximum degree of friendship connections an agent can have. We used the formula used by Jin et al. (2001) to select agents for a random connection at each time step to calculate n. The formula is as follows:

$$n = \frac{(N)(N-1)}{2} r_0,$$

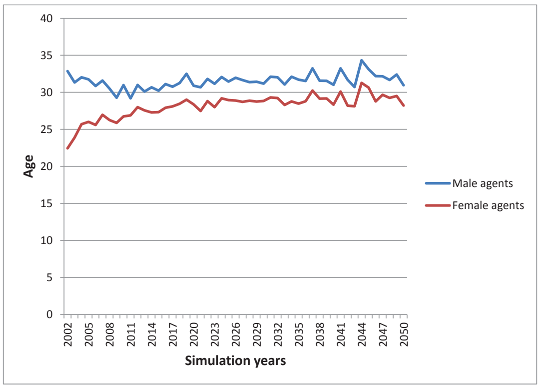
where $r_0 = 0{,}00005$. Initial population size, initial age distribution, sexual maturity and life expectancy distribution tables remain fixed in all scenarios being explored. The initial number of agents at model initialisation is set to 5000, which is the initial maximum that can be handled in a reasonable time by the available hardware resources.

We are interested in observing how the social and sexual network develops in a dynamically changing population size. At the beginning of each simulation year, we calculate the number of agents to be added to the model by multiplying the total population at the beginning of the year by 0,02. The proportion 0,02 is approximately equal to population growth rate[1] in South Africa. The calculated number of agents is divided by 12 to obtain the number of agents to be added to the population at the beginning of each simulation month. Our model is a discrete time model in which each step represents one week. Agents exit the model through death. Appendix A contains a table with all the parameters and parameter values used in the model.

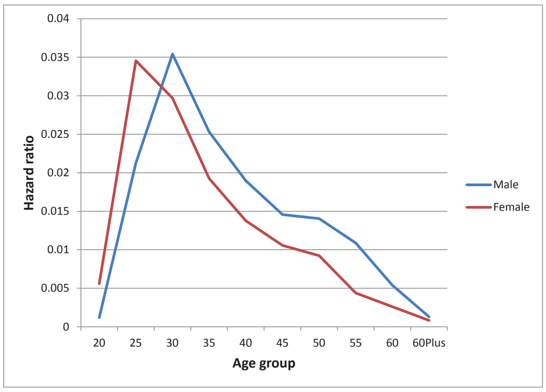
[1] Note that net population growth rate is affected by many factors, for example migration, death rate and birth rate. In this section of the model we do not take birth rate and migration into consideration hence the net growth rate of the population of our agents is not the same as the observed net population growth rate. We are interested in observing the results of the model with a varying population size, hence a simple addition of agents to the model at the beginning of each simulation year.

6.2.1 Marriage statistics

Age at first marriage produced by the model is on average 27 years for females and 31 years for males. This is quite comparable with what is observed in actual populations where there is an average age difference of approximately four to five years. Figure 6.1(a) shows a general increase in the median age at first marriage. Research done by Palamuleni (2010) has indicated that due to rapid socio-economic development in South Africa, the median age at first marriage, especially for women, has been increasing and the model results compare favourably with literature.

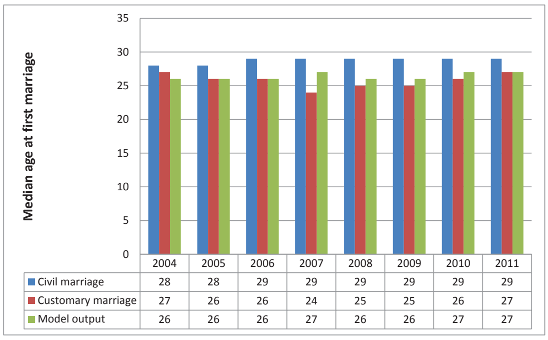


(a) Male and female median age at first marriage



(b) Age at first marriage hazard ratios

(c) Male age at first marriage (civil and customary) compared to model output 2004 to 2011

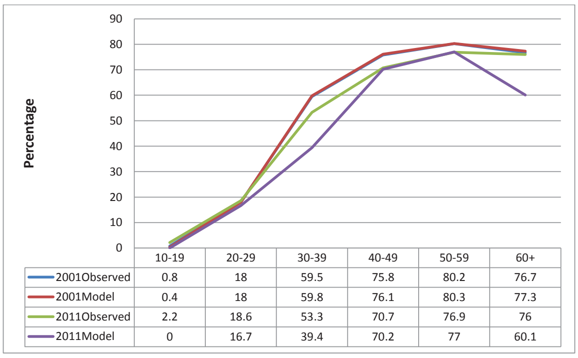


(d) Female age at first marriage (civil and customary) compared to model output 2004 to 2011

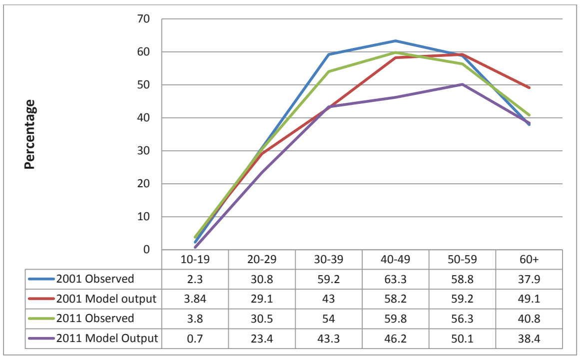
Figure 6.1: **Age at first marriage.**

Figure 6.1(c) and 6.1(d) show the median age at first marriage (male and female, respectively) for civil and customary marriage compared to model output as from 2004 to 2011. There is little variation for female median age at first marriage between model output results and the observed customary median age. Both observed data and model results show that males are generally older than females at first marriage. Customary marriage has the largest average age difference of six years, and civil marriage has the lowest average age difference of four years. Our model results lie between the two, with an average of five years.

Another interesting observation from the model results is that model results replicate the distribution of first marriage hazard ratio patterns observed in human populations. The calculated average marriage hazard ratios for each age group are quite similar to those observed. The peak hazard ratio for females lies between 20 and 25 years and it occurs earlier than that for males, which has a peak between 25 and 30 years. Model results for the hazard ratios are shown in Figure 6.1(b).



(a) Male percentage married by age group 2001 and 2011 compared to model output



(b) Female percentage married by age group 2001 and 2011 compared to model output

Figure 6.2: **Percentage married by age group 2001 and 2011**

Marriage percentage per age group has low percentages below age 19 for both genders, with the female gender having a slightly higher percentage for that age group. A peak is observed in the 40 to 49 year age group for females and in the 50 to 59 year age group for males. The percentage of women above 50 years drops as well as the percentage for males above 60 years. This may be due to the fact that most women are married by older males. As the couple ages, the man may die and leave the women as a widow who may not be willing to remarry due to age. Usually, males prefer younger women hence, even if the women passes on they can still get a woman to marry even at old age. Please refer to Figure 6.2 for the graphs.

At each time step, there are agents in the model that never had a mate. The propor-

Table 6.1: **Median age of widows, widowers and male and female divorcees at remarriage (2004 to 2011) compared with model output**

Attribute	2004	2005	2006	2007	2008	2009	2010	2011
Widows and widowers marriage age								
Female observed	33	28	29	29	29	30	30	30
Female model output	**30**	**33**	**39**	**37**	**40**	**50**	**45**	**43**
Male observed	39	39	42	43	45	46	47	48
Male model output	**35**	**35**	**39**	**38**	**45**	**50**	**48**	**50**
Divorcees marriage age								
Female observed	44	46	45	45	46	46	47	47
Female model output	**33**	**33**	**30**	**30**	**34**	**43**	**36**	**40**
Male observed	50	52	50	51	52	52	52	52
Male model output	**41**	**38**	**36**	**41**	**40**	**38**	**36**	**39**

tion of such never coupled agents is captured yearly in the model. The proportion is calculated by dividing the number of never coupled males or females greater or equal to 15 years by the total number of males or females greater than 15 years. There is a higher percentage of males (28%) who are never coupled as compared to females (18%). The larger portion of the never coupled agents comes from agents less than 25 years for both males and females. Agents in our model start building their social network connections from which they search for potential mates at age 15. This means that the chance of having a suitable partner increases as the social network links for an agent increases, hence a larger proportion of never coupled agents below 25 years.

The model also gives results for the ages of agents who remarry after divorce or death of a partner. Results in Table 6.1 considered only one strategy for divorce, that is, divorce once a more attractive agent is met. There is substantial variation in the model results compared to the variation in observed data. This may be due to the fact that the population size used to derive the model results does not give a large enough sample for the divorced and widowed sub-populations to make reliable estimates. In addition, divorce depends on a number of factors which are not considered in this model, hence the large variations in the median age at remarriage model results.

In real life settings, divorced and widowed agents re-enter the mate search pool. Studies have shown that individuals who remarry are more likely to be HIV-positive, and hence contribute to the spread of HIV in a community (Ramashwar, 2012). Therefore, it is important to understand the effect that such agents have in mate search models. Changing the agent population size and the default divorce criterion used in this model may increase the divorce sub-population, which may improve the understanding of how remarriages affect mate search behaviour.

6.2.2 Married partner correlation

Using the likeability index as a method to select mate partners, partner quality correlation of married agents which lies between 0,6 and 0,7 as shown in Figure 6.3 was obtained. This is in line with some studies (for example studies by Kalick and Hamilton (1986)) which illustrated that there is a high correlation in attractiveness for couples in sexual relationships. There are no studies done yet in the context of African countries, but it can be assumed that the studies done can also be generalised to African countries.

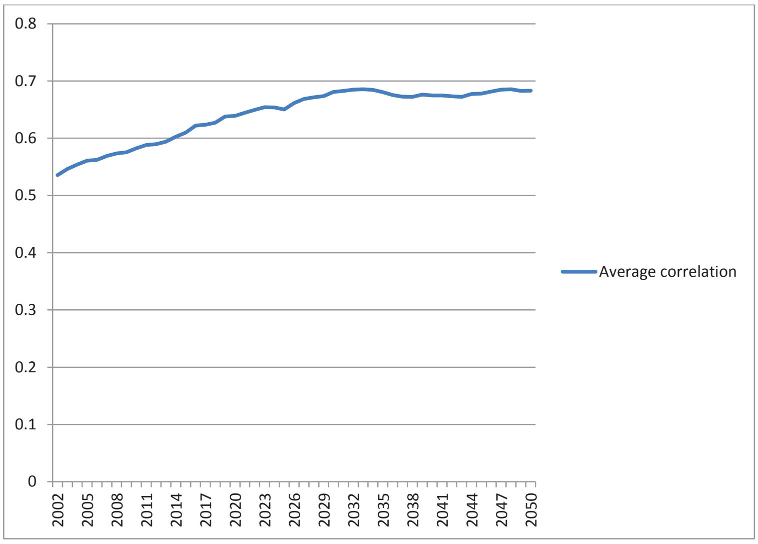


Figure 6.3: **Average married partner correlation**

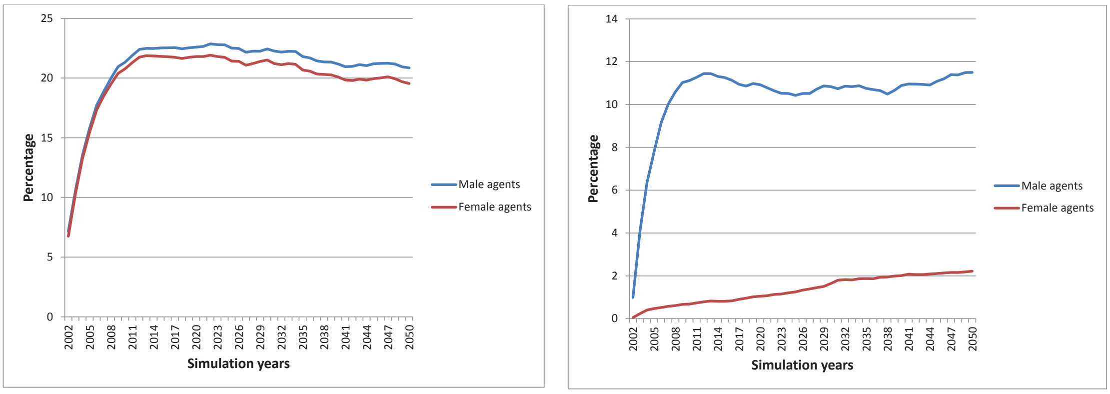
6.2.3 Concurrency and sexual relationships outside marriage

Model results for concurrency levels and the percentage of agents that are involved in sexual activities outside of marriage using the default parameter settings were also collected. From the model results, the percentage of male agents involved in sexual activities outside of marriage[2] is slightly more than that for female agents. The graph rises steadily and stabilises around 21% (see Figure 6.4(a)).

The percentage of coupled males and females with concurrent partners[3] stabilises at approximately 11% and 2%, respectively (see Figure 6.4(b)). From the model output, a larger fraction of males have concurrent partners than for females. This result is similar to the results obtained by Helleringer and Kohler (2007) from the Likoma Island in Malawi, which show that women have a much lower tendency of having multiple sexual partners. Research done in the United States by Adimora, Schoenbach and Doherty (2007) also indicated that males have a higher tendency (approximately 11%) of having concurrent partners compared to women (approximately 5,7% based on reported partnership; see Adimora et al. (2011)). This can be explained by the belief that men have a higher sexual desire and desire for sexual variety (Baumeister et al., 2001) than women.

Our model results for male concurrency compare favourably with the results obtained by Adimora et al. (2007). Female concurrency results are notably lower than those reported by Adimora et al. (2011). This result is more or less a reflection of the underlying assumption on the number of concurrent partners a female agent can have simultaneously. The distribution used to model the number of multiple sexual partners for females was adopted from a study done by Helleringer and Kohler (2007) which may be affected by under-reporting of concurrent sexual partners women have due to social and cultural reasons. This may have introduced bias in the parameters used in the model. Varying the parameter may increase the levels of concurrency for females.

[2]In our model the statistic for sexual relationships excludes married agents.
[3]In our model the statistic for concurrent relationships includes both single and married agents.



(a) Percentages of agents involved in sexual relationships outside marriage

(b) Percentage of agents with concurrent partners

Figure 6.4: **Model average results for sexual relationships outside marriage and concurrency.**

6.3 Parameter changes effect on model results

To enhance understanding of our model dynamics, some parameters were varied and the results were compared to the general simulation run results given in the previous section. It is important to evaluate how the model responds to various changes of parameter values and environmental assumptions. Given a large number of parameters in the model, it means that varying these parameters sequentially or simultaneously will result in different network structures for the social, sexual and marriage network. Therefore, a number of scenarios can be used as alternatives to those presented in this chapter. In this thesis, we consider two scenarios. For both scenarios, we vary eight parameters (Case I to VIII) listed in Table 6.2 one at a time. The rest of the parameters not listed in Table 6.2 remain fixed, as listed in Appendix A.

In Scenario 1, we use the general simulation model and vary eight parameters (Case I to VIII) listed in Table 6.2. In Scenario 2, we initialise the model with all agents having a random number of friendship connections between one and the maximum degree of friendship connections an agent can have. New agents entering the population during the simulation run will immediately create friendship connections as at model initialisation. The development and the density of the social network depends on the way initial connections are formed both at model initialisation and at the creation of a new agent. In Scenario 2, the social network grows faster than in Scenario 1. We found it necessary to consider these two scenarios since the development and density of our social network contributes to the rate at which agents find potential mates.

Parameters listed in Table 6.2 contribute significantly to the final structure of our sexual network. In our model, selection of potential sexual partners depends on the likeability index value of opposite sex agents. The process of sending and accepting date requests depends on the sex drive of an agent. These two parameters form the backbone of the development of the sexual network. Probability to initiate sexual activities, concurrency level for married agents, courtship duration, probability of random partner search, divorce criteria and the rate at which the population grows, dictate how the sexual and marriage network grows in the virtual society in our model. For example, a very short courtship duration will force agents in our model to marry too soon and to marry the first agent they propose to without having time to compare with other potential partners. This will lead to high divorce rates, as the married agents may encounter better mates during the simulation run. Varying these parameters will assist us in evaluating the sensitivity in these parameters on the romantic network structures.

Parameter settings for Scenario 2 are the same as those used in Scenario 1. The only major difference for Scenario 2 is the initialisation of the model with all agents having at least one friendship connection. We discuss the effect of varying each of the mentioned parameters on model results. As mentioned earlier on, a large number of scenarios can be explored; so the results presented here are just a subset of the possible alternatives.

6.3.1 Never coupled agents

Scenario 1

A change in likeability threshold (Case I) and probability of random partner search (Case III) resulted in a decrease in the yearly percentage of agents that are never cou-

Table 6.2: **Parameter variations for the social and sexual network model**

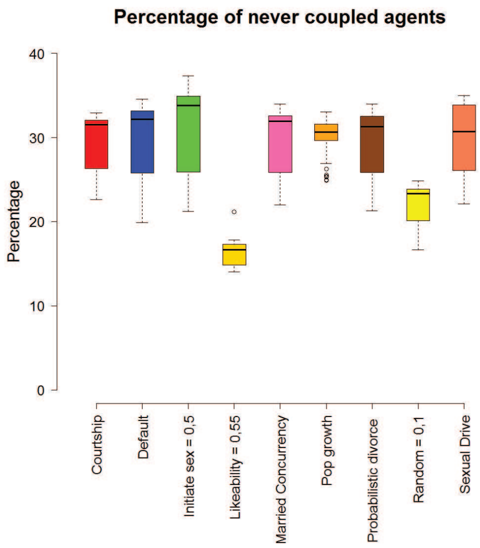
Case	**Varied Parameter**	**General setting**	**Variation setting**
Case I	Likeability threshold Female agents < 26 years Male agents < 30 years	uniform(0,55;0,9)	0,55
Case II	Initiate sexual activities probability	0,03	0,5
Case III	Random partner search probability	0,05	0,10
Case IV	Population growth rate,	0,02	0,03
Case V	Concurrency level for married agents	male = 0,5 Female = 0,2	male =0,8 Female = 0,5
Case VI	Courtship duration	Normal(26,156,78,10)	Normal(26,156,52,10)
Case VII	Sexual drive	Male = Beta(4;2;0;1) Female = Beta(1,5;3;0;1)	Male Beta(8;2;0;1) Female Beta(4;3;0;1)
Case VIII	Divorce criterion	Marriage duration and partner attractiveness	Age dependent probabilistic distribution[a]

[a]See the age dependent probabilistic distribution in Appendix A on page 224

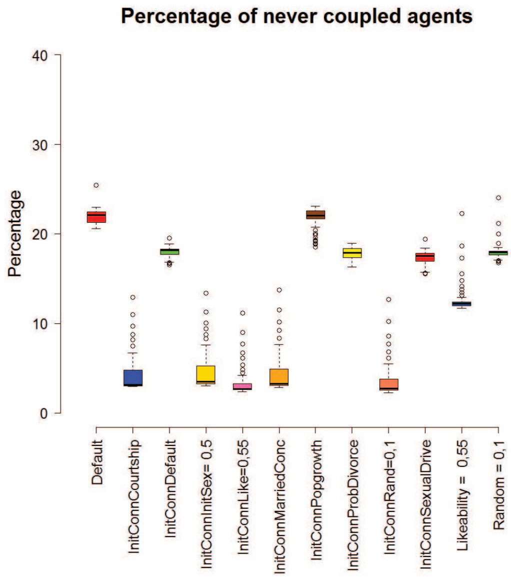
pled. Using the general model settings, the year-to-year percentage of never coupled agents stabilises at approximately 22,5%. Changing the likeability to 0,55 for agents below the mean age at first marriage reduces the percentage for never coupled agents to approximately 12% (see boxplots in Figure 6.5(a)). The decrease in the percentages of never coupled agents support the fact that agents with lower preference for high attractiveness agents can pair much faster than when there is a high preference for attractiveness (Simao and Todd, 2002, p. 3).

Increasing the probability for random partner search from 0,05 to 0,10 also resulted in a decrease in the percentage of never coupled agents. The percentage of never coupled agents decreases to approximately 18%. The decrease is less than the decrease caused by a change in the likeability index but it is significantly different from the general case and all other parameter variations (see boxplots in Figure 6.5(a)[4]). Random partner search allows agents to look for partners outside their social network. This increases the meeting chance of potential partners who may never get into one's social network; hence an increase in coupling of agents and a decrease in never coupled agents.

[4]Full description of the model names used in this thesis are Appendix A from page 226 to 228.



(a) Scenario 1



(b) Scenario 2

Figure 6.5: **Parameter effects on the percentage of never coupled agents**

To test if the decrease caused by varying likeability and probability of random search in the percentage of never coupled agents was significant, a one-way analysis of variance (ANOVA) was conducted. The ANOVA results confirm that there is a significant decrease with a p value of less than 2×10^{-16} which is less than 0,05 (see Appendix C.1). We conducted post-hoc comparisons using the Tukey multiple comparisons of means procedure to determine which pairs of the nine parameters differed significantly. Post-hoc comparisons revealed that setting the likeability index to 0,55 for agents below the median age of first marriage and increasing the probability for random partner search to 0,1 show significant decrease in the means compared to the other parameter variations and the general simulation run results.

Scenario 2

Initiating the model with all agents having at least one friendship connection (Scenario 2) resulted in a general decrease in the percentage of never coupled agents for all parameter variations with the exception of only one parameter, population growth rate (Case IV). Increasing the population growth rate to 0,03 under Scenario 2 gave the same results as the general simulation run results for never coupled agents.

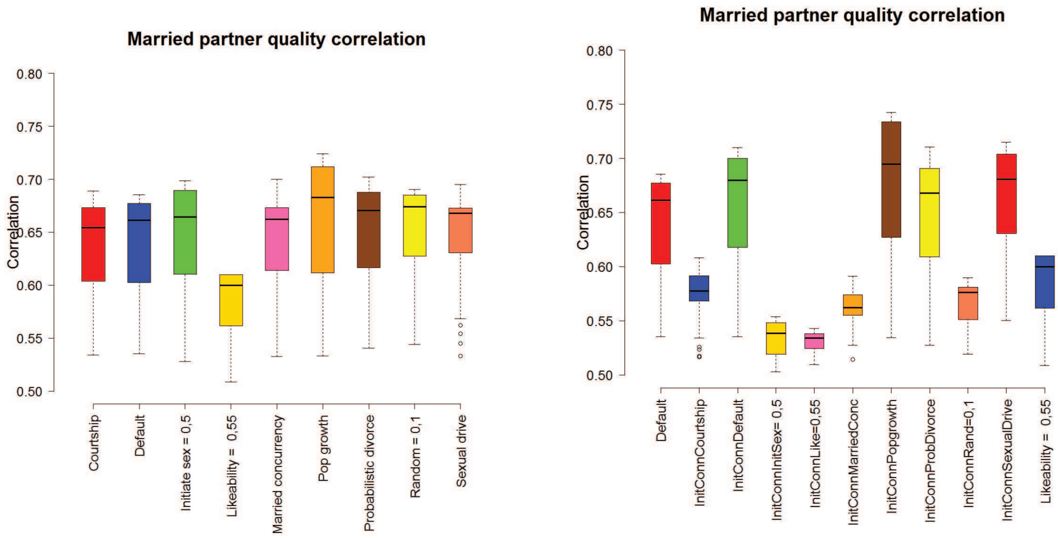
Increasing the probability of random partner search to 0,10 under Scenario 1, using an age dependent probabilistic distribution for divorce (Scenario 2) and changing the sexual drive parameters (Scenario 2) gave same results as the general simulation run under Scenario 2. The percentage of never coupled agents for these four cases is approximately 18%, which is higher than an average of approximately 12% when the likeability threshold is decreased to 0,55 for agents below the median age of marriage under Scenario 1.

All the other parameter variations (Case I to Case III, Case V and Case VI) under Scenario 2 decrease the never coupled percentage to approximately 3,5%. The general decrease in the percentage of never coupled agents under Scenario 2 shows that if there is a dense friendship network in a society, people tend to couple faster hence the decrease in the percentage of never coupled agents. Box plots and ANOVA results discussed here are in Figure 6.5(b) and Appendix C.1, respectively.

6.3.2 Partner quality correlation

Scenario 1

Partner quality correlation is one of the factors used by researchers (Simao and Todd, 2002; Kalick and Hamilton, 1986) in the mate search field to try to understand how individuals seek partners. From the parameters varied in the model, only one parameter managed to decrease the correlation in attractiveness. In the default, case correlation stabilises at about 0,7. When the likeability index was reduced to a maximum of 0,55 (Case I) for agents below the median age at first marriage, correlation dropped to an average of 0,6. Summary results for quality correlation are shown in the box plots in Figure 6.6(a). ANOVA results and post-hoc comparisons to further support the visual display in Figure 6.6(a) are in Appendix C.2.



(a) Scenario 1

(b) Scenario 2

Figure 6.6: **Parameter effects on married partner quality correlation**

Scenario 2

Scenario 2 general simulation results are not significantly different from the general simulation results. Quality correlation stabilises at approximately 0,7 in both instances. From these results, we can conclude that the quality correlation of married partners is not affected by a dense friendship network. Agents only marry if they meet a partner who meets their quality preference. Parameter variations for Case IV, VII and VIII (population growth rate, sexual drive and an age dependent probabilistic divorce criterion[5]) under Scenario 2 did not produce results significantly different from the general simulation results for the same scenario.

Increasing population growth (Case IV) means that the pool to select potential partners to marry increases; hence there is no need to adjust quality preferences for agents. Varying sexual drive (Case VII) also had similar results as the general simulation run. This is mainly because increasing sexual drive levels only gives a higher probability of agents proposing or accepting proposals, which may not necessarily lead to marriage. Hence it does not have a significant effect on the quality correlation of married

[5]Note that whenever we refer to the probabilistic divorce criterion, we use probabilities stated in this thesis. If the probabilities are varied, different results may be obtained.

agents. An age dependent probabilistic distribution divorce criterion (Case VIII) did not produce results with significant differences from the general simulation run. This may be supported by the fact that agents who initiate divorce marry a partner with a higher quality than the divorced one. Therefore, the correlation stabilises at very high levels.

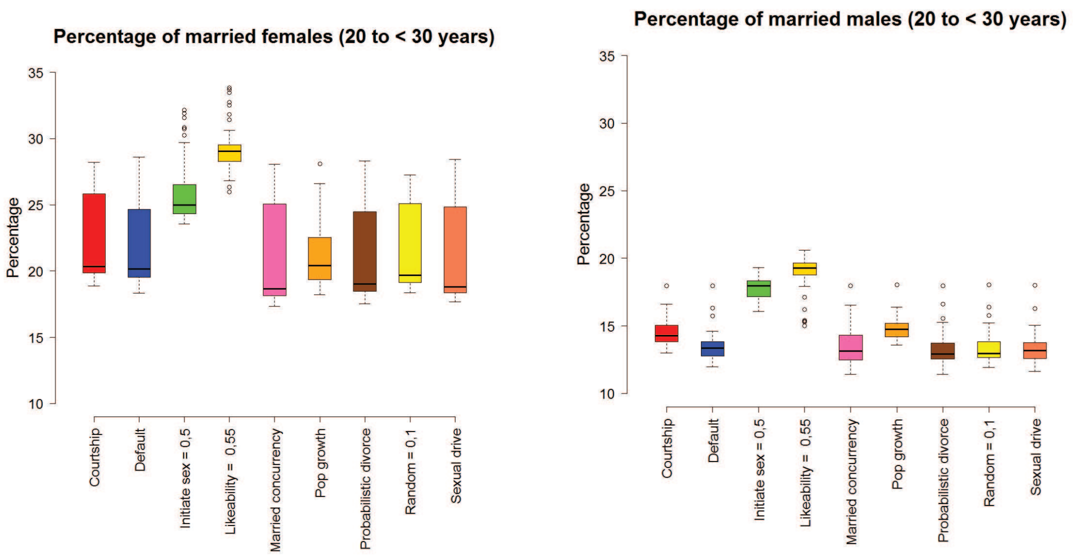
Parameter variations for Scenario 2, Case I to Case III, Case V and Case VI decreased the quality correlation. The largest decrease (to approximately 0,53) was observed when the likeability threshold (Case I) is decreased to 0,55 for all agents below the median age of marriage. Boxplot results and a summary of the ANOVA results are in Figure 6.6(b) and Appendix C.2, respectively.

6.3.3 Percentage of married agents per age group

Scenario 1

Decreasing the likeability threshold (Case I) to 0,55 for agents below the mean age at first marriage increases the percentage of married females and males in the age groups 20 to 29, 30 to 39, and 40 to 49 years. In the age group 20 to 29 years, the percentages increase by approximately 7% and 5% for females and males, respectively. In the 30 to 39 years age group, the percentage increases are approximately 9% and 12% for females and males, respectively. A significant increase is also observed in the 40 to 49 year age group. The increases are approximately 3% and 6% for females and males, repectively. Decreasing the likeability threshold to 0,55 does not have a significant effect on marriage percentages for agents less than 20 years and above 50 years for both genders. The increase in marriage percentage may be attributed to the fact that relaxing the likeability threshold leads to more agents coupling early, enabling marriage to happen earlier than when the likeability threshold is high.

Box plot results for female and male agents in the 20 to 29 year age group are in Figure 6.7(a) and 6.7(b). ANOVA results (see Appendix C: Figure C.3 and C.8) for



(a) Percentage of married females: Age 20 to 30 years (b) Percentage of married males: Age 20 to 30 years

Figure 6.7: **Parameter effects on the percentage of married agents (female and male) in the age group 20 to 29**

the percentage of married females and males in the age group 20 to 29, 30 to 39, and 40 to 49 years confirm that there is a significant increase in the married percentages.

Another parameter which has a significant impact on the percentage of married agents per age group is the probability to initiate a sexual relationship (Case II). Increasing this probability results in an increase in the percentage of married females and males in the 20 to 29 and 30 to 39 year age groups. Increasing the probability to initiate a sexual relationship from 0,03 to 0,5 increases the percentages by approximately 3% and 4% for females and males, respectively, in both age groups. No significant effects are observed in the other age groups.

Increasing population growth to 0,03 (Case IV) and decreasing the average courtship duration to 52 weeks (Case VI) increases the percentage of married males in the 20 to 29 year age group, but there are no significant differences for the females in the same age group. This may be due to the fact that as the courtship duration decreases, the chances of break-ups before marriage also decrease; hence, most courting couples will end up in marriage. An increase in the rate of population growth results in a larger population size, hence, an increase in a pool of new agents from which to choose potential partners. Since only male agents can ask for a date, it means that male agents have a large variety from which to select, and most probably propose to female agents with higher attractiveness, hence decreasing the probability of breakdowns. This leads to higher marriage rate for males and a lower marriage rate for females since those with low attractiveness levels are most likely to remain single.

Box plot results for all age groups are in Appendix B: Figures B.2 to B.13. ANOVA results for all age groups are in Appendix C Figure C.3 to C.13.

Scenario 2

Scenario 2 general simulation model results are not significantly different from the general simulation results for all age groups except for males under 30 years. Results obtained from Scenario 2 general simulation show an increase in marriage percentage for males under 30 years (see box plot diagrams in Appendix B, Figures B.8 and B.9). This shows that allowing male agents to have friendship connections as soon as they turn 15 years old increases their chances of finding partners to whom to propose, hence an increase in the number of married males under 30 years.

Varying parameters indicated in Table 6.2 under Scenario 2 increased the percentage of married agents below 30 years in all cases. In the 15 to 19 year age group, decreasing courtship (Case VI) and increasing the probability of initiating sex for courting agents (Case II) increased the percentage by more than 1,5%. The highest increase of 4% is observed for female agents when the probability of initiating sex is increased. Three parameter changes (Case IV, VII and Case VIII) give same results as the Scenario 2 general simulation run. Boxplots displaying results discussed here are in Appendix B.2 and B.8. ANOVA results are in Appendix C.3 and C.8.

In the 20 to 29 year age group, increasing the probability to initiate sex (Case II) has the most significant increase for both males and females (approximately 15% increase) under Scenario 2. This is followed by reducing the likeability threshold, (Case I) which increases the married percentage by approximately 12%. Reducing courtship period (Case VI), increasing concurrency probability for married agents (Case V) and probability for random search (Case III) also have significant increases in the married percentage as compared to the general simulation run under both scenarios. The increase in marriage percentage observed for Case IV, VII and Case VIII (increasing population growth rate, changing the sexual drive distribution and using an age dependent probabilistic divorce criterion, respectively) are significantly different from the general simulation results but not Scenario 2 general simulation results. Results for these three cases give marriage percentages less than the results obtained when likeability threshold is reduced to 0,55 under Scenario 1. This shows that reducing the likeability threshold in a society allows agents to marry at a faster rate since it is easy to meet a partner who meets one's quality requirements.

Decreasing the likeability threshold (Case I) and increasing the probability of initiating sex (Case II) increases the marriage percentage for females and males in the 30 to 39 year age group under Scenario 2. The largest increase is obtained under Case I. There are also significant increases in marriage percentage for females in the same age group when courtship duration is decreased (Case VI) and probability for random search is increased (Case III). Comparing the results obtained using Scenario 1 with a likeability threshold of 0,55 (Scenario 1, Case I), all other parameter variations under Scenario 2 have lower percentage increases with the exception of setting the likeability threshold to 0,55 under Scenario 2 (see box plot results in Appendix B.4 and B.10).

Model results obtained from the general simulation runs for the percentage of married agents in the 40 to 50 year age group are not significantly different for both scenarios. Parameter variations under Scenario 2 also give results similar to the general simulation results. Significant differences for both male and female agents are observed when the likeability threshold is decreased to 0,55 (Case I). The married percentage increases by approximately 6%. Increasing the probability to initiate sex (Case II) has a similar effect on the married percentage as reducing the likeability threshold to 0,55. Using an age dependent probabilistic divorce criterion (Case VIII) decreases the married percentage for female agents. This may be due to the fact that older divorced women are less likely to find a suitable partner to remarry as compared to men, hence a reduction in the married percentage in that age group.

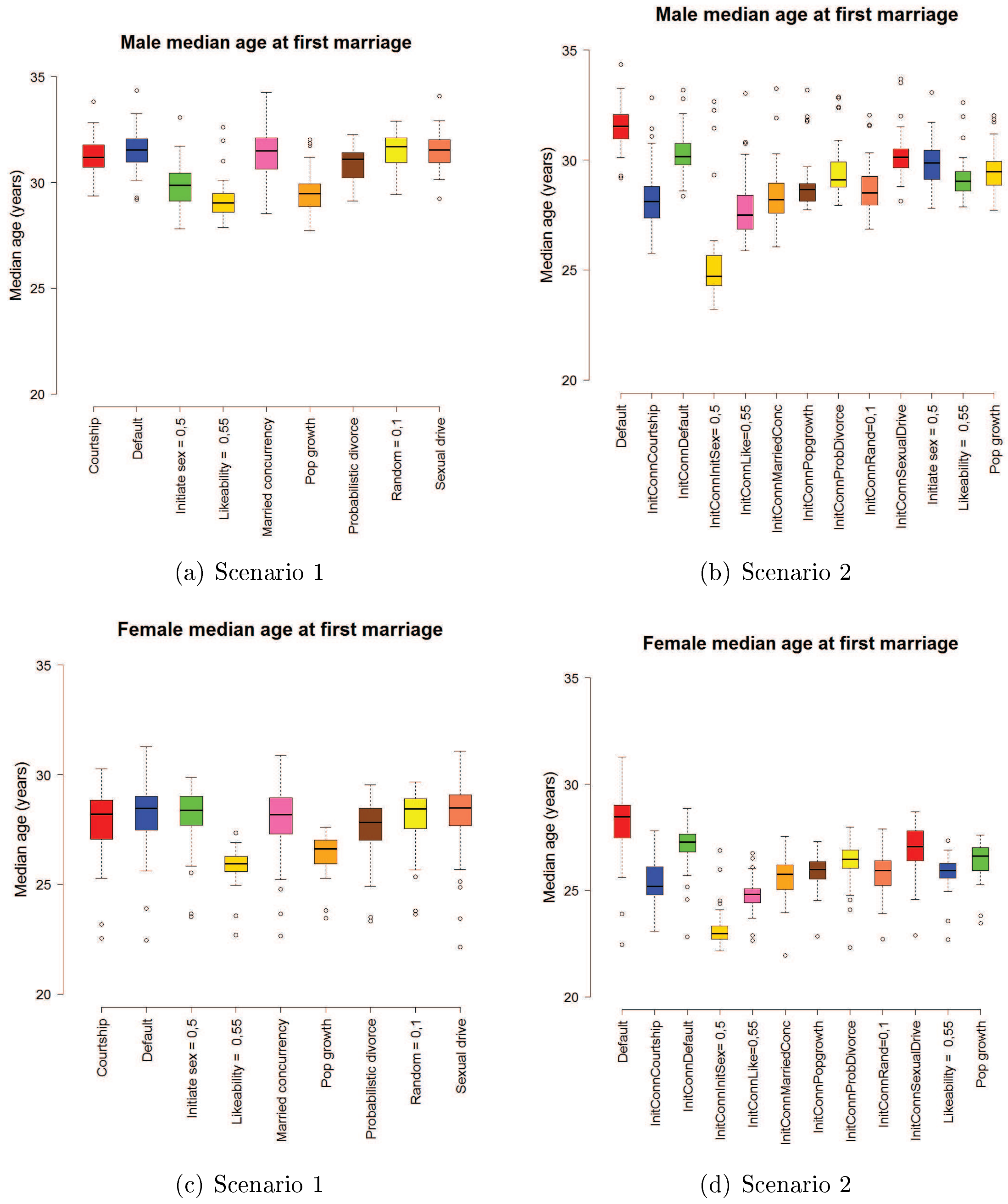
In the 50 to 60 year age group, only one parameter variation under Scenario 2 – using an age dependent probabilistic criterion for divorce (Case VIII) significantly decreases the married percentage for both genders. The general simulation results under Scenario 2 are not significantly different from all the parameter variation results under Scenario 2 for agents over 60 years. Box plots and ANOVA tables visually displaying all results discussed here are in Appendix B (Figures B.2 to B.13) and C (Figures C.3 to C.13).

6.3.4 Median age at first marriage

Scenario 1

Two parameters, namely, likeability threshold (Case I) and population growth rate (Case IV), have significant effects on median age at first marriage for both male and female agents. In both cases, there is a decrease in the median age at first marriage with decreasing the likeability threshold to 0,55 (for agents below the the mean age at first marriage) having the largest decrease. A likeability threshold of 0,55 for agents below the the mean age at first marriage decreases the median age at first marriage from approximately 27 to 26 years and from 31 to 29 years for female and male agents, respectively. Increasing the population growth rate from 0,02 to 0,03 decreases median age at first marriage by approximately 1,5 years (female agents) and 1 year (male agents) compared to the general simulation run. As the population increases at a faster rate, there is an increase in the number of agents added into the model and an increase in the number of female agents with different levels of attractiveness. This increases the chance of male agents (asking agent) to meet female agents of similar age, attractiveness and aspiration levels, hence a decrease in the median age at first marriage for male agents.

Increasing the probability of initiating a sexual relationship has significant effects only on male median age at first marriage. Median age at first marriage for male agents



(a) Scenario 1 (b) Scenario 2

(c) Scenario 1 (d) Scenario 2

Figure 6.8: **Male and female median age at first marriage**

decreases from 31 to 30 years. Box plots and ANOVA results displaying the results discussed here are in Figure 6.8 and Appendix C, Figure C.14, respectively.

Scenario 2

Initialising the model with all agents having at least one friendship connection decreases the median age at first marriage. The median age is reduced by approximately 2 years and 1 year for female and male agents, respectively (Scenario 2 general simulation run results). Varying parameters listed in Table 6.2 under Scenario 2 further decreases the median age at first marriage. The largest decrease is obtained when the probability to initiate sex is increased to 0,5 (Case II) for both male and female agents. The female median age at first marriage drops to approximately 22,5 years and male median age drops to approximately 25 years. Though the median age at first marriage drops for both genders, there is still evidence of male preference to marry younger females. Results obtained under Scenario 2 are all significantly different from the general simulation run. Box plots displaying the results discussed here are in Figure 6.8, and ANOVA results in Figure 6.9.

6.3.5 Percentage of agents in a sexual relationship outside marriage and concurrency

Scenario 1

Decreasing the likeability index (Case I), increasing the probability of initiating sexual relationships (Case II) and increasing the probability of concurrency for married agents (Case V) resulted in an increase in the percentage of agents involved in a sexual relationship outside marriage compared to other parameter variations and the general simulation run. Out of the three parameters, increasing the probability of initiating sexual relationships has the largest effect on the percentage of agents involved in a sexual relationship outside marriage (see box plot in Appendix B.14(a)). Changing this parameter to 0,5 increases the percentage of agents involved in a sexual relationship outside marriage from 21% (general simulation run results) to approximately 26%. Decreasing the likeability index and increasing the probability of concurrency for married agents increases the percentage to approximately 23% (see Figure 6.10(a)).

ANOVA results for median age at first marriage

Male agents

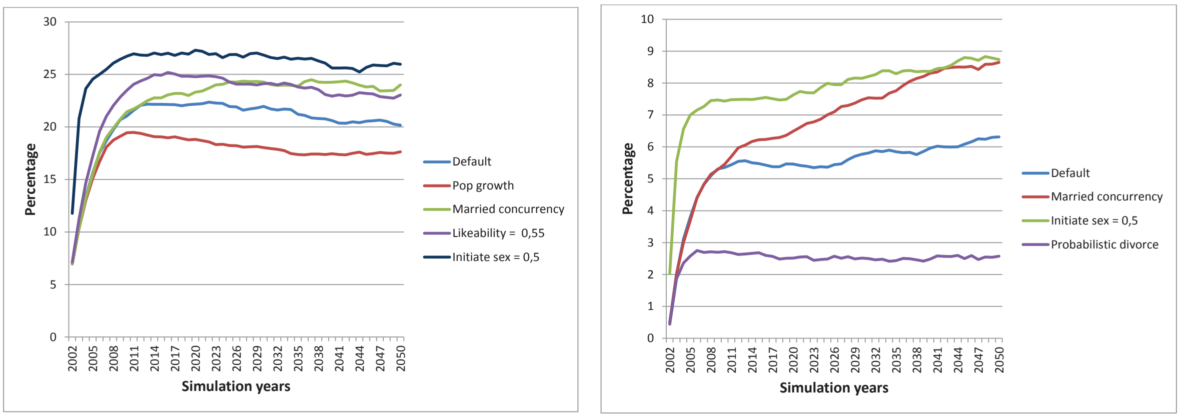
```
             Df Sum Sq Mean Sq F value Pr(>F)
Group        12 1298.9  108.24   69.03 <2e-16 ***
Residuals   624  978.5    1.57
Tukey multiple comparisons of means 95% confidence level
                                           p adj
InitConnCourtship-Default                 0.0000000
InitConnDefault-Default                   0.0059505
InitConnInitSex= 0,5-Default              0.0000000
InitConnLike=0,55-Default                 0.0000000
InitConnMarriedConc-Default               0.0000000
InitConnRand=0,1-Default                  0.0000000
Initiate sex = 0,5-Default                0.0000002
IntConnPopgrowth-Default                  0.0000000
IntConnProbDivorce-Default                0.0000000
IntConnSexualDrive-Default                0.0004350
Likeability =  0,55-Default               0.0000000
Pop growth-Default                        0.0000000
```

Female agents

```
             Df Sum Sq Mean Sq F value Pr(>F)
Group        11  818.3   74.39   72.59 <2e-16 ***
Residuals   576  590.2    1.02
Tukey multiple comparisons of means 95% confidence level
                                           p adj
InitConnCourtship-Default                 0.0000000
InitConnDefault-Default                   0.0126388
InitConnInitSex= 0,5-Default              0.0000000
InitConnLike=0,55-Default                 0.0000000
InitConnMarriedConc-Default               0.0000000
InitConnRand=0,1-Default                  0.0000000
IntConnPopgrowth-Default                  0.0000000
IntConnProbDivorce-Default                0.0000000
IntConnSexualDrive-Default                0.0000948
Likeability =  0,55-Default               0.0000000
Pop growth-Default                        0.0000000
Likeability =  0,55-InitConnDefault       0.0000000
Pop growth-InitConnDefault                0.0048293
```

Figure 6.9: **Scenario 2: ANOVA results for male and female median age at first marriage**

On the other hand, increasing the population growth rate from 0,02 to 0,03 (Case IV) decreases the percentage of agents in a sexual relationships outside marriage to



(a) Sexual relationships outside marriage (b) Concurrent relationships

Figure 6.10: **Parameter effects on the percentage of agents involved in sexual relationships and concurrent relationships**

17%. This is caused by the fact that the percentage is calculated over the number of agents in the model. As the rate of population growth increases, it also increases the total number of agents and not necessarily the number of agents involved in a sexual relationship; hence, a decrease in the percentage of agents involved in a sexual relationship.

ANOVA results confirm that there are significant differences in the percentage of agents in sexual relationships outside marriage when these four parameters are varied. Post-hoc comparisons using the Tukey multiple comparisons of means results are given in Appendix C.15. In addition, these results of increasing the probability to initiate sex is also significantly different from comparable results for the other seven parameter changes explored here.

Concurrency levels in the model are affected by a change in the decision to initiate a sexual relationship (Case II), increasing the probability of concurrency for married agents (Case V) and using an age dependent probabilistic divorce criterion (Case VIII). An increase in the probability to initiate a sexual relationship and concurrency for married agents increases concurrency levels in the model while using a probabilistic divorce criterion decreases them. The percentage of agents in concurrent relationships increases from approximately 6% to 8,5% when the probability to initiate sexual relationship is increased from 0,03 to 0,5.

Increasing concurrency probability to 0,8 and 0,5 for married male and female agents, respectively, resulted in a continuous increase in concurrency for about 42 years of the 50 simulation years. The increase starts to stabilise to approximately 8,5% from year 43 to year 50. We cannot conclude that the stability will continue if more simulation years are added. What we can conclude from our model results is that if there is an increase in the number of married agents who can maintain multiple partners at the same time, concurrency levels increase in a society.

Changing divorce criteria decreases concurrency levels in the model. Concurrency levels reduced to approximately 2,5% from 6% (general simulation run). This may be due to the fact that ending a marriage relationship is much easier when using probabilities than when using attractiveness and marriage duration (see Figure 6.10(b)); hence, a reduction in concurrency for married agents. Box plots and ANOVA results to confirm the differences in means are in Appendix B.15(a) and C.16, respectively.

Scenario 2

Case I, II and V parameter variations increase the percentage of agents in a sexual relationship outside marriage under Scenario 2. The same parameters had a similar effect in Scenario 1. The most increase for both scenarios is observed when the probability to initiate sexual activities (Case II) is increased to 0,5. Increasing the population growth rate (Case IV) decreases the percentage of agents in a sexual relationship. Percentage of agents in a sexual relationship is calculated as a fraction of the total population. If the population grows at a faster rate compared to the number of agents that initiate sexual activities, the percentage decreases. This explains why there is a decrease in the percentage of agents in a sexual relationship as the population growth rate increases. Box plots and ANOVA results are in Appendix B.14(b) and C.15.

A decrease in concurrency levels under Scenario 2 is observed when an age dependent probabilistic divorce criterion (Case VIII) is used. This result is similar to the one obtained under Scenario 1. Two other parameter variations: Case III and IV (random partner search and population growth rate) decrease the percentage of concurrent partners under Scenario 2. On the other hand, increasing the probability of initiating sex (Case II) and the probability of having concurrent partners for married agents (Case V) significantly increases the percentage of concurrent partners (see box plot diagrams Appendix B.15(b) and ANOVA results Appendix C.16).

6.3.6 Divorce rate and duration

Scenario 1

Changing the divorce criteria from one based on the duration of marriage and attractiveness of the potential marriage partner to a probabilistic age dependent approach (Case VIII) increased the divorce rate and the marriage duration of divorcing couples in the model. The median marriage duration of divorcing couples using the probabilistic age dependent approach is approximately equal to 270 weeks. When using the duration of marriage and the attractiveness of the potential marriage partner, which is the setting used in our general simulation run, the median marriage duration for divorcing couples is approximately equal to 70 weeks. Box plot and ANOVA results for the marriage duration of divorcing couples and crude divorce rate are in Appendix B, Figure B.16(a) and Appendix C, Figure C.17 and C.18, respectively. If divorce is based on an age dependent probability distribution, an increase in divorcing couples is observed. This increases the divorced sub-population in the model. This consequently increases the number of remarriages from divorced agents. As the divorced sub-population increases, the variation in the model results for the median remarriage age for divorced agents decreases. This shows that increasing the population size in the model may result in more accurate results for the median remarriage age for the divorced sub-population.

Scenario 2

An age dependent probabilistic divorce criterion (Case VIII) increases crude divorce rate and the marriage duration of divorcing couples under Scenario 2. This is the same result obtained under Scenario 1. The median duration under Scenario 2 is slightly less (approximately 260 weeks) than that obtained under Scenario 1. According to the ANOVA results, the difference is not significant. The crude divorce rate is significantly higher for Scenario 2 as compared to Scenario 1 results.

Another factor that increases, crude divorce rate under Scenario 2 is increasing the probability to initiate sexual activities (Case II) for courting couples. We are not sure why increasing the probability to initiate sexual activities has a significant effect on the crude divorce rate. Further analysis is needed to understand this result.

6.3.7 Concluding remarks: Social and sexual network results

From the parameter variations done, we can conclude that decreasing the likeability index to 0,55 for agents below the median age of first marriage and increasing the probability to initiate sexual activities have an impact on most of the model results under both scenarios. For example, decreasing the likeability threshold decreases the age at first marriage; decreases the percentage of never coupled agents; increases the percentage of married agents below 40 years; and also increases the percentage of agents involved in sexual relationships outside marriage.

Initialising the model with at least one connection for all agents (Scenario 2) did affect most of the results obtained as compared to Scenario 1 model settings where n agents are selected to have connections at model intialisation. Under Scenario 2, we observed that there was a significant decrease in the percentage of never coupled agents across all parameter variations. There were also significant increases in the percentage of married male and female agents below 30 years, and the percentage of agents in sexual and concurrent relationships. This shows that if the friendship network is dense, the interaction of agents and their sexual behaviour changes the structure of the sexual network. In the next section, we present results obtained when population growth is implemented using childbirth.

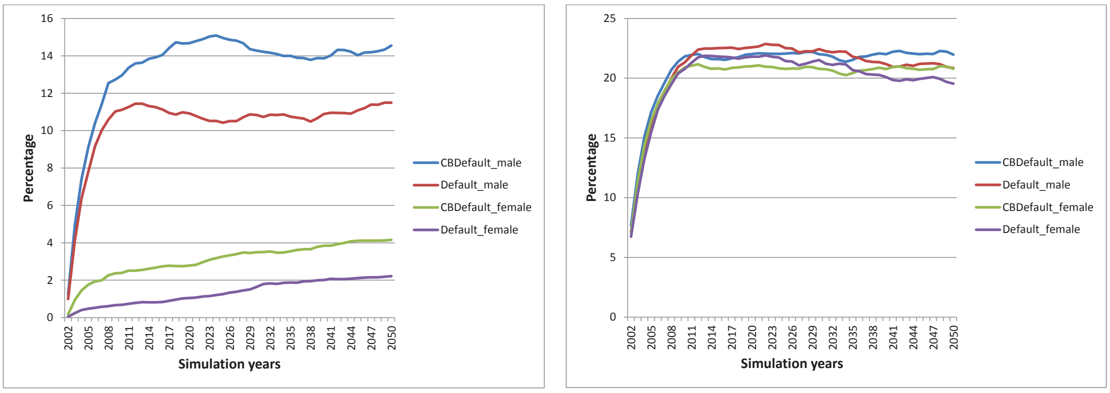
6.4 Simulation results: population growth through childbirth

This section presents results obtained for the social and sexual network when agents are added to the model through childbirth. Results that deal specifically with childbirth are presented in Section 6.4.3. Agents that are born during simulation run are assigned parameters just as all other agents at model initialistion. Social and sexual networking will only start when the new agents turn 15 years. The main aim of modelling childbirth is for us to investigate the parameters that are sensitive to child birth and how they affect population growth in a human society. The final objective of the model developed in this thesis is to include mother-to-child transmission of HIV. Understanding how childbirth is affected by the parameters in the model will help us to also understand the dynamics of mother-to-child transmission.

The general simulation model with child birth uses the same parameters as the general simulation model with results presented in Section 6.2. The only difference is that agents in this case are added through childbirth, which is dependent on the female's reproductive lifespan, sexual life and the number of children a female agent wishes to have. The birth rate in Scenario 3 and 4 mimics the fertility rate observed in South Africa. We gave a detailed description of how childbirth is implemented in our model in Section 5.6. In the following sub-section we compare the social and sexual network model results for the general simulation model with childbirth with those for the general simulation model presented in Section 6.2

6.4.1 General simulation model results with childbirth compared to the general simulation model results

An analysis of the marriage statistics results did not show significant differences in the median age at first marriage, marriage hazard ratios and divorce rate between the two general simulation models. Median age at first marriage remains at 27 years for females and 31 years for males. Divorce rate is basically the same in both models. There are also no significant differences in the marriage hazard ratios for both genders for the two models. However, significant differences are observed on the marriage percentages per age group and never coupled agents. The general simulation model with childbirth has higher percentages of married agents from 20 years and above for both genders. The never coupled population is also higher than that for the general simulation model without childbirth. The higher percentages in the general simulation model with childbirth are due to an increase in population size.



(a) Percentage of agents with concurrent partners

(b) Percentages of agents involved in sexual relationships outside marriage

Figure 6.11: Model average results over 10 model runs.

No significant differences are observed in the married partner quality correlation between the two general simulation models. Married partner quality correlation lies between 0,6 and 0,75 for both models. The results for the percentage of agents in sexual relationships are also similar in both general simulation models, with approximately 21% of agents being in a sexual relationship, excluding agents in marriage. Male agents have a slightly higher percentage (21,5%) than female agents. Significant differences, are, however observed in the percentage of agents in concurrent relationships. In the former general simulation model results, percentage of male and female agents in concurrent relationships stabilised at approximately 11% and 2%, respectively. In the general simulation model with childbirth, the percentage for male and female agents is higher, stabilising at approximately 14,5% and 4%, respectively, (see Figure 6.11 for the graphs of percentages of agents in sexual relationships and concurrent relationships).

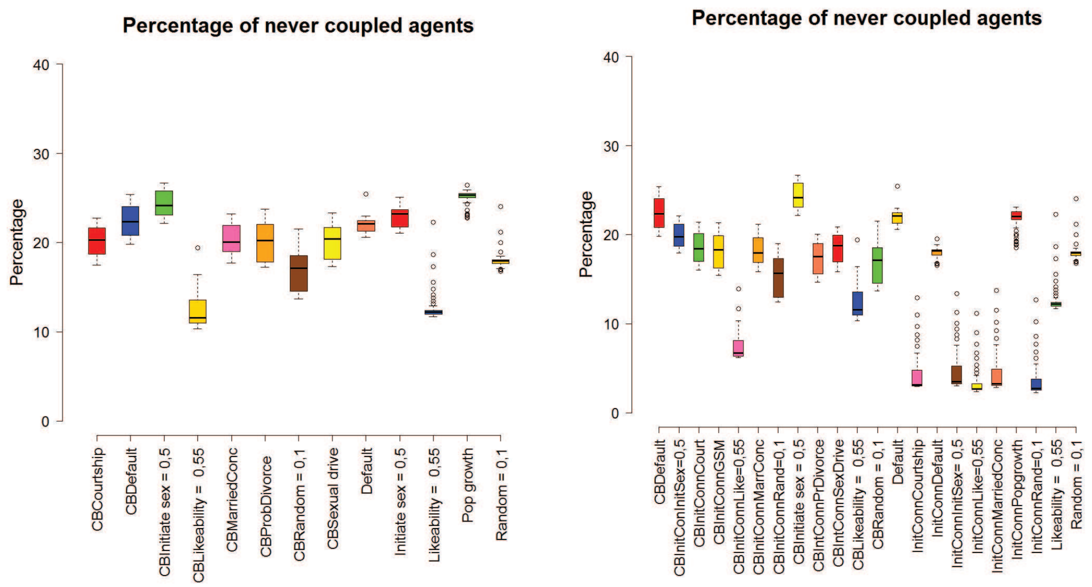
6.4.2 Comparison of simulation results: parameter changes effect on model results with childbirth

In this section, we present results related to childbirth in the model. We also consider two scenarios as described in Section 6.3, and we name them Scenario 3 and Scenario 4. As a reminder, in Scenario 1, we use the general simulation model settings and vary eight parameters (Case I to VIII) listed in Table 6.2. Introducing childbirth in Scenario 1 model settings results in a third scenario (Scenario 3).

In Scenario 2, we initialise the model with all agents having a random number of friendship connections between one and the maximum degree of friendship connections an agent can have. New agents entering the population during the simulation run will immediately create friendship connections as at model initialisation. Introducing childbirth in Scenario 2 model settings results in a fourth scenario (Scenario 4). The rate at which the population grows in Scenario 3 and 4 is significantly different from the increase observed under Scenario 1 and 2. The highest population growth rate in Scenario 3 and 4 is observed when likeablity threshold is decreased to 0,55 and the probability to initiate sex is increased to 0,5.

Never coupled agents

Decreasing the likeability threshold to 0,55 (Case I) and increasing the probability of random search to 0,1 (Case III) resulted in a decrease in the percentage of never coupled agents. The same adjustment of these two parameters had similar effects on



(a) Scenario 3 (b) Scenario 4

Figure 6.12: **Parameter effects on the percentage of never coupled agents**

never coupled agents under Scenario 1 and 2. Changing concurrency probability for married agents (Case V), courtship duration (Case VI), sexual drive (Case VII) and the divorce criterion to an age dependent probabilistic one (Case VIII) did not show significant differences with Scenario 3 general simulation run results.

Surprisingly, increasing the probability of initiating sex (Case II) resulted in an increase in the percentage of never coupled agents. An analysis of the population growth rate revealed that increasing the probability of initiating sex resulted in one of the highest population growth rates. An increased population growth rate means that agents will be added to the model faster than they are finding matching partners, hence an increase in the never coupled percentage. This could be one of the reasons why there is an increase in the percentage of never coupled agents when the probability to initiate sex is increased (see box plots and ANOVA results in Figure 6.12 and Appendix E, Figure E.1, respectively).

Initiating the model with all agents having at least one friendship connection and population growth through childbirth (Scenario 4) resulted in a general decrease in the percentage of never coupled agents for all parameter variations, including the general simulation run for Scenario 4 as compared to the general simulation run for

Scenario 3. However, the decrease is not as much as the one observed in Scenario 2. This may be due to the fact that in Scenario 4, the population is being added faster than it is in Scenario 2, hence more never coupled agents are added at each time step resulting in a lower decrease in the never coupled percentage.

Varying the concurrency probability for married agents (Case V), courtship duration (Case VI) and sexual drive (Case VII) did not have a significant impact on the model results for Scenario 4 simulation run results. This is similar to the result obtained in Scenario 3. Therefore, we can conclude that varying these three parameters do not have a significant effect in the rate at which uncoupled agents get partners. Box plots and ANOVA results for simulation results discussed here are in Figure 6.12 and Appendix E, Figure E.1, respectively.

Percentage of married agents per age group

The percentage of married agents per age group for all age groups and both genders in Scenario 3 and 4 are generally higher as compared to Scenario 1 and 2 though the increase in some of the female age groups (15 to 19 (for example see ANOVA results in Figure 6.13), 20 to 29 and 60 plus age groups) is not statistically significant. The general increase in the percentage of married agents per age group is attributed to an increase in the total population of agents in Scenario 3 and 4 model settings. An increase in total population increases the pool where agents can search for potential mates; hence more agents can marry. Box plot results in Appendix D from Figure D.2 to Figure D.13 confirm the significant increase in the percentage of married agents per age group.

A further increase in the percentage of married agents per age group for both genders is observed when the likeability threshold (Case I) is reduced to 0,55 for agents below the mean age at first marriage. The percentage increases are in the age groups 20 to 29, 30 to 39, and 40 to 49 years, compared to the general simulation run for both Scenario 3 and 4. In the age group 20 to 29 years, the percentage increases by approximately 8% (Scenario 3) and 11% (Scenario 4) for both females and males. In the 30

ANOVA results married females (less than 20 years)

Scenario 3

```
              Df Sum Sq Mean Sq F value Pr(>F)
Group          9   66.4   7.377   2.067 0.0509 *
Residuals    490 1748.3   3.568
```

Scenario 4

```
              Df Sum Sq Mean Sq F value Pr(>F)
Group         13  964.6   74.20   25.22 <2e-16 ***
Residuals    686 2017.9    2.94
Tukey multiple comparisons of means 95% confidence level
                                            p adj
CBInitConnGSM-CBDefault                 1.0000000
CBInitConnGSM-CBInitConInitSex=0,5      0.0345252
CBInitConnGSM-CBInitConnCourt           0.9666245
CBInitConnLike=0,55-CBInitConnGSM       0.3549438
CBInitConnMarrConc-CBInitConnGSM        1.0000000
CBInitConnRand=0,1-CBInitConnGSM        0.9999991
CBIntConnPrDivorce-CBInitConnGSM        0.9999727
CBIntConnSexDrive-CBInitConnGSM         1.0000000
Default-CBInitConnGSM                   0.6246726
InitConnCourtship-CBInitConnGSM         0.0000000
InitConnDefault-CBInitConnGSM           0.9997211
InitConnInitSex= 0,5-CBInitConnGSM      0.0000000
Pop growth-CBInitConnGSM                0.9956198
```

Figure 6.13: **ANOVA results for married female agents between 15 and less than 20 years**

to 39 year age group, the percentage increases for Scenario 3 are approximately 10% and 13% for females and males, respectively. Scenario 4 increases are approximately 11% and 15% for females and males, respectively. A significant increase is also observed in the 40 to 49 year age group. The increases are approximately 3,5% and 7% (Scenario 3 and 4) for females and males repectively. Age groups above 50 years and below 20 are not significantly affected by a decrease in the likeability threshold.

Increasing the probability to initiate a sexual relationship (Case II) caused significant increases in the percentages of married agents for some age groups. A significant increase is observed in the 20 to 29 year age group for both genders in both Scenario 3 (approximately 5%) and 4 (approximately 6%). An increase is also observed in the 30 to 39 year age group for both genders in Scenario 3 (approximately 3%), but only for female agents in scenario 4 (approximately 3%). Male agents do have an increase but ANOVA results show that the increase is not significantly different from the general simulation run results for Scenario 4. However, a significant increase is observed for the 15 to 19 year age group for male agents in Scenario 4 only.

An age dependent probabilistic divorce criterion (Case VIII) resulted in significant decreases in the percentage of married agents per age group in age groups above 50 years for male agents and in age groups above 40 for female agents compared to the general simulation run results for Scenario 3 and 4. Females have the largest decrease of approximately 8% in the age groups above 50 years in both scenarios.

Decreasing the mean for courtship duration (Case VI) significantly increased the percentage of married agents for both genders in the 20 to 29 year age group for Scenario 3 only. In Scenario 4, there is an increase in the percentage of married agents in the same age group but it is not significantly different from the general simulation run results for that scenario. In a normal society, the largest percentage of courting individuals are in the 20 to 29 year age group. Therefore, decreasing the courtship duration increases the number of agents who will marry in this age group. A longer courtship duration increases break up chances for courting agents if a better partner is encountered. Agents that break up start a new courting period when they initiate a new relationship. This lengthens the period an agent will marry and also increases the age at which the agent will finally settle down to marry. The average median age at first marriage results show that changing the courtship duration decreased the median age at first marriage by at most one year, but the decrease is not significantly different from the default median age at first marriage (see box plot results in Figure 6.14 and ANOVA results in Appendix E Figure E.14 and E.15).

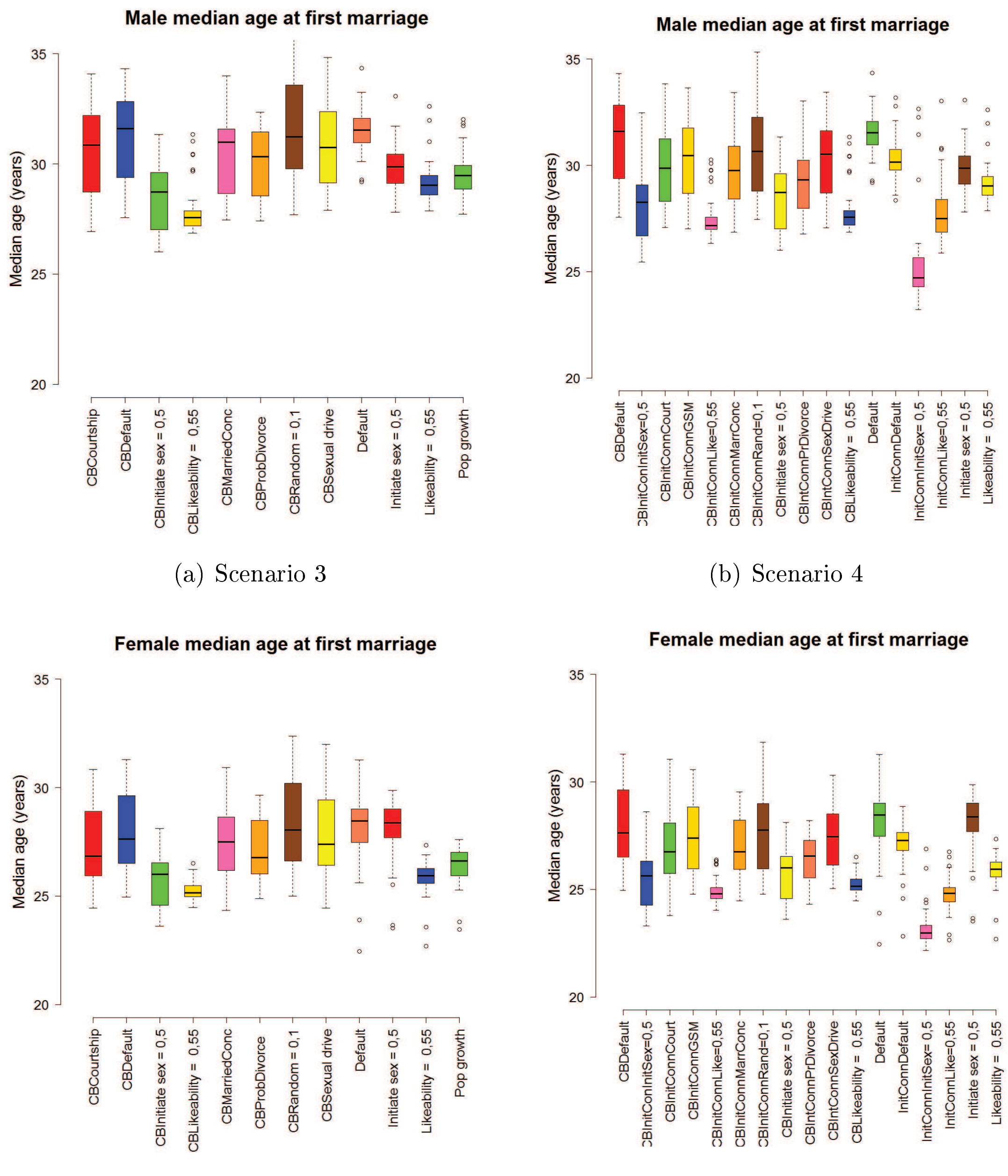
Increasing concurrency probability for married agents decreased the percentage of married agents in the 40 to 49 and 50 to 59 year age groups for female agents in Scenario 3 only. The percentage for male agents decreased slightly but the decrease is not significantly different from Scenario 3 general simulation run. This may be attributed to the fact that female agents above 40 years (never coupled, divorced and widowed) may be involved in romantic relationships that do not necessarily lead to marriage with married male agents above 40 years; hence the decrease in the percentage of married female agents in the age groups between 40 and 60. The reason stated here is one of the possibilities but there is need to investigate this result further. This can be done by collecting data about the marital status, the type of romantic relationships of agents that are in romantic relationships in this age group.

Results obtained here are quite comparable to results obtained under Scenario 1 and 2 model settings though two more parameters (Increasing concurrency probability for married agents and decreasing the mean for courtship duration (Case VI)) showed significant differences with the general simulation results for Scenario 3. Results obtained in Scenario 3 for varying the likeability threshold further supports the notion that relaxing the likeability threshold leads to more agents coupling early enabling marriage to happen earlier than when the likeability threshold is high. A decrease in the percentage of married agents per age group after changing the divorce criterion supports the fact that older divorced women and men are less likely to find a suitable partner to remarry after divorcing at age 50 or above, with women being affected the most.

Box plot results for all age groups are in Appendix D: Figures D.2 to D.13. ANOVA results for all age groups are in Figure 6.13 and Appendix E Figure E.3 to E.13.

Median age at first marriage

Median age at first marriage is affected by a decrease in likeability threshold (Case I) and an increase in the probability to initiate sex (Case II) in both Scenario 3 and 4. Varying these two parameters in Scenario 3 resulted in a decrease in median age at first marriage from 31 years to 28 years and 27 years to 25 years for both male and female agents, respectively.



(a) Scenario 3 (b) Scenario 4

(c) Scenario 3 (d) Scenario 4

Figure 6.14: **Male and female median age at first marriage**

In Scenario 4, decreasing likeability threshold (Case I) resulted in a decrease in median age at first marriage by approximately 4 and 3 years for male and female agents, respectively. An increase in the probability to initiate sex (Case II) decreased the median age at first marriage to 28 years (male) and 25,4 years (female). In addition to these two parameter variations, a third parameter, age dependent probabilistic divorce criterion (Case VIII), also decreased the median age at first marriage by approximately one year for both male and female agents.

In all instances, the male median age at first marriage remains higher than the female median age at first marriage. Decreasing likeability threshold (Case I) and increasing the probability to initiate sex (Case II) had similar effects in Scenario 1 and 2, with initiating sex affecting only male median age at first marriage in Scenario 1. An age dependent probabilistic divorce criterion had a significant effect on median age at first marriage only in Scenario 4. Box plot results for median age at first marriage are in Figure 6.14; ANOVA results are in Appendix E Figure E.14 to E.15.

Partner quality correlation

Only one parameter, likeability threshold, decreased the attractiveness correlation for married agents, to approximately 0,58. Correlation stabilises at about 0,7 for all other parameter variations, including the general simulation run for Scenario 3 and 4. Results obtained for Scenario 3 and 4 are not significantly different from those obtained in Scenario 1 and 2. Therefore, we can safely conclude that the quality correlation of married partners is not affected by childbirth or by an increase in the total population. Box plot results for quality correlation are in Appendix D, Figure D.1; ANOVA results are in Appendix E, Figure E.2.

Percentage of agents in a sexual relationship outside marriage and concurrency

Results obtained from Scenario 3 and 4 simulations (general simulation run and parameter variations) are quite similar to those obtained under scenario 1 and 2. Decreasing likeability threshold (Case I), increasing the probability of initiating a sexual relationship (Case II) and increasing the probability of concurrency for married agents

(Case V) resulted in an increase in the percentage of agents involved in a sexual relationship outside marriage compared to other parameter variations and Scenario 3 and 4 general simulation runs. In Scenario 1 and 2, the same 3 parameters also resulted in an increase in the percentage of agents involved in a sexual relationship outside marriage. The only difference is that, in Scenario 3 and 4, increasing the probability of concurrency for married agents (Case V) had the highest increase whereas under Scenario 1 and 2, increasing the probability of initiating sexual relationships had the largest effect.

The percentage of agents involved in a sexual relationship outside marriage increased from approximately 21% (general simulation run Scenario 1, 2, 3 and 4) to approximately 29% (Scenario 3 and 4) when the probability of concurrency for married agents is increased. This is the largest increase compared to the increase observed by varying the likeability threshold (Case I) and increasing the probability of initiating sexual relationships (Case II). This may be attributed to an increased population size. Increased population size increases variety for agents that prefer to have concurrent partners and can easily find mates in the population. The other two parameter adjustments (likeability threshold (Case I) and probability of initiating sexual relationships (Case II)) increased the percentage by approximately 4 to 6%.

Using an age dependent probabilistic divorce criterion decreased the percentage (from 21% to 18%) of agents involved in a sexual relationship outside marriage in both Scenario 3 and 4. This may be due to the fact that divorced agents can marry agents with whom they have a sexual relationship, hence decreasing the percentage of agents involved in a sexual relationship outside marriage. ANOVA results confirm that there are significant differences in the percentage of agents in a sexual relationships outside marriage when these four parameters are varied. ANOVA results and post-hoc comparisons results using the Tukey multiple comparisons of means are given in Appendix E, Figure E.16.

Two parameters: increasing the probability to initiate a sexual relationship (Case II) and increasing the probability of concurrency for married agents (Case V) resulted in an increase in concurrency levels in Scenario 3 and 4 model settings. The same parameters resulted in an increase in concurrency levels in Scenario 1 and 2. In Scenario 1 and 2, increasing the probability to initiate sex had the largest increase (from approximately 6% to 8,5%) but in Scenario 3 and 4, increasing the probability of concurrency for married agents has the largest increase (from 8,5% to approximately 15%). The increase in concurrency after increasing the probability of concurrency for married agents tallies with the result obtained for agents in a sexual relationship outside marriage in Scenario 3 and 4. Increasing the probability of concurrency for married agents also resulted in the highest percentage of agents involved in a sexual relationship outside marriage in the two scenarios.

Using an age dependent probabilistic divorce criterion decreases concurrency levels. This also happened under Scenario 1 and 2. The percentage of agents in concurrent relationships decreases by approximately 4,5% from 8,5% (Scenario 3 and 4 general simulation run). This further supports the idea that ending a marriage relationship in our model is much easier when using probabilities than when using attractiveness and marriage duration, hence a reduction in concurrency for married agents. Box plots and ANOVA results to confirm the differences in means are in Appendix D, Figure D.15 and Figure 6.15, respectively.

Divorce rate and duration

Changing the divorce criteria from one based on the duration of marriage and attractiveness of the potential marriage partner to an age dependent probabilistic approach (Case VIII) increased the divorce rate and the marriage duration of divorcing couples in Scenario 3 and 4 (same result obtained in Scenario 1 and 2). The median marriage duration of divorcing couples using the age dependent probabilistic approach remains approximately equal to 270 weeks (Scenario 1 and 2 result). When using the duration of marriage and the attractiveness of a potential marriage partner (the setting used in our general simulation run) the median marriage duration remains approximately equal to 70 weeks which is much lower than the empirical data value of approximately 260 weeks (StatsSA, 2012, p. 10). There is a need to refine the parameters for divorce

ANOVA results for concurrent agents (in or outside marriage)

Scenario 3

```
              Df Sum Sq Mean Sq F value Pr(>F)
Group         12   4982   415.2   181.8 <2e-16 ***
Residuals    624   1425     2.3
Tukey multiple comparisons of means 95% confidence level
                                              p adj
CBDefault-CBCourtship                         1.0000000
CBInitiate sex = 0,5-CBDefault                0.0000000
CBLikeability =  0,55-CBDefault               0.6111787
CBMarriedConc-CBDefault                       0.0000000
CBProbDivorce  -CBDefault                     0.0000000
CBRandom = 0,1-CBDefault                      0.9616609
CBSexual drive-CBDefault                      0.9932608
Default-CBDefault                             0.0000000
Initiate sex = 0,5-CBDefault                  1.0000000
Married concurrency-CBDefault                 0.0226272
Pop growth-CBDefault                          0.0000000
Probabilistic divorce  -CBDefault             0.0000000
```

Scenario 4

```
              Df Sum Sq Mean Sq F value Pr(>F)
Group         22   9596   436.2   256.6 <2e-16 ***
Residuals   1104   1877     1.7
Tukey multiple comparisons of means 95% confidence level
                                              p adj
CBInitConnGSM-CBDefault                       0.9979710
CBInitConnGSM-CBInitConInitSex=0,5            0.0000000
CBInitConnGSM-CBInitConnCourt                 1.0000000
CBInitConnLike=0,55-CBInitConnGSM             0.3859296
CBInitConnMarrConc-CBInitConnGSM              0.0000000
CBInitConnRand=0,1-CBInitConnGSM              1.0000000
CBInitiate sex = 0,5-CBInitConnGSM            0.0000000
CBIntConnPrDivorce-CBInitConnGSM              0.0000000
CBIntConnSexDrive-CBInitConnGSM               0.9726236
CBMarriedConc-CBInitConnGSM                   0.0000000
CBProbDivorce  -CBInitConnGSM                 0.0000000
Default-CBInitConnGSM                         0.0000000
InitConnCourtship-CBInitConnGSM               0.0000000
InitConnDefault-CBInitConnGSM                 0.0000001
InitConnInitSex= 0,5-CBInitConnGSM            1.0000000
InitConnMarriedConc-CBInitConnGSM             0.6916793
InitConnRand=0,1-CBInitConnGSM                0.0000000
Initiate sex = 0,5-CBInitConnGSM              0.9992180
IntConnPopgrowth-CBInitConnGSM                0.0000000
IntConnProbDivorce-CBInitConnGSM              0.0000000
Married concurrency-CBInitConnGSM             0.5477152
Probabilistic divorce  -CBInitConnGSM         0.0000000
```

Figure 6.15: **ANOVA results for agents with concurrent partners**

in our model using calibration. We leave this as area for further research. Box plot and ANOVA results for the marriage duration of divorcing couples and crude divorce rate are in Appendix D, Figure D.16 and D.17 and Appendix E, Figure E.17 and

E.18, respectively.

6.4.3 Child birth results

The percentage of pregnant females in a population dictates how population grows in a society. In our model, increasing probability to initiate a sexual relationship (Case II) and decreasing likeability threshold (Case I) resulted in an increase in the percentage of pregnant females as compared to Scenario 3 general simulation results. An increase in the percentage of pregnant females consequently led to an increase in the percentage of females waiting in-between[6] childbirth. The percentage of single fertile females in the population decreases with a decrease in likeability threshold and an increase in the probability to initiate sex. Also, there is a significant increase in total fertility and the percentage of first marriages when the probability to initiate a sexual relationship (Case II) is increased and likeability threshold (Case I) is decreased. The decrease on the percentage of single fertile females and an increase in total fertility ties well with an increase in the percentage of pregnant females in this model. Box plots and ANOVA outputs for childbirth results discussed in this section are in Appendix F and G, respectively.

These two parameters (probability to initiate a sexual relationship (Case II) and likeability threshold (Case I)) also caused a significant increase in the percentage of agents involved in sexual relationships in Scenario 1 to 4 simulation runs. Therefore, we can conclude that variations in these two parameters have a significant impact on sexual activities in a society and population growth.

There is an increase in the marriage rate when the divorce criteria is changed to an age dependent probabilistic based one (Appendix F, Figure F.5) but this does not directly lead to an increase in pregnancy or fertility levels (Appendix F, Figure F.1 and F.4, respectively), in the model. Divorced agents remarry irrespective of their age and their decision to have children. If divorced female agents remarry after their

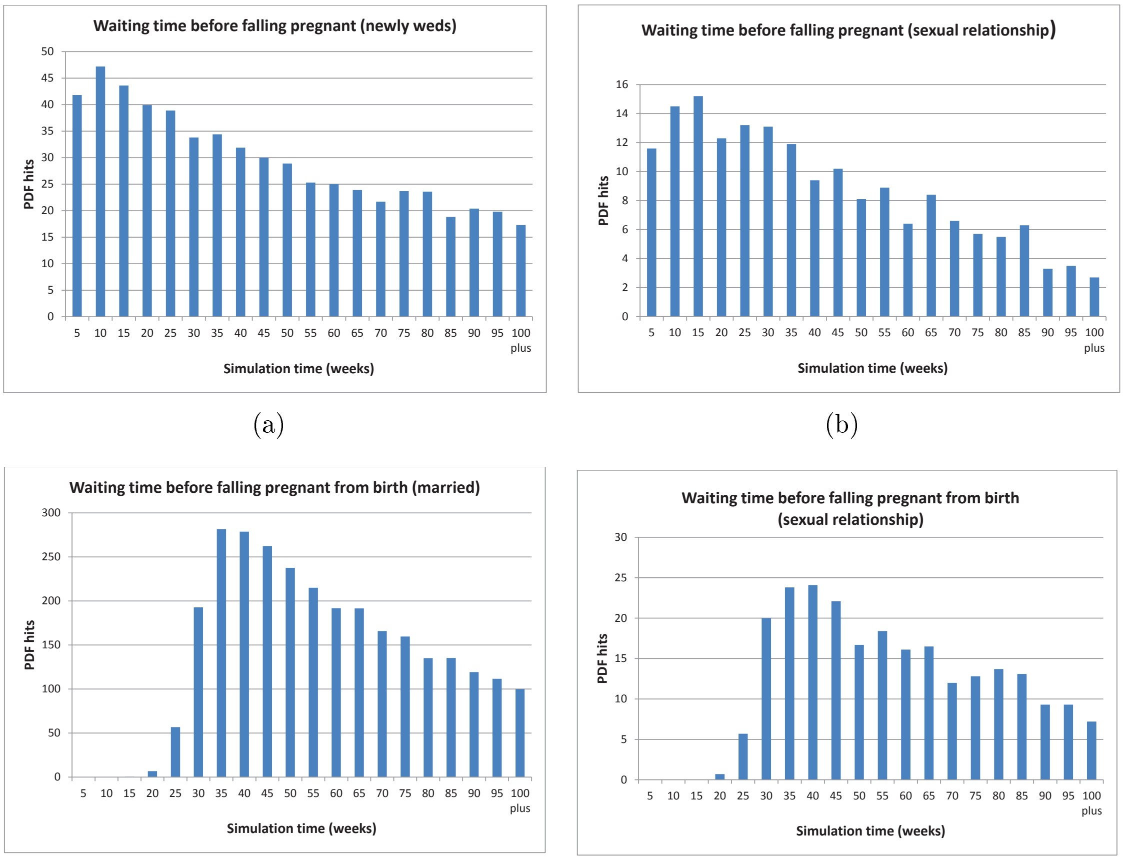
[6]In-between birth refers to fertile female agents that are still willing to have more children

fertility lifespan or after making a decision of not having more children, the marriage is recorded but it will not contribute to pregnancy rate and fertility levels. Hence, a change in the divorce criteria does not have a significant impact on fertility and pregnancy levels in Scenario 3 and 4 general simulation results.

Although increasing the probability for random partner search resulted in a decrease in the percentage of never coupled agents, it does not have a direct effect on the percentage of pregnant women (Appendix F, Figure F.1). An increase in the probability of random partner search increases the mixing chances of agents in the model which in turn increases the chance of meeting more attractive partners. Hence, relationships formed when the probability for random partner search is increased may not last long enough to result in pregnancy. Results collected also indicate that there is a significant increase in the number of agents that are fertile and single when the probability for random search is increased. In this thesis, the fertile single subset includes never coupled fertile females and those that have coupled at least once but have gone through a breakup.

There is a need to investigate more why a decrease in never coupled agents does not automatically lead to an increase in pregnancy and a significant increase in agents in a sexual relationship. This might be attributed to a quick break up of couples who mate through random search or a delay in initiating sexual activities. A simultaneous increase in the probability for random partner search and the probability to initiate a sexual relationship may result in a high pregnancy rate. We leave this as an area for further research. In this thesis, we do not investigate the impact of varying parameters simultaneously on model results.

In our model, pregnancy is only possible if a female agent is involved in a sexual relationship or is married and is still within the fertility age group. Not all female agents in a sexual relationship can fall pregnant. Female agents that initiate a sexual relationship have a 0,2 chance of being put in the subset of agents that can fall pregnant during the course of the sexual relationship. Married females and females in a sexual relationship (only those selected to fall pregnant) have a probability of 0,01 of falling pregnant at each model time step. Female agents that give birth during the simulation run and those that have children at model initialisation have a 0,015 chance of falling pregnant at each model time step.



(a) (b) (c) (d)

Figure 6.16: **Waiting time before falling pregnant**

Using probabilities for falling pregnant as described in the previous paragraph, we obtained an asymmetrical distribution for pregnancy waiting times that tails off to the right (positively skewed) (see Figure 6.16). In this thesis, pregnancy waiting time is the time a woman spends before falling pregnant after marriage, initiating a sexual relationship or after birth. Pregnancy waiting time between births, is on average 81 weeks with a maximum of 532 weeks and a minimum of 15 weeks. Pregnancy waiting time from birth has a fixed minimum of 6 weeks set for all women regardless of the type of romantic relationship (see Section 5.6 for justification of six weeks fixed minimum). Waiting times for female agents initially married, that get married during the simulation run and those in a sexual relationship is on average 85 weeks with a maximum of 617 weeks and a minimum of 0,5 weeks.

Simulation results also give the number of children born to a female before the end of the reproductive lifespan. Figure F.6(a) in Appendix F shows the distribution of number of children per female. The distribution is positively skewed. Approximately 13% of female agents who have children in their lifetime have eight or more children. Most of the women (87%) have less than eight children. Our model result for women with more than eight children is higher by approximately 5,4% compared to the data obtained in literature (StatsSA, 2003, p. 49) and vise-versa. Researchers who compiled the StatsSA (2003) noted that the data provided should be treated with caution since there were possibilities of under-reporting of births. Our model counts the number of births for a female agent. We do not track if the child survives or not. This may explain why we have a higher percentage of females with eight or more children compared to empirical data. Not all females in the model have children before death. There are some females who die before getting a mate hence die without having children. From the data collected, most of the women who die before coupling and having children are below 20 years. The numbers decrease with age (see Figure F.6(b) in Appendix F).

6.4.4 Conclusion

Introducing childbirth in the model resulted in a general increase in the total population at the end of each simulation run. This consequently increased the percentage of married agents per age group, agents in sexual relationships outside marriage, agents with concurrent partners and never coupled agents. An increase in the total population results in an increase in the pool from which agents search for potential partners. This increases the chances of partnering hence an increase in the percentage of married agents, agents in sexual relationships outside marriage and agents with concurrent partners. Child birth resulted in an increase in the population below 15 years. As the agents below 15 years mature they get into the never coupled group. The rate at which people enter the never coupled population increased compared to the previous scenarios. This, in turn, increased the percentage of never coupled agents in the model. Results for varying parameters in Scenario 3 and 4 are quite similar to those obtained in Scenario 1 and 2 though with higher percentages in all categories discussed in this thesis.

An age dependent probabilistic divorce criterion significantly increased marriage and divorce rate. It decreased the percentage of agents involved in a sexual relationship outside marriage, agents with concurrent partners and the percentage of married agents above 40 and 50 years for female and male agents, respectively, in all scenarios. Decreasing the likeability threshold to 0,55 for agents below the mean age at first marriage decreased married partner correlation, percentage of never coupled agents and the median age at first marriage. A decrease in partner correlation, median age at first marriage and never coupled agents lead to an increase in the percentage of agents involved in sexual relationships outside marriage and the percentage of married agents between 20 and 50 years for both male and female agents. However, it did not have any significant impact on the percentage of agents with concurrent partners and of married agents below 20 years and above 50 years.

Increasing the probability to initiate a sexual relationship caused a significant decrease in the median age at first marriage in all four scenarios and married partner correlation only in Scenario 2. Significant increases are observed in the percentage of agents involved in a sexual relationship outside marriage, agents with concurrent partners and the percentage of married agents between 20 and 50 years for female and male agents. A significant increase is also observed for the percentage of married male agents below 20 years.

Varying the probability for concurrency levels of married agents significantly increased the percentage agents involved in a sexual relationship outside marriage and agents with concurrent partners. It caused significant decreases in the percentage of married agents in the 40 to 60 age range only in Scenario 3 and 4 and an increase in the 15 to 30 year age range only in Scenario 2.

Decreasing the courtship duration resulted in an increase in the percentage of married agents in the 20 to 40 year age group in Scenario 3 and 4. Random partner search decreased the percentage of never coupled agents in all scenarios and caused an increase in the percentage of married agents below 30 years in Scenario 2 only. Changing the sexual drive parameters as indicated in Table 6.2 did not result in any significant differences in model results in all scenarios. Increasing the population growth rate to 0,03 in Scenario 1 and 2 did not show significant differences. This may be due to the fact that the increase was not large enough to warranty differences. Using population growth through childbirth had a much higher impact in population growth and resulted in significant differences in model results.

We varied eight parameters in the model. Out of the eight parameters, two parameter variations had significant impact on model results for all scenarios, including use of childbirth statistics. These two parameters are decreasing likeability threshold to 0,55 for agents below the mean age at first marriage and increasing the probability to initiate a sexual relationship. These two parameters will be closely analysed in the model for the progression of HIV in a society. The next section presents results obtained for the progression of HIV in a society.

6.5 HIV/AIDS progression in a society

This section presents simulation model results focusing on HIV progression in a society. It is crucial to understand the factors that suppress or advance the pandemic. Micro and macrosimulation models have been developed to try and understand these factors but new infections are still being observed. More research must be done to assess how the interaction effects of bio-behavioural factors contribute to the new infections. However, it is not easy to physically measure the number of new HIV infections in different risk groups (UNAIDS, 2010, p. 6). Given such difficulties, simulation models may help in assessing and measuring the significance of the different risk behaviours.

In this thesis, the HIV pandemic drivers analysed are implicitly developed from the model assumptions. The model assumptions, among others, include partnership formation, the presence of CSWs, OPSWs and their clients in a population and probability of HIV transmission. Most of the HIV/AIDS parameter values used in the model were derived from literature. Where data were unavailable or unreliable, we used population-level pandemic trends to find the best set of parameters to use in the model.

We use the social and sexual network model with results presented in the previous section as our base model to analyse the drivers of HIV. Therefore, base simulation model is simply the social sexual network model superimposed with HIV infection without ART, sex work and condom use. We then modify the base model by introducing commercial and opportunistic sex activities as described in Section 5.5. We also include ART and a chance for protection from HIV infection (condom use and circumcision) to obtain our HIV/AIDS general simulation model. Parameters used in this model are explained in Section 5.7.1 to Section 5.7.3.

During parameter variation, we vary three bio-behavioural factors that affect HIV transmission and two model parameters from the social and sexual network model. The three bio-behavioural factors analysed are:

1. infection probability per coital act for agents who dropout of ART and agents who engage in commercial sex work;
2. ART enrolment; and
3. dropout of ART.

We derived ART uptake probabilities using population level ART uptake trends published by HSRC (2014, p. 100). The probabilities for ART uptake used in our model are on page 119 Table 5.4. Infection probability depends on the stage of HIV infection of the agent. Table 5.6 on page 127 shows the default infection probabilities used in our model. In our general simulation model, we multiply the default infection probabilities by five for CSWs, OPSWs and their clients as explained on page 128.

Two model parameters from the social and sexual network model, likeability threshold and probability to initiate sex, are also analysed during parameter variation. These two parameters had a significant impact on model results for all scenarios investigated under the social and sexual network model results, including use of child birth statistics. In our HIV general simulation model, we fix likeability threshold at 0,55 and probability to initiate sex at 0,03. During parameter variation, these two parameters are changed to values shown in Table 6.3.

Table 6.3: **Social and sexual network model parameter variations in the HIV general simulation model**

Parameter	**Value**
Likeability threshold	uniform(0,55;0,9)
Initiate sexual activities	0,5

It is important to note that there are many bio-behavioural factors that affect the transmission of HIV in a society and parameters which relate to various social and sexual aspects of the model, but due to time constraints only parameters and bio-behavioural factors mentioned here are considered in this thesis. We leave an analysis of other bio-behavioural factors and their interaction effects as an area that requires further research.

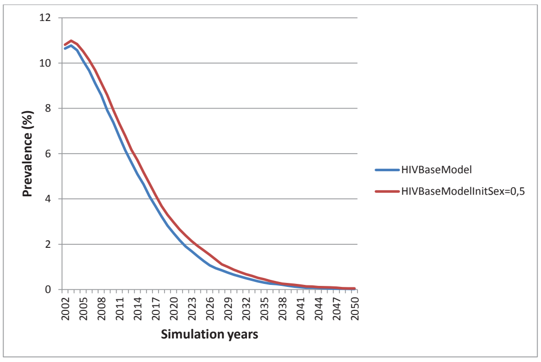
As discussed in the previous chapter in Section 5.8.1, we initialise HIV in the agent population using 2002 HIV prevalence data grouped by age and gender. The progression of HIV in our model depends upon the agents' interaction discussed in Chapter 5, including birth and death of agents. HIV positive agents may die prematurely due to AIDS. Children born to HIV infected mothers have a chance of being infected during birth.

No new infections are observed in the 2 to 15 year age group in all our model results. There is zero incidence in this age group since our model does not allow agents below 15 years to be in a sexual relationship. Prevalence levels in this age group depends on the new infections that happen during birth. In the following subsections, we discuss model results for the base simulation model, HIV general simulation model and results obtained after varying the two bio-behavioural factors and the two model parameters from the social and sexual network model.

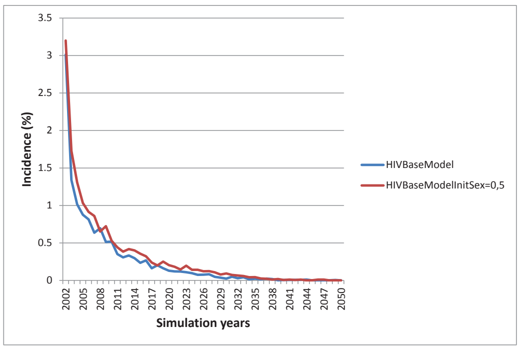
6.5.1 HIV base simulation model results

Basic results for HIV progression from the base simulation model are presented in this section. Results for HIV prevalence and incidence show a continuous drop over the 50 simulation years. Prevalence level falls below 0,1% from approximately 42 simulation years to the end of the simulation. The same trend in prevalence levels is observed after adjusting likeability threshold and probability to initiate sex to values indicated in Table 6.3. Though model results for adjusted likeability threshold and probability to initiate a sexual relationship resulted in an increase (compared to the base model simulation results) in prevalence levels, the increase is not statistically significant (See Figure 6.17(a)).

This shows that if the pattern of sexual relationships in a society are the same as those represented by our model, HIV progression will come to an end in approximately 42 years without social or biological interventions based on an initial 2002 HIV prevalence data. The drivers of HIV progression in the base model are agents with concurrent partners, HIV positive widows who remarry and mother to child transmission. The transmission of the virus through this sexual network is relatively slow, hence the decline observed in the model results.



(a) HIV prevalence

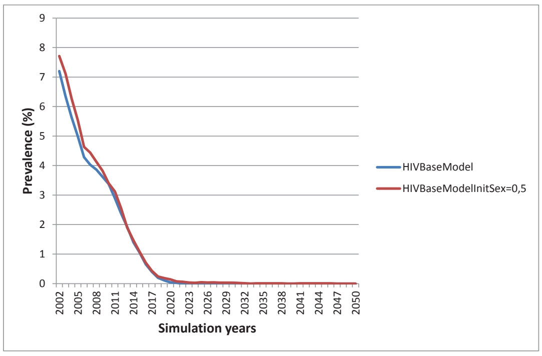


(b) HIV incidence

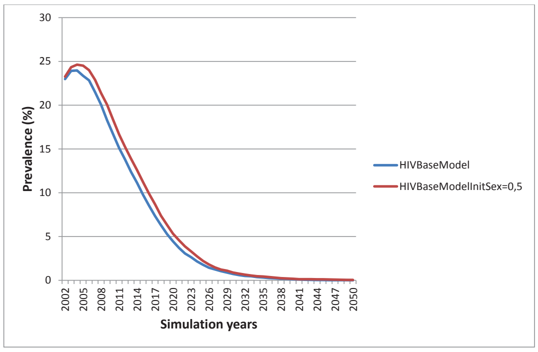
Figure 6.17: **Prevalence and incidence results for the base model.**

HIV prevalence level for female agents is higher compared to male prevalence (Figure 6.18(d) even with a continuous decrease in prevalence levels. This result compares well with real data, which always depicts a higher prevalence for females as compared to male prevalence. Results for age group prevalence show that the virus will disappear in the 15 to 25 years age group in approximately 20 years and in approximately 40 years in the 25 to 50 year age group.

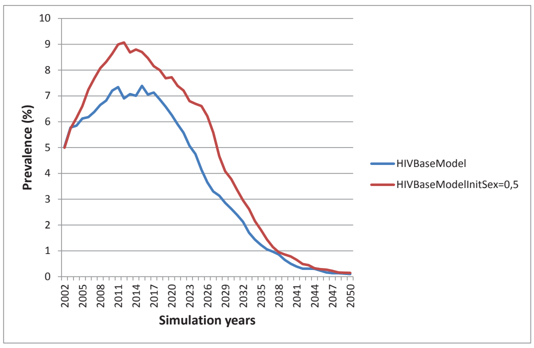
One interesting thing to note about age group prevalence is the prevalence for agents above 50 years. The prevalence level for this age group initially increases from approximately 5,2% and stabilises at 7% in 10 simulation years for the base simulation model. It then remains constant for approximately eight simulation years and starts to decrease for the remaining 32 simulation years (Figure 6.18).



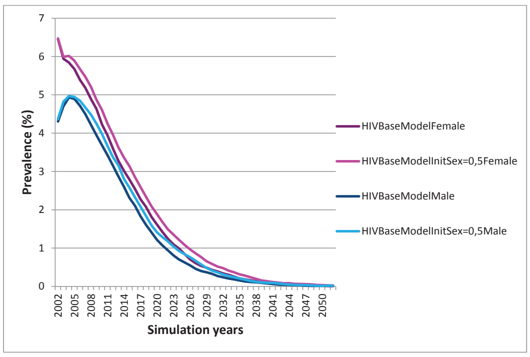
(a) HIV prevalence for 15 to 25 year age group



(b) HIV prevalence for 25 to 50 year age group



(c) HIV prevalence for 50 years and over age group



(d) Female and Male HIV prevalence

Figure 6.18: **Age group and gender based HIV prevalence results for the base model.**

HIV prevalence data for 2002 reveal that the highest prevalence levels are within the 25 to 50 year age group. With an average prognosis of 10 years for HIV positive agents it follows that as the infected agents grow older, they add to the prevalence levels of the next age group. Given the lower percentages of old age (above 50 years) individuals in a population, a slight increase in infected agents in that age group leads to an increase in prevalence; hence the increase observed for the first 10 simulation years, as well as the stability over the eight simulation years.

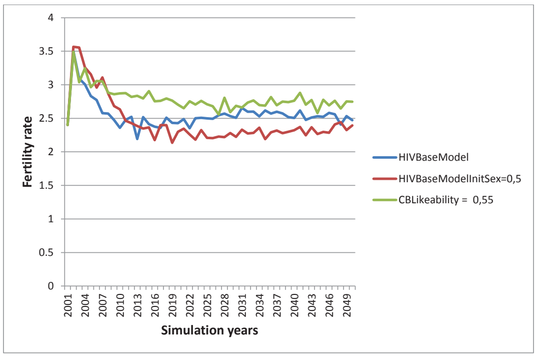
HIV incidence measures more recent dynamics of the HIV pandemic. It is a proportion estimate of new infections in a specified time period. An increase in incidence usually indicates a presence of a risk factor that contribute to new infections. In our base model results, incidence[7] continually decreases and falls below 0,1% in approximately 22 simulation years. The same trend is observed after changing the probability to initiate sex to 0,5 but with a slight increase in incidence levels. It takes five more years for incidence to be below 0,1% when the probability to initiate sex is equal to 0,5 (see Figure 6.17(b)).

The number of new HIV infections caused by a single HIV infected agent for both male and female agents ranged from zero to three in the base simulation model and zero to four when likeability and probability to initiate sex were adjusted. This range is quite low compared to the range produced by the EMOD-HIV model developed by Bershteyn et al. (2012). The low number of new HIV infections caused by a single HIV infected agent causes the decrease in prevalence. The low figures in new HIV infections per agent may be attributed to the low sexual mixing activities in the model. We can conclude that given the sexual network structure described in this thesis there is a possibility that HIV can be eradicated in approximately 45 to 50 years without any intervention using 2002 HIV prevalence data at model initialisation.

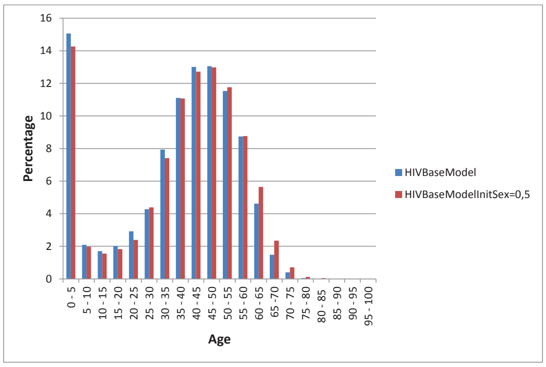
The introduction of HIV in the social sexual network resulted in a decrease in fertility levels compared to the results of the childbirth model where likeability threshold was equal to 0,55 (see Figure 6.19(a)). The decrease in fertility levels is due to premature death of both male and female agents in the model. HIV/AIDS deaths are concentrated between the zero to five year age group and between the 25 and 50 year age group (Figure 6.19(b)). The latter age group represents more than 60% of the

[7] A high incidence level observed at model initialisation for all our incidence model results is a consequence of the random initialisation of HIV infected agents in the model. This means that some married agents and agents in sexual relationships at model initialisation are discordant couples hence by the end of the first simulation year most of the discordant couples will be infected causing a spike in incidence in the first simulation year.

female fertile life span. The high death rate in this age group results in a decrease in total fertility rate.



(a) Fertility rate for the base model compared to fertility rate when likeability threshold equal to 0,55 for the child birth model



(b) AIDS mortality

Figure 6.19: **Fertility rate and AIDS mortality for the base model.**

Though results for concurrency levels from our social and sexual network closely matched data in literature, HIV prevalence results from the model are quite low compared to results observed in real life. This leads to the question posed by Sawers and Stillwaggon (2010) about concurrent partnerships and the HIV pandemic in Africa. Sawers and Stillwaggon (2010) did a systematic review of mathematical models that support the notion that concurrent sexual partnerships are the major drivers of HIV transmission in sub-Saharan Africa. From the systematic review, Sawers and Stillwaggon (2010) concluded that concurrency is not the major driver of the pandemic since the type of concurrent partnerships considered in the reviewed models are not unique to sub-Saharan Africa. From our model results, we can also conclude that if in a society there is only concurrency that is guided by the parameters in our model, concurrency will not drive the HIV pandemic to the levels that are currently evident in African countries.

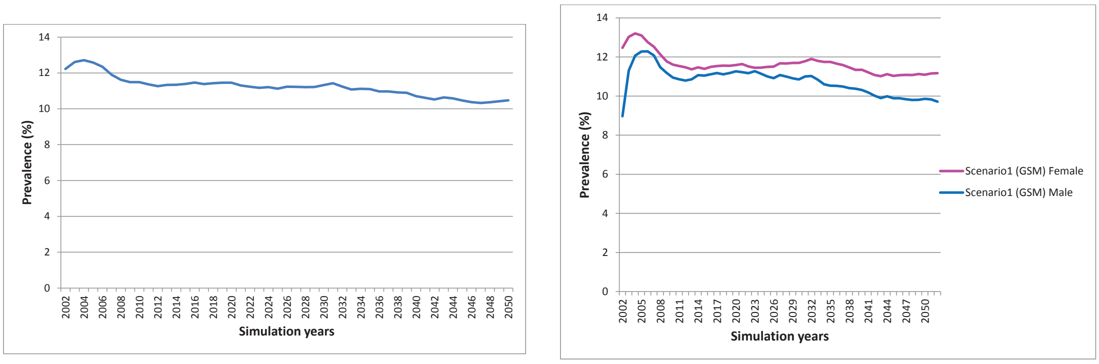
In conclusion, we can say that a slight increase in prevalence observed when the probability to initiate sex is increased ties well with the results obtained in the simulations done for the social and sexual network models. An increase in the probability to initiate sex resulted in an increase in concurrency levels as well as an increase in the percentage of agents in a sexual relationship outside marriage. A change in prevalence levels after adjusting the likeability threshold and probability to initiate sex shows that if the amount of sexual activities is increased in a population, HIV progresses faster. But a change in only these parameters still cannot explain the pandemic levels being observed. This shows that there is more to the sexual mixing happening in the sexual network which leads to the pandemic levels being observed. In the next subsection, we present model results from our HIV general simulation model.

6.5.2 HIV general simulation model results

In the general setting of our model, we include CSWs, OPSWs and their clients as explained in Section 5.5. ART for HIV positive agents and treatment for HIV positive pregnant mothers not on ART is also implemented (See page 120). Agents who engage in commercial sex activities and those in sexual relationships outside marriage can use condoms during sexual encounters. We multiply infection probability for CSWs, OPWSs and their clients by five to cater for risky sexual behaviours they practice and the prevalent STI infections within these groups. Agents can drop out of treatment and re-enrol as described in Section 5.7.2. Simulation results obtained after making these changes to the model are discussed here.

HIV prevalence remains between 10 and 13% throughout the 50 simulation years (See Figure 6.20(a)). The maximum prevalence level is observed in the 2004 simulation year. From 2004, HIV prevalence constantly decreases, but does not go below 10%. HIV will not disappear in the population within a 50 year period given the model parameters used in our general simulation model. Female agents' prevalence is generally higher than male agents' prevalence over the duration of the simulation. Male and female prevalence levels are approximately 9,8% and 11,1%, respectively, at the end of the 50 simulation years (Figure 6.20(b)). The total prevalence level is approximately 10,5% at the end of the 50 simulation years.

Our model results are quite close to results of the HRSC 2002, 2005, 2008 and 2012 HIV surveys. Table 6.4 contains data about the observed prevalence levels and model



(a) Total HIV prevalence (b) Female and male HIV prevalence

Figure 6.20: **HIV general simulation model results for HIV prevalence.**

results. Model results are mostly within the confidence levels calculated for observed data except for the total prevalence for simulation year 2005.

Surveys done by HRSC tried to establish incidence levels in the South African population. Measuring incidence levels provides a more direct way of assessing the impact of implemented HIV prevention programmes. Only 2012 HIV incidence estimates from empirical data are available in literature. Emprical data for 2002, 2005 and 2008 HIV incidence estimates from the surveys is not available in literature. Therefore, we compare our model results to the mathematically derived incidence estimates published by HSRC (2014).

The mathematically derived incidence estimates and our model results are presented in Table 6.4. We also included the 2012 survey estimates and our 2012 model results in the same table. Our model results for the total and female incidence in the 15 to 24 year age group lie below the lower confidence interval limit of the mathematically calculated estimates. In the 15 to 49 year age group, our model results fall within the mathematically calculated values as well as the observed incidence levels for 2012.

Our model does not allow agents below 15 years of age to engage in sexual relationships and we do not take into account gender-based violence and rape, which are believed to be risky factors for contracting HIV for females (Kenya School of Monetary Studies, 2012). HIV incidence data from the study carried out by HSRC (2014) shows that there is zero incidence in the 2 to 15 year age group for males but a 0,49%

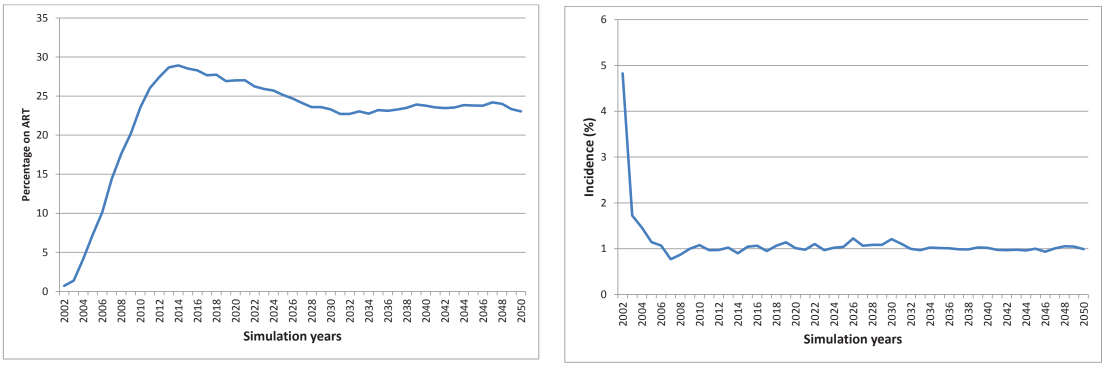
Table 6.4: **Prevalence and incidence levels for 2002, 2005, 2008 and 2012: Model results compared to observed data**

Prevalence						
	Total		Female		Male	
Year	**Model**	**Observed (CI)**	**Model**	**Observed (CI)**	**Model**	**Observed (CI)**
2002	12,2	11,4 (10,0-12,7)	12,5	12,8 (10,9-14,6)	9,0	9,5 (8,0-11,1)
2005	12,6	10,8 (9,9-11,6)	13,2	13,3 (12,1-14,6)	12,2	8,2 (7,1-9,6)
2008	11,6	10,9 (10,0-11,9)	12,3	13,8(12,9-13,5)	11,5	9,7(9,1-10,6)
2012	11,5	12,2 (11,4-13,1)	11,8	14,4 (13,3-15,6)	11,0	10,9 (8,9-11,0)
Incidence 15-24 year age group						
	Total		**Female**		**Male**	
Year 20–	**Model**	**Derived estimates (CI)**	**Model**	**Derived estimates (CI)**	**Model**	**Derived estimates (CI)**
02-05	0,7	2,8 (1,7–4,2)	0,6	5,3 (3,6–7,1)	0,7	0,6 (0,1–1,6)
05-08	0,5	2,3 (1,2–3,5)	0,5	3,5 (2,1–4,9)	0,6	1,4 (0,5–2,3)
08-12	0,5	1,5 (0,8–2,3)	0,6	2,1 (1,2–3,1)	0,6	1,0 (0,4-1,6)
12	0,9	1,49 (1,21–1,88)	0,7	2,54 (2,04–3,04)	0,9	0,55 (0,45–0,65)
Incidence 15-49 year age group						
	Total		**Female**		**Male**	
Year 20–	**Model**	**Derived estimates (CI)**	**Model**	**Derived estimates (CI)**	**Model Model**	**Derived estimates (CI)**
02-05	2,1	2,2 (0,9–4,0)	1,9	3,2 (1,8–5,0)	2,4	1,2 (0,1–3,0)
05-08	1,3	1,9 (0,8–3,3)	1,4	2,2 (1,0–3,6)	1,3	1,6 (0,6–3,0)
08-12	1,2	1,9 (0,8–3,1)	1,2	2,1 (1,0–3,4)	1,2	1,6 (0,6-2,7)
12	1,5	1,72 (1,38–2,06)	1,4	2,28 (1,84-2,74)	1,6	1,21 (0,97–1,45)

incidence for females in the same age group. The study does not disclose why we have HIV incidence for females in this age group. This may explain why our model results for the female agents in the 15 to 24 year age are below the confidence levels from the mathematically calculated incidence estimates. There is a need to include behavioural rules in the model to include the impact of gender-based violence and rape. This may give an insight of how these behaviours contribute to the HIV pandemic. We leave this as an area that requires further research.

Since the introduction of ART in public clinics and hospitals in 2004, there has been an increase in ART uptake. According to the 2008 and 2012 HSRC (2014) HIV incidence and prevalence study, approximately 16,6% and 31,2% (confidence interval: 28,1–34,5%) of people living with HIV were on ART, respectively. In our model, we used probabilities to allow agents to initiate ART. The probabilities used were selected to achieve a similar ART uptake percentage by 2008 and 2012 simulation years. Our model results show that 19,2% and 28,3% of agents are on ART by 2008 and 2012 simulation years, respectively.

An increase in ART uptake in the model is observed from the beginning of the simulation until year 2012, after which it starts to decline and stabilises at approximately 25% in approximately 25 simulation years. This means that ART uptake gets to a saturation point. At model initialisation, there is a large a number of agents eligible to enrol for ART not on treatment. This contributes to the increase in ART uptake observed during the first 10 to 13 simulation years. Changes in ART initiation guidelines also contribute to the increase in ART uptake observed in the model results. Possible reasons for the observed decline are a decrease in the number of agents eligible to enrol for ART. We assumed that guidelines for ART uptake remain the same as from 2012 simulation year to the end of the simulation time. This may have contributed to the decline in ART uptake observed in our model results, since the eligibility to enrol for ART remains constant. Figure 6.21(b) contains the ART enrolment and the HIV incidence graphs for our general simulation model.



(a) Percentage of people living with HIV on ART

(b) Total HIV incidence

Figure 6.21: **Percentage of people living with HIV on ART and total HIV incidence for the HIV general simulation model.**

To increase the rate at which agents enrol for ART, there is need to increase the probabilities for ART uptake in the model. This means that in real life settings, there is a need to continue educating people about the advantages of taking ART and improving access and the way the drugs are administered; for example, the introduction of a single dose pill. This makes it easier for people on ART to take their medication since they have to take only one pill once a day instead of three or more pills twice a day.

Our model results indicate that the average drop out rate per year is approximately 9%. In a two-year period, approximately 18% of the agents on ART will have dropped out of ART. The drop out percentage from our model results is within the limits of drop out rate observed in studies carried out in South Africa (Rosen et al., 2007). This shows that the probabilities we assigned to model dropout rate are quite close to what is happening in real life settings. We acknowledge that sensitivity analysis of different dropout rate probabilities is required to improve the understanding of how drop out impacts HIV progression, but for the purpose of our model, we maintain the probability distribution used in the general simulation model during the parameter variation phase.

We assigned probabilities equal to 0,001, 0,002 and 0,003 at each time step to model ART failure or drug resistance for the asymptomatic, symptomatic and AIDS stage of infection, respectively. Using these probabilities, a yearly average of 2,6% of agents on ART suffer from ART failure or drug resistance. This average is within the limits (1,73 to 9,09%) of the clinical and virological failure results found in a study carried out by Renaud-Thery et al. (2010). Therefore, we maintain the ART failure probabilities for the three stages of HIV infection used in the HIV general simulation model as our default probability settings for ART failure during parameter variation.

Our HIV general simulation model takes into consideration commercial sex work. We derived model parameters for commercial sex work using data found in literature, as described in Section 5.5. Model results for the average number of clients per week for a sex worker is nine. Repeat visits are not considered in our model. From literature, the number of clients that CSWs may have in a week range from 5 to 23 (Richter et al., 2012). Our model results are within the range recorded in literature.

The average number of visits per year for each male sex worker visitor is 8,7. This means that each male agent in our model selected to make use of CSW services is expected to have approximately nine CSW contact visits a year on average. The number of visits made by male agents who use CSWs services reported from literature range from 1 to 60 visits, with most men ranging between 4 and 6 visits a year (Suiming et al., 2011). Our model results are within the ranges observed in literature.

The maximum number of new male clients that a female sex worker can have from our model results is approximately 1 713 with an average of 1 032 and a minimum of 77 in an average career duration of eight years. A study carried out by Brewer et al. (2000) found that active adult prostitutes have an estimated mean of 2 171 new male partners in a period of five years. The number of clients reported by sex workers ranges between 5 to 23 clients per week (Richter et al., 2012). This translates to a minimum of 1 300 new male partners in a five-year period assuming no repeat visits. Our model results are within the values quoted in literature.

Clients for sex workers have an average of 57 new CSW sexual contacts in their lifetime, with a minimum of one and a maximum of 138. Research done by Miller et al. (1990, p. 261) found an average of 94 CSW sexual contacts for males who used CSW services. The highest number of lifetime CSW contacts reported by males in the study was 575.

In our model, the average number of years that a man can visit CSWs is approximately 24 years. If we assume that an average sex worker visitor has a minimum of four visits a year, it translates to 98 CSW contacts in a lifetime. Comparing this with our model results, we found that our average is below the theoretical average. Our model does not consider repeat visits and we are not sure if the statistics from literature takes into consideration repeat visits. The data reported in literature does not take into consideration the length of time a male is in contact with CSWs. For the purpose of this thesis, we maintain the parameters we have for male sex visitors. More research needs to be done to establish better parameter values.

The average number of new infections caused by an HIV positive CSW is five with a maximum and minimum of 14 and zero, respectively. The average number of new infections for an HIV positive OPSW is 0,5 with a maximum of six. Non-CSW and non-OPSW women have an average of 0,2 new infections with a maximum of two and a minimum of zero. Male sex worker visitors have an average of 0,8 new infections with a maximum of four and a minimum of zero. A concurrent male can infect a maximum of two new agents in a lifetime, while male agents who are both non-concurrent and not commercial sex worker visitors infect a maximum of 1,7 on average in a lifetime. Results obtained from the model suggest that female sex workers are the major drivers of the HIV pandemic, since they have the highest number of new infections followed by male sex worker visitors. A formal test for this result can be done by running different scenarios for sex workers. We leave this as an area for further research.

Although the average number of new infections caused by male sex worker visitors is low as compared to that of sex workers, male sex worker visitors facilitate the transference of the virus from a group with a higher risk of HIV exposure to a group with a lower risk of HIV exposure. Male sex worker visitors have sexual relationships with non sex workers. This allows the virus to progress in the population.

Agents in the model can drop out of ART and re-enrol for treatment. Our model results indicate that the maximum number of times an agent can dropout of ART is four, which leads to at most five re-enrollments. In real life settings, we can compare such dropout and re-enrollments with missing treatment or failing to get treatment due to drug shortages. A study carried out by Abdissa (2014) in Ethiopia revealed that being busy with other things, forgetfulness and running out of pills were the most common reasons for missing ART. Unfortunately, we are not aware of a study that has quantified the number of times HIV infected patients can drop out and re-enrol for medication. Therefore, we cannot evaluate the results obtained from our model. In the next section, we present results when we vary model parameters and bio-behavioural factors for the HIV general simulation model.

6.5.3 Parameter variation for the HIV general simulation model

In this section, we present results obtained when some parameters in the general simulation model are varied. Firstly, we present results obtained after varying the infection probability per coital act for agents who drop out of ART and agents who engage in commercial sex activities. We then present results obtained after allowing all HIV infected agents to enrol for ART as from the 2016 simulation year. We also analyse the effect of having no drop outs as from 2016 simulation year. We compare results obtained with our HIV general simulation model results.

Infection probability per coital act

We varied the infection probability for agents who drop out of ART. We are not aware of any study that has been carried out to establish the infection probability of people who drop out of ART. We therefore use two scenarios to understand the impact the difference in infection probability of agents who drop out of treatment has on the progression of HIV. In Scenario 1,[8] the infection probability of agents who drop out of ART is classified into three categories depending on CD4 cell count. The three infection probability categories for the agents who drop out of ART are:

1. asymptomatic stage infection probability if CD4 cell count is greater than 350 cells/μL;

2. symptomatic stage infection probability if CD4 cell count is between 200 cells/μL and 350 cells/μL; and

3. AIDS stage infection probability if CD4 cell count is below 200 cells/μL.

The infection probability of agents that drop out of ART is updated as their CD4 cell count decreases.

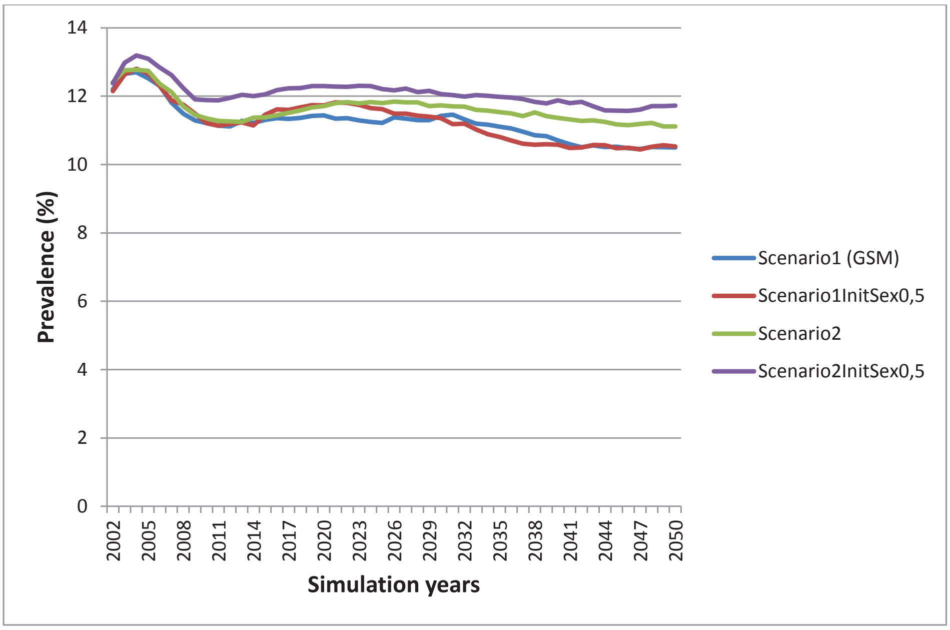
[8] We refer to the HIV general simulation model as Scenario 1 during all parameter variations

In Scenario 2, we assume that agents who drop out of ART will have an infection probability equal to the symptomatic HIV infection stage if their CD4 cell count is greater than 200 cells/μL. If the CD4 cell count is less than 200 cells/μL, infection probability is equal to the AIDS infection stage. Infection probability of agents that drop out of ART is updated as their CD4 cell count decreases. We also investigate the effect of changing the two parameters (likeability index and probability to initiate sex) as stated in Table 6.3 on HIV prevalence for the two scenarios.

From the simulation model results, Scenario 2 parameter settings resulted in an increase in prevalence. ANOVA results (see Figure 6.22) confirm that the increase in prevalence is statistically significant. Changing the likeability index and probability to initiate sex resulted in a further statistically significant increase in prevalence under Scenario 2 but no difference under Scenario 1. Time series plot for the different prevalence levels are shown in Figure 6.22.

There are no statistically significant differences for incidence levels though there are significant differences in prevalence. Looking at the time series graph, slight differences in incidence are observed (see Figure 6.23(a)). This shows that a slight increase in incidence may lead to a significant difference in prevalence. Also, an increase in the maximum average number of new infections over realisations caused by a CSW under Scenario 2 is observed. Using Scenario 2 model settings, the maximum average number of new infections by a CSW increases from 15 to approximately 18. No differences are observed for the frequency of dropping out of treatment and re-enrolment in both scenarios.

In our HIV general simulation model, we assumed that the infection probability for each stage of HIV infection for agents who engage in commercial sex work is multiplied by five. We multiplied the infection probability for CSWs by five to take into account higher rates of STIs incidence (Cowan et al., 2005) and the practice of risky sexual behaviour in this group of the population. However, during parameter variation we dropped this assumption and use the default infection probability for each stage of HIV infection as listed in Table 5.6. This was done to investigate the effect on incidence if there is a drop in infection probability in this group of the population. The

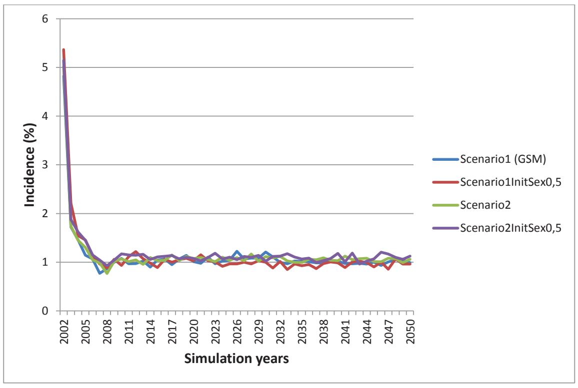


ANOVA results dropout infection probabilities

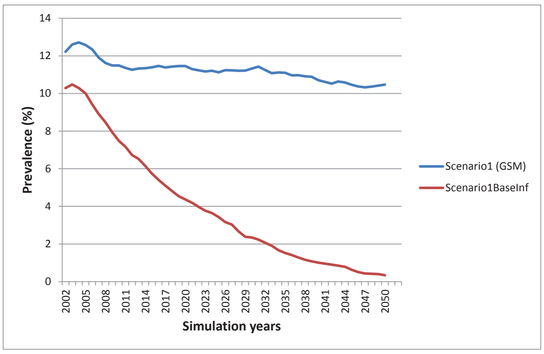
```
             Df Sum Sq Mean Sq F value   Pr(>F)
Group         3  24.67   8.222   23.28 6.76e-13 ***
Residuals   192  67.81   0.353
Tukey multiple comparisons of means95% family-wise confidence level

                                              p adj
Scenario1(GSM)-Scenario2InitSex0,5          0.0000000
Scenario1(GSM)-Scenario1InitSex0,5          0.5709257
Scenario1(GSM)-Scenario2                   0.0161953
```

Figure 6.22: **HIV prevalence results when infection probability for ART dropouts is varied**

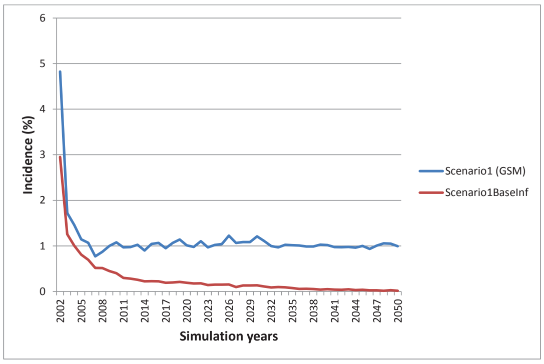
decrease in infection probability can be achieved by enrolling all CSWs into ART. This assumption is valid for this scenario only. All scenarios after this include the elevated risk of infection among CSWs. A decrease in the infection probability assumption for CSWs resulted in a decrease in prevalence and incidence levels (see Figure 6.23(b) and 6.23(c)). From this result, we conclude that if HIV infection probabilities are equal to those proposed by Orroth et al. (2007, p. i6) then HIV would not have progressed as it is today even with commercial sex work. Therefore, this calls for more research in the factors that contribute to an increase in HIV infection probability. In our model, we also assumed a coital act distribution which may need further investigation.



(a) HIV incidence results when infection probability for ART dropouts is varied



(b) HIV prevalence when default HIV infection probabilities are used



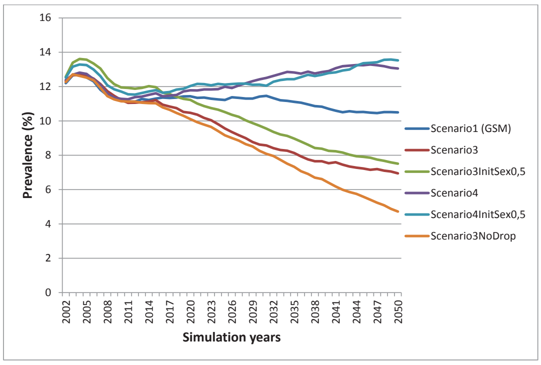
(c) HIV incidence when default HIV infection probabilities are used

Figure 6.23: Incidence and prevalence results for parameter variation.

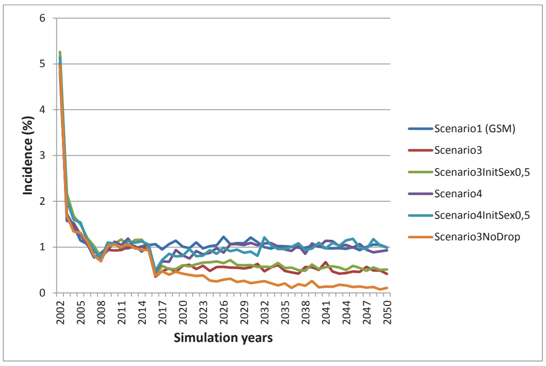
ART for all HIV positive agents as from 2016 simulation year

Simulation model results obtained after allowing all HIV infected agents to enrol for ART and the effect of having no dropouts after introducing ART for all infected agents as from 2016 simulation year are presented in this section. Scenario 3 and Scenario 4 are simply an extension of Scenario 1 and 2 model settings. We maintain the same infection probabilities for agents who dropout of ART as in Scenario 1 and 2 model settings in Scenario 3 and 4, respectively. In Scenario 3 and 4, we assume that all HIV infected agents enrol for ART as from 2016 simulation year. We analyse the effect of having dropouts and no dropouts given that all infected agents enrol for ART from 2016 simulation year. We also present results for Scenario 3 and 4 after varying the two parameters from the social and sexual network model (likeability and probability to initiate sex).

Figure 6.24(a) shows the prevalence levels that will be observed if ART is given to all HIV positive agents as from the beginning of 2016 simulation year. Prevalence increases as from 2016 when Scenario 4 model settings are used. Incidence levels remain at the same level as the incidence level for the HIV general simulation model. Initiating ART to all HIV infected agents decreases the number of premature deaths caused by HIV hence an increase in prevalence even with an incidence level equal to the HIV general simulation model.



(a) HIV prevalence



(b) HIV incidence

Figure 6.24: **HIV prevalence and incidence when all HIV infected agents enrol for ART from 2016 simulation year for five scenarios compared to the general simulation results (Scenario 1 (GSM) line).**

If we use Scenario 3 model settings, prevalence and incidence levels decrease as from year 2016. Prevalence will be approximately 7,5% at the end of the 50 simulation year. A sharp decrease from approximately 1% to approximately 0,35% in incidence is observed in 2016. This sharp decrease can be attributed to the decrease in infection probability of agents that are on ART. Incidence then stabilises between 0,45 and 0,65% as from 2017 simulation year to the end of the simulation (see Figure 6.24(b)). The increase in incidence from 0,35% to 0,45% is due to a gradual drop out of agents from ART. If we assume that all agents that enrol for ART from 2016 simulation year do not drop out Scenario 3 and 4 will have the same model settings. The no dropouts assumption for all agents that enrol for ART as from 2016 simulation year results in a further decrease in prevalence levels (Scenario NoDrop line) compared to Scenario 3 results.

The average number of new HIV infections caused by a CSW remains at five for

Scenario 3 model settings after the introduction of ART for all HIV positive agents from 2016 simulation year. In our data collection, we did not distinguish number of new infections caused by CSW dropouts from those who remain on treatment. After assuming no dropouts as from 2016 simulation year, the average number of new infections per CSW decreased to four. The maximum number of new infections decreased to an average of 12 from 14 (HIV general simulation model results).

From the results obtained here, we can conclude that infection probability for agents who dropout of ART contributes significantly to the progression of HIV in a society. Allowing all HIV infected agents to enrol for ART increases the number of agents who drop out of treatment. An increase in the number of people who drop out of ART leads to an increase in the number of HIV dropouts who can transmit the virus to the susceptible population. Therefore, we can conclude that if ART is introduced to all HIV infected agents, there is a need to reduce the number of dropouts. In the next chapter, we present the implications of our model results and limitations of our simulation model. We also highlight areas that require further research.

Chapter 7

Discussions and Conclusions

Four research questions were laid out in Chapter 1 of this thesis. The four research questions are as follows:

1. How well can such an approach be used to model the spread of HIV/AIDS in a closed mixed population?
2. How can the "saturation" prevalence level of HIV infections in the same population be found for the HIV pandemic?
3. How does sexual behaviour impact on the spread of HIV in a closed mixed population?
4. How does the use of antiretroviral therapy (ART) by infected individuals impact on the spread of HIV/AIDS in the stated population?

To answer these research questions, we developed a social and sexual agent-based model. We then implemented the HIV infection process in the social and sexual agent based model.

The social and sexual network model developed in this thesis extends on work done in mate search agent-based models by allowing marriage, divorce, widowhood, aging of agents, remarriage, concurrent sexual relationships at all levels of romantic relationships and commercial sex work. A dynamic network structure and population size is maintained throughout the simulation runs.

In this chapter, we present a summary of the simulation results presented in Chapter 6 of this thesis. Next, we present a discussion about how the research questions for this thesis were answered. This is followed by a discussion on implications of this research in agent-based mate choice social simulation discipline and its contribution to the modelling of the HIV epidemic. We then present limitations of the model developed in this thesis and highlight areas that need further research.

7.1 Discussion on simulation results

In Chapter 5, we presented an agent-based model framework used to answer research questions for this thesis. A number of agent-based models have been developed to address the spread of HIV in communities using different behaviour rules in the social and sexual model as well as for the spread of HIV. In this thesis, we developed an agent-based model that takes into consideration social and sexual structure of people living in a closed mixed society. We used the data available in literature to develop parameters and probability distributions used in the model. Where data were not available, we used reasonable unvalidated assumptions based on what is reported in literature. Simulation results obtained from the model were compared to statistics in literature. We summarise results presented in Chapter 6 for the different aspects of the model in the following two subsections.

It is important to acknowledge that the model developed in this thesis represents a closed mixed society and does not include all the aspects encountered in social and sexual relationship formation in real life settings – for example, gay and bisexual relationships. To reduce the complexity of our model, we excluded some aspects of social and sexual network development as well as other HIV transmission routes (for example, transmission through blood transfusion). We acknowledge that there is high

HIV prevalence and incidence within some of the sub-populations excluded in this thesis. This is one of the major improvements that can be included in the model in future. We only considered heterosexual and vertical transmission of HIV, since they are the predominant modes of HIV transmission in the settings considered in our model (see report by Health and Development Africa (2010, p. 10)). We have used data collected from the South African population through South African Demographic and Health Surveys (SADHS) and South African censuses to benchmark our model.

7.1.1 Social and sexual network model

Results for the model developed in this thesis are based on an initial population size of 5 000 agents. Friendship links were formed based on age differences. The development of our social network builds upon the rules proposed by Jin et al. (2001). Agents with an age difference less than 5 years had a 100% chance of forming a friendship link. The probability of creating a friendship link decreased as the age gap between agents increased.

The main driver of partnership formation is the likeability index calculated using age, aspiration and attractiveness level of a potential partner. Population growth for the social and sexual network is implemented in two different ways: through child birth and a simple addition of agents to the model. Agents exit the model through death. Migration is not considered in our model.

Previous models of sexual partnership formation focused mainly on first marriage (French and Kus, 2008; Hills and Todd, 2008; Simao and Todd, 2002). The possibility of multiple non concurrent and concurrent sexual partners and remarriage after divorce or death of a partner are excluded in most models. Although Knittel et al. (2011) and Alam (2008) addressed the issue of multiple sexual partnerships, either overlapping or serial in nature, they did not consider divorce and remarriage. For example, Knittel et al. (2011) simulation model only considered five years (260 time steps) and age did not contribute to relationship formation, since they assumed that agents in their model were from a young adult population approximately 20 to 25 year age group.

Our model extends what is in the literature. Agents in our model exit the model at death. They go through the process of romantic partnership formation, marriage, divorce, widowhood and death. Our model can be used as a test-bed where divorce and remarriage rules of widowed and divorced agents can be investigated. Given the increase in divorces (news24, Downloaded 31 july 2015) there is a need to understand how this impacts the social and sexual networks as well as the progression of the HIV epidemic.

Using the general simulation model for our social sexual network model, median age at first marriage is on average 27 years for females and 31 years for males. The age difference of approximately 4 years between female and male median age at first marriage is maintained throughout the 50 simulation years. A general increase in the median age at first marriage for both genders is observed from the 2017 simulation year to the end of the simulation. Results for median age at first marriage produced by our model lie in between civil and customary median age at first marriage published by StatsSA (2010a). The peak for the age at first marriage hazard ratio for female agents occurs five years earlier (20 to 25 years) than the peak of the hazard ratio for male agents (25 to 30 years).

The highest number of married agents is observed in the 40 to 49 and 50 to 59 year age groups for female and male agents respectively. Never coupled agents in the model are mainly below 25 years of age, with males having a higher percentage (28%) of never coupled agents compared to female agents (18%). Our model allowed divorced and widowed agents to remarry. Our results had substantial variations in the age at remarriage due to a small population size of divorced and widowed agents who remarry in a year. Hills and Todd (2008) included remarriage of divorced agents in their model, but excluded remarriage for widowed agents. Agent-based models that we are aware of did not explicitly model remarriage of divorced and widowed agents.

Under parameter variations, decreasing the likeability threshold decreased the age at first marriage, the percentage of never coupled agents, increased the percentage of married agents below 40 years, concurrency and the percentage of agents involved in sexual relationships outside marriage. Differences in model results were observed when the model was initialised with at least one connection for all agents greater or equal to 15 years (Scenario 2) as compared to when a certain number of agents were selected to have connections at model intialisation (Scenario 1). Under Scenario 2, we observed that there was a significant decrease in the percentage of never coupled agents across all parameter variations. An increase in the percentage of married male and female agents below 30 years, and the percentage of agents in sexual and concurrent relationships was also observed. This shows that if the friendship network is dense, the interaction of agents and their sexual behaviour changes the structure of the sexual network.

Sexual and social simulation model results from the model developed in this thesis suggest several interesting conclusions about sexual and social decision making. Firstly, the model highlights parameters that influence global patterns of social and sexual behaviour. Parameters investigated in our thesis that influenced global results of social and sexual behaviour are likeability index, probability to initiate sex and concurrency probability for married agents. For example, decreasing the likeability index resulted in a decrease in married partner quality correlation, median age at first marriage, an increase in percentage of married agents below 30 years of age, percentage of agents in sexual relationships outside marriage and concurrency levels.

Secondly, the effect of using different decision algorithms yield different results. In our model, divorce was implemented using two different algorithms: divorce based on a probability distribution and an approach based on marriage duration and attractiveness of the potential partner. The probability distribution used for divorce in our model was derived from divorce distribution data published by StatsSA (2010a). Using these two different divorce approaches resulted in differences in the number of divorces per given time period. More divorces were observed when divorce was based on a probability distribution. This shows that results obtained for agent-based sexual network models depend on the algorithms used to develop it.

7.1.2 HIV/AIDS progression

We superimposed HIV infection on the dynamic social and sexual network developed in this thesis. In addition to the standard social and sexual network, we included commercial sex work to develop an HIV general simulation model. A proportion of female agents (1% of females above 15 years of age) are selected to be commercial sex workers (CSWs) and opportunistic sex workers (OPSWs) for an average of eight years, after which they may decide to marry. We assume that 90% of males over 15 years of age will visit CSWs in their lifetime. Each model time step, we randomly select 10% of the males selected to visit CSWs to have one sexual encounter with a CSW. We further assume that 3% of the females above 15 years of age are OPSWs and 3% of the males who can visit CSWs visit OPSWs. A sexual relationship with an OPSW lasts for 6 months with an average of 4 sexual encounters during the six months.

CSWs and OPSWs in our model have an age range between 15 and 45 years. Clients for CSWs and OPSWs are between 15 and 55 years of age. There is no age restriction on sexual encounters between CSWs, OPSWs and their clients. We introduced a chance of protection against HIV transmission for commercial and opportunistic sexual encounters. We assume that the chance of protection takes into account condom use and circumcision. The probability distribution we use in this model increases from 2002 (0,471) to 2008 (0,852). From 2009 to 2012 protection chance decreases due to a reported decrease in condom use (HSRC, 2014). During that same period, there was a recorded increase in circumcision. The increase in male circumcision is taken into account in our model by decreasing the protection chance to a level that is 10% higher compared to the 2002 protection chance. We do not adjust protection chance as from the 2012 simulation year (see Section 5.7.2 on page 128 for more information).

HIV positive agents enrol for ART using enrolment guidelines for South Africa. Enrolment guidelines are updated until the 2012 simulation year. We use HIV infection stage dependent probabilities to select agents to enrol for ART. Agents in the AIDS stage have the highest probability to enrol for ART. The ART enrolment probabilities used in this thesis were selected based on the 2008 and 2012 percentages of people living with HIV on ART. Agents on ART can dropout from treatment using a probability distribution. Agents who dropout may re-enrol for ART using probabilities equal to the initial enrolment probabilities.

Results from the HIV base simulation model clearly show that if sexual partnerships are formed based on the behaviour rules used in our social and sexual network model HIV prevalence decreases and is finally eradicated without any intervention (see Section 6.5.1). HIV ages with the aging population and as agents die due to old age and HIV related illnesses, whichever comes first, and HIV becomes extinct. For the virus to keep on spreading in a population there must be a way of getting it to the younger population.

Introducing commercial and opportunistic sex work sustains the HIV epidemic even with the introduction of ART and a protection chance (condom use and circumcision combined) from HIV transmission. Introduction of a population at high risk of HIV transmission (CSWs, OPSWs and their clients) allows the virus to keep in pace with the aging of infected agents through finding new younger victims at a faster rate than the rate at which the infected agents die. CSWs, OPSWs and their clients facilitate the sexual mixing required by the virus to survive even with interventions in place. HIV incidence is on average 1% throughout the 50 simulation years. Prevalence stabilises above 10%. Results obtained from our HIV general simulation model are comparable to data in literature.

We investigated how model assumptions about the effect of varying the infection probability per coital act for agents who drop out from ART and agents who engage in commercial sex, allowing all HIV infected agents to enrol for ART and no ART dropout as from 2016 simulation year can change prevalence and incidence levels. Using the default infection probability for CSWs, OPSWs and their clients resulted in a decrease in prevalence and incidence levels throughout the 50 simulation years. Increasing the infection probability for agents who drop out from ART resulted in an increase in prevalence and a slight increase in incidence (see Figure 6.22 and Figure

6.23(a) respectively). From these results, we can conclude that more research needs to be done to establish the actual infection probabilities.

Allowing all HIV positive agents to enrol for ART from the 2016 simulation year under different infection probabilities for agents who drop out from ART resulted in different prevalence and incidence levels compared to the general simulation model. An increase in HIV prevalence (compared to our HIV general simulation model results) is observed when infection probability for agents who drop out from ART with a CD4 cell count greater than 200 cells/μL is equal to the symptomatic infection probability and equal to the AIDS stage infection probability if CD4 cell count is less than 200 cells/μL (Scenario 4).

A decrease in incidence and prevalence is observed if infection probability for agents who drop out with a CD4 cell count greater than 350 cells/μL is equal to the asymptomatic infection probability, CD4 cell count between 200 and 350 cells/μL is equal to the symptomatic infection probability and equal to the AIDS infection probability if CD4 cell count is below 200 cells/μL (Scenario 3). Assuming zero dropout from ART from 2016 simulation year resulted in a continuous decrease in prevalence and incidence level. Incidence level drops below 1% during the last four simulation years when zero dropout rate from ART is introduced in the model.

Our findings suggest that should the government of South Africa allow all HIV positive infection agents to enrol for ART in future, there is a need to put measures in place to avoid ART dropouts. Introducing ART to all without concomitant action to avoid dropouts from ART will prolong the process of eradicating HIV. This may make the ART treatment program financially unsustainable.

7.2 Reflection on achievements of this research

The model developed in this thesis managed to address the four research questions laid out in Chapter 1 of this thesis. We developed an agent-based model which took into consideration marriage, divorce, widowhood, aging of agents, remarriage, concurrent sexual relationships at all levels of romantic relationships and commercial sex work. We implemented HIV transmission in the model. We compared results obtained from the model with data recorded in literature. Model results are comparable to data published in literature.

The first research question was to see if agent-based modelling can be used to model the spread of HIV/AIDS in a closed mixed society. From the model developed, we managed to implement the HIV transmission process where population growth is only through child birth. However, we did not consider in or out migration of agents. Agents were removed from the model through death caused either by AIDS related illnesses or non-AIDS illnesses and other causes (for example, accidents). HIV transmission in the society was through heterosexual contact or mother-to-child transmission. Some agents exited the model without finding a partner.

We have used data collected from the South African population to evaluate our HIV general simulation model results. We found that if a closed mixed society does not contain a group with high risk behaviours that facilitate HIV transmission, HIV incidence and prevalence decreases as the population ages and die from HIV related illnesses. Existence of a group that engage in high risk sexual behaviour of acquiring HIV, in this case, CSWs, OPSWs and their clients, facilitate the spread of the virus. Incidence and prevalence remain high even with interventions to curb the epidemic.

Saturation of HIV prevalence is driven by network structure, behaviour change as well as biologic factors. HIV prevalence and incidence decreased continuously in our base simulation model where sexual relationship formation was guided by behaviour rules set in our social and sexual network without commercial sex work. Introducing commercial sex work resulted in an increase in prevalence and incidence. Reducing the number of dropouts from ART to zero resulted in a decrease in incidence as well as a decrease in prevalence. Different infection probabilities resulted in different prevalence and incidence levels. This shows that saturation of HIV prevalence in a closed mixed society is driven by behaviour, biological factors and the sexual network structure formed by agents in a society.

We varied the probability to initiate sex for courting couples in our HIV general simulation model. An increase in the probability to initiate sex for courting couples, one of the parameters that govern the sexual behaviour in our model, resulted in a slight increase in HIV prevalence and incidence under the two scenarios analysed in this thesis (see prevalence graph in Figure 6.22). Results form the HIV base simulation model clearly show that if sexual partnerships are guided by behaviour rules used to develop our social and sexual network model, HIV prevalence and incidence decreases and is finally eradicated without any intervention (see Section 6.5.1). If we include commercial and opportunistic sex work in the social and sexual network model, HIV prevalence and incidence increase. Sexual behaviour does impact the spread of HIV in a closed mixed society.

We addressed the last research question by introducing ART to all HIV positive agents as from 2016 simulation year. We performed simulation runs under two conditions, namely; one with a chance for dropping out of ART and the second one which assumes zero dropout rate. We considered two cases for the infection probability of agents who dropout from treatment. The first case (Scenario 3 – see Section 6.5.3) is when the infection probability of agents who drop out with a CD4 cell count greater than 350 cells/μL is equal to the asymptomatic infection probability, CD4 cell count between 200 and 350 cells/μL is equal to the symptomatic infection probability and equal to the AIDS infection probability if CD4 cell count is below 200 cells/μL. Prevalence decreased from 2016 up to the end of the simulation. HIV prevalence is approximately 7,5% at the end of the simulation. Incidence varies between 0,3% and 0,8% from 2016 to 2050 simulation years (see Figure 6.24).

Changing the infection probability for agents who drop out from ART to Scenario 4 settings (CD4 cell count greater than 200 cells/μL symptomatic infection probability and AIDS stage infection probability if CD4 cell count is less than 200 cells/μL) resulted in an increase in prevalence and a slight but not statistically significant increase in incidence. Introducing ART for all HIV positive agents from simulation year 2016 resulted in a statistically significant decrease in prevalence and incidence if we assume zero dropout rate (Fugure 6.24).

Based on our model settings, we can conclude that introducing ART for all has positive results in eradicating the epidemic if there is a decrease in people who drop out from treatment. There is also a need to understand the dynamics of the infection probability for agents who drop out from treatment. Our model results indicate that assuming different infection probabilities for agents who drop out from treatment result in different prevalence and incidence levels. If dropping out from treatment cannot be avoided, there is a need to educate those who drop out from ART about prevention methods to avoid transmission of the virus.

7.3 Model limitations and possible extensions

The model presented in this thesis is not without limitations. Our simulation model does not have a defined "burn in" period. Having a "burn in" period allows the model to get past gratuitous transient artifacts at the initial state. We expect to introduce a defined "burn in" period in future research. There is also a need to refine some parameters used in our model for both networks (social and sexual) and the HIV transmission process. This can be done using calibration. During model calibration priority should be given to parameters that satisfy the following criteria:

1. empirical evidence to support a specific value for the parameter is weak or flawed.

2. model outputs that can be compared with data, such as HIV prevalence trends, are highly sensitive to the parameter value.

3. the effect of the parameter value on model outputs is not strongly redundant or there is evidence of collinearity with another parameter already chosen for calibration. For example, the rate of transmission per coital act and the probability of condom usage can be highly collinear.

We leave this as an area that requires attention in future research. In the next subsections, we present limitations from the social and sexual network model and possible extensions to the model. This is followed by limitation and possible extensions for the model after introducing HIV infection.

7.3.1 Social and sexual network model

Although we have added a number of ideas to the mate search literature, the social and sexual network model developed in this thesis has its own limitations. First, lack of reliable sexual behaviour data makes it difficult to set up sexual behaviour parameters in the model. Our model therefore relies on assumptions based on incomplete information about sexual behaviour.

Secondly, formation of friendship links does not take into consideration physical proximity of agents. To model physical proximity, there is a need to have geographical coordinates for the area under study. Physical proximity contributes quite significantly to how social and sexual networks develop, but including it into the model will increase the complexity of the model. The implementation of physical proximity is therefore left as a possible extension to the social and sexual network model developed in this thesis.

Our sexual network develops from an agent's friendship network. We did not consider the possibility of romantic relationships developing from the network of an agent's siblings and other family friendship networks. In real life, romantic relationships develop between a person and friends of his or her family members. To include this aspect in the model there is a need to introduce family structures and family friendship networks. Another aspect that we did not take into consideration is the formation of same sex relationships. This phenomenon occurs in real life settings and in South Africa same sex relationships are legal (Rule and Mncwango, 2006). Including these aspects in the model may contribute to the dynamics of sexual network formation. We leave these as possible extensions of the model developed in this thesis.

In the default case of our model, one divorce strategy was considered (divorce once a more attractive agent is encountered). The variation in the results obtained using this divorce approach was very high. In analysing the model, default case results were compared when a divorce approach based on an age dependent probability distribution was used. Using the approach based on a probability distribution resulted in an increase in the number of divorces and number of remarriages for divorced agents, although the sample sizes for each sub-population remained significantly small (< 30). The size of the initial population used in our simulations also contributes to small sub-populations observed in our model results. We maintained an initial population size of 5 000 agents for all simulation runs since it is the initial maximum that could be handled in a reasonable time by the available hardware resources.

The increase in the number of divorces after changing the divorce criterion shows that there is a need to investigate more divorce strategies closer to reality. The presence of children and the existence of concurrent relationships are among some of the factors that need to be considered when making a decision to divorce. Adding these factors may add value to the model. Another aspect that requires further investigation is the break up of romantic relationships before marriage, since there are other reasons that may lead to the break up of such relationships other than the acquisition of a more attractive partner.

There is a need to improve on the way remarriage is represented. When a person remarries, there are a number of factors that are taken into consideration. The factors include number of children, if any, age, the degree of depression suffered from the divorce *etc.* These factors contribute significantly to the decision to remarry. Above all, formation and dissolution of romantic relationships in any setting is usually governed by the social norms, economic environment and civil laws of a society. The model developed in this thesis did not include these factors, and there is a need to conduct more research in this area.

Besides gender differences in sexual drive, research has shown that ageing decreases sex drive. Menopause, which occurs in women at an average age of 50 and factors associated with being older such as the onset of several health-related and sexual problems have been shown to decrease sexual drive in older people (Bradford and Meston, 2007; DeLamater and Sill, 2005). The age at which the drive starts to decrease is not very specific due to the difficulty associated with collecting sex related data. This aspect needs to be included in the model and may increase the accuracy in determining the remarriage age for divorced and widowed agents.

Results for the social and sexual network model are based on an initial population size of 5 000 agents. Population growth was implemented in two different ways: through child birth and a simple addition of agents to the model. Migration was not considered in this model though it contributes quite significantly to population size changes, especially when dealing with small population groups. Using a relatively small population size resulted in some of the sub-populations having very small sample sizes. Hence, the results obtained from the small sample sizes were not very close to reality. Given more computer resources and time, results obtained may be refined by having a larger population size and also including migration of agents in the model. Introducing migration and increasing the population size will definitely add value to the understanding of mate choice behaviour.

In our model we considered commercial sex work. Obtaining statistics and information about the clients of commercial sex workers (CSWs) is not easy, partly because they do not have sex work venues where one can find them. Most of the men who visit CSWs are married or have regular girlfriends (Suiming et al., 2011). In our model we therefore estimated that 90% of males have the potential to visit CSWs. At each time step 10% of the males with a potential to visit CSWs are randomly selected. The selection of the set of men who visit CSW is independent for each time step. We used this as a starting point to model the mixing between CSWs and their clients. Given more data and time other strategies of selecting clients that visit CSWs must be explored.

Above all, our social and sexual network model uses estimated parameter values if data to support decision making was not available. Decision rules used to send and accept date and marriage proposals are based on the current understanding of sexual decision making. Collecting data about how partnerships are formed will improve model fit to empirical data.

7.3.2 HIV simulation model

Adding HIV in the model resulted in more complicated interactions among the agents. Though HIV general simulation model results obtained for HIV prevalence and incidence are quite close to reality, there is a need to improve the model in a number of ways. To start with, we assumed one strategy of increasing CD4 count after ART initiation. In reality, not all people who start ART therapy have the same rate of CD4 cell count increase. Prognosis of a person on ART must depend on the increase in CD4 count. This may improve model results if taken into consideration.

STDs, viral blips and the presence of immune cells in the vagina that favour the transmission of HIV are not explicitly modelled in our model. The presence of STDs increases probability of infection, hence contributes to the incidence levels of HIV. More immune cells in the vagina that are "friendly" to HIV transmission increases the risk of contacting HIV regardless of the number (non-zero) of coital acts, number of sexual partners or the presence of STDs (Child, 2015). Viral blips increase HIV viral load in the blood of an infected person (Lee et al., 2006). Viral blips occur at random and may last for about 20 to 30 days (Mascio et al., 2003). The occurrence of viral blips do not lead to a generation of resistant strains or warranty a change in the HIV treatment regimen (Lee et al., 2006), but causes an increase in viral load. An increase in viral load increases the probability of HIV transmission (Baeten et al., 2011). The total effect this may have on the incidence rate has not been measured. We leave these as possible extensions of the model developed in this thesis.

Research done by McGrath et al. (2013, p. 3) found that a person with full blown AIDS will rarely engage in sex. This means that even with a very high infection probability, the chances of infecting a susceptible person are reduced because of the reduction in coital acts. In our model, we assume that if an agent is a sex worker or visitor and is in the AIDS stage they are removed from the sex worker and sex worker visitor group. We do not consider coital dilution when an agent is in the AIDS stage, for all other agents. Introducing coital dilution for agents in the AIDS stage for all agents may have an impact on incidence levels. We leave this as an area that requires further research.

We did introduce coital dilution for agents with multiple sexual partners in our model. The parameters used to model the coital dilution are unvalidated. More research about the number of coital acts that an individual has in a specified time period must be conducted. It is quite evident from literature that some men and women engage in sexual relationships with more than one partner concurrently (Jewkes et al., 2002; Dunkle et al., 2004b). What is lacking in literature is the average number of coital acts that such individuals have in a specified period of time with each of the multiple partners. We acknowledge the difficult encountered when trying to get information about the number of coital acts since in most cases this is regarded as private information. Therefore there is a need to design research methods that can elicit this information from people.

We investigated the impact of universal ART enrolment for all HIV infected agents from the 2016 simulation year. However we did not analyse the impact of sexual behaviour change concurrently with the introduction of universal enrolment of HIV positive agents. Studies carried out by Kalichman et al. (2006) have indicated that HIV infected individuals tend to engage in unprotected sex due to the the fact that ART prevents or reduces HIV transmission (Cohen et al., 2011). It is important to note that the risk of HIV transmission is not eliminated by use of ART and may not be maximally reduced at all times due to factors which include co-infection by STDs, varying degree to which different ART reduce viral load in genital fluids, *etc* (CDC, 2009). We may extend our model by further decreasing the chance of protection against HIV transmission once universal ART is introduced in the model. Explicitly introducing viral blips and co-infection with STDs and lower chance of protection from HIV transmission in the model may give more insight in the progression of HIV under universal ART for HIV positive individuals.

We did not take into consideration a decrease in fertility caused by HIV infection. Fertility has been noted to decrease with the stage of HIV infection (Alam, 2008, p. 110). Use of ART has been reported to increase pregnancy incidence in HIV positive women compared to those not on ART (Myer et al., 2010). We did not adjust our fertility levels using the HIV infection status of agents in our model but in future modelling one can explicitly model the effect that the use and non-use of ART by HIV positive women has on pregnancy incidence.

Another factor which affects childbirth is the use of condoms. Use of condoms has simultaneous effects on childbirth, transmission of HIV and other STIs. We did not explicitly consider the effect of the use of condoms on childbirth and the simultaneous impact it has on HIV and STI transmission in our model. There is, however, a need to first obtain statistics about the number of couples who use condoms solely as contraception in South Africa before this can be incorporated in the model.

Lastly, we did not consider same sex and bisexual relationships in our model. Hence transmission of the virus among same sex relationships, bisexual relationships and the heterosexual community is beyond the scope of this thesis but may warrant further study.

7.4 Conclusion

The primary objective of our thesis was to develop an agent-based model that represent social and sexual networks formed in real life setting as closely as possible and to investigate how HIV progresses in such a society. The model developed in this thesis has contributed to the understanding of mate search models by allowing agents to go through the major stages in life, which include marrying, widowhood, divorce and remarriage, among others. Implementing the HIV transmission process in the model contributed to understanding of the progression of HIV/AIDS in a society that may be represented by agents in our model. The model suggests that:

1. a change in sexual behaviour in a society results in a change in the pattern of sexual network. For example, changing the likeability threshold in our model resulted in an increase in concurrency levels as well as the percentage of agents involved in a sexual relationship outside marriage;

2. dense social networks result in formation of more sexual relationships as compared to sparse network structures. There was significant statistical variation in model results obtained when we intialised our model with friendship connections only for a few selected agents as compared to when we allowed all agents to have more than one connection at model initialisation;

3. introducing ART for all HIV positive agents will help in curbing HIV, but there is a need to decrease the rate at which patients drop out from treatment. Our model conclusion on this aspect concurs with conclusions drawn by Klein et al. (2014), though we have used different pair formation algorithms; and

4. infection probability for agents who drop out from treatment (if dropout rate remains unchanged) has to be quite low (less than asymptomatic HIV stage infection probability) for HIV incidence to decrease after introducing ART for all HIV infected individuals.

We have managed to demonstrate how a theoretical agent-based model can be used to understand the progression of HIV in a closed mixed society. We conclude this thesis by acknowledging that results obtained from a model are as good as the assumptions used to develop the model. We recommend model-to-model analysis to reveal the model's dependence on specific assumptions with more emphasis on parameters not supported by evidence.

Appendix A

Model Parameters

Table A.1: **Social and sexual network agent attributes**

Parameter/Variable	**Default value**	Description	**Source**
		Social and sexual network	
Environmental parameters			
intialSexualRelationships	0,5	Proportion of agents in a sexual relationship at model initialisation	Assumed
initialPregnancy	0,019	Proportion of pregnant female agents married at model initialisation	Myatt (2012)
r_0	0,00002	Proportion of agents chosen to make random friendship connections	Based on Jin et al. (2001)
r_1	2	Multiplier to determine number of agents chosen to make neighbour meetings	Based on Jin et al. (2001)
Gamma	0,05	Probability of removing a friendship connection	Assumed
beta1F	0,2	Female multiplier used to calculate the upper acceptable age limit for a male potential date	Assumed
beta2F	0,8	Female multiplier used to calculate the lower acceptable age limit for a male potential date	Assumed
beta1M	0,5	Male multiplier used to calculate the lower acceptable age limit for a female potential date	Assumed
beta2M	0	Male multiplier used to calculate the upper acceptable age limit for a female potential date	Assumed
α_1	0,4	Probability of creating a friendship connection for agents with 5 to 10 years age difference	Assumed
α_2	0,01	Probability of creating a friendship connection for agents with 10 to 15 years age difference	Assumed
α_3	0,001	Probability of creating a friendship connection for agents with age difference greater than 15 years	Assumed

Table A.2: **Social and sexual network agent attributes continued**

Parameter/Variable	**Default value**	Description	**Source**
Agent related			
gender	Male or Female	Male or female	
sexRatio:0.5		Proportion for each gender	Assumed
attractiveness	normal(50;25)	Attractiveness levels assigned to agents	Alam et al. (2008)
aspirationLevel	normal(50;25)	Aspiration levels assigned to agents	Alam et al. (2008)
noSexDatingDuration (weeks)	normal(10;2)	Distribution of time spend dating without enganging in a sexual partnership	Knittel et al. (2011)
courtshipDuration (weeks)	lognormal(48;144)	Distribution of time from dating until marriage	Alam (2008, p. 119)
maxDeg	uniform(12;15)	Maximum number of social connections for each agent	Allan (2006)
maxDating	lognormal(0,4;0,7) lognormal(0,2;0,3)	Maximum number of dating partners an agent can have at any given time (male and female respectively)	Assumed
maxSexualPartners	lognormal(0,4;0,7) lognormal(0,2;,0,3)	Maximum number of sexual partners an agent can have at any given time (male and female respectively)	Alam (2008, p. 293)
deathAge (years)	Acturial life table	Natural death age	Actuarial Society of South Africa (ASSA) (2007)
sexualMaturityAge (years)	Sexual maturity distribution table	The age at which an agent can be involved in sexual relationships	SADHS (2003, p. 98)

Table A.3: **Social and sexual network agent attributes continued**

Parameter/Variable	**Default value**	Description	**Source**
likeabilityThreshold	0,5	An index used to select a potential date	Assumed
sexualDrive	beta(1,5;3) beta(4;2)	Desire for sexual variety value assigned to male and female agents respectively	Assumed
probRandomPartner		Probability of selecting a date partner outside the social network	Alam (2008, p. 117)
ConcurrentPenalty	0,6	A penalty used to adjust parther quality when concurrency is identified	Knittel et al. (2011)
probRecognizeConcurrentFalse	0,15	Probability of failing to recongnise true concurrency	Knittel et al. (2011)
probRecognizeConcurrentTrue	0,3	Probability of recongnising true concurrency	Knittel et al. (2011)
Couple related			
initialNumWeeksDating (weeks)	uniform(0;156)	Number of weeks dating for dating couples at model initialisation where 156 is the maximum courtship duration for any dating couple	Assumed
initialPregnancyDuration (weeks)	uniform(0;42)	Weeks pregnant for female agents initialised as pregnant	Assumed
marriageProbability		The probability of marrying for dating couples It depends on age and marital status	Assumed
Divorce probability (age in years)		The age dependent probability of couples divorcing	Assumed
male age < 25	0,1		
$25 \leq$ male age < 35	0,15		
$35 \leq$ male age < 49	0,25		
$49 \leq$ male age < 54	0,15		
$54 \leq$ male age < 69	0,05		
male age > 69	0,01		

Table A.4: **HIV transmission and progression agent attributes**

HIV transmission and progression			
Environmental parameters			
		Proportion of agents initiating ART in ...	
ARTAsympPro	0	HIV asymptomatic stage	Assumed
ARTSympPro	0,03	HIV symptomatic stage	Assumed
ARTAIDSPro	0,5	AIDS stage	Assumed
		Proportion of ART dropout ...	
ARTAsympDropPro	0,01	HIV symptomatic stage	Assumed
ARTSympDropPro	0,5	HIV symptomatic stage	Assumed
ARTAIDSDropPro	0,5	AIDS stage	Assumed
Agent related			
intialCD4Count	normal(1179;36)	CD4 count for an HIV negative agent	Williams et al. (2006)
prognosisWithoutART	weibull($\lambda;2$) (age>15)	Time since infection to death without	Bershteyn et al. (2012)
(years)	weibull($\lambda;\kappa$)	ART treatment (age dependant).	Bershteyn et al. (2012)
	λ and κ	Formulae to calculate is on page 115	
primaryInfDuration (weeks)	normal(10;2)	Time period: primary infection stage	**?**
prognosisAfterDropingART	weibull($\lambda;2$) (age>15)	Time since dropping ART to death	Bershteyn et al. (2012)
(years)	weibull($\lambda;\kappa$)	Formulae to calculate is on page 115	
infectionProb	0,014; 0,001; 0,003	Female to male infection probability	Orroth et al. (2007, p. i6)
(Female to male)	0,007; 0,00004; 0,007	i.e Primary, asymptomatic, symptomatic,	and Cohen et al. (2011)
		AIDS,on ART and drop out respectively	
infectionProb (per coital act)	0,028; 0,002; 0,006	Male to female infection probability	Orroth et al. (2007)
(Male to female)	0,0014; 0,00008; 0,014	i.e Primary, asymptomatic, symptomatic,	and Cohen et al. (2011)
		AIDS, on ART and drop out respectively	

Table A.5: **Description of social and sexual network model names used in thesis**

Default	Default model when agents are added using a proportion of the total population at the beginning of the simulation year
Courtship	Average courtship duration is decreased
Initiate sex=0,5	Probability to initiate sex for courting couples is increased
Likeability = 0,55	Likeability threshold decreased
Married Concurrency	Probability of having concurrent partners for married agents is increased
Probabilistic Divorce	Divorce criteria depends on a probabilistic distribution
Random=0,1	Probability for random partner selection is increased
Sexual Drive	Parameters for sexual drive are adjusted
Pop growth	Population growth rate is increased from 0,02 to 0,03
InitConn... – means all agents have at least one friendship link at model initialisation and agents are added into the model through child birth	
InitConnDefault	General simulation model
InitConnCourtship	Average courtship duration is decreased
InitConnInitSex=0,5	Probability to initiate sex for courting couples is increased
InitConnLike=0,55	Likeability threshold decreased
InitConnMarrConc	Probability of having concurrent partners for married agents is increased
InitConnRand=0,1	Probability for random partner selection is increased
InitConnProbDivorce	Divorce criteria depends on a probabilistic distribution
InitConnSexDrive	Parameters for sexual drive are adjusted
InitConnPopgrowth	Population growth rate is increased from 0,02 to 0,03

Table A.6: **Description of social and sexual network model names used in thesis**

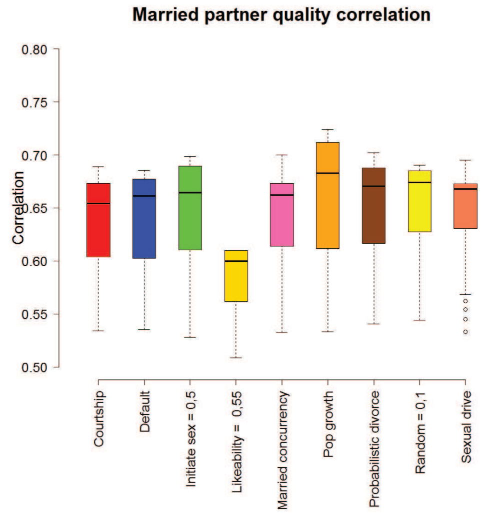
CB. . . – means agents are added into the model through child birth	
CBDefault	Default model when agents are added through child birth
CBCourtship	Average courtship duration is decreased
CBInitiate sex=0,5	Probability to initiate sex for courting couples is increased
CBLikeability = 0,55	Likeability threshold decreased
CBMarriedConc	Probability of having concurrent partners for married agents is increased
CBProbDivorce	Divorce criteria depends on a probabilistic distribution
CBRandom	Probability for random partner selection is increased
CBSexual drive	Parameters for sexual drive are adjusted
CBInitCon. . . - means all agents have at least one friendship link at model initialisation and agents are added into the model through child birth	
CBInitConInitGSM	general simulation model with child birth and initial connections
CBInitConCourt	Average courtship duration is decreased
CBInitConInitSex=0,5	Probability to initiate sex for courting couples is increased
CBInitConLike=0,55	Likeability threshold decreased
CBInitConnMarrConc	Probability of having concurrent partners for married agents is increased
CBInitConnRand	Probability for random partner selection is increased
CBInitConnPrDivorce	Divorce criteria depends on a probabilistic distribution
CBInitConnSexDrive	Parameters for sexual drive are adjusted

Table A.7: **Description of HIV model names used in thesis**

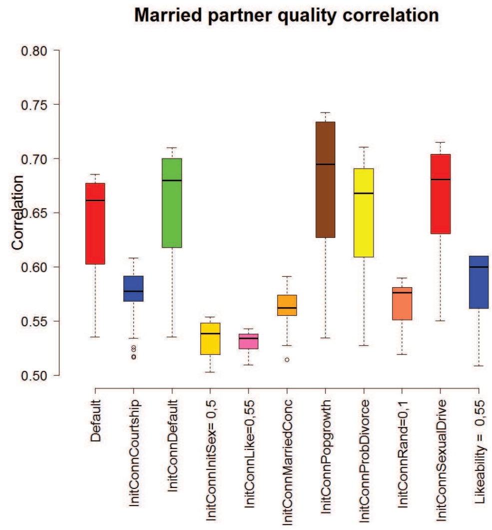
HIVBaseModel	Base model for HIV simulations (no commercial sex)
HIVBaseModelInitSex=0,5	Base model for HIV simulations with an increased probability to initiate sex for courting couples
Scenario1(GSM)	HIV general simulation model with commercial sex work and three infection probabilities for agents who drop out from treatment
Scenario2	HIV general simulation model with commercial sex work and two infection probabilities for agents who drop out from treatment
Scenario1IniSex0,5	Scenario1(GSM) model settings with an adjustment in the likeability threshold and probability to initiate sex for courting couples
Scenario2IniSex0,5	Scenario2 model settings with an adjustment in the likeability threshold and probability to initiate sex for courting couples
Scenario1BaseInf	Scenario1 model settings with base infection probabilities for all agents see page 127, Table 5.6
Scenario2BaseInf	Scenario2 model settings with base infection probabilities for all agents
Scenario3	Scenario1 model settings with all HIV positive agents allowed to enroll for ART
Scenario4	Scenario2 model settings with all HIV positive agents allowed to enroll for ART
Scenario3IniSex0,5	Scenario1 model settings with an adjustment in likeability threshold and probability to initiate sex for courting couples
Scenario4IniSex0,5	Scenario2 model settings with an adjustment in likeability threshold and probability to initiate sex for courting couples

Appendix B

Box plots for social and sexual network

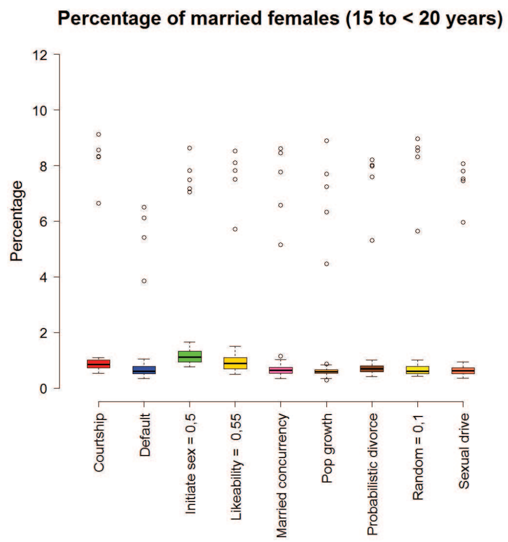


(a) Scenario 1

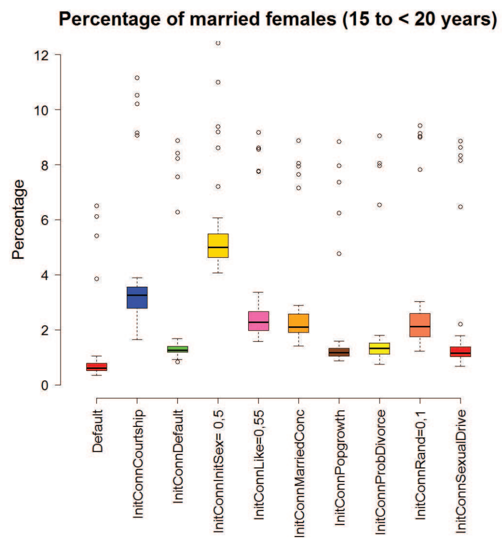


(b) Scenario 2

Figure B.1: **Married partner correlation**

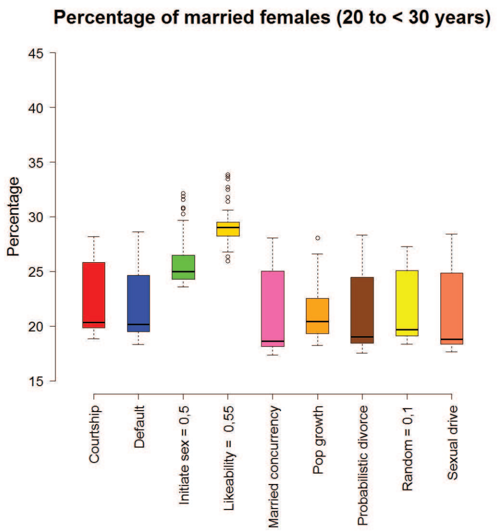


(a) Scenario 1

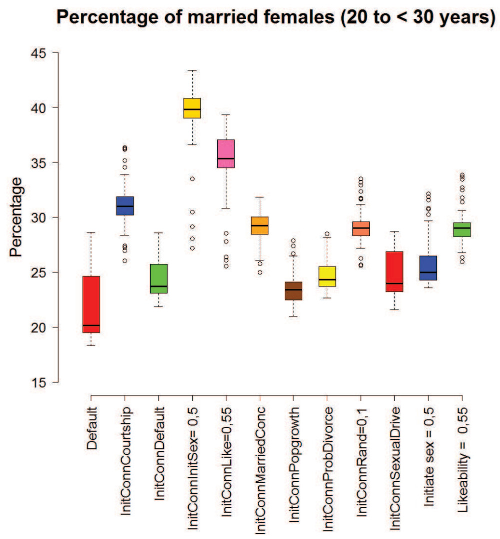


(b) Scenario 2

Figure B.2: **Percentage of married female agents between 15 and less than 20 years**

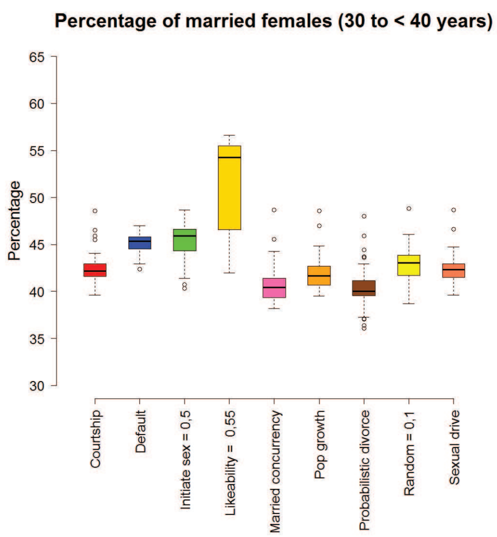


(a) Scenario 1

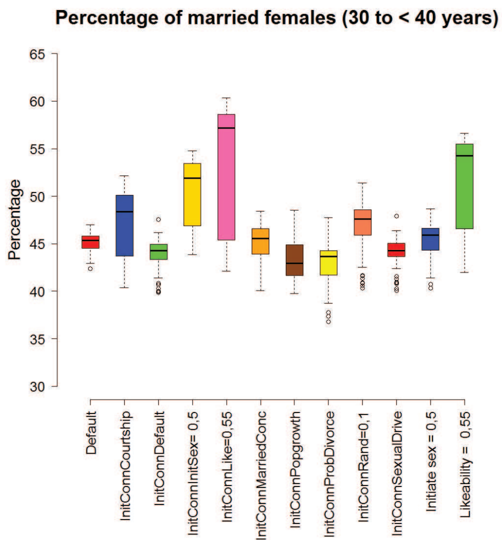


(b) Scenario 2

Figure B.3: **Percentage of married female agents between 20 and less than 30 years**

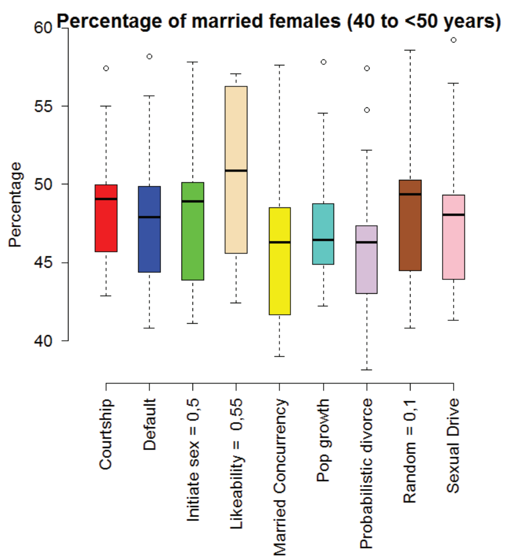


(a) Scenario 1

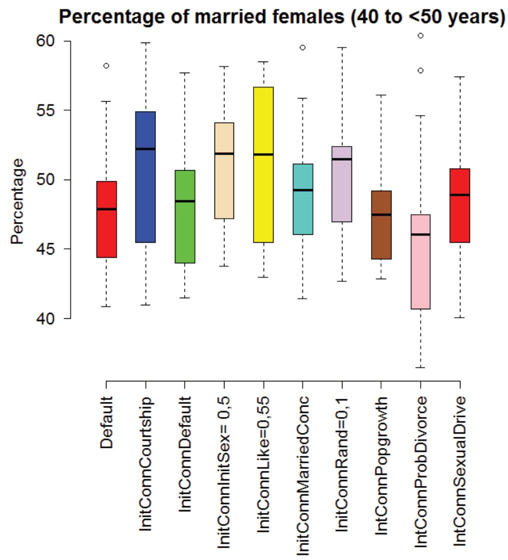


(b) Scenario 2

Figure B.4: **Percentage of married female agents between 30 and less than 40 years**

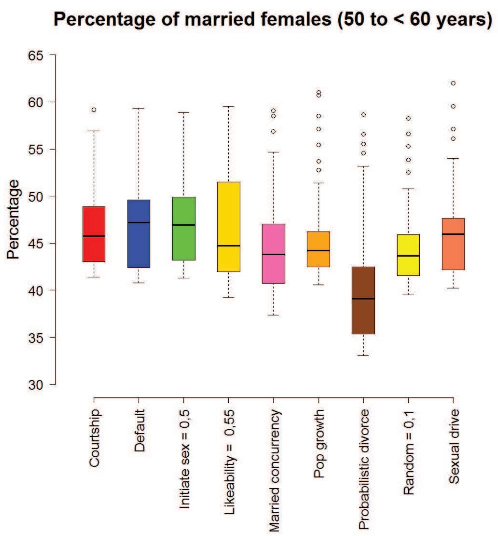


(a) Scenario 1

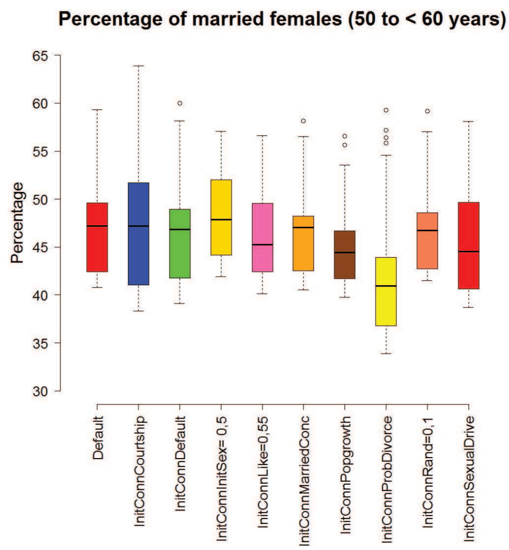


(b) Scenario 2

Figure B.5: **Percentage of married female agents between 40 and less than 50 years**

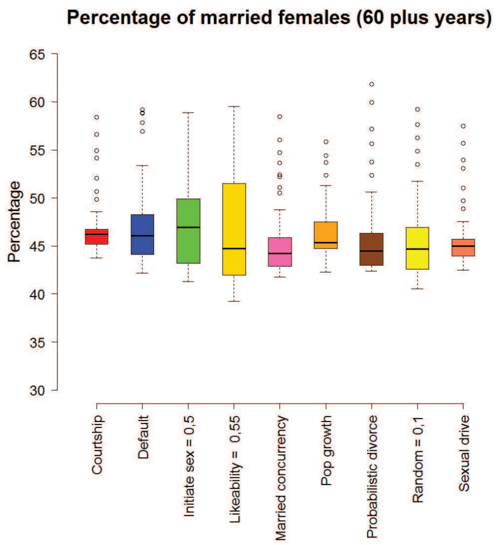


(a) Scenario 1

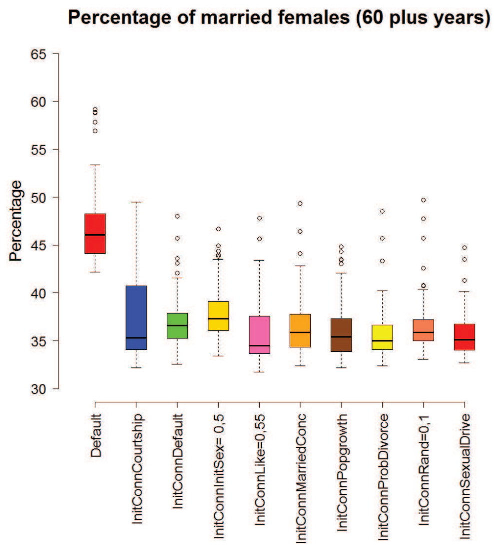


(b) Scenario 2

Figure B.6: **Percentage of married female agents between 50 and less than 60 years**

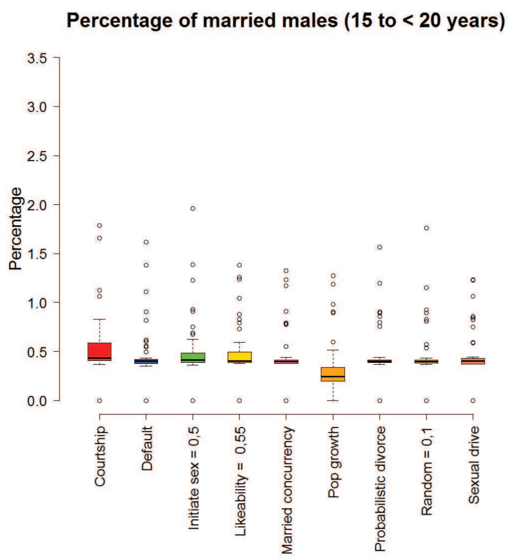


(a) Scenario 1

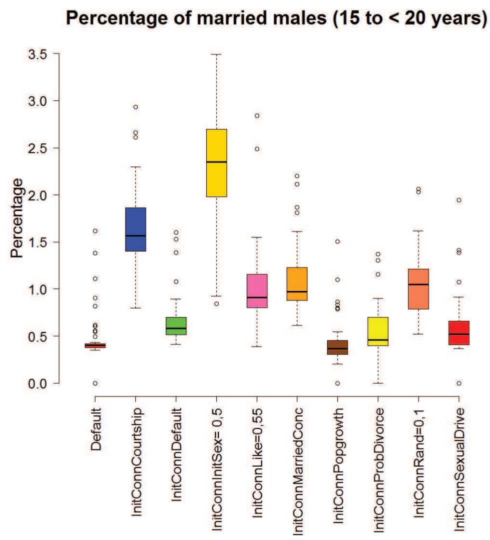


(b) Scenario 2

Figure B.7: **Percentage of married female agents 60 plus years**

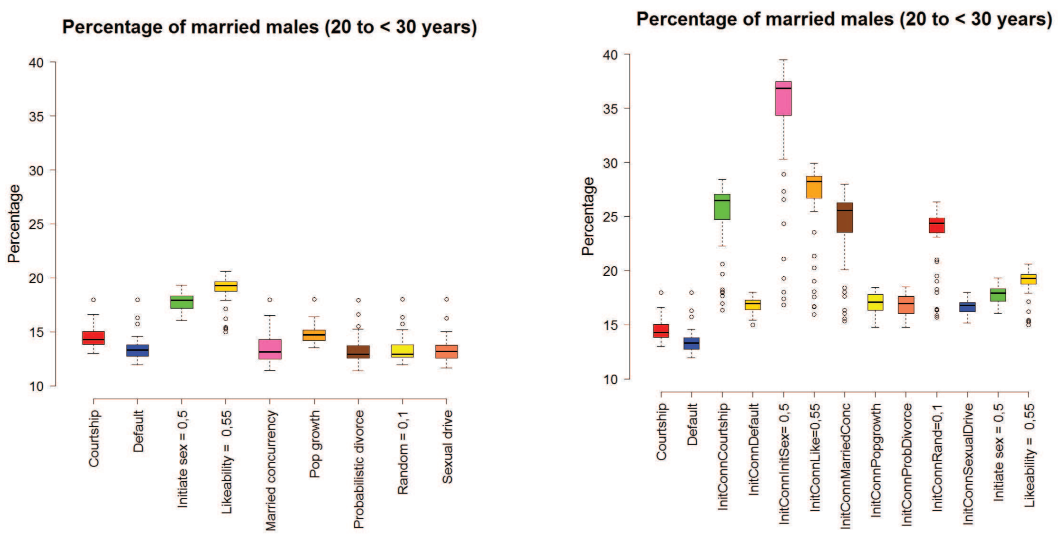


(a) Scenario 1



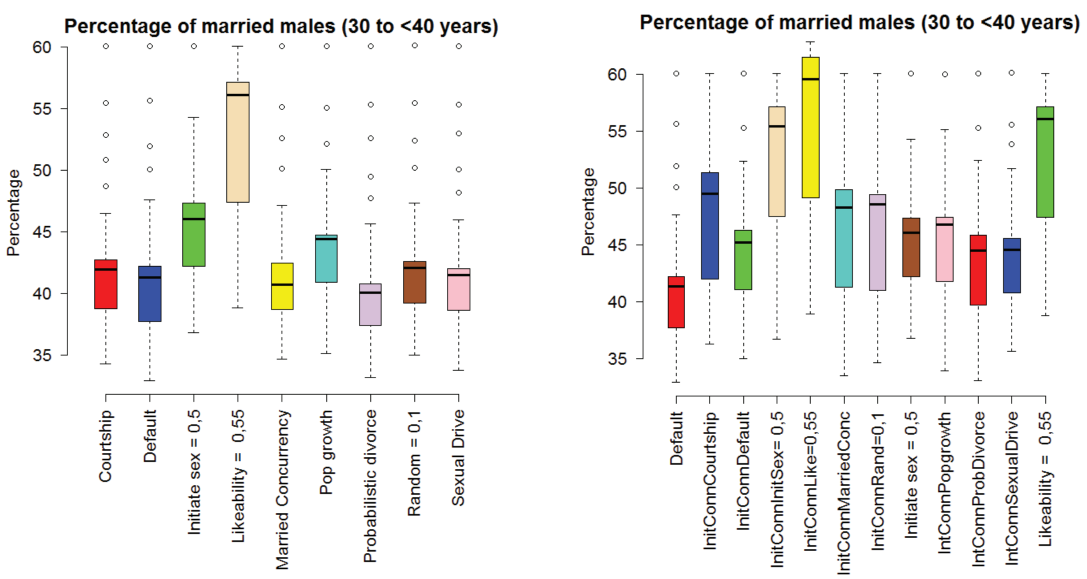
(b) Scenario 2

Figure B.8: **Percentage of married male agents between 15 and less than 20 years**



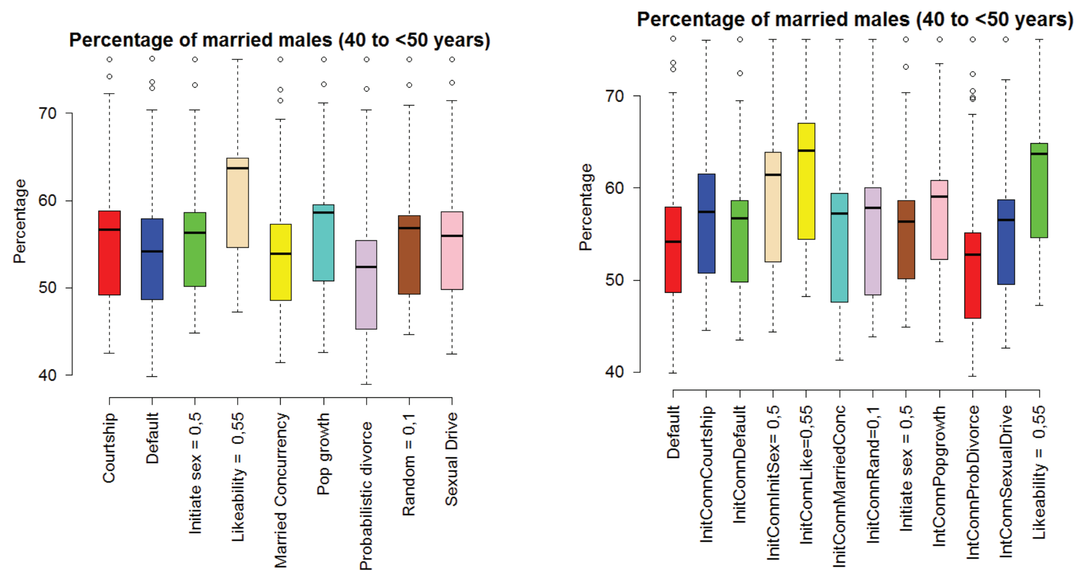
(a) Scenario 1 (b) Scenario 2

Figure B.9: **Percentage of married male agents between 20 and less than 30 years**



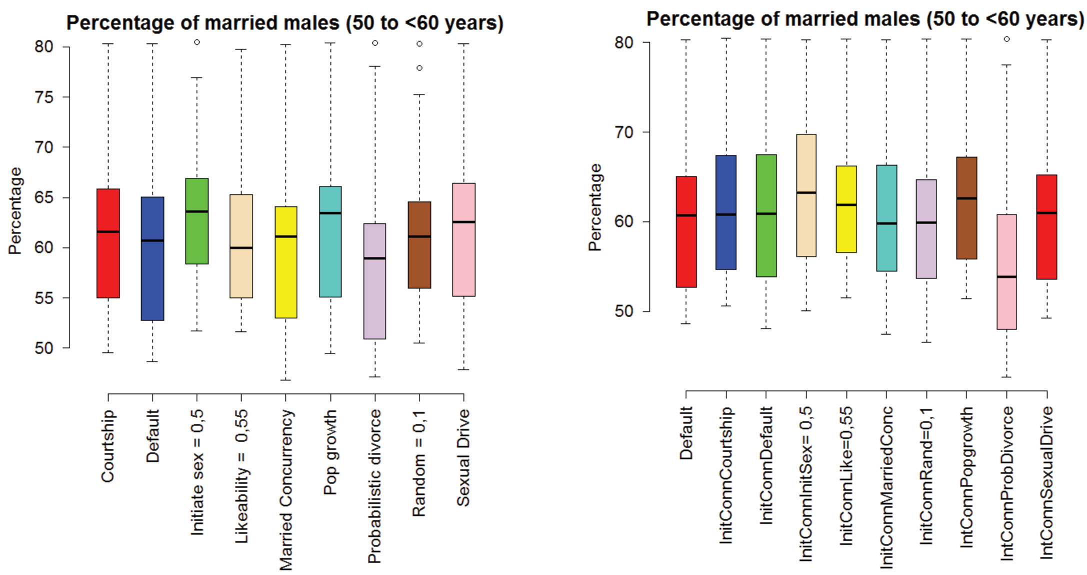
(a) Scenario 1 (b) Scenario 2

Figure B.10: **Percentage of married male agents between 30 and less than 40 years**



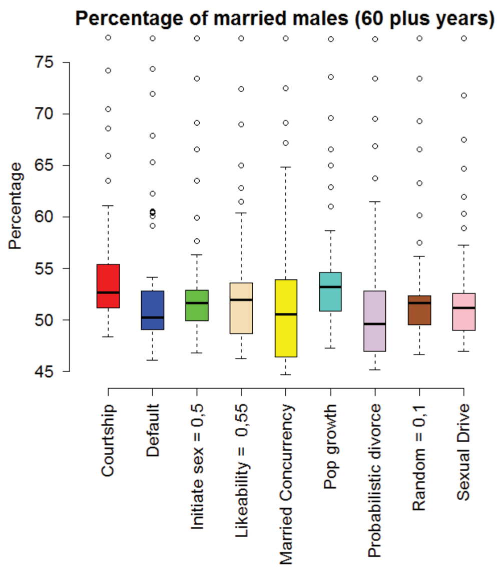
(a) Scenario 1 (b) Scenario 2

Figure B.11: **Percentage of married male agents between 40 and less than 50 years**

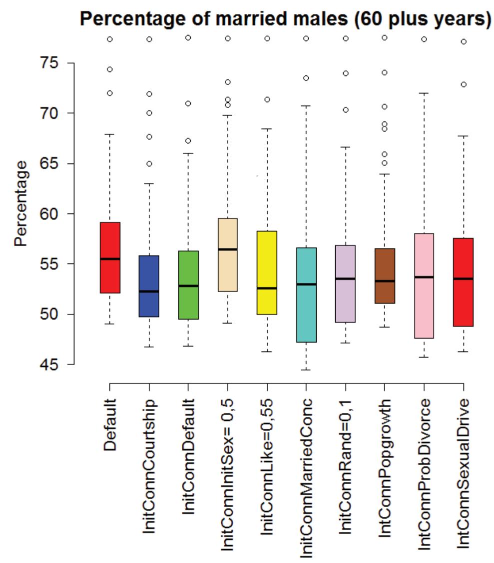


(a) Scenario 1 (b) Scenario 2

Figure B.12: **Percentage of married male agents between 50 and less than 60 years**

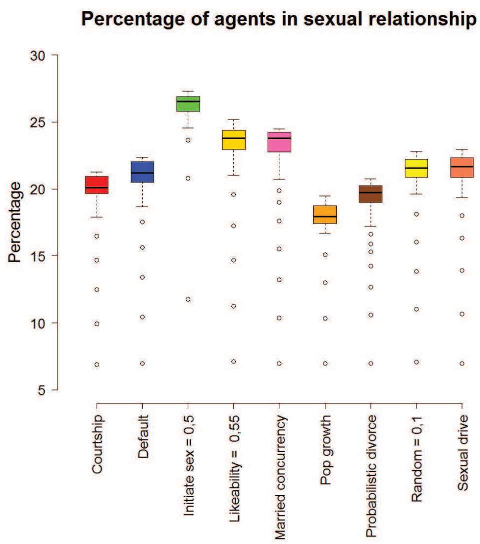


(a) Scenario 1

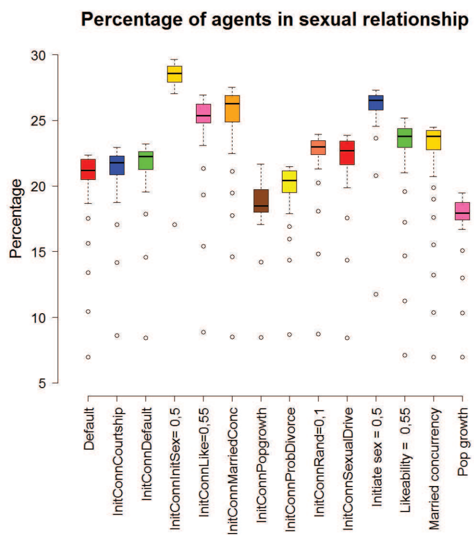


(b) Scenario 2

Figure B.13: **Percentage of married male agents 60 plus years**

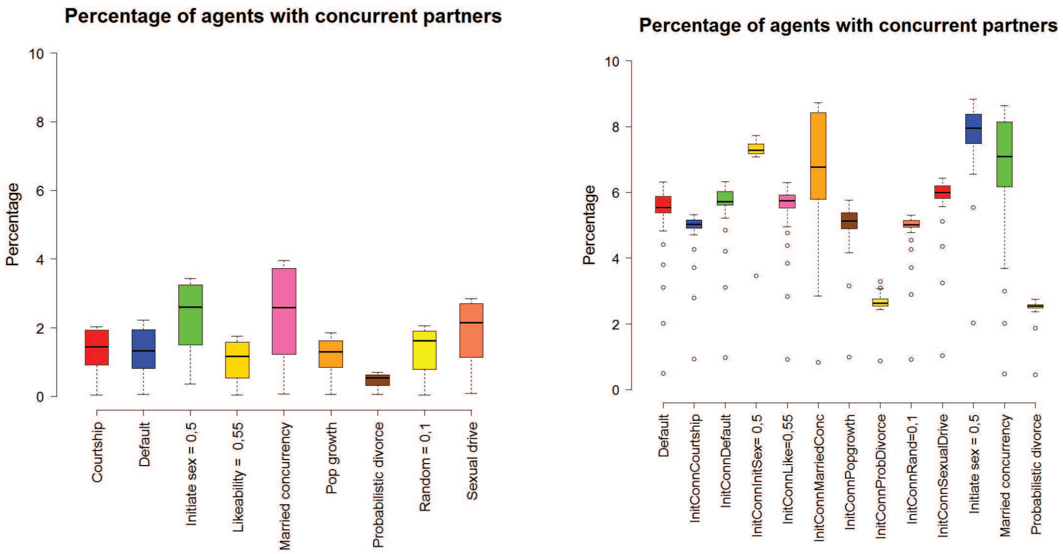


(a) Scenario 1



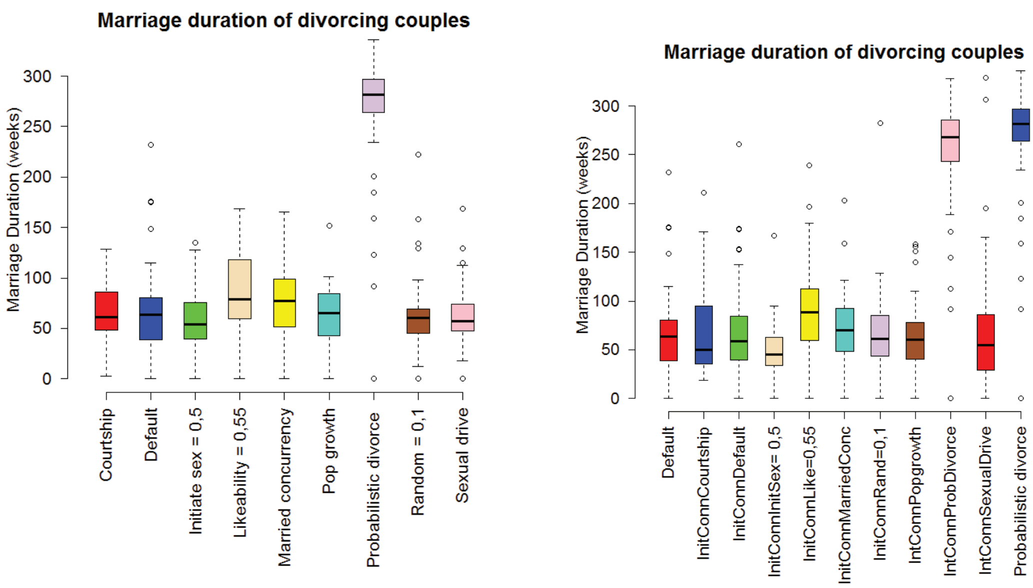
(b) Scenario 2

Figure B.14: **Percentage of agents in a sexual relationships outside marriage**



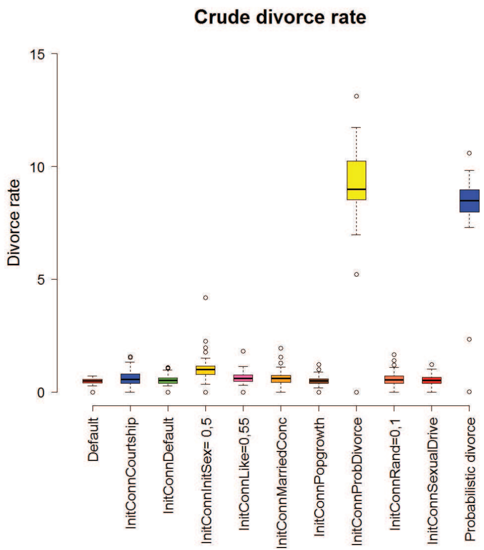
(a) Scenario 1 (b) Scenario 2

Figure B.15: **Percentage of agents with concurrent partners (in or outside marriage)**

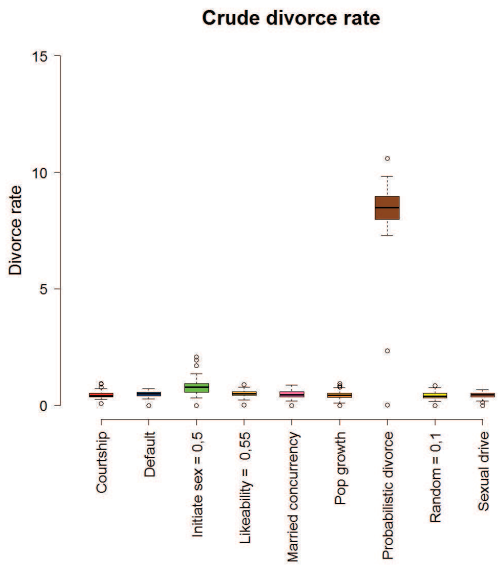


(a) Scenario 1 (b) Scenario 2

Figure B.16: **Marriage duration of divorcing couples**



(a) Scenario 1



(b) Scenario 2

Figure B.17: **Crude divorce rate**

Appendix C

ANOVA results for social and sexual network

ANOVA results for never coupled agents

Scenario 1

```
              Df Sum Sq Mean Sq F value Pr(>F)
Parameter      8   9512  1189.0   83.72 <2e-16 ***
Residuals    432   6135    14.2
  Tukey multiple comparisons of means 95% confidence level
                                                 p adj
  Default-Courtship                          1.0000000
  Initiate sex = 0.5-Default                 0.6101909
  Likeability = 0.55-Default                 0.0000000
  Married Concurrency-Default                0.9999988
  Pop growth-Default                         0.9997010
  Probabilistic divorce -Default             0.9994784
  Random = 0.1-Default                       0.0000000
  Sexual Drive-Default                       1.0000000
```

Scenario 2

```
              Df Sum Sq Mean Sq F value Pr(>F)
Group         11  31398  2854.3   995.1 <2e-16 ***
Residuals    576   1652     2.9
Tukey multiple comparisons of means 95% confidence level
                                               p adj
InitConnCourtship-Default                  0.0000000
InitConnDefault-Default                    0.0000000
InitConnInitSex= 0,5-Default               0.0000000
InitConnLike=0,55-Default                  0.0000000
InitConnMarriedConc-Default                0.0000000
InitConnRand=0,1-Default                   0.0000000
IntConnPopgrowth-Default                   0.9953460
IntConnProbDivorce-Default                 0.0000000
IntConnSexualDrive-Default                 0.0000000
Likeability =  0,55-Default                0.0000000
Random = 0.1-Default                       0.0000000
InitConnDefault-InitConnCourtship          0.0000000
InitConnInitSex= 0,5-InitConnDefault       0.0000000
InitConnLike=0,55-InitConnDefault          0.0000000
InitConnMarriedConc-InitConnDefault        0.0000000
InitConnRand=0,1-InitConnDefault           0.0000000
IntConnPopgrowth-InitConnDefault           0.0000000
IntConnProbDivorce-InitConnDefault         0.9210545
IntConnSexualDrive-InitConnDefault         0.4382466
Likeability =  0,55-InitConnDefault        0.0000000
Random = 0.1-InitConnDefault               0.9996781
```

Figure C.1: **ANOVA results for never coupled agents**

ANOVA results for quality correlation of married agents

Scenario 1

```
              Df Sum Sq  Mean Sq F value   Pr(>F)
Parameter      8 0.2030 0.025380   11.95 1.96e-15 ***
Residuals    432 0.9179 0.002125
```

Tukey multiple comparisons of means 95% confidence interval

	p adj
Default-Courtship	1.0000000
Initiate sex = 0.5-Default	0.9938439
Likeability = 0.55-Default	0.0000001
Married Concurrency-Default	0.9998645
Pop growth-Default	0.3766873
Probabilistic divorce -Default	0.9701602
Random = 0.1-Default	0.8438039
Sexual Drive-Default	0.9852212

Scenario 2

```
              Df Sum Sq Mean Sq F value Pr(>F)
Group         10 1.3743 0.13743   85.59 <2e-16 ***
Residuals    528 0.8478 0.00161
```

Tukey multiple comparisons of means 95% confidence interval

	p adj
InitConnCourtship-Default	0.0000000
InitConnDefault-Default	0.9510162
InitConnInitSex= 0,5-Default	0.0000000
InitConnLike=0,55-Default	0.0000000
InitConnMarriedConc-Default	0.0000000
InitConnRand=0,1-Default	0.0000000
IntConnPopgrowth-Default	0.0016161
IntConnProbDivorce-Default	0.9956666
IntConnSexualDrive-Default	0.1591806
Likeability = 0,55-Default	0.0000000
InitConnDefault-InitConnCourtship	0.0000000
InitConnInitSex= 0,5-InitConnDefault	0.0000000
InitConnLike=0,55-InitConnDefault	0.0000000
InitConnMarriedConc-InitConnDefault	0.0000000
InitConnRand=0,1-InitConnDefault	0.0000000
IntConnPopgrowth-InitConnDefault	0.1597573
IntConnProbDivorce-InitConnDefault	0.9999993
IntConnSexualDrive-InitConnDefault	0.9440903
Likeability = 0,55-InitConnDefault	0.0000000

Figure C.2: **ANOVA results for married agents quality correlation**

ANOVA results married females (less than 20 years)

Scenario 1

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Group	8	24.9	3.113	0.747	0.65
Residuals	441	1839.0	4.170		

Scenario 2

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Group	9	772.4	85.83	23.28	<2e-16	***
Residuals	490	1806.6	3.69			

Tukey multiple comparisons of means 95% confidence level

	p adj
InitConnCourtship-Default	0.0000000
InitConnDefault-Default	0.1415306
InitConnInitSex= 0,5-Default	0.0000000
InitConnLike=0,55-Default	0.0000122
InitConnMarriedConc-Default	0.0000872
InitConnRand=0,1-Default	0.0000326
IntConnPopgrowth-Default	0.3824094
IntConnProbDivorce-Default	0.1630529
IntConnSexualDrive-Default	0.2816407
InitConnDefault-InitConnCourtship	0.0000578
InitConnInitSex= 0,5-InitConnDefault	0.0000000
InitConnLike=0,55-InitConnDefault	0.3168692
InitConnMarriedConc-InitConnDefault	0.5876265
InitConnRand=0,1-InitConnDefault	0.4434322
IntConnPopgrowth-InitConnDefault	0.9999791
IntConnProbDivorce-InitConnDefault	1.0000000
IntConnSexualDrive-InitConnDefault	0.9999995

Figure C.3: **ANOVA results for married female agents between 15 and less than 20 years**

ANOVA results married females (20 to less than 30 years)

Scenario 1

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Group	8	2858	357.3	54.88	<2e-16	***
Residuals	441	2871	6.5			

Tukey multiple comparisons of means 95% confidence level

	p adj
Default-Courtship	0.9223579
Initiate sex = 0,5-Default	0.0000000
Likeability = 0,55-Default	0.0000000
Married Concurrency-Default	1.0000000
Pop growth-Default	0.0801096
Probabilistic divorce-Default	0.9537789
Random = 0.1-Default	0.0756250
Sexual Drive-Default	0.9612141

Scenario 2

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Group	11	13623	1238.4	235.4	<2e-16	***
Residuals	588	3093	5.3			

Tukey multiple comparisons of means 95% confidence level

	p adj
InitConnCourtship-Default	0.0000000
InitConnDefault-Default	0.0661919
InitConnInitSex= 0,5-Default	0.0000000
InitConnLike=0,55-Default	0.0000000
InitConnMarriedConc-Default	0.0000000
InitConnRand=0,1-Default	0.0000000
Initiate sex = 0,5-Default	0.0000000
IntConnPopgrowth-Default	0.7364290
IntConnProbDivorce-Default	0.0006397
IntConnSexualDrive-Default	0.0002570
Likeability = 0,55-Default	0.0000000
InitConnDefault-InitConnCourtship	0.0000000
InitConnInitSex= 0,5-InitConnDefault	0.0000000
InitConnLike=0,55-InitConnDefault	0.0000000
InitConnMarriedConc-InitConnDefault	0.0000000
InitConnRand=0,1-InitConnDefault	0.0000000
Initiate sex = 0,5-InitConnDefault	0.0032437
IntConnPopgrowth-InitConnDefault	0.9844133
IntConnProbDivorce-InitConnDefault	0.9836530
IntConnSexualDrive-InitConnDefault	0.9500275
Likeability = 0,55-InitConnDefault	0.0000000

Figure C.4: **ANOVA results for married female agents between 20 and less than 30 years**

ANOVA results married females (30 to less than 40 years)

Scenario 1

```
              Df Sum Sq Mean Sq F value Pr(>F)
Group          8   4281   535.1   97.99 <2e-16 ***
Residuals    441   2408     5.5

  Tukey multiple comparisons of means 95% confidence level
                                              p adj
Default-Courtship                           0.9999999
Initiate sex = 0,5-Default                  0.0000000
Likeability =  0,55-Default                 0.0000000
Married Concurrency-Default                 0.7351223
Pop growth-Default                          0.9910620
Probabilistic divorce-Default               0.1904957
Random = 0,1-Default                        0.9989311
```

Scenario 2

```
              Df Sum Sq Mean Sq F value Pr(>F)
Group         11   6687   607.9   54.21 <2e-16 ***
Residuals    588   6594    11.2
Tukey multiple comparisons of means 95% confidence level
                                             p adj
InitConnCourtship-Default                  0.0402510
InitConnDefault-Default                    0.3650536
InitConnInitSex= 0,5-Default               0.0000000
InitConnLike=0,55-Default                  0.0000000
InitConnMarriedConc-Default                1.0000000
InitConnRand=0,1-Default                   0.2430947
Initiate sex = 0,5-Default                 0.9999728
IntConnPopgrowth-Default                   0.1969605
IntConnProbDivorce-Default                 0.0354457
IntConnSexualDrive-Default                 0.9404809
Likeability =  0,55-Default                0.0000000
InitConnDefault-InitConnCourtship          0.0000007
InitConnInitSex= 0,5-InitConnDefault       0.0000000
InitConnLike=0,55-InitConnDefault          0.0000000
InitConnMarriedConc-InitConnDefault        0.3932011
InitConnRand=0,1-InitConnDefault           0.0000246
Initiate sex = 0,5-InitConnDefault         0.0860666
IntConnPopgrowth-InitConnDefault           1.0000000
IntConnProbDivorce-InitConnDefault         0.9988211
IntConnSexualDrive-InitConnDefault         0.9983266
Likeability =  0,55-InitConnDefault        0.0000000
```

Figure C.5: **ANOVA results for married female agents between 30 and less than 40 years**

ANOVA results married females (40 to less than 50 years)

Scenario 1

```
              Df Sum Sq Mean Sq F value Pr(>F)    
Group          8    898  112.19   7.301  4e-09 ***
Residuals    441   6777   15.37                   
```

Tukey multiple comparisons of means 95% confidence level

	p adj
Default-Courtship	0.9907701
Initiate sex = 0,5-Default	0.9999949
Likeability = 0,55-Default	0.0008785
Married Concurrency-Default	0.5176364
Pop growth-Default	0.9997865
Probabilistic divorce-Default	0.3346727
Random = 0,1-Default	0.9990657
Sexual Drive-Default	1.0000000

Scenario 2

```
              Df Sum Sq Mean Sq F value   Pr(>F)    
Group          9   1826  202.88   11.14 6.85e-16 ***
Residuals    490   8923   18.21                     
```

Tukey multiple comparisons of means 95% confidence level

	p adj
InitConnCourtship-Default	0.0345357
InitConnDefault-Default	0.9999938
InitConnInitSex= 0,5-Default	0.0011244
InitConnLike=0,55-Default	0.0001926
InitConnMarriedConc-Default	0.9479946
InitConnRand=0,1-Default	0.1394227
IntConnPopgrowth-Default	1.0000000
IntConnProbDivorce-Default	0.0676904
IntConnSexualDrive-Default	0.9999564
InitConnDefault-InitConnCourtship	0.1133090
InitConnInitSex= 0,5-InitConnDefault	0.0058547
InitConnLike=0,55-InitConnDefault	0.0011894
InitConnMarriedConc-InitConnDefault	0.9962650
InitConnRand=0,1-InitConnDefault	0.3389933
IntConnPopgrowth-InitConnDefault	0.9999410
IntConnProbDivorce-InitConnDefault	0.0185952
IntConnSexualDrive-InitConnDefault	1.0000000

Figure C.6: **ANOVA results for married female agents between 40 and less than 50 years**

ANOVA results married females (50 to less than 60 years)

Scenario 1

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Group	8	306	38.27	1.694	0.0975
Residuals	441	9959	22.58		

Scenario 2

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Group	9	1494	166.04	6.325	1.71e-08	***
Residuals	490	12864	26.25			

Tukey multiple comparisons of means 95% confidence level

	p adj
InitConnCourtship-Default	0.9828971
InitConnDefault-Default	0.4967865
InitConnInitSex= 0,5-Default	1.0000000
InitConnLike=0,55-Default	0.3702433
InitConnMarriedConc-Default	0.8847785
InitConnRand=0,1-Default	0.7202582
IntConnPopgrowth-Default	0.0195877
IntConnProbDivorce-Default	0.0000001
IntConnSexualDrive-Default	0.1225292
InitConnDefault-InitConnCourtship	0.9904748
InitConnInitSex= 0,5-InitConnDefault	0.5279254
InitConnLike=0,55-InitConnDefault	1.0000000
InitConnMarriedConc-InitConnDefault	0.9998016
InitConnRand=0,1-InitConnDefault	0.9999994
IntConnPopgrowth-InitConnDefault	0.9460792
IntConnProbDivorce-InitConnDefault	0.0035622
IntConnSexualDrive-InitConnDefault	0.9994681

Figure C.7: **ANOVA results for married female agents between 50 and less than 60 years**

ANOVA results married males (less than 20 years)

Scenario 1

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Group	8	0.51	0.06397	0.588	0.788
Residuals	441	47.95	0.10874		

Scenario 2

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Group	9	209.72	23.302	163	<2e-16	***
Residuals	490	70.06	0.143			

Tukey multiple comparisons of means 95% confidence level

	p adj
InitConnCourtship-Default	0.0000000
InitConnDefault-Default	0.0069542
InitConnInitSex= 0,5-Default	0.0000000
InitConnLike=0,55-Default	0.0000000
InitConnMarriedConc-Default	0.0000000
InitConnRand=0,1-Default	0.0000000
IntConnPopgrowth-Default	0.1550430
IntConnProbDivorce-Default	0.2637411
IntConnSexualDrive-Default	0.0823378
InitConnDefault-InitConnCourtship	0.0000000
InitConnInitSex= 0,5-InitConnDefault	0.0000000
InitConnLike=0,55-InitConnDefault	0.0000010
InitConnMarriedConc-InitConnDefault	0.0000000
InitConnRand=0,1-InitConnDefault	0.0000000
IntConnPopgrowth-InitConnDefault	0.9912693
IntConnProbDivorce-InitConnDefault	0.9622706
IntConnSexualDrive-InitConnDefault	0.9989664

Figure C.8: **ANOVA results for married male agents between 15 and less than 20 years**

ANOVA results married males (20 to less than 30 years)

Scenario 1

```
               Df Sum Sq Mean Sq F value Pr(>F)
Group           8 1809.4  226.17   180.2 <2e-16 ***
Residuals     441  553.4    1.25
Tukey multiple comparisons of means 95% confidence level
                                            p adj
Default-Courtship                       0.0013370
Initiate sex = 0,5-Default              0.0000000
Likeability =  0,55-Default             0.0000000
Married Concurrency-Default             1.0000000
Pop growth-Default                      0.0000064
Probabilistic divorce-Default           0.8274020
Random = 0,1-Default                    0.9822822
Sexual Drive-Default                    0.9539524
```

Scenario 2

```
               Df Sum Sq Mean Sq F value Pr(>F)
Group          12  20551  1712.6   237.4 <2e-16 ***
Residuals     637   4596     7.2
Tukey multiple comparisons of means 95% confidence level
                                            p adj
Default-Courtship                       0.8822749
InitConnDefault-Courtship               0.0020316
InitConnCourtship-Default               0.0000000
InitConnDefault-Default                 0.0000004
InitConnInitSex= 0,5-Default            0.0000000
InitConnLike=0,55-Default               0.0000000
InitConnMarriedConc-Default             0.0000000
InitConnRand=0,1-Default                0.0000000
Initiate sex = 0,5-Default              0.0000000
IntConnPopgrowth-Default                0.0000001
IntConnProbDivorce-Default              0.0000001
IntConnSexualDrive-Default              0.0000005
Likeability =  0,55-Default             0.0000000
InitConnDefault-InitConnCourtship       0.0000000
InitConnInitSex= 0,5-InitConnDefault    0.0000000
InitConnLike=0,55-InitConnDefault       0.0000000
InitConnMarriedConc-InitConnDefault     0.0000000
InitConnRand=0,1-InitConnDefault        0.0000000
Initiate sex = 0,5-InitConnDefault      0.7780772
IntConnPopgrowth-InitConnDefault        1.0000000
IntConnProbDivorce-InitConnDefault      1.0000000
IntConnSexualDrive-InitConnDefault      1.0000000
Likeability =  0,55-InitConnDefault     0.0036393
```

Figure C.9: **ANOVA results for married male agents between 20 and less than 30 years**

ANOVA results married males (30 to less than 40 years)

Scenario 1

```
               Df Sum Sq Mean Sq F value Pr(>F)
Group           8   5895   736.9   27.28 <2e-16 ***
Residuals     441  11913    27.0
Tukey multiple comparisons of means 95% confidence level
                                                 p adj
Default-Courtship                            0.9983566
Initiate sex = 0,5-Default                   0.0012429
Likeability =  0,55-Default                  0.0000000
Married Concurrency-Default                  0.9999997
Pop growth-Default                           0.3491341
Probabilistic divorce-Default                0.9980082
Random = 0,1-Default                         0.9958690
Sexual Drive-Default                         1.0000000
```

Scenario 2

```
               Df Sum Sq Mean Sq F value Pr(>F)
Group          11   9966   906.0   26.41 <2e-16 ***
Residuals     588  20171    34.3
Tukey multiple comparisons of means 95% confidence level
                                                p adj
InitConnCourtship-Default                    0.0000180
InitConnDefault-Default                      0.2229720
InitConnInitSex= 0,5-Default                 0.0000000
InitConnLike=0,55-Default                    0.0000000
InitConnMarriedConc-Default                  0.0034958
InitConnRand=0,1-Default                     0.0018598
Initiate sex = 0,5-Default                   0.0127639
IntConnPopgrowth-Default                     0.0372680
IntConnProbDivorce-Default                   0.6565693
IntConnSexualDrive-Default                   0.2948441
Likeability =  0,55-Default                  0.0000000
InitConnDefault-InitConnCourtship            0.3510721
InitConnInitSex= 0,5-InitConnDefault         0.0000000
InitConnLike=0,55-InitConnDefault            0.0000000
InitConnMarriedConc-InitConnDefault          0.9753708
InitConnRand=0,1-InitConnDefault             0.9447748
Initiate sex = 0,5-InitConnDefault           0.9980089
IntConnPopgrowth-InitConnDefault             0.9999538
IntConnProbDivorce-InitConnDefault           0.9999576
IntConnSexualDrive-InitConnDefault           1.0000000
Likeability =  0,55-InitConnDefault          0.0000000
```

Figure C.10: **ANOVA results for married male agents between 30 and less than 40 years**

ANOVA results married males (40 to less than 50 years)

Scenario 1

```
              Df Sum Sq Mean Sq F value  Pr(>F)
Group          8   1857  232.12   3.339 0.00101 **
Residuals    441  30658   69.52
Tukey multiple comparisons of means 95% confidence level
                                                  p adj
Default-Courtship                             0.9992616
Initiate sex = 0,5-Default                    0.9952566
Likeability =  0,55-Default                   0.0208361
Married Concurrency-Default                   1.0000000
Pop growth-Default                            0.9389733
Probabilistic divorce  -Default               0.8951626
Random = 0,1-Default                          0.9983704
Sexual Drive-Default                          0.9999252
```

Scenario 2

```
              Df Sum Sq Mean Sq F value   Pr(>F)
Group         11   3101  281.87   3.953 1.46e-05 ***
Residuals    588  41932   71.31
Tukey multiple comparisons of means 95% confidence level
                                                p adj
InitConnCourtship-Default                   0.8884285
InitConnDefault-Default                     0.9998518
InitConnInitSex= 0,5-Default                0.1925283
InitConnLike=0,55-Default                   0.0051904
InitConnMarriedConc-Default                 0.9999872
InitConnRand=0,1-Default                    0.9989424
Initiate sex = 0,5-Default                  0.9995503
IntConnPopgrowth-Default                    0.8984292
IntConnProbDivorce-Default                  0.9985651
IntConnSexualDrive-Default                  0.9997303
Likeability =  0,55-Default                 0.0395933
InitConnDefault-InitConnCourtship           0.9990601
InitConnInitSex= 0,5-InitConnDefault        0.6725238
InitConnLike=0,55-InitConnDefault           0.0654586
InitConnMarriedConc-InitConnDefault         1.0000000
InitConnRand=0,1-InitConnDefault            1.0000000
Initiate sex = 0,5-InitConnDefault          1.0000000
IntConnPopgrowth-InitConnDefault            0.9992768
IntConnProbDivorce-InitConnDefault          0.8701023
IntConnSexualDrive-InitConnDefault          1.0000000
Likeability =  0,55-InitConnDefault         0.2763757
```

Figure C.11: **ANOVA results for married male agents between 40 and less than 50 years**

ANOVA results married males (50 to less than 60 years)

Scenario 1

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Group	8	359	44.85	0.772	0.628
Residuals	441	25634	58.13		

Scenario 2

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Group	9	1973	219.17	3.151	0.00104	**
Residuals	490	34083	69.56			

Tukey multiple comparisons of means 95% confidence level

	p adj
InitConnCourtship-Default	0.9999081
InitConnDefault-Default	0.9999765
InitConnInitSex= 0,5-Default	0.7793811
InitConnLike=0,55-Default	0.9424473
InitConnMarriedConc-Default	0.9999927
InitConnRand=0,1-Default	1.0000000
IntConnPopgrowth-Default	0.9379288
IntConnProbDivorce-Default	0.1388092
IntConnSexualDrive-Default	1.0000000
InitConnDefault-InitConnCourtship	1.0000000
InitConnInitSex= 0,5-InitConnDefault	0.9654496
InitConnLike=0,55-InitConnDefault	0.9975239
InitConnMarriedConc-InitConnDefault	1.0000000
InitConnRand=0,1-InitConnDefault	0.9999744
IntConnPopgrowth-InitConnDefault	0.9971229
IntConnProbDivorce-InitConnDefault	0.0358106
IntConnSexualDrive-InitConnDefault	0.9999999

Figure C.12: **ANOVA results for married male agents between 50 and less than 60 years**

ANOVA results married females (60 plus years)

Scenario 1

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Group	8	201	25.17	1.439	0.178
Residuals	441	7712	17.49		

Scenario 2

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Group	9	210	23.30	1.824	0.0616
Residuals	490	6257	12.77		

(a) ANOVA results for married female agents above 60 plus years

ANOVA results married males (60 plus years)

Scenario 1

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Group	8	325	40.57	0.879	0.534
Residuals	441	20348	46.14		

Scenario 2

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Group	9	634	70.40	1.503	0.144
Residuals	490	22952	46.84		

(b) ANOVA results for married male agents above 60 plus years

Figure C.13: **ANOVA results for married female and male agents 60 plus years**

ANOVA results for median age at first marriage

Male agents

```
               Df Sum Sq Mean Sq F value Pr(>F)
Group           8  349.0   43.62    48.5 <2e-16 ***
Residuals     432  388.6    0.90
Tukey multiple comparisons of means 95% confidence level

                                              p adj
Default-Courtship                           0.9978947
Initiate sex = 0.5-Default                  0.0000000
Likeability =  0.55-Default                 0.0000000
Married Concurrency-Default                 1.0000000
Pop growth-Default                          0.0000000
Probabilistic divorce-Default               0.1414344
Random = 0.1-Default                        0.9999980
Sexual Drive-Default                        0.9970820
```

Female agents

```
               Df Sum Sq Mean Sq F value Pr(>F)
Group           8  252.7  31.584   15.78 <2e-16 ***
Residuals     432  864.8   2.002

Tukey multiple comparisons of means 95% confidence level
                                               p adj
Default-Courtship                            0.9996917
Initiate sex = 0.5-Default                   1.0000000
Likeability =  0.55-Default                  0.0000000
Married Concurrency-Default                  1.0000000
Pop growth-Default                           0.0000026
Probabilistic divorce -Default               0.7271326
Random = 0.1-Default                         1.0000000
Sexual Drive-Default                         0.9999994
```

Figure C.14: **ANOVA results for male and female median age at first marriage**

ANOVA results for agents in sexual relationships outside marriage

Scenario 1

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Parameter	8	2390	298.71	34.82	<2e-16	***
Residuals	432	3706	8.58			

Tukey multiple comparisons of means 95% confidence level

	p adj
Default-Courtship	0.8079519
Initiate sex = 0.5-Default	0.0000000
Likeability = 0.55-Default	0.0015254
Married Concurrency-Default	0.0314395
Pop growth-Default	0.0001013
Probabilistic divorce -Default	0.1506696
Random = 0.1-Default	0.9994283
Sexual Drive-Default	0.9963583

Scenario 2

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Group	13	5372	413.2	56.8	<2e-16	***
Residuals	672	4889	7.3			

Tukey multiple comparisons of means 95% confidence level

	p adj
InitConnCourtship-Default	0.9875731
InitConnDefault-Default	0.6326021
InitConnInitSex= 0,5-Default	0.0000000
InitConnLike=0,55-Default	0.0000000
InitConnMarriedConc-Default	0.0000000
InitConnRand=0,1-Default	0.0211737
IntConnPopgrowth-Default	0.1424625
IntConnProbDivorce-Default	0.9998676
IntConnSexualDrive-Default	0.1026277
InitConnDefault-InitConnCourtship	0.9998769
InitConnInitSex= 0,5-InitConnDefault	0.0000000
InitConnLike=0,55-InitConnDefault	0.0000008
InitConnMarriedConc-InitConnDefault	0.0000000
InitConnRand=0,1-InitConnDefault	0.9778129
Initiate sex = 0,5-InitConnDefault	0.0000000
IntConnPopgrowth-InitConnDefault	0.0000245
IntConnProbDivorce-InitConnDefault	0.1214361
IntConnSexualDrive-InitConnDefault	0.9997112
Likeability = 0,55-InitConnDefault	0.5770091
Married concurrency-InitConnDefault	0.9862458
Pop growth-InitConnDefault	0.0000000

Figure C.15: **ANOVA results for agents in a sexual relationships outside marriage**

ANOVA results for concurrent agents (in or outside marriage)

Scenario 1

```
               Df Sum Sq Mean Sq F value Pr(>F)
Parameter       8  812.5   101.6   84.49 <2e-16 ***
Residuals     432  519.3     1.2
Tukey multiple comparisons of means 95% confidence level
                                                p adj
Default-Courtship                           1.0000000
Initiate sex = 0.5-Default                  0.0000000
Likeability = 0.55-Default                  0.9999962
Married Concurrency-Default                 0.0000000
Pop growth-Default                          0.3252216
Probabilistic divorce -Default              0.0000000
Random = 0.1-Default                        0.9463368
Sexual Drive-Default                        0.6982866
```

Scenario 2

```
               Df Sum Sq Mean Sq F value Pr(>F)
Group          12 1465.3  122.11   125.2 <2e-16 ***
Residuals     624  608.7    0.98
Tukey multiple comparisons of means 95% confidence level
                                             p adj
InitConnCourtship-Default                0.4616760
InitConnDefault-Default                  0.7535589
InitConnInitSex= 0,5-Default             0.0000000
InitConnLike=0,55-Default                0.9997536
InitConnMarriedConc-Default              0.0000000
InitConnRand=0,1-Default                 0.4161704
Initiate sex = 0,5-Default               0.0000000
IntConnPopgrowth-Default                 0.9507426
IntConnProbDivorce-Default               0.0000000
IntConnSexualDrive-Default               0.4695743
Married concurrency-Default              0.0000000
Probabilistic divorce-Default            0.0000000
InitConnDefault-InitConnCourtship        0.0011514
InitConnInitSex= 0,5-InitConnDefault     0.0000000
InitConnLike=0,55-InitConnDefault        0.9963563
InitConnMarriedConc-InitConnDefault      0.0000203
InitConnRand=0,1-InitConnDefault         0.0008724
Initiate sex = 0,5-InitConnDefault       0.0000000
IntConnPopgrowth-InitConnDefault         0.0296436
IntConnProbDivorce-InitConnDefault       0.0000000
IntConnSexualDrive-InitConnDefault       0.9999999
Married concurrency-InitConnDefault      0.0000681
Probabilistic divorce-InitConnDefault    0.0000000
```

Figure C.16: **ANOVA results for agents with concurrent partners**

ANOVA results for marriage duration of divorcing couples

Scenario 1

```
               Df  Sum Sq Mean Sq F value Pr(>F)
Parameter       8 1730415  216302   150.7 <2e-16 ***
Residuals     432  620132    1435

  Tukey multiple comparisons of means 95% confidence level

                                             p adj
Default-Courtship                        0.9999998
Initiate sex = 0.5-Default               0.9809489
Likeability = 0.55-Default               0.2706605
Married Concurrency-Default              0.9209649
Pop growth-Default                       0.9999817
Probabilistic divorce -Default           0.0000000
Random = 0.1-Default                     0.9999937
Sexual Drive-Default                     0.9999390
```

Scenario 2

```
               Df  Sum Sq Mean Sq F value Pr(>F)
Group          10 2944133  294413   126.4 <2e-16 ***
Residuals     528 1230242    2330

Tukey multiple comparisons of means 95% confidence level
                                            p adj
InitConnCourtship-Default                1.0000000
InitConnDefault-Default                  0.9999976
InitConnInitSex= 0,5-Default             0.7357224
InitConnLike=0,55-Default                0.3546280
InitConnMarriedConc-Default              0.9994950
InitConnRand=0,1-Default                 1.0000000
IntConnPopgrowth-Default                 1.0000000
IntConnProbDivorce-Default               0.0000000
IntConnSexualDrive-Default               1.0000000
Probabilistic divorce-Default            0.0000000
InitConnDefault-InitConnCourtship        0.9999996
InitConnInitSex= 0,5-InitConnDefault     0.4293943
InitConnLike=0,55-InitConnDefault        0.6598943
InitConnMarriedConc-InitConnDefault      0.9999998
InitConnRand=0,1-InitConnDefault         1.0000000
IntConnPopgrowth-InitConnDefault         0.9997836
IntConnProbDivorce-InitConnDefault       0.0000000
IntConnSexualDrive-InitConnDefault       1.0000000
Probabilistic divorce-InitConnDefault    0.0000000
```

Figure C.17: **ANOVA results for marriage duration of divorcing couples**

ANOVA results for crude divorce rate

Scenario 1

```
              Df Sum Sq Mean Sq F value Pr(>F)
Group          8 2660.7   332.6   969.1 <2e-16 ***
Residuals    432  148.3     0.3

  Tukey multiple comparisons of means
    95% family-wise confidence level
                                          p adj
Default-Courtship                     1.0000000
Initiate sex = 0.5-Default            0.0916409
Likeability =  0.55-Default           0.9999790
Married Concurrency-Default           0.9999999
Pop growth-Default                    1.0000000
Probabilistic divorce-Default         0.0000000
Random = 0.1-Default                  0.9999831
Sexual Drive-Default                  1.0000000
```

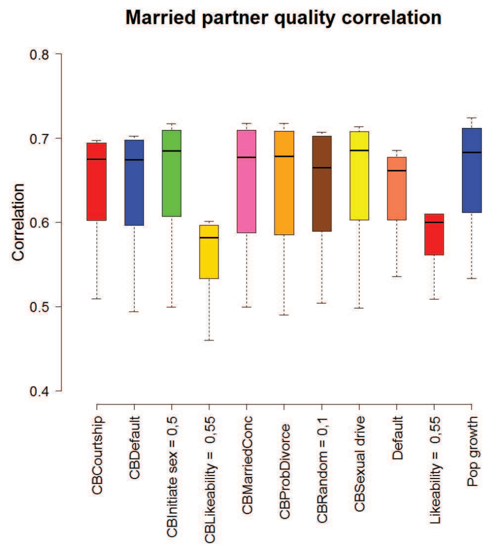
Scenario 2

```
              Df Sum Sq Mean Sq F value Pr(>F)
Group         10   5318   531.8   802.3 <2e-16 ***
Residuals    528    350     0.7
Tukey multiple comparisons of means 95% confidence level
                                          p adj
InitConnCourtship-Default              0.9959086
InitConnDefault-Default                0.9999996
InitConnInitSex= 0,5-Default           0.0135871
InitConnLike=0,55-Default              0.9932751
InitConnMarriedConc-Default            0.9894922
InitConnRand=0,1-Default               0.9996605
IntConnPopgrowth-Default               1.0000000
IntConnProbDivorce-Default             0.0000000
IntConnSexualDrive-Default             0.9999983
Probabilistic divorce-Default          0.0000000
InitConnDefault-InitConnCourtship      0.9999287
InitConnInitSex= 0,5-InitConnDefault   0.0453613
InitConnLike=0,55-InitConnDefault      0.9998275
InitConnMarriedConc-InitConnDefault    0.9996250
InitConnRand=0,1-InitConnDefault       0.9999994
IntConnPopgrowth-InitConnDefault       1.0000000
IntConnProbDivorce-InitConnDefault     0.0000000
IntConnSexualDrive-InitConnDefault     1.0000000
Probabilistic divorce-InitConnDefault  0.0000000
```

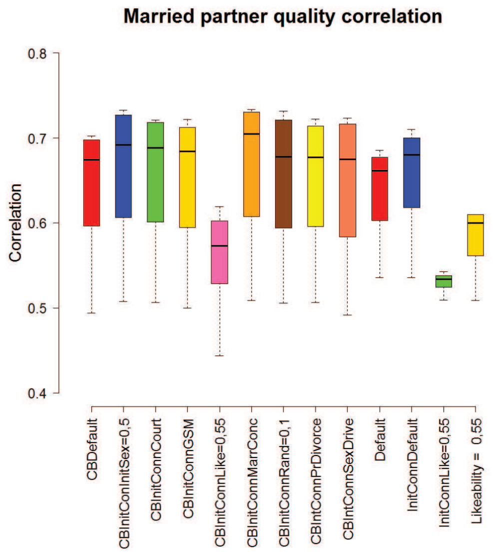
Figure C.18: **ANOVA results for crude divorce rate**

Appendix D

Box plots for social and sexual network with child birth

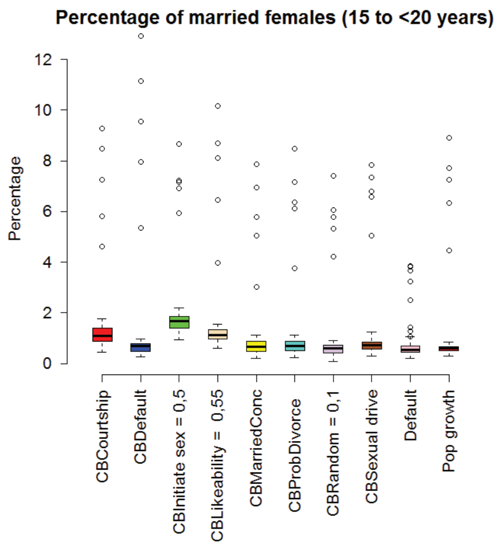


(a) Scenario 3

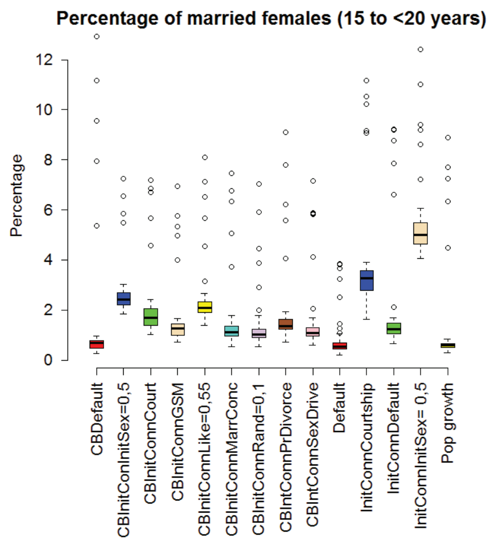


(b) Scenario 4

Figure D.1: **Married partner correlation**

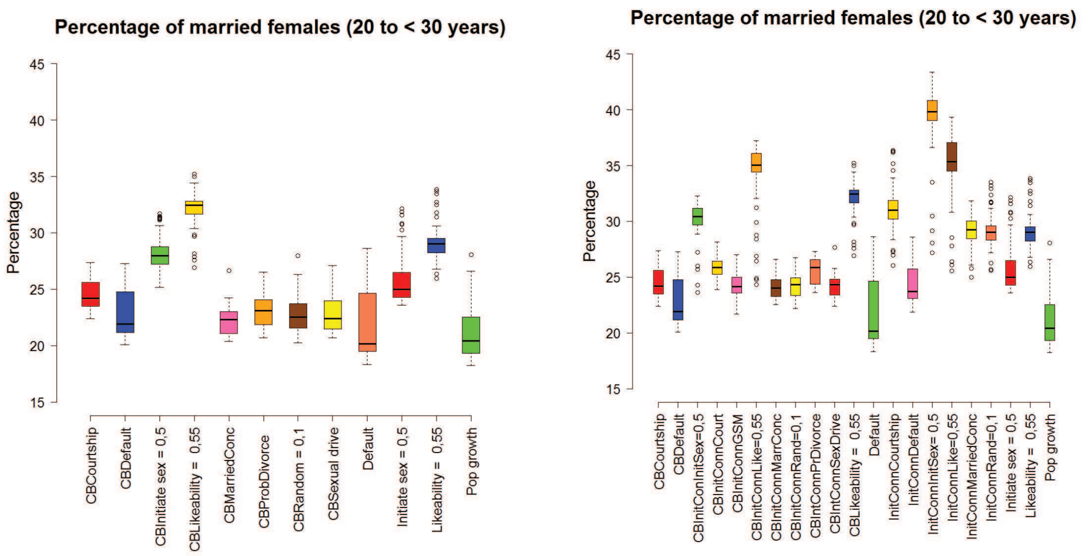


(a) Scenario 3



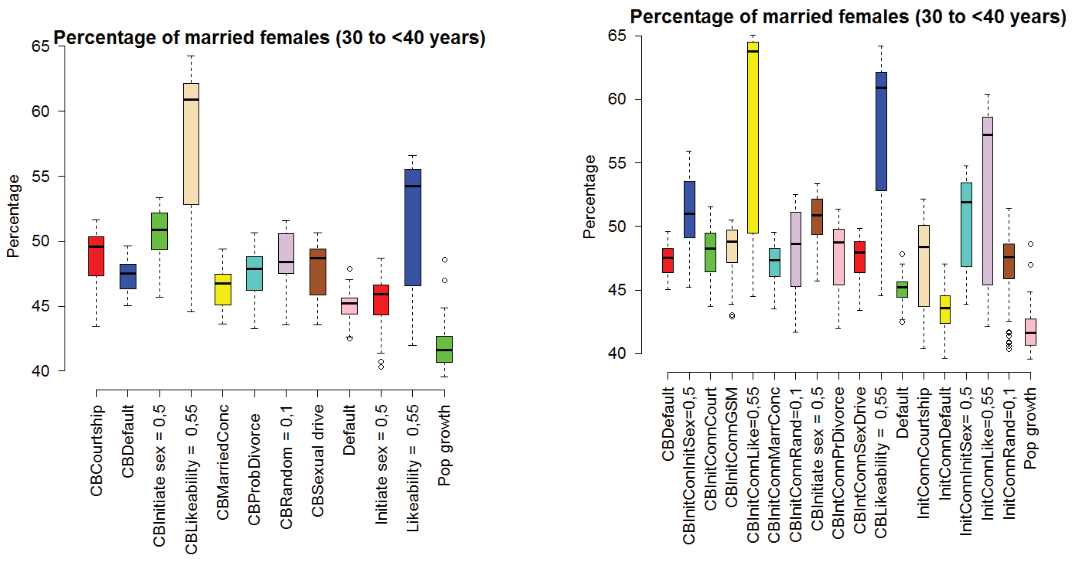
(b) Scenario 4

Figure D.2: **Percentage of married female agents between 15 and less than 20 years**



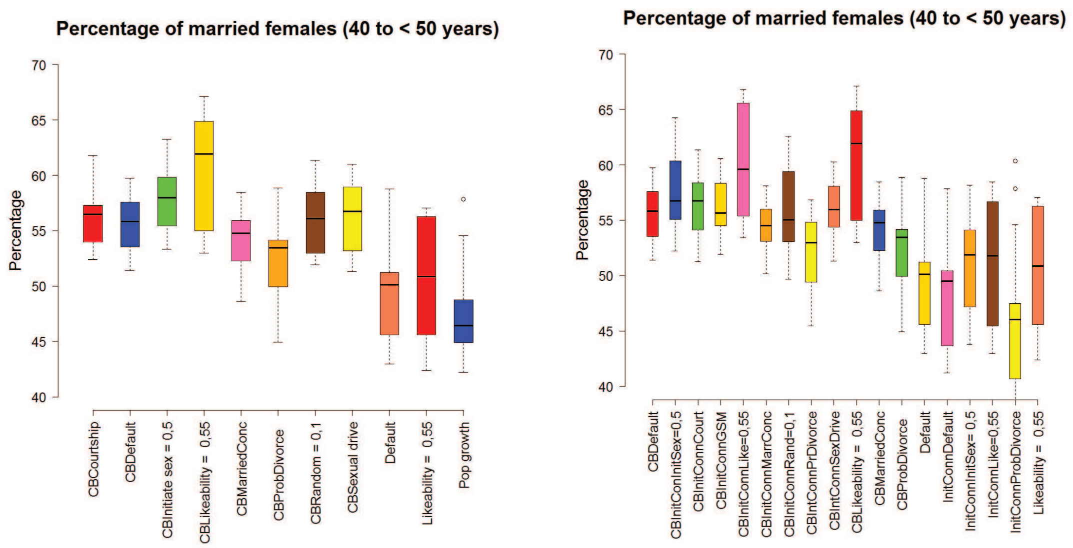
(a) Scenario 3 (b) Scenario 4

Figure D.3: **Percentage of married female agents between 20 and less than 30 years**



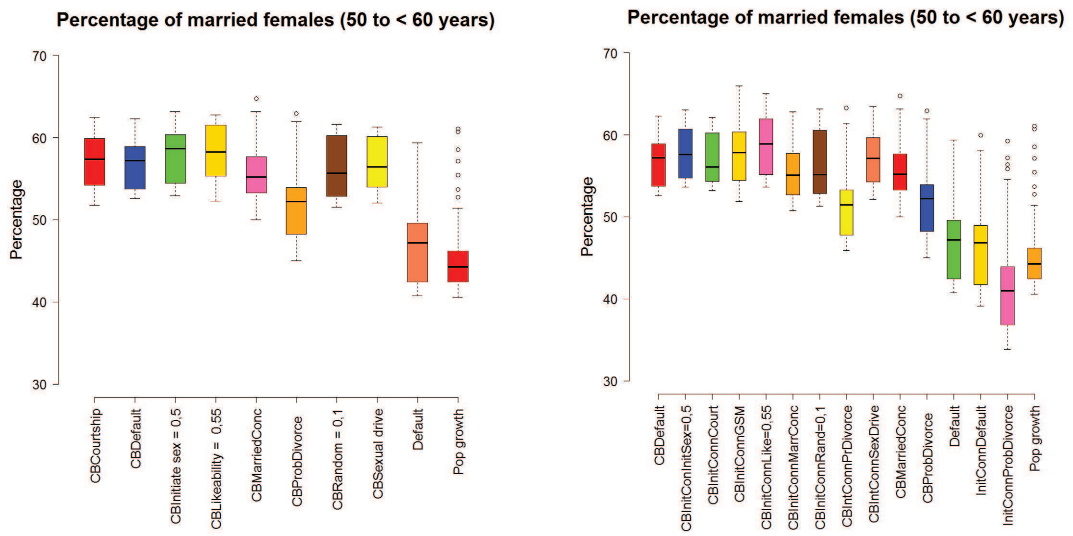
(a) Scenario 3 (b) Scenario 4

Figure D.4: **Percentage of married female agents between 30 and less than 40 years**



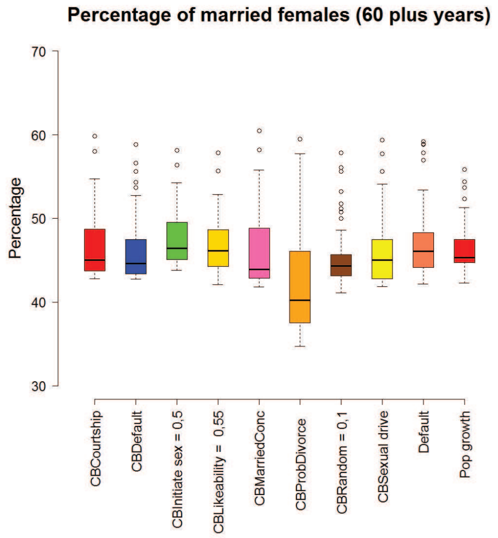
(a) Scenario 3 (b) Scenario 4

Figure D.5: **Percentage of married female agents between 40 and less than 50 years**

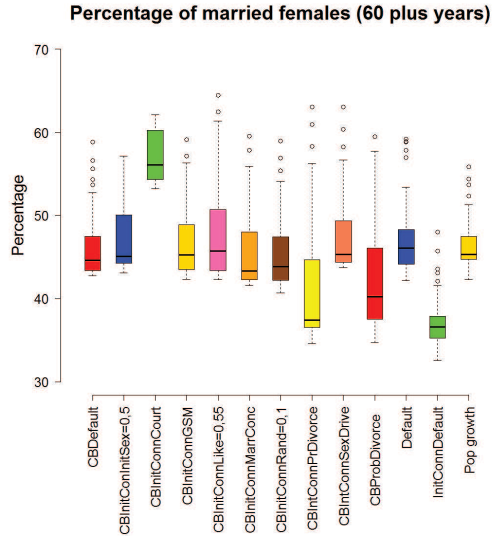


(a) Scenario 3 (b) Scenario 4

Figure D.6: **Percentage of married female agents between 50 and less than 60 years**

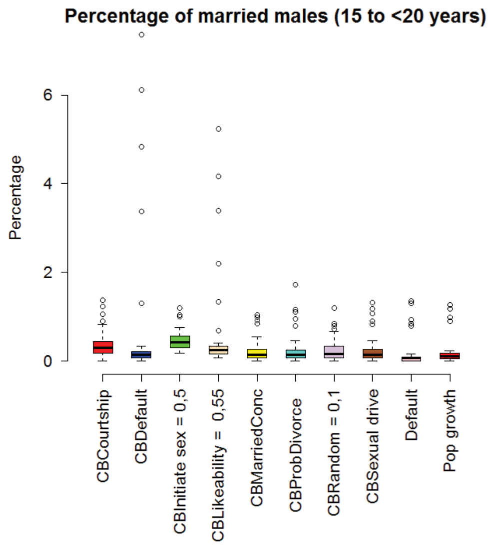


(a) Scenario 3

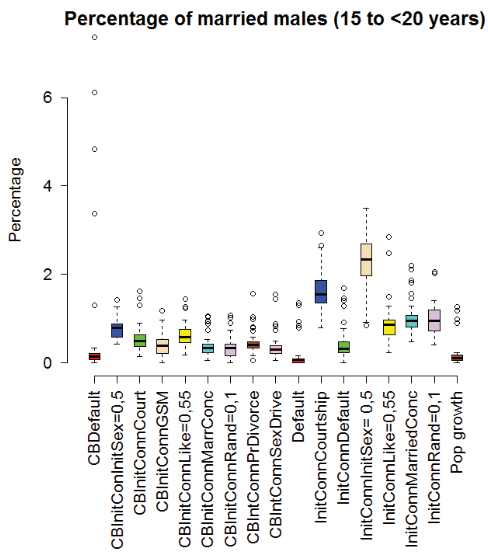


(b) Scenario 4

Figure D.7: **Percentage of married female agents above 60 years**

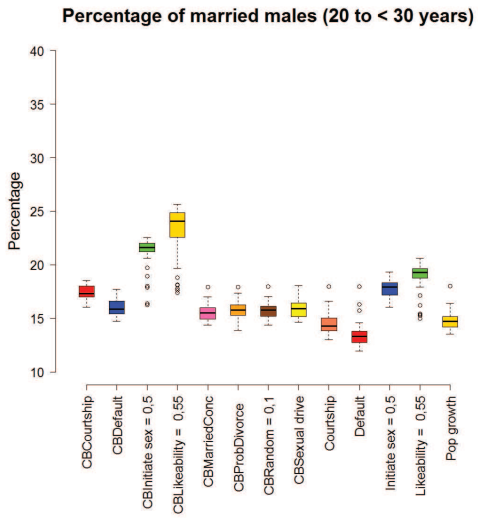


(a) Scenario 3

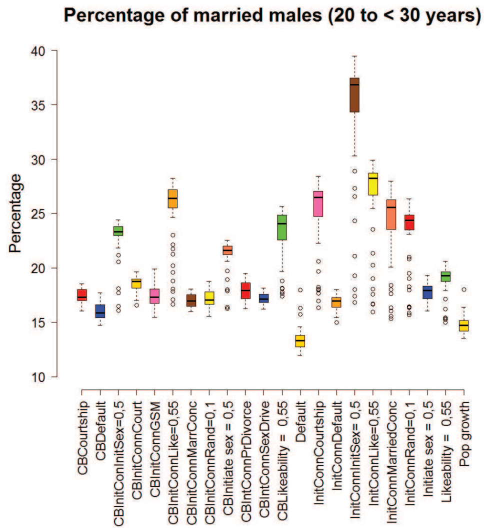


(b) Scenario 4

Figure D.8: **Percentage of married male agents between 15 and less than 20 years**

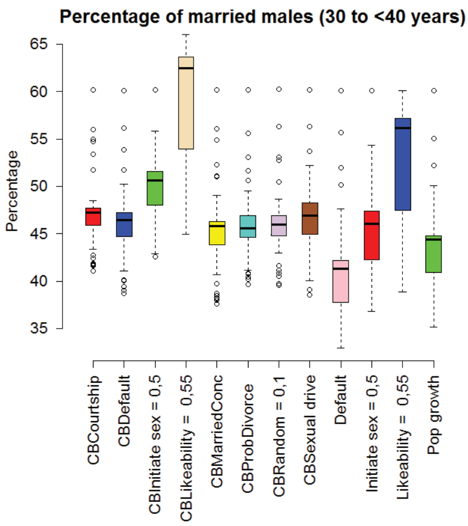


(a) Scenario 3

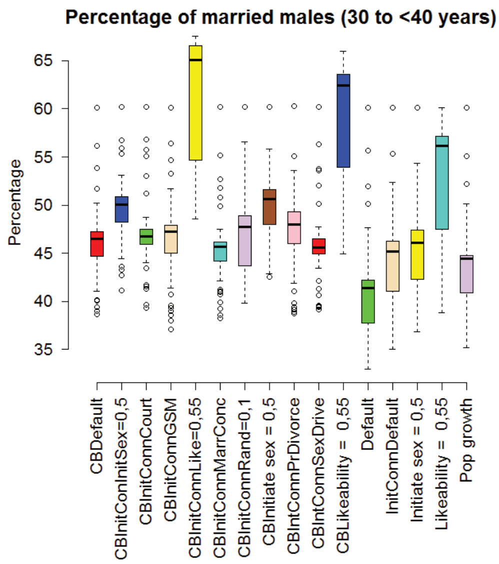


(b) Scenario 4

Figure D.9: **Percentage of married male agents between 20 and less than 30 years**

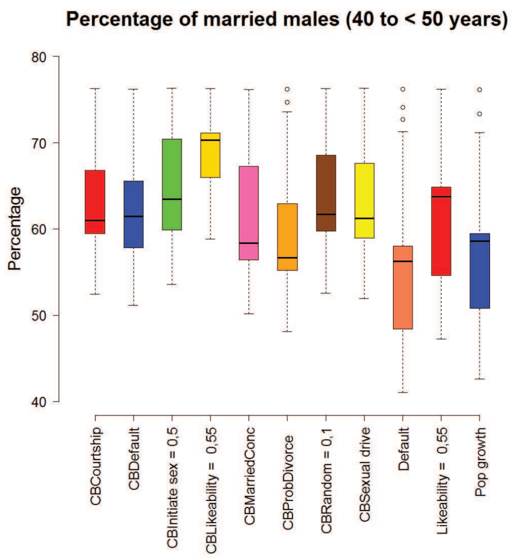


(a) Scenario 3

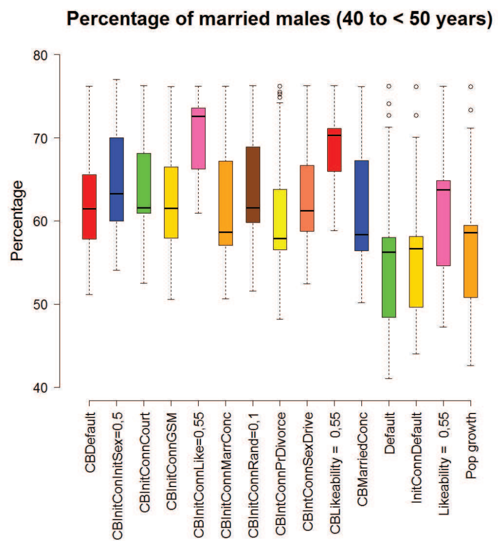


(b) Scenario 4

Figure D.10: **Percentage of married male agents between 30 and less than 40 years**

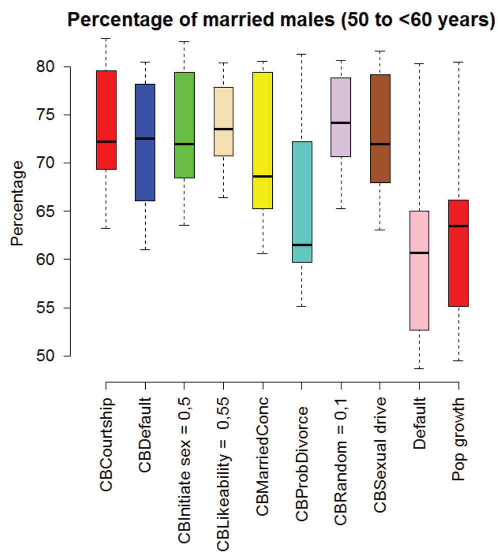


(a) Scenario 3

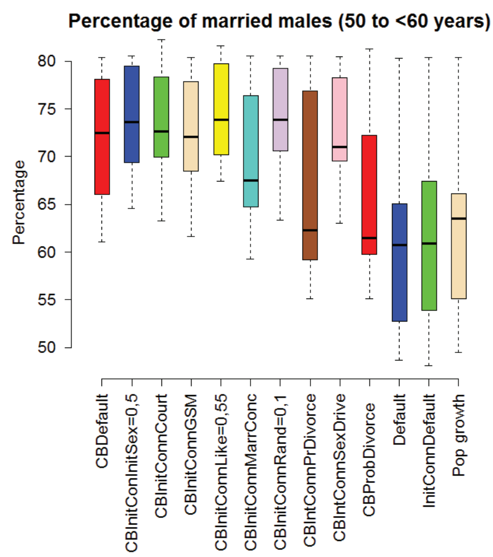


(b) Scenario 4

Figure D.11: **Percentage of married male agents between 40 and less than 50 years**

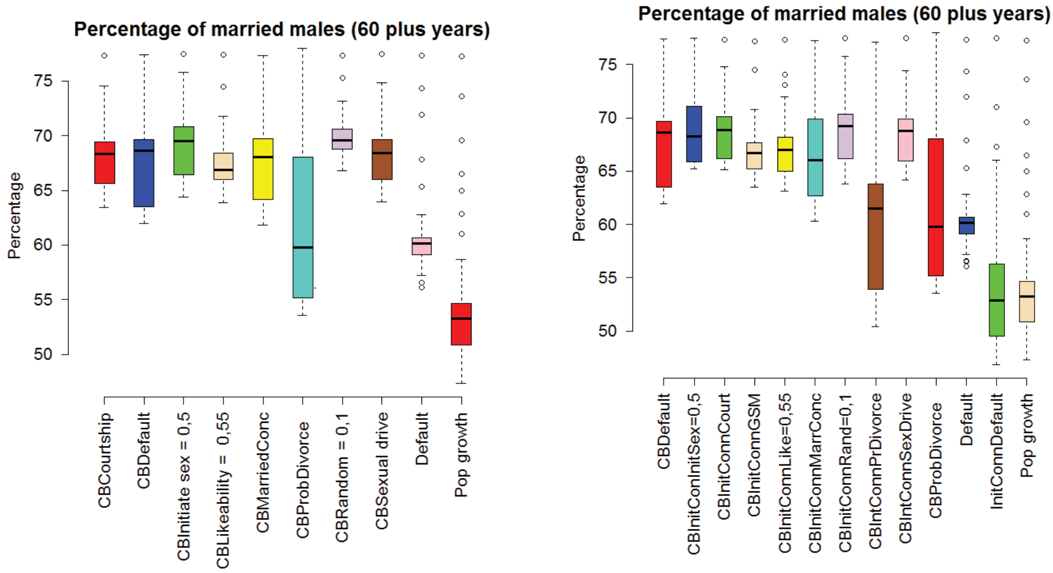


(a) Scenario 3



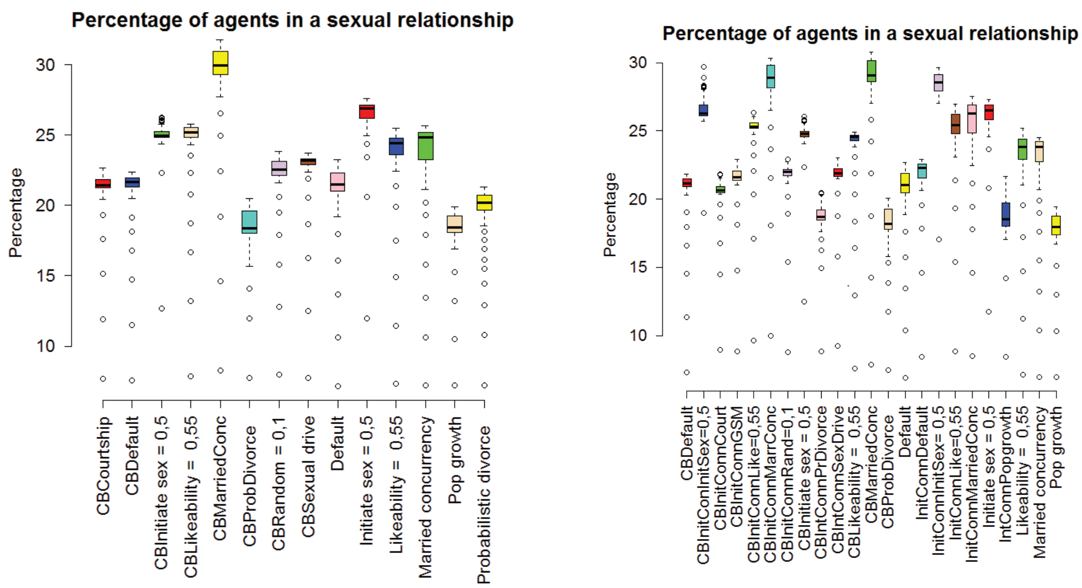
(b) Scenario 4

Figure D.12: **Percentage of married male agents between 50 and less than 60 years**



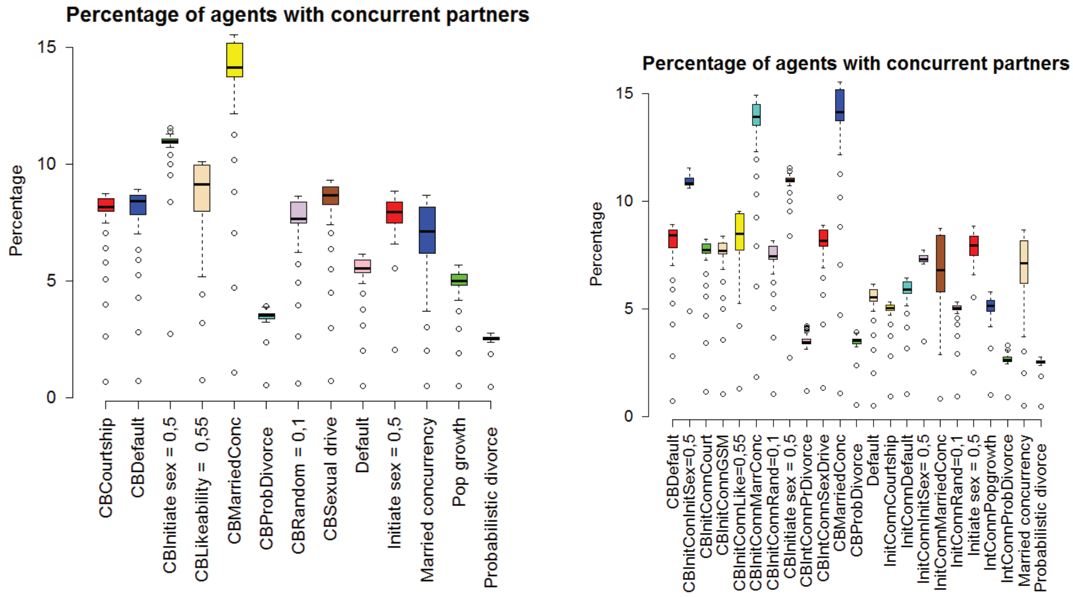
(a) Scenario 3 (b) Scenario 4

Figure D.13: **Percentage of married male agents above 60 years**



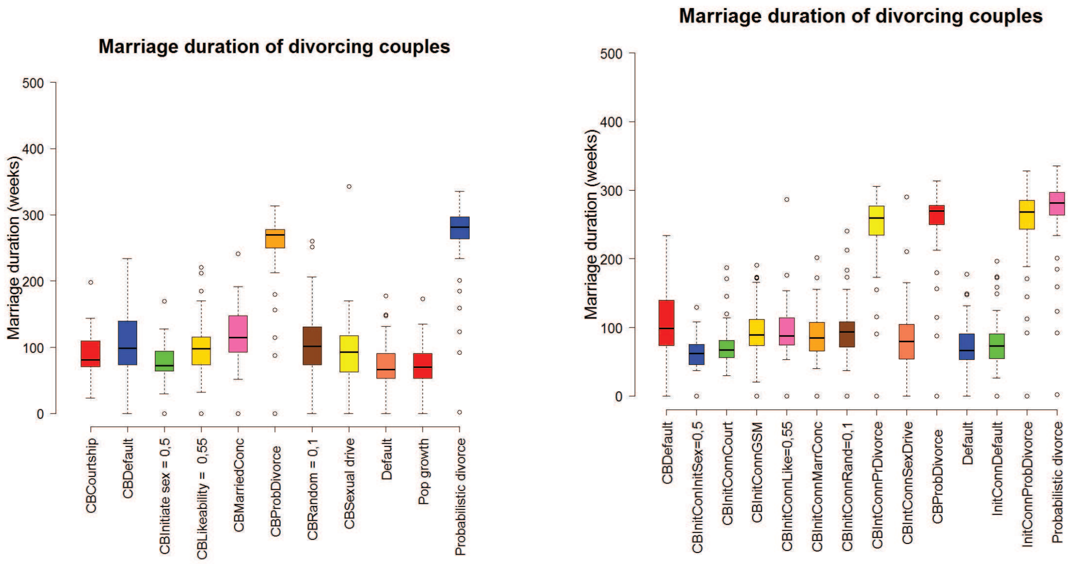
(a) Scenario 3 (b) Scenario 4

Figure D.14: **Percentage of agents in sexual relationships outside marriage**



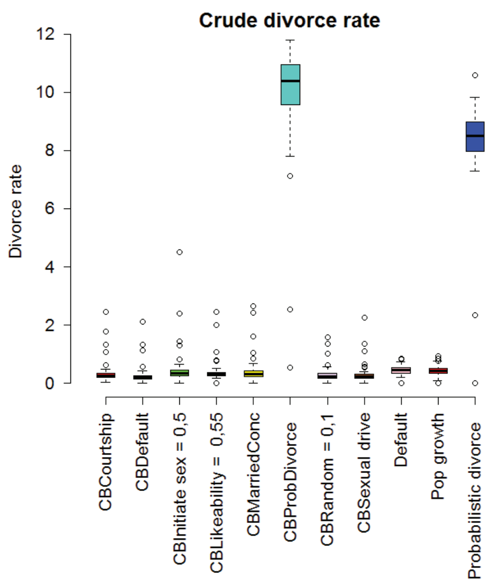
(a) Scenario 3 (b) Scenario 4

Figure D.15: **Percentage of agents with concurrent partners (in or outside marriage)**

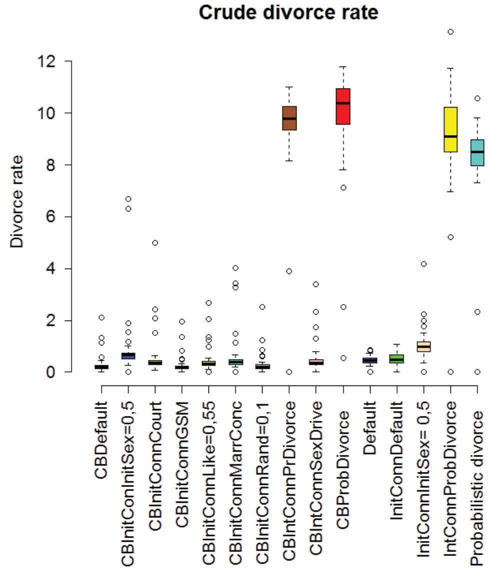


(a) Scenario 3 (b) Scenario 4

Figure D.16: **Marriage duration of divorcing couples**



(a) Scenario 3



(b) Scenario 4

Figure D.17: **Crude divorce rate**

Appendix E

ANOVA results for social and sexual network with child birth

ANOVA results for never coupled agents

Scenario 3

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Group	12	9241	770.0	300.3	<2e-16	***
Residuals	624	1600	2.6			

Tukey multiple comparisons of means 95% confidence level

	p adj
CBDefault-CBCourtship	0.8049072
CBInitiate sex = 0,5-CBDefault	0.0000000
CBLikeability = 0,55-CBDefault	0.0000000
CBMarriedConc-CBDefault	0.7230051
CBProbDivorce -CBDefault	0.9605511
CBRandom = 0,1-CBDefault	0.0000000
CBSexual drive-CBDefault	1.0000000
Default-CBDefault	0.0000000
Initiate sex = 0,5-CBDefault	0.0000000
Likeability = 0,55-CBDefault	0.0000000
Pop growth-CBDefault	0.0000000
Random = 0,1-CBDefault	0.1038453

Scenario 4

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Group	21	51701	2461.9	776.2	<2e-16	***
Residuals	1056	3349	3.2			

Tukey multiple comparisons of means 95% confidence level

	p adj
CBInitConnGSM-CBDefault	0.0000000
CBInitConnGSM-CBInitConInitSex=0,5	0.0000327
CBInitConnGSM-CBInitConnCourt	0.9803755
CBInitConnLike=0,55-CBInitConnGSM	0.0000000
CBInitConnMarrConc-CBInitConnGSM	1.0000000
CBInitConnRand=0,1-CBInitConnGSM	0.0000000
CBInitiate sex = 0,5-CBInitConnGSM	0.0000000
CBIntConnPrDivorce-CBInitConnGSM	0.0004056
CBIntConnSexDrive-CBInitConnGSM	0.9998939
CBLikeability = 0,55-CBInitConnGSM	0.0000000
CBRandom = 0,1-CBInitConnGSM	0.0000009
Default-CBInitConnGSM	0.0000000
InitConnCourtship-CBInitConnGSM	0.0000000
InitConnDefault-CBInitConnGSM	1.0000000
InitConnInitSex= 0,5-CBInitConnGSM	0.0000000
InitConnLike=0,55-CBInitConnGSM	0.0000000
InitConnMarriedConc-CBInitConnGSM	0.0000000
InitConnRand=0,1-CBInitConnGSM	0.0000000
IntConnPopgrowth-CBInitConnGSM	0.0000000
Likeability = 0,55-CBInitConnGSM	0.0000000
Random = 0,1-CBInitConnGSM	1.0000000

Figure E.1: **ANOVA results for never coupled agents**

ANOVA results for quality correlation of married agents

Scenario 3

```
              Df Sum Sq Mean Sq F value Pr(>F)
Group         10 0.6677 0.06677   21.07 <2e-16 ***
Residuals    528 1.6737 0.00317
Tukey multiple comparisons of means 95% confidence level
                                           p adj
CBDefault-CBCourtship                      1.0000000
CBInitiate sex = 0,5-CBDefault             0.9983654
CBLikeability =  0,55-CBDefault            0.0000000
CBMarriedConc-CBDefault                    0.9999993
CBProbDivorce  -CBDefault                  0.9891927
CBRandom = 0,1-CBDefault                   1.0000000
CBSexual drive-CBDefault                   0.9593608
Default-CBDefault                          0.9999999
Likeability =  0,55-CBDefault              0.0001805
Pop growth-CBDefault                       0.5461791
```

Scenario 4

```
              Df Sum Sq Mean Sq F value Pr(>F)
Group         13  1.657 0.12750    35.2 <2e-16 ***
Residuals    672  2.434 0.00362

Tukey multiple comparisons of means 95% confidence level
                                           p adj
CBInitConnGSM-CBDefault                    0.7712970
CBInitConnGSM-CBInitConInitSex=0,5         1.0000000
CBInitConnGSM-CBInitConnCourt              1.0000000
CBInitConnLike=0,55-CBInitConnGSM          0.0000000
CBInitConnMarrConc-CBInitConnGSM           1.0000000
CBInitConnRand=0,1-CBInitConnGSM           1.0000000
CBIntConnPrDivorce-CBInitConnGSM           0.9386666
CBIntConnSexDrive-CBInitConnGSM            0.9625766
CBLikeability =0,55-CBInitConnGSM          0.0000000
Default-CBInitConnGSM                      0.9121700
InitConnDefault-CBInitConnGSM              0.9999530
InitConnLike=0,55-CBInitConnGSM            0.0000000
Likeability =  0,55-CBInitConnGSM          0.0000000
```

Figure E.2: **ANOVA results for married agents quality correlation**

ANOVA results married females (20 to less than 30 years)

Scenario 3

```
               Df Sum Sq Mean Sq F value Pr(>F)
Group          11   6145   558.6   135.2 <2e-16 ***
Residuals     588   2430     4.1
Tukey multiple comparisons of means 95% confidence level
                                              p adj
CBDefault-CBCourtship                     0.0000168
CBInitiate sex = 0,5-CBDefault            0.0000000
CBLikeability =  0,55-CBDefault           0.0000000
CBMarriedConc-CBDefault                   0.9999813
CBProbDivorce  -CBDefault                 0.2543890
CBRandom = 0,1-CBDefault                  0.9999987
CBSexual drive-CBDefault                  0.9945273
Default-CBDefault                         0.7379404
Initiate sex = 0,5-CBDefault              0.0000001
Likeability =  0,55-CBDefault             0.0000000
Pop growth-CBDefault                      0.0000018
```

Scenario 4

```
                Df Sum Sq Mean Sq F value Pr(>F)
Group           21  22693  1080.6   240.1 <2e-16 ***
Residuals     1078   4852     4.5
Tukey multiple comparisons of means 95% confidence level
                                            p adj
CBInitConnGSM-CBCourtship                 0.5074185
CBInitConnGSM-CBDefault                   0.7548591
CBInitConnGSM-CBInitConInitSex=0,5        0.0000000
CBInitConnGSM-CBInitConnCourt             0.3985575
CBInitConnLike=0,55-CBInitConnGSM         0.0000000
CBInitConnMarrConc-CBInitConnGSM          1.0000000
CBInitConnRand=0,1-CBInitConnGSM          0.9998647
CBInitiate sex = 0,5-CBInitConnGSM        0.0000000
CBIntConnPrDivorce-CBInitConnGSM          0.0001354
CBIntConnSexDrive-CBInitConnGSM           0.9994462
CBLikeability =  0,55-CBInitConnGSM       0.0000000
Default-CBInitConnGSM                     0.0058414
InitConnCourtship-CBInitConnGSM           0.0000000
InitConnDefault-CBInitConnGSM             1.0000000
InitConnInitSex= 0,5-CBInitConnGSM        0.0000000
InitConnLike=0,55-CBInitConnGSM           0.0000000
InitConnMarriedConc-CBInitConnGSM         0.0000000
InitConnRand=0,1-CBInitConnGSM            0.0000000
Initiate sex = 0,5-CBInitConnGSM          0.0433523
Likeability =  0,55-CBInitConnGSM         0.0000000
Pop growth-CBInitConnGSM                  0.0000000
```

Figure E.3: **ANOVA results for married female agents between 20 and less than 30 years**

ANOVA results married females (30 to less than 40 years)

Scenario 3

```
             Df Sum Sq Mean Sq F value Pr(>F)
Group        11   8591   781.0   93.26 <2e-16 ***
Residuals   588   4924     8.4
Tukey multiple comparisons of means 95% confidence level
                                               p adj
CBDefault-CBCourtship                      0.3279123
CBInitiate sex = 0,5-CBDefault             0.0000005
CBLikeability =  0,55-CBDefault            0.0000000
CBMarriedConc-CBDefault                    0.9603970
CBProbDivorce  -CBDefault                  1.0000000
CBRandom = 0,1-CBDefault                   0.4176640
CBSexual drive-CBDefault                   0.9972406
Default-CBDefault                          0.0048752
Initiate sex = 0,5-CBDefault               0.0593089
Likeability =  0,55-CBDefault              0.0000000
Pop growth-CBDefault                       0.0000000
```

Scenario 4

```
             Df Sum Sq Mean Sq F value Pr(>F)
Group        17  15879   934.1   70.23 <2e-16 ***
Residuals   882  11731    13.3
Tukey multiple comparisons of means 95% confidence level
                                           p adj
CBInitConnGSM-CBDefault                    0.9999127
CBInitConnGSM-CBInitConInitSex=0,5         0.0031505
CBInitConnGSM-CBInitConnCourt              1.0000000
CBInitConnLike=0,55-CBInitConnGSM          0.0000000
CBInitConnMarrConc-CBInitConnGSM           0.9974786
CBInitConnRand=0,1-CBInitConnGSM           1.0000000
CBInitiate sex = 0,5-CBInitConnGSM         0.0349336
CBIntConnPrDivorce-CBInitConnGSM           1.0000000
CBIntConnSexDrive-CBInitConnGSM            0.9999999
CBLikeability =  0,55-CBInitConnGSM        0.0000000
Default-CBInitConnGSM                      0.0043777
InitConnCourtship-CBInitConnGSM            0.9998115
InitConnDefault-CBInitConnGSM              0.0000000
InitConnInitSex= 0,5-CBInitConnGSM         0.1078785
InitConnLike=0,55-CBInitConnGSM            0.0000000
InitConnRand=0,1-CBInitConnGSM             0.9636561
Pop growth-CBInitConnGSM                   0.0000000
```

Figure E.4: **ANOVA results for married female agents between 30 and less than 40 years**

ANOVA results married females (40 to less than 50 years)

Scenario 3

```
              Df Sum Sq Mean Sq F value Pr(>F)
Group         10   7449   744.9   56.01 <2e-16 ***
Residuals    539   7168    13.3
Tukey multiple comparisons of means 95% confidence level
                                                p adj
CBDefault-CBCourtship                       0.9999999
CBInitiate sex = 0,5-CBDefault              0.8492396
CBLikeability =  0,55-CBDefault             0.0000093
CBMarriedConc-CBDefault                     0.0140498
CBProbDivorce  -CBDefault                   0.0000014
CBRandom = 0,1-CBDefault                    1.0000000
CBSexual drive-CBDefault                    1.0000000
Default-CBDefault                           0.0000000
Likeability =  0,55-CBDefault               0.0000000
Pop growth-CBDefault                        0.0000000
```

Scenario 4

```
              Df Sum Sq Mean Sq F value Pr(>F)
Group         17  14671   863.0   55.76 <2e-16 ***
Residuals    882  13650    15.5
Tukey multiple comparisons of means 95% confidence level
                                            p adj
CBInitConnGSM-CBDefault                     0.9999998
CBInitConnGSM-CBInitConInitSex=0,5          0.9583673
CBInitConnGSM-CBInitConnCourt               0.9999999
CBInitConnLike=0,55-CBInitConnGSM           0.0022712
CBInitConnMarrConc-CBInitConnGSM            0.8006214
CBInitConnRand=0,1-CBInitConnGSM            0.9935807
CBIntConnPrDivorce-CBInitConnGSM            0.0000001
CBIntConnSexDrive-CBInitConnGSM             0.9978153
CBLikeability =  0,55-CBInitConnGSM         0.0034127
CBMarriedConc-CBInitConnGSM                 0.0077674
CBProbDivorce  -CBInitConnGSM               0.0000008
Default-CBInitConnGSM                       0.0000000
InitConnDefault-CBInitConnGSM               0.0000000
InitConnInitSex= 0,5-CBInitConnGSM          0.0000000
InitConnLike=0,55-CBInitConnGSM             0.0000000
IntConnProbDivorce-CBInitConnGSM            0.0000000
Likeability =  0,55-CBInitConnGSM           0.0000000
```

Figure E.5: **ANOVA results for married female agents between 40 and less than 50 years**

ANOVA results married females (50 to less than 60 years)

Scenario 3

```
              Df Sum Sq Mean Sq F value Pr(>F)
Group          9   8424   936.0   59.55 <2e-16 ***
Residuals    490   7701    15.7
Tukey multiple comparisons of means 95% confidence level
                                   p adj
CBDefault-CBCourtship              0.9923947
CBInitiate sex = 0,5-CBDefault     0.9998587
CBLikeability =  0,55-CBDefault    0.9999188
CBMarriedConc-CBDefault            0.0059990
CBProbDivorce  -CBDefault          0.0000000
CBRandom = 0,1-CBDefault           0.9478377
CBSexual drive-CBDefault           0.9976074
Default-CBDefault                  0.0000000
Pop growth-CBDefault               0.0000000
```

Scenario 4

```
              Df Sum Sq Mean Sq F value Pr(>F)
Group         14  19481  1391.5   77.75 <2e-16 ***
Residuals    735  13155    17.9
Tukey multiple comparisons of means 95% confidence level
                                   p adj
CBInitConnGSM-CBDefault            0.9999991
CBInitConnGSM-CBInitConInitSex=0,5 0.9999998
CBInitConnGSM-CBInitConnCourt      0.9954776
CBInitConnLike=0,55-CBInitConnGSM  0.9999993
CBInitConnMarrConc-CBInitConnGSM   0.9678492
CBInitConnRand=0,1-CBInitConnGSM   0.2815792
CBIntConnPrDivorce-CBInitConnGSM   0.0000000
CBIntConnSexDrive-CBInitConnGSM    0.9714733
CBMarriedConc-CBInitConnGSM        0.0028965
CBProbDivorce  -CBInitConnGSM      0.0000000
Default-CBInitConnGSM              0.0000000
InitConnDefault-CBInitConnGSM      0.0000000
IntConnProbDivorce-CBInitConnGSM   0.0000000
Pop growth-CBInitConnGSM           0.0000000
```

Figure E.6: **ANOVA results for married female agents between 50 and less than 60 years**

ANOVA results married females (60 plus years)

Scenario 3

```
              Df Sum Sq Mean Sq F value Pr(>F)
Group          9   5633   625.9   31.09 <2e-16 ***
Residuals    490   9864    20.1
Tukey multiple comparisons of means 95% confidence level
                                          p adj
CBDefault-CBCourtship                 0.9990473
CBInitiate sex = 0,5-CBDefault        0.9674230
CBLikeability =  0,55-CBDefault       1.0000000
CBMarriedConc-CBDefault               0.9729619
CBProbDivorce  -CBDefault             0.0000072
CBRandom = 0,1-CBDefault              0.9519945
CBSexual drive-CBDefault              0.9920319
Default-CBDefault                     0.6983578
Pop growth-CBDefault                  0.0000000
```

Scenario 4

```
              Df Sum Sq Mean Sq F value Pr(>F)
Group         12  11262   938.5    35.6 <2e-16 ***
Residuals    637  16794    26.4
Tukey multiple comparisons of means 95% confidence level
                                        p adj
CBInitConnGSM-CBDefault               1.0000000
CBInitConnGSM-CBInitConInitSex=0,5    1.0000000
CBInitConnGSM-CBInitConnCourt         1.0000000
CBInitConnLike=0,55-CBInitConnGSM     0.6639508
CBInitConnMarrConc-CBInitConnGSM      1.0000000
CBInitConnRand=0,1-CBInitConnGSM      0.9995393
CBIntConnPrDivorce-CBInitConnGSM      0.0000036
CBIntConnSexDrive-CBInitConnGSM       0.9998552
CBProbDivorce  -CBInitConnGSM         0.0003785
Default-CBInitConnGSM                 0.9060317
InitConnDefault-CBInitConnGSM         0.0000000
Pop growth-CBInitConnGSM              0.0000000
```

Figure E.7: **ANOVA results for married female agents 60 plus years**

ANOVA results married males (less than 20 years)

Scenario 3

```
              Df Sum Sq Mean Sq F value   Pr(>F)
Group          9  10.39  1.1541   2.903 0.00234 **
Residuals    490 194.79  0.3975
Tukey multiple comparisons of means 95% confidence level
                                           p adj
CBDefault-CBCourtship                      0.7948639
CBInitiate sex = 0,5-CBDefault             0.9947859
CBLikeability =  0,55-CBDefault            0.9999999
CBMarriedConc-CBDefault                    0.1361691
CBProbDivorce  -CBDefault                  0.2177179
CBRandom = 0,1-CBDefault                   0.1831751
CBSexual drive-CBDefault                   0.2033180
Default-CBDefault                          0.0276506
Pop growth-CBDefault                       0.0811817
```

Scenario 4

```
              Df Sum Sq Mean Sq F value Pr(>F)
Group         16  242.5  15.158   63.99 <2e-16 ***
Residuals    833  197.3   0.237
Tukey multiple comparisons of means 95% confidence level
                                         p adj
CBInitConnGSM-CBDefault                  0.9257206
CBInitConnGSM-CBInitConInitSex=0,5       0.0245630
CBInitConnGSM-CBInitConnCourt            0.9957671
CBInitConnLike=0,55-CBInitConnGSM        0.5927265
CBInitConnMarrConc-CBInitConnGSM         1.0000000
CBInitConnRand=0,1-CBInitConnGSM         1.0000000
CBIntConnPrDivorce-CBInitConnGSM         1.0000000
CBIntConnSexDrive-CBInitConnGSM          1.0000000
Default-CBInitConnGSM                    0.4654198
InitConnCourtship-CBInitConnGSM          0.0000000
InitConnDefault-CBInitConnGSM            1.0000000
InitConnInitSex= 0,5-CBInitConnGSM       0.0000000
InitConnLike=0,55-CBInitConnGSM          0.0002435
InitConnMarriedConc-CBInitConnGSM        0.0000001
InitConnRand=0,1-CBInitConnGSM           0.0000015
Pop growth-CBInitConnGSM                 0.8038642
```

Figure E.8: **ANOVA results for married male agents between 15 and less than 20 years**

ANOVA results married males (20 to less than 30 years)

Scenario 3

```
               Df Sum Sq Mean Sq F value Pr(>F)
Group          12   4952   412.7   284.2 <2e-16 ***
Residuals     637    925     1.5
Tukey multiple comparisons of means 95% confidence level
                                                p adj
CBDefault-CBCourtship                       0.0000001
CBInitiate sex = 0,5-CBDefault              0.0000000
CBLikeability =  0,55-CBDefault             0.0000000
CBMarriedConc-CBDefault                     0.6244327
CBProbDivorce  -CBDefault                   1.0000000
CBRandom = 0,1-CBDefault                    0.9999997
CBSexual drive-CBDefault                    0.9999736
Courtship-CBDefault                         0.0000000
Default-CBDefault                           0.0000000
Initiate sex = 0,5-CBDefault                0.0000132
Likeability =  0,55-CBDefault               0.0000000
Pop growth-CBDefault                        0.0000000
```

Scenario 4

```
               Df  Sum Sq Mean Sq F value Pr(>F)
Group          21  24499  1166.6   213.1 <2e-16 ***
Residuals    1078   5901     5.5
Tukey multiple comparisons of means 95% confidence level
                                            p adj
CBInitConnGSM-CBCourtship                   1.0000000
CBInitConnGSM-CBDefault                     0.6051182
CBInitConnGSM-CBInitConInitSex=0,5          0.0000000
CBInitConnGSM-CBInitConnCourt               0.9999332
CBInitConnLike=0,55-CBInitConnGSM           0.0000000
CBInitConnMarrConc-CBInitConnGSM            0.9999464
CBInitConnRand=0,1-CBInitConnGSM            0.9997987
CBInitiate sex = 0,5-CBInitConnGSM          0.0000000
CBIntConnPrDivorce-CBInitConnGSM            0.7436839
CBIntConnSexDrive-CBInitConnGSM             0.9993141
CBLikeability =  0,55-CBInitConnGSM         0.0000000
Default-CBInitConnGSM                       0.0000000
InitConnCourtship-CBInitConnGSM             0.0000000
InitConnDefault-CBInitConnGSM               0.9182950
InitConnInitSex= 0,5-CBInitConnGSM          0.0000000
InitConnLike=0,55-CBInitConnGSM             0.0000000
InitConnMarriedConc-CBInitConnGSM           0.0000000
InitConnRand=0,1-CBInitConnGSM              0.0000000
Initiate sex = 0,5-CBInitConnGSM            1.0000000
Likeability =  0,55-CBInitConnGSM           0.5206034
Pop growth-CBInitConnGSM                    0.0000001
```

Figure E.9: **ANOVA results for married male agents between 20 and less than 30 years**

ANOVA results married males (30 to less than 40 years)

Scenario 3

```
             Df Sum Sq Mean Sq F value Pr(>F)
Group        11  12029  1093.6   50.47 <2e-16 ***
Residuals   588  12740    21.7
Tukey multiple comparisons of means 95% confidence level
                                              p adj
CBDefault-CBCourtship                     0.9938190
CBInitiate sex = 0,5-CBDefault            0.0059570
CBLikeability =  0,55-CBDefault           0.0000000
CBMarriedConc-CBDefault                   0.9999340
CBProbDivorce  -CBDefault                 1.0000000
CBRandom = 0,1-CBDefault                  1.0000000
CBSexual drive-CBDefault                  0.9999947
Default-CBDefault                         0.0000036
Initiate sex = 0,5-CBDefault              0.9994543
Likeability =  0,55-CBDefault             0.0000000
Pop growth-CBDefault                      0.1283029
```

Scenario 4

```
             Df Sum Sq Mean Sq F value Pr(>F)
Group        15  21534  1435.6   63.13 <2e-16 ***
Residuals   784  17829    22.7
Tukey multiple comparisons of means 95% confidence level
                                          p adj
CBInitConnGSM-CBDefault                   1.0000000
CBInitConnGSM-CBInitConInitSex=0,5        0.0907546
CBInitConnGSM-CBInitConnCourt             0.9999996
CBInitConnLike=0,55-CBInitConnGSM         0.0000000
CBInitConnMarrConc-CBInitConnGSM          0.9996847
CBInitConnRand=0,1-CBInitConnGSM          1.0000000
CBInitiate sex = 0,5-CBInitConnGSM        0.0608983
CBIntConnPrDivorce-CBInitConnGSM          0.9999919
CBIntConnSexDrive-CBInitConnGSM           0.9999998
CBLikeability =  0,55-CBInitConnGSM       0.0000000
Default-CBInitConnGSM                     0.0000011
InitConnDefault-CBInitConnGSM             0.4904007
Initiate sex = 0,5-CBInitConnGSM          0.9968103
Likeability =  0,55-CBInitConnGSM         0.0000000
Pop growth-CBInitConnGSM                  0.0740129
```

Figure E.10: ANOVA results for married male agents between 30 and less than 40 years

ANOVA results married males (40 to less than 50 years)

Scenario 3

```
              Df  Sum Sq  Mean Sq  F value  Pr(>F)
Group         10    7535    753.5    14.35  <2e-16 ***
Residuals    539   28297     52.5
Tukey multiple comparisons of means 95% confidence level
                                                p adj
CBDefault-CBCourtship                       0.9999780
CBInitiate sex = 0,5-CBDefault              0.9884358
CBLikeability =  0,55-CBDefault             0.0009510
CBMarriedConc-CBDefault                     0.9717801
CBProbDivorce  -CBDefault                   0.3649195
CBRandom = 0,1-CBDefault                    0.9999959
CBSexual drive-CBDefault                    1.0000000
Default-CBDefault                           0.0000023
Likeability =  0,55-CBDefault               0.8598965
Pop growth-CBDefault                        0.0023471
```

Scenario 4

```
              Df  Sum Sq  Mean Sq  F value  Pr(>F)
Group         14   12729    909.2    17.72  <2e-16 ***
Residuals    735   37719     51.3
Tukey multiple comparisons of means 95% confidence level
                                            p adj
CBInitConnGSM-CBDefault                     1.0000000
CBInitConnGSM-CBInitConInitSex=0,5          0.9985613
CBInitConnGSM-CBInitConnCourt               0.9999988
CBInitConnLike=0,55-CBInitConnGSM           0.0000108
CBInitConnMarrConc-CBInitConnGSM            0.9695437
CBInitConnRand=0,1-CBInitConnGSM            0.9999935
CBIntConnPrDivorce-CBInitConnGSM            0.9639369
CBIntConnSexDrive-CBInitConnGSM             1.0000000
CBLikeability =  0,55-CBInitConnGSM         0.0008744
CBMarriedConc-CBInitConnGSM                 0.9974111
Default-CBInitConnGSM                       0.0000048
InitConnDefault-CBInitConnGSM               0.0003978
Likeability =  0,55-CBInitConnGSM           0.9652367
Pop growth-CBInitConnGSM                    0.0051723
```

Figure E.11: **ANOVA results for married male agents between 40 and less than 50 years**

ANOVA results married males (50 to less than 60 years)

Scenario 3

```
              Df Sum Sq Mean Sq F value Pr(>F)
Group          9  12637  1404.1   31.99 <2e-16 ***
Residuals    490  21504    43.9
Tukey multiple comparisons of means 95% confidence level
                                             p adj
CBDefault-CBCourtship                      0.9355551
CBInitiate sex = 0,5-CBDefault             0.9310485
CBLikeability =  0,55-CBDefault            0.9026005
CBMarriedConc-CBDefault                    0.9999441
CBProbDivorce  -CBDefault                  0.0001857
CBRandom = 0,1-CBDefault                   0.8413800
CBSexual drive-CBDefault                   0.9917837
Default-CBDefault                          0.0000000
Pop growth-CBDefault                       0.0000000
```

Scenario 4

```
              Df Sum Sq Mean Sq F value Pr(>F)
Group         12  17147  1428.9   30.57 <2e-16 ***
Residuals    637  29776    46.7
Tukey multiple comparisons of means 95% confidence level
                                          p adj
CBInitConnGSM-CBDefault                 0.9999993
CBInitConnGSM-CBInitConInitSex=0,5      0.9992654
CBInitConnGSM-CBInitConnCourt           0.9996462
CBInitConnLike=0,55-CBInitConnGSM       0.9872337
CBInitConnMarrConc-CBInitConnGSM        0.7541747
CBInitConnRand=0,1-CBInitConnGSM        0.9980874
CBIntConnPrDivorce-CBInitConnGSM        0.0009744
CBIntConnSexDrive-CBInitConnGSM         1.0000000
CBProbDivorce  -CBInitConnGSM           0.0000553
Default-CBInitConnGSM                   0.0000000
InitConnDefault-CBInitConnGSM           0.0000000
Pop growth-CBInitConnGSM                0.0000000
```

Figure E.12: **ANOVA results for married male agents between 50 and less than 60 years**

ANOVA results married males (60 plus years)

Scenario 3

```
               Df Sum Sq Mean Sq F value Pr(>F)
Group           9  10797  1199.7   71.85 <2e-16 ***
Residuals     490   8182    16.7
Tukey multiple comparisons of means 95% confidence level
                                                   p adj
CBDefault-CBCourtship                          0.9999011
CBInitiate sex = 0,5-CBDefault                 0.7914538
CBLikeability =  0,55-CBDefault                0.9999983
CBMarriedConc-CBDefault                        1.0000000
CBProbDivorce  -CBDefault                      0.0000000
CBRandom = 0,1-CBDefault                       0.2533547
CBSexual drive-CBDefault                       0.9994410
Default-CBDefault                              0.0000000
Pop growth-CBDefault                           0.0000000
```

Scenario 4

```
               Df Sum Sq Mean Sq F value Pr(>F)
Group          12  16945  1412.1   65.93 <2e-16 ***
Residuals     637  13644    21.4
Tukey multiple comparisons of means 95% confidence level
                                               p adj
CBInitConnGSM-CBDefault                        0.9998815
CBInitConnGSM-CBInitConInitSex=0,5             0.4576714
CBInitConnGSM-CBInitConnCourt                  0.7999623
CBInitConnLike=0,55-CBInitConnGSM              1.0000000
CBInitConnMarrConc-CBInitConnGSM               0.9999987
CBInitConnRand=0,1-CBInitConnGSM               0.7457358
CBIntConnPrDivorce-CBInitConnGSM               0.0000000
CBIntConnSexDrive-CBInitConnGSM                0.8888577
CBProbDivorce  -CBInitConnGSM                  0.0000010
Default-CBInitConnGSM                          0.0000000
InitConnDefault-CBInitConnGSM                  0.0000000
Pop growth-CBInitConnGSM                       0.0000000
```

Figure E.13: **ANOVA results for married male agents between 60 plus years**

ANOVA results for median age at first marriage for male agents

Scenario 3

```
              Df Sum Sq Mean Sq F value Pr(>F)
Group         11    659   59.91   28.32 <2e-16 ***
Residuals    576   1219    2.12
Tukey multiple comparisons of means 95% confidence level
                                                p adj
CBDefault-CBCourtship                       0.7541544
CBInitiate sex = 0,5-CBDefault              0.0000000
CBLikeability =  0,55-CBDefault             0.0000000
CBMarriedConc-CBDefault                     0.9467593
CBProbDivorce  -CBDefault                   0.0579962
CBRandom = 0,1-CBDefault                    0.8310790
CBSexual drive-CBDefault                    1.0000000
Default-CBDefault                           0.3617338
Initiate sex = 0,5-CBDefault                0.2139801
Likeability =  0,55-CBDefault               0.0000164
Pop growth-CBDefault                        0.0047117
```

Scenario 4

```
              Df Sum Sq Mean Sq F value Pr(>F)
Group         16   1938  121.14    47.9 <2e-16 ***
Residuals    816   2064    2.53
Tukey multiple comparisons of means 95% confidence level
                                            p adj
CBInitConnGSM-CBDefault                     0.9973979
CBInitConnGSM-CBInitConInitSex=0,5          0.0000000
CBInitConnGSM-CBInitConnCourt               0.9999999
CBInitConnLike=0,55-CBInitConnGSM           0.0000000
CBInitConnMarrConc-CBInitConnGSM            0.7267354
CBInitConnRand=0,1-CBInitConnGSM            0.9923075
CBInitiate sex = 0,5-CBInitConnGSM          0.0000000
CBIntConnPrDivorce-CBInitConnGSM            0.0038230
CBIntConnSexDrive-CBInitConnGSM             1.0000000
CBLikeability =  0,55-CBInitConnGSM         0.0000000
Default-CBInitConnGSM                       0.0382918
InitConnDefault-CBInitConnGSM               1.0000000
InitConnInitSex= 0,5-CBInitConnGSM          0.0000000
InitConnLike=0,55-CBInitConnGSM             0.0000000
Initiate sex = 0,5-CBInitConnGSM            0.9988914
Likeability =  0,55-CBInitConnGSM           0.0488371
```

Figure E.14: **ANOVA results for male median age at first marriage**

ANOVA results for median age at first marriage for female agents

Scenario 3

```
             Df Sum Sq Mean Sq F value Pr(>F)
Group        11  554.8   50.44   24.76 <2e-16 ***
Residuals   576 1173.4    2.04
Tukey multiple comparisons of means 95% confidence level
                                          p adj
CBDefault-CBCourtship                     0.9344891
CBInitiate sex = 0,5-CBDefault            0.0000000
CBLikeability =  0,55-CBDefault           0.0000000
CBMarriedConc-CBDefault                   0.9477227
CBProbDivorce  -CBDefault                 0.1465955
CBRandom = 0,1-CBDefault                  0.9064717
CBSexual drive-CBDefault                  1.0000000
Default-CBDefault                         0.8552082
Initiate sex = 0,5-CBDefault              0.8449116
Likeability =  0,55-CBDefault             0.0000018
Pop growth-CBDefault                      0.0124544
```

Scenario 4

```
             Df Sum Sq Mean Sq F value Pr(>F)
Group        15   1434   95.57   54.74 <2e-16 ***
Residuals   768   1341    1.75
Tukey multiple comparisons of means 95% confidence level
                                          p adj
CBInitConnGSM-CBDefault                   0.9999999
CBInitConnGSM-CBInitConInitSex=0,5        0.0000000
CBInitConnGSM-CBInitConnCourt             0.9999998
CBInitConnLike=0,55-CBInitConnGSM         0.0000000
CBInitConnMarrConc-CBInitConnGSM          0.6780606
CBInitConnRand=0,1-CBInitConnGSM          0.9472134
CBInitiate sex = 0,5-CBInitConnGSM        0.0000000
CBIntConnPrDivorce-CBInitConnGSM          0.0000239
CBIntConnSexDrive-CBInitConnGSM           0.9999998
CBLikeability =  0,55-CBInitConnGSM       0.0000000
InitConnDefault-CBInitConnGSM             1.0000000
InitConnInitSex= 0,5-CBInitConnGSM        0.0000000
InitConnLike=0,55-CBInitConnGSM           0.0000000
Initiate sex = 0,5-CBInitConnGSM          0.5169784
Likeability =  0,55-CBInitConnGSM         0.0000052
```

Figure E.15: **ANOVA results for female median age at first marriage**

ANOVA results for agents in sexual relationships outside marriage

Scenario 3

```
               Df Sum Sq Mean Sq F value Pr(>F)
Group          13   5865   451.1   50.68 <2e-16 ***
Residuals     672   5982     8.9
```

	p adj
CBDefault-CBCourtship	1.0000000
CBInitiate sex = 0,5-CBDefault	0.0000000
CBLikeability = 0,55-CBDefault	0.0000053
CBMarriedConc-CBDefault	0.0000000
CBProbDivorce -CBDefault	0.0014316
CBRandom = 0,1-CBDefault	0.9104506
CBSexual drive-CBDefault	0.4286825
Default-CBDefault	1.0000000
Initiate sex = 0,5-CBDefault	0.0000000
Likeability = 0,55-CBDefault	0.0041599
Married concurrency-CBDefault	0.0130909
Pop growth-CBDefault	0.0005207
Probabilistic divorce -CBDefault	0.3578530

Scenario 4

```
               Df Sum Sq Mean Sq F value Pr(>F)
Group          22  11592   526.9   73.68 <2e-16 ***
Residuals    1104   7895     7.2
```

	p adj
CBInitConnGSM-CBDefault	0.9979476
CBInitConnGSM-CBInitConInitSex=0,5	0.0000000
CBInitConnGSM-CBInitConnCourt	0.9873856
CBInitConnLike=0,55-CBInitConnGSM	0.0000000
CBInitConnMarrConc-CBInitConnGSM	0.0000000
CBInitConnRand=0,1-CBInitConnGSM	1.0000000
CBInitiate sex = 0,5-CBInitConnGSM	0.0000002
CBIntConnPrDivorce-CBInitConnGSM	0.0002507
CBIntConnSexDrive-CBInitConnGSM	1.0000000
CBLikeability = 0,55-CBInitConnGSM	0.0060380
CBMarriedConc-CBInitConnGSM	0.0000000
CBProbDivorce -CBInitConnGSM	0.0000005
Default-CBInitConnGSM	0.9959788
InitConnDefault-CBInitConnGSM	1.0000000
InitConnInitSex= 0,5-CBInitConnGSM	0.0000000
InitConnLike=0,55-CBInitConnGSM	0.0000000
InitConnMarriedConc-CBInitConnGSM	0.0000000
Initiate sex = 0,5-CBInitConnGSM	0.0000000
IntConnPopgrowth-CBInitConnGSM	0.0010620
Likeability = 0,55-CBInitConnGSM	0.3287938
Married concurrency-CBInitConnGSM	0.9368497
Pop growth-CBInitConnGSM	0.0000000

Figure E.16: **ANOVA results for agents in a sexual relationships outside marriage**

ANOVA results for marriage duration of divorcing couples

Scenario 3

```
              Df  Sum Sq Mean Sq F value Pr(>F)
Group         10 2272004  227200   73.04 <2e-16 ***
Residuals    528 1642422    3111
Tukey multiple comparisons of means 95% confidence level
                                               p adj
CBDefault-CBCourtship                        0.9914127
CBInitiate sex = 0,5-CBDefault               0.9976269
CBLikeability =  0,55-CBDefault              0.9926501
CBMarriedConc-CBDefault                      0.9992207
CBProbDivorce  -CBDefault                    0.0000000
CBRandom = 0,1-CBDefault                     0.9998504
CBSexual drive-CBDefault                     1.0000000
Default-CBDefault                            0.1154297
Pop growth-CBDefault                         0.0542692
Probabilistic divorce  -CBDefault            0.0000000
```

Scenario 4

```
              Df  Sum Sq Mean Sq F value Pr(>F)
Group         13 4280996  329307   116.5 <2e-16 ***
Residuals    672 1899528    2827
Tukey multiple comparisons of means 95% confidence level
                                             p adj
CBInitConnGSM-CBDefault                    0.3173814
CBInitConnGSM-CBInitConInitSex=0,5         1.0000000
CBInitConnGSM-CBInitConnCourt              0.9999973
CBInitConnLike=0,55-CBInitConnGSM          0.0685143
CBInitConnMarrConc-CBInitConnGSM           0.9989429
CBInitConnRand=0,1-CBInitConnGSM           1.0000000
CBIntConnPrDivorce-CBInitConnGSM           0.0000000
CBIntConnSexDrive-CBInitConnGSM            0.9999999
CBProbDivorce  -CBInitConnGSM              0.0000000
Default-CBInitConnGSM                      1.0000000
InitConnDefault-CBInitConnGSM              1.0000000
IntConnProbDivorce-CBInitConnGSM           0.0000000
Probabilistic divorce  -CBInitConnGSM      0.0000000
```

Figure E.17: **ANOVA results for marriage duration of divorcing couples**

ANOVA results for crude divorce rate

Scenario 3

```
              Df Sum Sq Mean Sq F value Pr(>F)
Group         10   6163   616.3   809.3 <2e-16 ***
Residuals    528    402     0.8
Tukey multiple comparisons of means 95% confidence level
                                              p adj
CBDefault-CBCourtship                       0.9999924
CBInitiate sex = 0,5-CBDefault              0.9772314
CBLikeability =  0,55-CBDefault             0.9997808
CBMarriedConc-CBDefault                     0.9965536
CBProbDivorce  -CBDefault                   0.0000000
CBRandom = 0,1-CBDefault                    1.0000000
CBSexual drive-CBDefault                    1.0000000
Default-CBDefault                           0.9970442
Pop growth-CBDefault                        0.9990387
Probabilistic divorce  -CBDefault           0.0000000
```

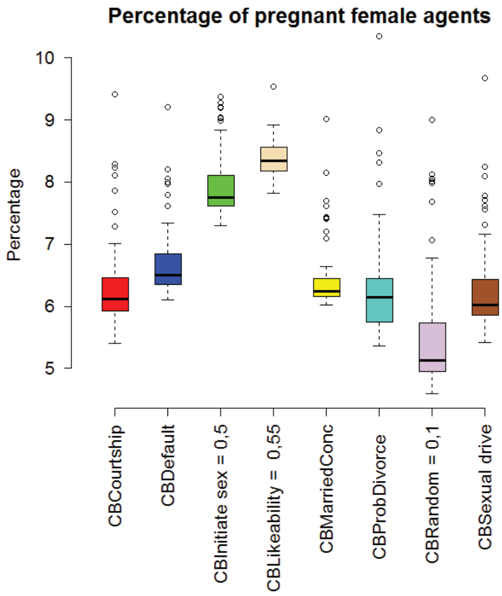
Scenario 4

```
              Df Sum Sq Mean Sq F value Pr(>F)
Group         14  10928   780.5   666.2 <2e-16 ***
Residuals    720    844     1.2
Tukey multiple comparisons of means 95% confidence level
                                            p adj
CBInitConnGSM-CBDefault                   1.0000000
CBInitConnGSM-CBInitConInitSex=0,5        0.1890793
CBInitConnGSM-CBInitConnCourt             0.9940261
CBInitConnLike=0,55-CBInitConnGSM         0.9999156
CBInitConnMarrConc-CBInitConnGSM          0.9628551
CBInitConnRand=0,1-CBInitConnGSM          1.0000000
CBIntConnPrDivorce-CBInitConnGSM          0.0000000
CBIntConnSexDrive-CBInitConnGSM           0.9968451
CBProbDivorce  -CBInitConnGSM             0.0000000
Default-CBInitConnGSM                     0.9998746
InitConnDefault-CBInitConnGSM             0.9975140
InitConnInitSex= 0,5-CBInitConnGSM        0.0226461
IntConnProbDivorce-CBInitConnGSM          0.0000000
Probabilistic divorce  -CBInitConnGSM     0.0000000
```

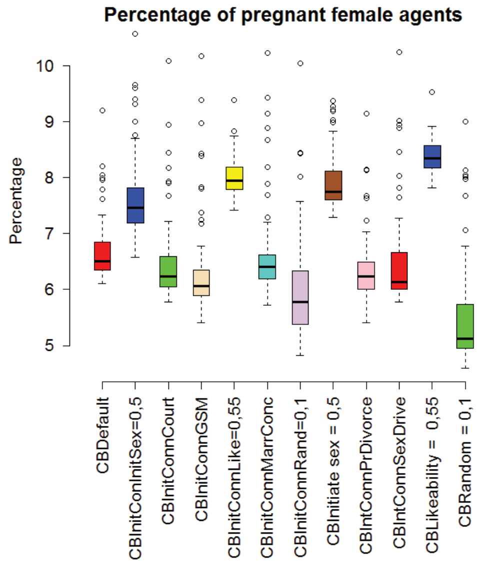
Figure E.18: **ANOVA results for crude divorce rate**

Appendix F

Box plots for child birth statistics

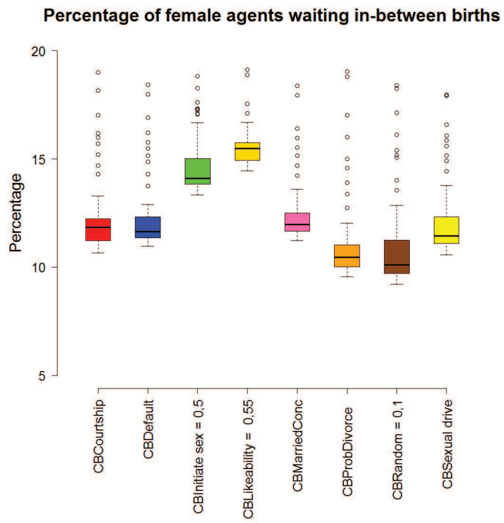


(a) Scenario 3

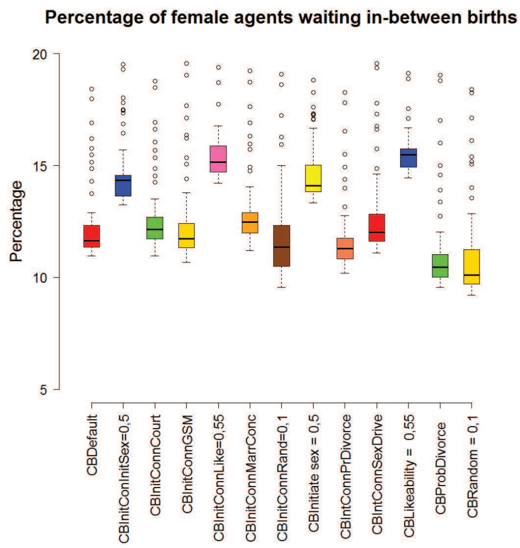


(b) Scenario 4

Figure F.1: **Percentage of pregnant females**

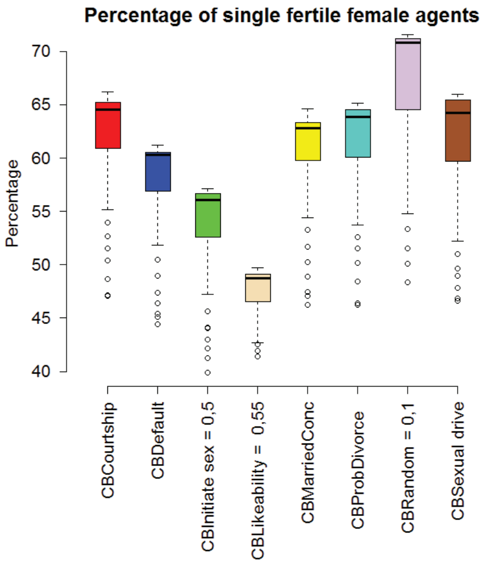


(a) Scenario 3

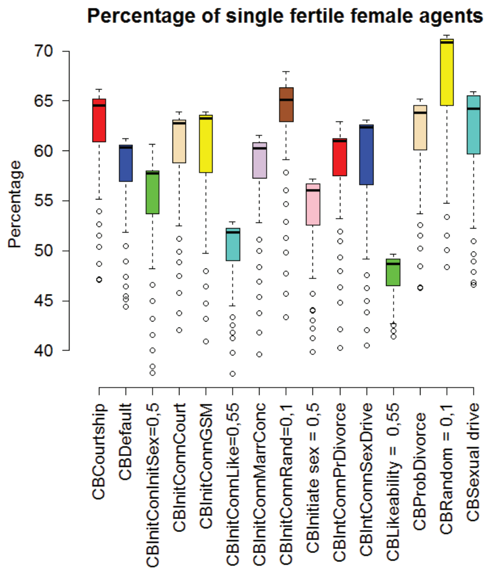


(b) Scenario 4

Figure F.2: **Percentage females waiting in-between births**

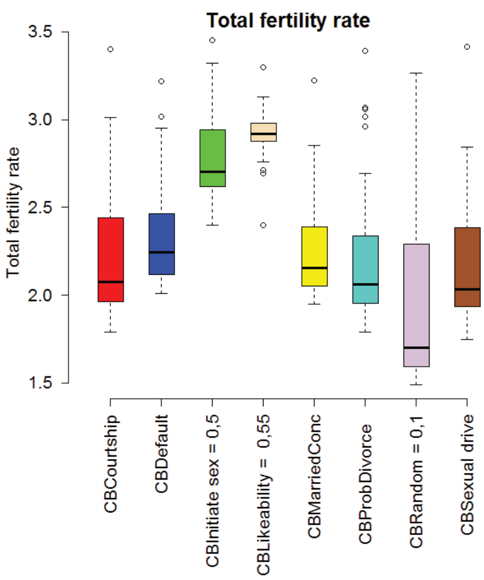


(a) Scenario 3

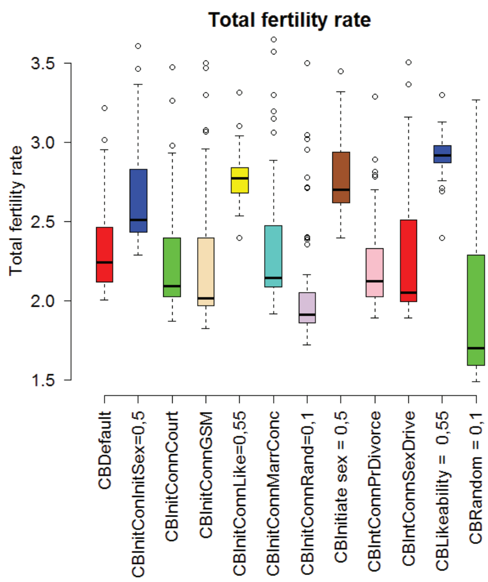


(b) Scenario 4

Figure F.3: **Percentage single fertile female above 15 years**



(a) Scenario 3



(b) Scenario 4

Figure F.4: **Total fertility rate**

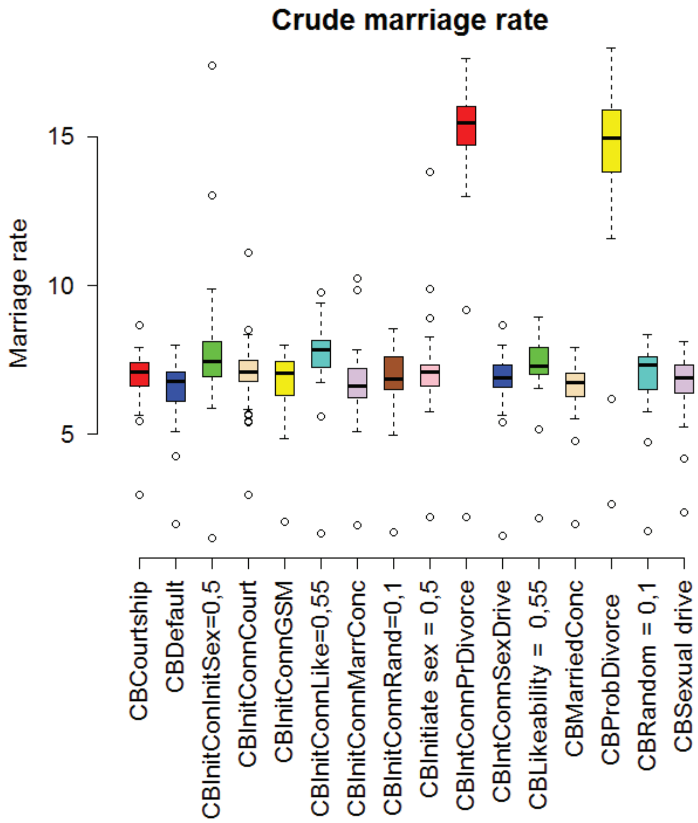
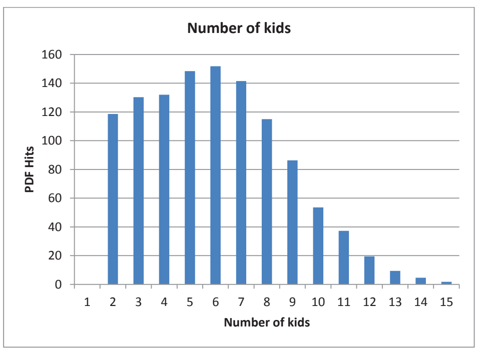
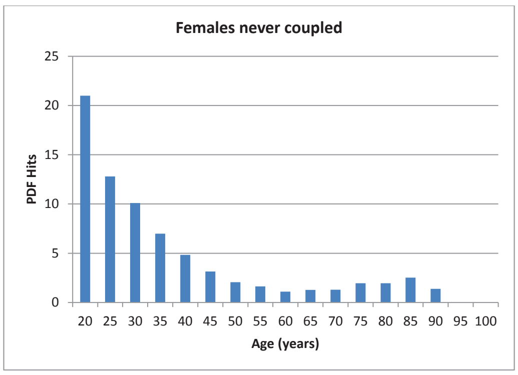


Figure F.5: **Scenario 3 and 4: Marriage rate**



(a) Number of kids at the end of the female reproductive lifespan



(b) Age distribution of never coupled females at death

Figure F.6: **Number of children per female agent at the end of reproductive lifespan and the age distribution of females who die before finding a mate.**

Appendix G

ANOVA results for child birth statistics

ANOVA results for pregnant female agents

Scenario 3

```
             Df Sum Sq Mean Sq F value Pr(>F)
Group         7  291.8   41.68   68.69 <2e-16 ***
Residuals   384  233.0    0.61
Tukey multiple comparisons of means 95% confidence level
                                              p adj
CBDefault-CBCourtship                     0.3958971
CBInitiate sex = 0,5-CBDefault            0.0000000
CBLikeability =  0,55-CBDefault           0.0000000
CBMarriedConc-CBDefault                   0.8068893
CBProbDivorce  -CBDefault                 0.3102631
CBRandom = 0,1-CBDefault                  0.0000000
CBSexual drive-CBDefault                  0.1509810
```

Scenario 4

```
             Df Sum Sq Mean Sq F value Pr(>F)
Group        11  401.9   36.53   51.16 <2e-16 ***
Residuals   576  411.4    0.71
Tukey multiple comparisons of means 95% confidence level
                                            p adj
CBInitConnGSM-CBDefault                   0.9071018
CBInitConnGSM-CBInitConInitSex=0,5        0.0000000
CBInitConnGSM-CBInitConnCourt             0.9999982
CBInitConnLike=0,55-CBInitConnGSM         0.0000000
CBInitConnMarrConc-CBInitConnGSM          0.9159634
CBInitConnRand=0,1-CBInitConnGSM          0.3658989
CBInitiate sex = 0,5-CBInitConnGSM        0.0000000
CBIntConnPrDivorce-CBInitConnGSM          1.0000000
CBIntConnSexDrive-CBInitConnGSM           0.9999226
CBLikeability =  0,55-CBInitConnGSM       0.0000000
CBRandom = 0,1-CBInitConnGSM              0.0001390
```

Figure G.1: **ANOVA results percentage of pregnant females**

ANOVA results for female agents waiting in-between births

Scenario 3

```
                Df Sum Sq Mean Sq F value Pr(>F)
Group            7   1052   150.2   51.81 <2e-16 ***
Residuals      384   1113     2.9
Tukey multiple comparisons of means 95% confidence level
                                                 p adj
CBDefault-CBCourtship                        0.7168780
CBInitiate sex = 0,5-CBDefault               0.0000000
CBLikeability =  0,55-CBDefault              0.0000000
CBMarriedConc-CBDefault                      0.9202649
CBProbDivorce  -CBDefault                    0.0002971
CBRandom = 0,1-CBDefault                     0.0000041
CBSexual drive-CBDefault                     0.2941993
```

Scenario 4

```
                Df Sum Sq Mean Sq F value Pr(>F)
Group           12   1640  136.62   39.79 <2e-16 ***
Residuals      624   2143    3.43
Tukey multiple comparisons of means 95% confidence level
                                             p adj
CBInitConnGSM-CBDefault                      0.9757071
CBInitConnGSM-CBInitConInitSex=0,5           0.0000000
CBInitConnGSM-CBInitConnCourt                0.9999999
CBInitConnLike=0,55-CBInitConnGSM            0.0000000
CBInitConnMarrConc-CBInitConnGSM             0.9614955
CBInitConnRand=0,1-CBInitConnGSM             0.7214845
CBInitiate sex = 0,5-CBInitConnGSM           0.0000000
CBIntConnPrDivorce-CBInitConnGSM             0.6619834
CBIntConnSexDrive-CBInitConnGSM              0.9975279
CBLikeability =  0,55-CBInitConnGSM          0.0000000
CBProbDivorce  -CBInitConnGSM                0.2541915
CBRandom = 0,1-CBInitConnGSM                 0.0260732
```

Figure G.2: **ANOVA results percentage of females waiting in-between child birth**

ANOVA results for single fertile female agents

Scenario 3

```
             Df Sum Sq Mean Sq F value Pr(>F)
Group         7  11983  1711.8   60.65 <2e-16 ***
Residuals   384  10839    28.2
Tukey multiple comparisons of means 95% confidence level
                                                 p adj
CBDefault-CBCourtship                        0.0026001
CBInitiate sex = 0,5-CBDefault               0.0030511
CBLikeability =  0,55-CBDefault              0.0000000
CBMarriedConc-CBDefault                      0.2317771
CBProbDivorce  -CBDefault                    0.0255041
CBRandom = 0,1-CBDefault                     0.0000000
CBSexual drive-CBDefault                     0.0135619
```

Scenario 4

```
             Df Sum Sq Mean Sq F value Pr(>F)
Group        14  17027  1216.2   38.55 <2e-16 ***
Residuals   720  22713    31.5
Tukey multiple comparisons of means 95% confidence level
                                             p adj
CBInitConnGSM-CBCourtship                    0.8419410
CBInitConnGSM-CBDefault                      0.9018193
CBInitConnGSM-CBInitConInitSex=0,5           0.0019438
CBInitConnGSM-CBInitConnCourt                1.0000000
CBInitConnLike=0,55-CBInitConnGSM            0.0000000
CBInitConnMarrConc-CBInitConnGSM             0.8548239
CBInitConnRand=0,1-CBInitConnGSM             0.3190307
CBInitiate sex = 0,5-CBInitConnGSM           0.0000067
CBIntConnPrDivorce-CBInitConnGSM             0.9903251
CBIntConnSexDrive-CBInitConnGSM              0.9996986
CBLikeability =  0,55-CBInitConnGSM          0.0000000
CBProbDivorce  -CBInitConnGSM                0.9935371
CBRandom = 0,1-CBInitConnGSM                 0.0000001
CBSexual drive-CBInitConnGSM                 0.9776558
```

Figure G.3: **ANOVA results percentage of single fertile females**

ANOVA results for total fertility rate

Scenario 3

```
             Df Sum Sq Mean Sq F value Pr(>F)
Group         7  39.42   5.632   53.06 <2e-16 ***
Residuals   392  41.61   0.106
Tukey multiple comparisons of means 95% confidence level
                                          p adj
CBDefault-CBCourtship                   0.4506093
CBInitiate sex = 0,5-CBDefault          0.0000000
CBLikeability =  0,55-CBDefault         0.0000000
CBMarriedConc-CBDefault                 0.8576134
CBProbDivorce  -CBDefault               0.3597415
CBRandom = 0,1-CBDefault                0.0000000
CBSexual drive-CBDefault                0.2497717
```

Scenario 4

```
             Df Sum Sq Mean Sq F value Pr(>F)
Group        11  52.72   4.793   38.93 <2e-16 ***
Residuals   588  72.40   0.123
Tukey multiple comparisons of means 95% confidence level
                                        p adj
CBInitConnGSM-CBDefault                 0.9730178
CBInitConnGSM-CBInitConInitSex=0,5      0.0000005
CBInitConnGSM-CBInitConnCourt           1.0000000
CBInitConnLike=0,55-CBInitConnGSM       0.0000000
CBInitConnMarrConc-CBInitConnGSM        0.9579223
CBInitConnRand=0,1-CBInitConnGSM        0.4610979
CBInitiate sex = 0,5-CBInitConnGSM      0.0000000
CBIntConnPrDivorce-CBInitConnGSM        1.0000000
CBIntConnSexDrive-CBInitConnGSM         0.9999944
CBLikeability =  0,55-CBInitConnGSM     0.0000000
CBRandom = 0,1-CBInitConnGSM            0.0007817
```

Figure G.4: **ANOVA results for total fertility**

Bibliography

Abdissa, A. E.: 2014, *Determinant factors affecting adherence to antiretroviral therapy among HIV infected patients in Addis Ababa*, Master's thesis, Health Studies.

Abel, G., Fitzgerald, L. and Brunton, C.: 2007, *The impact of the Prostitution Reform Act on the Health and Safety Practice of Sex Workers*, Health Research Council of New Zealand and the Ministry of Justice. Available from: http://www.otago.ac.nz/christchurch/otago018607.pdf.

Abu-Raddad, L., Patnaik, P. and Kublin, J. G.: 2006, Dual infection with HIV and malaria fuels the spread of both diseases in sub-Saharan Africa, *Science* **314**, pp. 1603–1606.

Actuarial Society of South Africa (ASSA): 2007, Period Life Table, 2007, Electronic. Available from: http://trustsestateselderlawct.com/eldersolutionscenter/wp-content/uploads/2011/05/2007-Period-Life-Table1.pdf.

Adams, A., Barth-Jones, Chick, S. E. and Koopman, J.: 1998, Simulations to evaluate HIV Vaccine Trial Designs, *Simulation* **71(4)**, pp. 228–241.

Adams, A. L., Koopman, J. S., Chick, S. E. and Yu, P. J.: 1999, GERMS: An epidemiologigal simulation tool for studying geographic and social effects on infection transmission, *Proceedings of the 1999 Winter Simulation Conference* .

Adimora, A. A., Schoenbach, V. J. and Doherty, I. A.: 2007, Concurrent Sexual Partnerships Among Men in the United States, *American Journal of Public Health* **97 No. 12**, pp. 2230–2237.

Adimora, A. A., Schoenbach, V. J., Taylor, E. M., Khan, M. R. and Schwartz, R. J.: 2011, Concurrent Partnerships, Nonmonogamous Partners, and Substance Use Among Women in the United States, *American Journal of Public Health* **101 No. 1**, pp. 128–136.

Adu-Oppong, A., Grimes, R. M., Ross, M. W., Risser, J. and Kessie, G.: 2007, Social an behavioral determinants of consistent condom use among female commercial sex workers in Ghana, *AIDS Education and Prevention* **19(2)**, pp. 160–172.

Alam, S. J.: 2008, *Understanding Social complexity in the Context of HIV/AIDS: A Case Study in Rural South Afica*, PhD thesis, Manchester Metropolitan University Business School.

Alam, S. J. and Meyer, R.: 2006, Towards Finding Suitable Analysis Techniques for Agent-based Networks Generated form Social Processes, *Proceedings of the Social Network Analysis: Second Forum on Advances and Empirical Applications* .

Alam, S. J., Meyer, R. and Norling, E.: 2008, A model for HIV Spread in a South African Village, *Proceedings of the Ninth International workshop on Multi-Agent Simulations* .

Alam, S. J., Meyer, R. and Ziervogel, G.: 2006, Modelling the Socio-Economic Impact of HIV/AIDS in South Africa, *Proceedings of the First world Congress on Social Simulation (WCS'06)* **2**, 281–288.

Alimadad, A., Dabbaghian, V., Singh, S. K. and Tsang, H. H.: 2009, Examining HIV Transmission Rate through Sexual Contact with the Cellular Automata Model, *2nd Annual MoCSSy Symposium* .

Allan, G.: 2006, *Social networks and personal communities*, Cambridge University Press, Cambridge, United Kingdom.

Amin, S. and Bajracharya, A.: 2011, Marriage and First Birth Intervals in Early and Late Marrying Societies: An Exploration of Determinants, *Paper prepared for* *the 2011 Annual Meetings of the Population Association of America, 31 March – 2 April, Washington, DC – 2 April, Washington, DC* .

Anderson, N., Ho-Foster, A., Matthis, J., Marokoane, N., Mashiane, V., Mhatre, S., Mitchell, S., Mokoena, T., Monasta, L., Ngxowa, N., Salcedo, M. P. and Sonnekus, H.: 2004, National cross sectional study of views on sexual violence and risk of HIV infection and AIDS among South African school pupils, *British Medical Journal* **329**, p. 952.

Anderson, R. and Hanson, M.: 2005, Potential public health impact of imperfect HIV type 1 vaccines, *J. of Infectious Diseases* **191(Suppl 1)**, pp. S85–S96.

Anderson, R. M., May, R. M., Boily, M. C., Garnett, G. P. and Rowley, J. T.: 1991, The spread of HIV-1 in Africa: sexual contact patterns and the predicted demographic impact of AIDS, *Nature* **352(6336)**, pp. 581–589.

Asmal, K.: 2003, *National Policy on RELIGION AND EDUCATION*, Council of Education Ministers, http://www.info.gov.za/view/DownloadFileAction?id=70211.

ASSA: 2011, ASSA 2008 AIDS and demographic model. User guide , online. Available from: `http://www.actuarialsociety.org.za/Societyactivities/CommitteeActivities/AidsCommittee/Models.aspx`.

Attiaa, S., Egger, M., Muller, M., Zwahlena, M. and Lowa, N.: 2009, Sexual transmission of HIV according to viral load and antiretroviral therapy: systematic review and meta-analysis, *AIDS* **23**, pp. 1397 –1404.

Auvert, B., Buve, A., Ferry, B., Carael, M., Morison, L., Lagarde, E., Robinson, N. J., Kahindo, M., Chege, J., Rutenberg, N., Musonda, R., Laourou, M. and for the Study Group on the Heterogeneity of HIV Epidemics in African Cities., E. A.: 2001, Ecological and individual level analysis of risk factor for HIV infection in four urban populations in sub-Saharan Africa with different level of HIV infection, *AIDS* **15 (suppl 4)**, pp. S15–S30.

Auvert, B., Males, S., Puren, A., Carel, D. T. W. and Williams, B.: 2004, Can Highly Active Antiretroviral Therapy Reduce the spread of HIV? A study in a township of South Africa, *Journal of Acquired Immune Deficiency Syndrome* **36**, pp. 613–621.

AVERT: 2010a, History of HIV & AIDS in South Africa, Electronic. Available from: www.avert.org/history-aids-south-africa.htm.

AVERT: 2010b, HIV and AIDS in South Africa, Electronic. Available from: https://www.avert.org/professionals/hiv-around-world/sub-saharan-africa/south-africa.

AVERT: 2012, Children Orphaned by HIV and AIDS, Electronic. Available from: http://www.avert.org/children-orphaned-hiv-and-aids.htm.

Axelrod, R.: 1984, *The Evolution of Cooperation*, Basic Books: New York:.

Axelrod, R.: 1997, *The Complexity of Cooperation: Agent-Based Models of Competition and Cooperation*, NJ: Princeton University Press.

Babiker, A. G., Peto, T., Porter, K., Walker, A. S. and Darbyshire, J. H.: 2001, "Age as a determinant of survival in HIV infection", *Journal of Clinical Epidemiology* **54 Supplement 1**, pp. S16–S21.

Baeten, J. M., Kahle, E., Lingappa, J. R., Coombs, R. W., Delany-Moretlwe, S., Nakku-Joloba, E., Mugo, N. R., Wald, A., Corey, L., Donnell, D., Campbell, M. S., Mullins, J. I. and Celum, C.: 2011, Genital HIV-1 RNA predicts risk of heterosexual HIV-1 transmission, *Science Translational Medicine* **3(77)**, pp. 1–15.

Bagni, R., Berchi, R. and Cariello, P.: 2002, A comparison of simulation models applied to epidemics, *Journal of Artificial Societies and Social Simulation* **5**, p. 33.

Bailey, R. C., Moses, S., Parker, C. B., Agot, K., Maclean, I., Krieger, J. N., Williams, C. F. M., Campbell, R. T. and Ndinya-Achola, J. O.: 2007, Male circumcision for HIV prevention in young men in Kisumu, Kenya: a randomised controlled trial, *Lancet* **369**, pp. 643–656.

Bakilana, A.: 2005, Age at sexual debut in South Africa, *African Journal of AIDS* **4**, pp. 1–6.

Balasch, J.: 2010, Ageing and infertility: an overview, *Gynecological Endocrinology* pp. pp. 1–6.

Baral, S., Katende, S., Green, J. L., Chen, P.-A., Grosso, A., Sithole, B., Ntshangase, C., Yam, E., Kerrigan, D., Kennedy, C. E. and Adams, D.: 2014, Reconceptualizing the HIV Epidemiology and Prevention needs of Female Sex Workers (FSW) in Swaziland, *PLoS ONE* **9(12)**, e115465. doi:10.1371/journal.pone.0115465.

Baumeister, R. F., Catanese, K. R. and Vohs, K. D.: 2001, Is There a Gender Difference in Strength of Sex Drive? Theoretical Views, Conceptual Distinctions, and a Review of Relevant Evidence, *Personality and Social Psychology Review* **5(3)**, pp. 242–273.

BBC News: 2002, Homosexuality in Africa, *Technical report*, British Broadcasting Corporation BBC News.

Becquet, R., Ekouevi, D. K., Menan, H., Amani-Bosse, C., Bequet, L., Viho, I., Dabis, F., Timite-Konan, M. and Leroy, V.: 2008, Early mixed feeding and breastfeeding beyond 6 months increase the risk of postnatal HIV transmission: ANRS 1201/1202 Ditrame Plus, Abidjan Cote d'lvore, *Preventive Medicine* **47(1)**, pp. 27–33.

Bekker, L. G., Myer, L., Orrell, C. and Wood, R.: 2006, Rapid scale-up of a community-based HIV treatment service: programme performance over 3 consecutive years in Guguletu, South Africa, *South African Medical Journal* **96(4)**, pp. 315–320.

Benatar, S. R.: 2013, The challenges of health disparities in South Africa, *South African Medical Journal* **103 No 3**, pp. 154–155.

Bendavid, E., Brandeau, M. L., Wood, R. and Owens, D. K.: 2010, Comparative effectiveness of HIV testing and treatment in highly endemic regions, *Arch Intern Med* **170**, pp. 1347–1354.

Benyoussef, A., HafidAllah, N. E., ElKenz, A., Ez-Zahraouy, H. and Loudlidi, M.: 2003, Dynamics of HIV infection on 2D cellular automata, *Physica A* **322**, pp. 506–520.

Bershteyn, A., Klein, D. J., Wenger, E. and Eckhoff, P. A.: 2012, Description of the EMOD-HIV Model v0.7, *Cornell University Library* . Available from: http://arxiv.org/abs/1206.3720.

Black, J., Conradie, F., Cox, V., Dlamini, S., Fabian, J., Maartens, G., Manzini, T., Mathe, M., Menezes, C., Moorhouse, M., Moosa, Y., Nash, J., Orrell, C., Pakade, Y., Venter, F. and Wilson, D.: 2014, Adult antiretroviral therapy guidelines 2014, *S Afr J HIV Med* **15(4)**, pp. 121–143.

Blower, S. M., Aschenbach, A. N., Gershengorn, H. B. and Kahn, J. O.: 2001, Predicting the unpredictable: transmission of drug resistant HIV, *Nat. Med.* **7**, p. 1016.

Blower, S. M., Bodine, E. N. and K, K. G.-F.: 2005, Predicting the potential public health impact of disease-modifying HIV vaccines in South Africa: The problem subtype, *Current drug targets-Infectious disorders* **5(2)**, pp. 179–192.

Blower, S. M., Ma, L., Farmer, P. and Koenig, S.: 2003, Predicting the impact of Antiretrovirals in Resource-Poor Settings: Preventing HIV Infections whilst Controlling Drug Resistance, *Current drug targets-Infectious disorders* **3(4)**, pp. 345–353.

Blower, S. M. and Mclean, A. R.: 1995, AIDS: modeling epidemic control, *Science* **267**, pp. 1252–1253.

Boccara, N. and Cheong, K.: 1993, Critical behaviour of a probabilistic automata network SIS model for the spread of an infectious disease in a population of moving individuals, *J. Phys. A: Math. Gen* **26**, pp. 3707–3717.

Boer, R. J. D. and Hogeweg, P.: 1992, Growth and Recruitment in the Immune Network, *Theoretical and Experimental Insights into Immumology* **66**, pp. 223–247.

Boily, M.-C., Baggaley, R. F., Wang, L., Masse, B., White, R. G., Hayes, R. J. and Alary, M.: 2009, Heterosexual risk of HIV-1 infection per sexual act: systematic review and meta-analysis of observational studies, *Lancet Infectious Diseases* **9**, pp. 118–129.

Bonabeau, E.: 2002, Agent-based modelling: Methods and Techniques for simulating human systems, *Proceedings of the National Academy of Sciences* **99**, pp. 7280–7287.

Boulle, A., Bock, P., Osler, M., Cohen, K., Channing, L., Hilderbrand, K., Mothibi, E., Zweigenthal, V., Slingers, N., Cloetec, K. and Abdullah, F.: 2008, Antiretroviral therapy and early mortality in South Africa, *Bulletin of the World Health Organization* **86**, pp. 678–687.

Bracher, M., Santow, G. and Watkins, S. C.: 2003, "Moving" and Marrying:Modelling HIV Infection among Newly-weds in Malawi, *Demographic Research* **Special Collection, Article 7**, pp. 208–244.

Bradford, A. and Meston, C. M.: 2007, Senior sexual health: The effects of aging on sexuality, *Innovations in clinical practice: Focus on sexual health* **In L. VandeCreek, F. L. Peterson, & J. W. Bley (Eds.)**, pp. 35–45.

Brewer, D. D., Potterat, J. J., Garrett, S. B., Muth, S. Q., Roberts, J. M., Kasprzyk, D., Montano, D. E. and Darrow, W. W.: 2000, Prostitution and the Sex Discrepancy in Reported Number of Sexual Partners, *Proceedings of the National Academy of Sciences of the United States of America* **97 No 22**, pp. 12385–12388.

Budlender, D., Chobokoane, N. and Simelane, S.: 2004, Marriage patterns in South Africa: Methodological and substantive issues, *Southern African Journal of Demography* **9(1)**, pp. 1–26.

Burger, R. and Woolard, I.: 2005, The State of the Labour Market in South Africa after the First Decade of Democracy, *CSSR Working Paper No. 133* .

Buss, D. M.: 2006, Strategies of Human Mating, *Phychological Topics* **15**, pp. 239–260.

Cabinet of South Africa: 2002, Statement on Cabinet meeting of 17 April 2002. Available from: http://www.gcis.gov.za/content/newsroom/media-releases.

Cabinet of South Africa: 2003, Operational plan for comprehensive HIV and AIDS care, management and treatment for South Africa . Available from: http://www.hst.org.za/sites/default/files/aidsplan.pdf.

Carael, M., Slaymaker, E., Lyerla, R. and Sarkar, S.: 2006, Clients of sex workers in different regions of the world: hard to count, *Sex Transm Infect* **82 Suppl 3**, pp. iii26–iii33.

Carr, D. and Bodnar-Deren, S.: 2009, *Gender, Aging and Widowhood*, Sringer, Netherlands, Chapter 32, pp. 705–728.

Cassels, S., Clark, S. and Morris, M.: 2008, Mathematical models for HIV transmission dynamics: Tools for social and behavioral science research, *Journal of Acquired Immune Deficiency Syndromes* **47(Suppl. 1)**, pp. S34–S39.

Castiglione, F., Pappalardo, F., Bernaschi, M. and Motta, S.: 2007, Optimization of HAART with genetic algorithms and agent based models of HIV infection, *Bioinformatics Journal* **23**, pp. 3350–3355.

CATALYST Consortium: 2002, Optional Birth Spacing: New Research from Latin America on the Association of Birth Intervals and Perinatal, Mate and Adolescent Health, *CATALYST Consortium* pp. pp. 1–35.

CDC: 1982, Kaposi's sarcoma and pneumocystis pneumonia among homosexual men - New York City and California, *Centers for Disease Control* **30**, pp. 305–308.

CDC: 1994, Revised Classification System for Human Immumodeficiency Virus Infection in Children Less than 13 Years of Age, *Mort. and Mord. Wkly Rep.* **43**, pp. 12–15.

CDC: 2003, HIV and Its Transmission CDC Fact Sheet. Available from: www.chsourcebook.com/articles/hivtransmission.html.

CDC: 2008, TB and HIV/AIDS: CDC HIV/AIDS facts. Available from: http://www.cdc.gov/tb/publications/factseries/tbandhiv_eng.htm.

CDC: 2009, Effect of Antiretroviral Therapy on Risk of Sexual Transmission of HIV Infection and Superinfection. Available from: http://www.cdc.gov/hiv/pdf/prevention_art_factsheet.pdf.

CDC: 2011, HIV transmission. Available from: http://www.cdc.gov/hiv/basics/transmission.html.

Celada, F. and Seiden, P. E.: 1992, A computer Model of Cellular Interactions in the Immune System, *Immumology Today* **13**, pp. 56–62.

Centres for Disease Control and Prevention (CDC): 1982, Kaposi's sarcoma and pneumocystis pneumonia among homosexual men - New York City and California., *Centers for Disease Control* **30**, pp. 305–308.

Chersich, M., Rees, H., Scorgie, F. and Martin, G.: 2009, Enhancing global control of alcohol to reduce unsafe sex and HIV in sub-Saharan Africa, *Global health* **5:16**, pp. 1–6.

Child, K.: 2014, ARVs drodrop rate worries UN, *TimeLive* . Available from: www.timeslive.co.za/thetimes/2014/04/04/arvs-dropout-rate-worries-un.

Child, K.: 2015, SA's women most at risk of getting HIV, *TimesLive* . Available from: http://www.timeslive.co.za/thetimes/2015/06/29/SAs-women-most-at-risk-of-getting-HIV.

Chuenyane, G.: 2010, School drop out mystery, *City Press* . Available from: http://www.news24.com/Archives/City-Press/School-drop-out-mystery-20150430.

Cichocki, M. R. N.: 2007, HIV Around the World - South Africa: Political Turmoil and Denial Feeds a Raging Epidemic, *Medical Review Board* .

Cohen, M. S., Chen, Y. Q., McCauley, M., Gamble, T., Hosseinipour, M. C., Kumarasamy, N., Hakim, J. G. and et al.: 2011, Prevention of HIV-1 Infection with Early Antiretroviral Therapy, *The New England Journal of Medicine* **365 (6)**, pp. 493–505.

Collinson, M., Tollman, S., Kahn, K. and Clark, S.: 2003, Highly prevalent circular migration: Households, mobility and economic status in rural South Africa, *Conference on African Migration in Comparative Perspective, Johannesburg, South Africa, 4-7 June, 2003* . Available from: http://www.queensu.ca/samp/migrationresources/Documents/Collinson_highly.pdf.

Colvin, M.: 2011, *End of Term Review of the NSP 2007-2011*, final report edn, South African National AIDS Council.

Connell, R., Dawson, P. and Skvortsov, A.: 2009, Comparison of an Agent-based Model of Disease Propagation with the Generalised SIR Epidemic Model, *Technical report*, Australian Government, Department of Defence, Defence Science and Technology Organisation.

Cooper, E. R., Charurat, M., Mofenson, L., Hanson, I. C., Pitt, J., Diaz, C., Hayani, K., Handelsman, E., Smeriglio, V., Hoff, R., Blattner, W., Women and Group., I. T. S.: 2002, Combination antiretroviral strategies for the treatment of pregnant HIV-1-infected women and prevention of perinatal HIV-1 transmission, *Journal of Acquired Immune Deficiency Syndromes* **29 (5)**, pp. 484–494.

Coplan, D.: 2000, Culture of South Africa. Available from: www.everyculture.com/Sa-Th/South-Africa.html.

Corey, L., Wald, A., Celum, C. L. and Quinn, T. C.: 2004, The Effects of Herpes Simplex Virus-2 on HIV-1 Acquisition and Transmission: A Review of Two Overlapping Epidemics, *Journal of Acquired Immune Deficiency Syndrome* **35**, pp. 435–455.

Corey, M. D.: 2009, A statement by Larry Corey, M.D., on the success of the HIV Vaccine Trial in Thailand, *Technical report*, HIV Vaccine Trials Network.

Council, S. A. N. A.: 2010, The National HIV Counselling and Testing Campaign Strategy, *Technical report*, South African National AIDS Council.

Cowan, F., Langhaug, L. F., Hargrove, J. W., Shabbar, S., Mhuriyengwe, L., Swarthout, T. D., Peeling, R., Latif, A., Basset, M. T., Brown, D. W., Mabey, D., Hayes, R. J. and Wilson, D.: 2005, Is Sexual Contact With Sex Workers Important in Driving the HIV Epidemic Among Men in Rural Zimbabwe?, *Journal of Acquired Immune Deficiency Syndromes* **40**, pp. 371–376.

Crush, J., Jeeves, A. and Yudelman, D.: 1993, South Africa's Labour Empire: A History of Black Migrancy to the Gold Mines, *Journal of the International African Institute* **63**, pp. 282–284.

Crush, J. and Williams, V.: 2002, *Southern African Migration Project Regionalizing International Migration: Lessons for SADC*, migration policy brief no. 11 edn, Southern African Migration Project. Retrieved on 11 October 2010. Available from: http://www.queensu.ca/samp/sampresources/samppublications/policybriefs/brief11.pdf.

Dabbaghian, V., Richardson, N., Rutherford, A. and Vasarhelyi, K.: 2006, A Cellular Automata Model of the Spread of HIV in a community of Injection Drug Users, *Complex Systems modelling group, The IRMACS centre* . Available from: http://www.cecm.sfu.ca/research/posters/richardson07.pdf.

Dailey, R. M., Pfiester, A., Jin, B., Beck, G. and Clark, G.: 2009, On-again/off-again dating relationships: How are they different from other dating relationships, *Personal Relationships* **16**, pp. 23–47.

Davidsson, P.: 2002, Agent Based Social Simulation: A computer Science View, *Journal of Artificial Societies and Social Simulation* **5 no. 1**. Available from: http://jasss.soc.surrey.ac.uk/5/1/7.html.

de Ruiter, J., Weston, G. and Lyon, S. M.: 2011, Dunbar's Number: Group Size and Brain Physiology in Humans Reexamined, *American Anthropologist* **113**, 557–568.

Deeks, S. G., Gange, S. J., Kitahata, M. M., Saag, M. S., Hogg, A. C. J. R. S., Eron, J. J., Brooks, J. T., Rourke, S. B., Gill, M. J., Bosch, R. J., Benson, C. A., Collier, A. C., Martin, J. N., Klein, M. B., Jacobson, L. P., Rodriguez, B., Sterling, T. R., Kirk, G. D., Napravnik, S., Rachlis, A. R., Calzavara, L. M., Horberg, M. A., Silverberg, M. J., Gebo, K. A., Kushel, M. B., Goedert, J. J., McKaig, R. G. and Moore, R. D.: 2009, Trends in multidrug treatment failure and subsequent mortality among antiretroviral therapy-experienced patients with HIV infection in North America, *Cinical Infectious Diseases* **49(10)**, pp.1582–1590.

DeLamater, J. D. and Sill, M.: 2005, Sexual desire in later life, *Journal of Sex Research* **42:2**, pp. 138–149.

DeLoach, A. S. and Valenzuela, J. L.: 2007, An Agent-Environment Interaction Model, *in L Padgham & F Zambonelli (eds), Agent Oriented Software Engineering VII* **Lecture Notes in Computer Science 4405**, pp. 1–18.

Department of Health Republic of South Africa: 2011, Policy on national health insurance, *GOVERNMENT GAZETTE* **No. 34523**.

Department of Health, Republic of South Africa: 2015, MSM in South Africa: Data Triangulation Project, *Technical report*, Department of Health.

DePaulo, B. M. and Morris, W. L.: 2005, Singles in Society and in science, *Phychological Inquiry* **16**, pp. 57–83.

DiClemente, R. J., Wingood, G. M., Blank, M. B. and Metzger, D. S.: 2008, Future Directions for HIV Prevention Research, *Journal of Acquired Immune Deficiency Syndromes* **47**, pp. S47–S48.

Dietz, K. and Hadeler, K. P.: 1988, Epidemiological models for sexually transmitted diseases, *Journal of Mathematical Biology* **26**, pp. 1–25.

Dietz, K. and Heesterbeek, J. A. P.: 2000, Bernoulli was ahead of modern epidemiology, *Nature* **408**, pp. 513–514.

Dorrington, R. and Schneider, D.: 2001, Fitting the ASSA2000 Urban-rural AIDS and Demographic Model to 10 Sub-Saharan countries, *Annual Convention of the Actuarial Society of South Africa, Johannesburg, 30-31 October 2001.*

Doyle, P. R. and Millar, D. B.: 1990, A general description of an acturial model applicable to the HIV epidemic in South Africa, *Transactions of the Acturial Society of South Africa* **8**, pp. 561–593.

Dunbar, R.: 2010, *How many friends Does One Person Need? "Dunbar's Number" and Other Evolutionary Quirks*, Faber and Faber Limited, London.

Dunbar, R. I. M.: 1992, Neocortex size as a constraint on group size in primates, *Journal of Human Evolution* **22(6)**, pp. 469–493.

Dunkle, K. L., Beksinska, M. E., Rees, V. H., Ballard, R. C., Htun, Y. and Wilson, M. L.: 2005, Risk factor for HIV infection among sex workers in Johannesburg, South Africa., *International Journal of STD and AIDS* **16(3)**, pp. 256–261.

Dunkle, K. L., Jewkes, R. K., Brown, H. C., Gray, G. E., McIntryre, J. A. and Harlow, S. D.: 2004a, Gender-based violence, relationship power, and risk of HIV infection in women attending antenatal clinics in South Africa, *The Lancet* **363**, pp. 1415–1429.

Dunkle, K. L., Jewkes, R. K., Brown, H. C., Gray, G. E., McIntryre, J. A. and Harlow, S. D.: 2004b, Transactional sex among women in Soweto, South Africa: prevalence, risk ffactor and association with HIV infection., *Social Science & Medicine* **59**, pp. 1581–1592.

Eaton, J. W., Johnson, L. F., Salomon, J. A., Barnighausen, T. and E. Bendavid E, e. a.: 2012, HIV Treatment as Prevention: Systematic Comparison of Mathematical Models of the Potential Impact of Antiretroviral Therapy on HIV Incidence in South Africa, *PLoS Med* **9(7)**, pp. 1–19.

Eckhardt, R.: 1987, Stan Ulam, John Von Neumann, and the Monte Calo Method.

Edelstein-Keshet, L.: 1988, *Mathematical models in in Biology*, Random House, New York.

Edginton, M.: 2000, Tuberculosis in South Africa, *Health Systems Trust update* **56**. Available from: http://www.hst.org.za/publications/tuberculosis-south-africa.

Edmonds, B.: 1998, Modelling Bounded Rationality In Agent-Based Simulations using the Evolution of Mental Models, *Computational Techniques for Modelling Learning Economics* pp. 305–332.

Epstein, M. J. and Robert, A.: 1996, *Growing Artificial Societies: Social Science from Bottom Up*, MIT Press: Cambridge.

Erasmus, J.: 2010, Afrcan TB nurses lauded, *Media Club South Africa* .

Fang, C., Kimbrough, S. O., Pace, S., Valluri, A. and Zheng, Z.: 2002, On Adaptive Emergence of Trust Behavior in the Game Stag Hunt, *Group Decision and Negotiation* **11**, pp. 449–567.

Fazito, E., Cuchi, P., Mahy, M. and Brown, T.: 2012, Analysis of duration of risk behaviour for key populations: a literature review, *Sex Transm Infect* **88**, pp. i24–i32.

Ferber, J.: 1999, *Multi-Agent Systems - An Introduction to Distributed Artificial Intelligence*, Addison-Wesley, Harlow.

Ferguson, S. J.: 2000, Challenging traditional marriage: Never married Chinese American and Japanese American women, *Gender & Society* **14**, pp. 136–159.

Folcik, V. and Orosz, C. G.: 2006, An Agent-based Model Demonstrates that the Immune System Behaves Like a Complex System and a scale free network, *SwarmFest, University of Notre Dame, South Bend, IN, June* .

Fraser-Hurt, N., Njuho, K. Z. Z., Chikwava, F., Hosegood, E. S. S. and Gorgens, M.: 2011, *The HIV epidemic in South Africa: What do we know and how* *has it changed?*, World Bank, Human Sciences Research Council, Health and Development Africa. UNAIDS. Available from: http://www.hsrc.ac.za/en/research-data/view/5686.

Frater, A. J., Dunn, D. T., Beardall, A. J., Ariyoshi, K., Clarke, J. R., McClure, M. O. and Weber, J. N.: 2002, Comparative response of African HIV-1 infected individuals to highly active antiretroviral therapy, *AIDS* **16**, pp. 1139–1146.

French, R. M. and Kus, E. T.: 2008, KAMA: A Temperature-Driven Model of Mate Choice Using Dynamic Partner Representations, *Adaptive Behavior* **16(1)**, pp. 71–94.

Fu, S. C. and Milne, G.: 2003, Epidemic Modelling Using Cellular Automata, *In proceedings of the Australian conference on artificial life* .

Ganguly, N., Sikdar, B. K., Deutsch, A., Canright, G. and Chaudhuri, P. P.: 2003, A Survey on Cellular Automata, *Technical Report Centre for High Performance Computing, Dresden University of Technology, 30 p* . Available from: http://www.cs.unibo.it/bison/publications/CAsurvey.pdf.

Gao, B. J., Xuan, H. Y. and Zhang, T.: 2006, A heterogeneous cellular automata model for SARS transmission, *Systems Engineering Theory Methodology Applications* **15**, pp. 205–209.

Garcia, C. Y.: 1998, Temporal course of the basic components of love throughout relationships, *Phychology in Spain* **2 Number 1**, pp. 76–86.

Ghani, A. C., Swinton, S. and Garnett, G. P.: 1997, "The role of Sexual Partnership Networks in the Epidemiology of Gonorrhea", *Sexually transmitted Diseases* **24(1)**, pp. 45–56.

Gilbert, N. and Terna, P.: 2000, How to build and use agent-based models in social science, *Mind & Society* **1**, pp. 57–72.

Gilbert, N. and Troitzsch, K.: 2005, *Simulation for the social Scientist*, Open University Press, Berkshire, England.

Goncalves, B., Perra, N. and Vespignani, A.: 2011, Validation of Dunbar's number in Twitter conversations, *PLoS ONE* pp. 1–8.

Gordon, G.: 1978, *System Simulation*, Prentice-Hall, Engelwood Cliffs, NJ.

Gordon, T. J.: 2003, A simple agent model of an epidemic, *Technological Forecasting and Social Change* **70**, pp. 397–417.

Government Communications-(GCIS): 2010, Statement on the Cabinet meeting held 10 March 2010. Available from: http://www.gcis.gov.za/content/newsroom/media-releases/cabinet-statements/statement-cabinet-meeting-held-10-march-2010.

Government of South Africa: 2007, *HIV and AIDS and STI Strategic Plan for South Africa, 2007-2011*, Health Department of South Africa.

Gray, R. G., Kigozi, G., Serwadda, D., Makumbi, F., Watya, S., Nalugoda, F. and et al.: 2007, Male circumcision for HIV prevention in men in Rakai, Uganda: a randomised trial, *Lancet* **369**, pp. 657–666.

Gray, R. H., Kigozi, G., Serwadda, D., Makumbi, F., Nalugoda, F., Watya, S., Moulton, L., Chen, M. Z., Sewankambo, N. K., Kiwanuka, N., Sempijja, V., Lutalo, T., Kagayii, J., Wabwire-Mangen, F., Ridzon, R., Bacon, M. and Wawer, M. J.: 2009, The effects of male circumcision on female partners' genital tract symptoms and vaginal infections in a randomized trial in Rakai, Uganda.

Gray, R., Wawer, M. J., Brookmeyer, R., Sewankambo, N. K. and et. al: 2001, Probability of HIV-1 transmission per coital act in monogamous, heterosexual, HIV-1-discordant couples in Rakai, Uganda, *The Lancet* **357**, pp. 1149–1153.

Groeneveld, H. and Padayachee, N.: 1992, A Stochastic model for medium-term estimation of the prevalence of HIV infection in a South African heterosexual population, *South African Medical Journal* **81**, pp. 67–70.

Groenewald, P., Nannan, N., Bourne, D., Laubscher, R. and Bradshaw, D.: 2005, Identifying deaths from AIDS in South Africa, *AIDS* **19**, pp. 193–201.

Guay, L. A., Musoke, P., Fleming, T., Bagenda, D., Allen, M., Nakabiito, C., Sherman, J., Bakaki, P., Ducar, C., Deseyve, M., Emel, L., Mirochnick, M., Fowler, M. G., Mofenson, L., Miotti, P., Dransfield, K., Bray, D., Mmiro, F. and Jackson, J. B.: 1999, Intrapartum and neonatal single-dose nevirapine compared with zidovudine for prevention of mother-to-child transmission of HIV-1 in Kampala, Uganda: HIVNET 012 randomised trial, *The Lancet* **354 No. 9181**, pp. 795–802.

Guo, Z., Han, H. K. and Tay, J. C.: 2005, Sufficiency verification of HIV-1 pathogenesis based on multi-agent simulation, *Proceedings of the ACM Genetic and Evolutionary Computation Conference 2005 (GECCO'05), Washington D. C., USA.* pp. 305–312.

Gupta, S., Anderson, R. M. and May, R. M.: 1989, Networks of sexual contacts: implications for the pattern of spread of HIV, *AIDS* **3**, pp. 807–817.

Haidt, J.: 2006, *The HAPPINESS HYPOTHESIS*, Arrow Books, London.

Halperin, D. T. and Epstein, H.: 2004, Concurrent sexual partnerships help to explain Africa's high HIV prevalence: implications for prevention, *Lancert* **364**, pp. 4–6.

Halperin, D. T. and Epstein, H.: 2007, Why is HIV prevalence so severe in southern Africa, *Southern African Journal of HIV Medicine* pp. pp. 19–25.

Harcourt, C. and Donovan, B.: 2005, The many faces of sex work, *Sex Transm Infect* **81**, pp. 201–206.

Hargreaves, J. R.: 2005, *The social epidemiology of HIV infection: A study among unmarried young rural South Africa in 2001*, PhD thesis, London School of Hygiene and Tropical Medicine, United Kingdom.

Harrison, A., Cleland, J., Gouws, E. and Frohlich, J.: 2005, Early sexual debut among young men in rural South Africa: heightened vulnerability to sexual risk?, *Sexually transmitted Infections* **81**, pp. 259–261.

Health and Development Africa: 2010, Cuntry progress report on the declaration of commitment on HIV/AIDS., *Technical report*, Health and Development Africa (Pty) Ltd. Available from: http://data.unaids.org/pub/report/2010/southafrica_2010_country_progress_report_en.pdf.

Heaton, T. B. and Jacobson, C. K.: 2004, Cross-Cultural Patterns of Interracial Marriage, *Department of Sociology, Brigham Young University* pp. pp. 1–27.

Helleringer, S. and Kohler, H.-P.: 2007, Sexual Network Structure and the Spread of HIV in Africa: Evidence from LikomaIsland, Malawi, *AIDS* **21 no. 17**, pp. 2323–2332.

Hethcote, H. W.: 2000, The mathematics of infectious disease, *SIAM Rev* **42**, p. 599.

Hethcote, H. W. and Ark, J. W. V.: 1980, Modelling HIV transmission and AIDS in the United States, *Lect. Notes in Biomath., Springer-Verlag, Berlin, Heidelberg* .

Hethcote, H. W., Stech, H. W. and van den Driessche: 1981, Periodicity and stability in epidemic models: A survey, in differential equations and applications in ecology, Epidemics and population problems, *Academic Press, New York* pp. 62–82.

Heuveline, P., Sallach, D. and Howe, T.: 2004, The structure of an epidemic: Modelling AIDS transmission in Southern Africa, *Annual Meeting of the Population Association of America, Boston* .

Hills, T. and Todd, P.: 2008, Population Heterogeneity and Individual Differences in an Assortative Agent-Based Marriage and Divorce Model (MADAM) Using Search with Relaxing Expectations, *Journal of Artificial Societies and Social Simulation* **11**.

HIV/AIDS: 2014, Course of HIV/AIDS, On-line. Available from: http://www.health24.com/Medical/HIV-AIDS/Overview.

Hogg, C.: 2004, Mandela urges action to fight TB, *Technical report*, British Broadcasting Corporation BBC News. Available from: http://news.bbc.co.uk/2/hi/asia-pacific/3895525.stm.

Hollingsworth, T. D., Anderson, R. M. and Fraser, C.: 2008, HIV-1 Transmission, by Stage of Infection, *Journal of Infectious Diseases* **198**, pp. 687–693.

Holmes, C. B., Wood, R., Badri, M., Zilber, S., Wang, B., Maartens, G., Zheng, H., Lu, Z., Freedberg, K. A. and Losina, E.: 2006, CD4 Decline and Incidence of Opportunistic Infections in Cape Town, South Africa: Implications for Prophylaxis and Treatment, *Journal of Acquired Immune Deficiency Syndrome* **42(4)**, pp. 464–469.

Hontelez, J., Nagelkerke, N., Barnighausen, T., Tanser, R. B. B., Newell, M. L., Lurie, M. . N., Baltussen, R. and de Vlas, S. J.: 2011, The potential impact of RV144-like vaccines in rural South Africa: a study using the STDSIM microsimulation model, *Vaccine* **29**, pp. 6100–6106.

HSRC: 2008, A national health system: opportunities and challenges for South Africa, pp. 17–22.

HSRC: 2009, South African HIV Prevalence, Incidence, Behaviour and Communication Survey, 2008: A Turning Tide Among Teenagers. Available from: http://www.health-e.org.za/wp-content/uploads/2013/05/2966e129fc39e07486250fd47fcc266e.pdf.

HSRC: 2014, South African National HIV Prevalence, Incidence and Behaviour Survey, 2012. Available from: http://www.hsrc.ac.za/uploads/pageContent/4565/SABSSM%20IV%20LEO%20final.pdf.

Huang, C. Y., Sun, C. T., Hsieh, J. L. and Lin, H.: 2004, Simulating SARS: Small -World Epidemiological Modelling and Public Health Policy Assessments, *Journal of Artificial Societies and Social Simulation* **7 no. 4**, pp. 100–131.

Hunter, M.: 2002, The materiality of everyday sex: Thinking beyond ‘prostitution’, *African Studies* **61(1)**, pp. 99–120.

Huston, T. L., Niehuis, S. and Smith, S. E.: 2000, Courtship and the newlywed years: What they tell us about the future of a marriage, *Revista de Psicologia Socialy Personalidad* **16**, pp. 155–178.

Ijsselmuiden, C. B., Padayachee, G. N., Mashaba, W., Martiny, O. and Staden, H. P. V.: 1990, Knowledge, beliefs and practices among black goldminers relating to the transmission of human immunodeficiency virus and other sexually transmitted diseases, *SAMJ* **78**, pp. 520–523.

Iliff, P. J., Piwoz, E. G., Tavengwa, N. V., Zunguza, C. D., Marinda, E. T., Nathoo, K. J., Moulton, L. H., Ward, B. J. and the ZVITAMBO study group; Humphrey: 2005, Early exclusive breastfeeding reduces the risk of postnatal HIV-1 transmission and increases HIV-free survival, *AIDS* **19 Issue 7**, pp. 699–708.

IRINPlusNews: 2008, SOUTH AFRICA:Sex education – the ugly stepchild in teacher training, *Global HIV/AIDS news and analysis* .

Jacobson, C. K., Amoateng, A. Y. and Heaton, T. B.: 2004, Inter-racial Marriage in South Africa, *Journal of Comparative Family Studies* **35(1)**, pp. 443–459.

Jewkes, R., Dunkle, K., Nduna, M. and Shai, N.: 2010, Intimate partner violence, relationship power inequity, and incidence of HIV infection in young women in South Africa: a cohort study, *The Lancet* **376**, pp. 41–48.

Jewkes, R. K., Nduna, M., Jama, P. N., Dunkle, K. L. and Levin, J. B.: 2002, Steadys, roll-ons and hit and runs: Using indigenous typology to measure number of sexual partners, *The XIV International AIDS Conference, Barcelona* .

Jewkes, R., Vundule, C., Maforah, F. and Jordaan, E.: 2001, Relationship dynamics and teenage pregnancy in South Africa, *Social Science and Medicine* **52**, pp. 733–744.

Jin, E. M., Girvan, M. and Newman, M. E. J.: 2001, The structure of growing social networks, *Physical review* **64 no. 4**, 46132.

Johnson, L.: 2014, THEMBISA version 1.0: A model for evaluating the impact of HIV/AIDS in South Africa., *Technical report*, Centre for Infectious Disease Epidemiology and Research working paper.

Kaiser family foundation: 2009, Population density. Available from: http://www.globalhealthfacts.org/topic.jsp?i=87.

Kaleebu, P., Ross, A., Morgan, D., Yirrella, D., Oramb, J., Rutebemberwa, A., Lyagoba, F., Hamilton, L., Biryahwaho, B. and Whitworth, J.: 2001, Relationship between HIV-1 Env subtypes A and D and disease progression in a rural Ugandan cohort, *AIDS* **15**, pp. 293–299.

Kalichman, S. C., Eaton, L., Cain, D., Cherry, C., Pope, H. and Kalichman, M.: 2006, HIV treatment beliefs and sexual transmission risk bbehaviour among HIV positive men and women, *Journal of Behavioral Medicine* **29**, pp. 401–410.

Kalichman, S. C., Simbayi, L. C., Kaufman, M., Cain, D. and Jooste, S.: 2007, Alcohol Use and Sexual Risks for HIV/AIDS in Sub-Saharan Africa: Systematic Review of Empirical Findings, *Prevention Science* **8(2)**, pp. 141–151.

Kalick, S. M. and Hamilton, T. E.: 1986, The matching hypothesis reexamined , *Journal of Personality and Social Psychology* **51(4)**, pp. 673–682.

Kalman, R. E.: 1960, A New Approach to Linear Filtering and Prediction Problems, *Journal of Basic Engineering* **82 (Series D)**, pp. 35–45.

Karim, S., Churchyard, G. J., Abdool, Q. and Lawn, S.: 2009, HIV infection and tuberculosis in South Africa: an urgent need to escalate the public health response, *Lancet* **374**, pp. 921–933.

Kenya School of Monetary Studies: 2012, Strengthening Gender Based Violence and HIV Response in Sub-Saharan Africa. Report of Workshop Organised by Liverpool VCT, Care and Treatment (LVCT), World Health Organization (WHO) and Sexual Violence Research Initiative (SVRI), *Technical report*.

Kermack, W. O. and Mckendrick, A. G.: 1927, Contributions to the mathematical theory of epidemics, Part 1, *Proceedings of the Royal Society of London A115* .

Kesaniemi, J. and Terziyan, V.: 2011, Agent-Environment Interaction in MAS - Introduction and Survey, *Multi-Agent Systems – Modeling, Interactions, Simulations and Case Studies*, InTech, pp. 203–226.

Kiarie, J. N., Richardson, B. A., Mbori-Ngacha, D., Nduati, R. W. and John-Stewart, G. C.: 2004, Infant Feeding Practices of Women in a Perinatal HIV-1 Prevention Study in Nairobi, Kenya, *Journal of Acquired Immune Deficiency Syndrome* **35(1)**, pp. 75–81.

Kieler, H., Axelsson, O., Nilsson, S. and Waldenstrom, U.: 1995, The length of human pregnancy as calculated by ultrasonographic measurement of the fetal biparietal diameter, *Ultrasound in Obstetrics and Gynecology* **6**, pp. 353–357.

Kilian, D., Fiehn, H., Ball, J. and Howells, M.: 2005, NATIONAL STATE OF THE ENVIRONMENT PROJECT HUMAN SETTLEMENTS, *Background Research Paper:Human Settlements South Africa Environment Outlook* .

Kimberley, M.: 2012, Groups warn of ARV crisis.

Kingdon, G. and Knight, J.: 2007, Unemployment in South Africa, 1995-2003: Causes, Problems and Policies, *Journal of African Economies* **16**, pp. 813–848.

Klein, D. J., Bershteyn, A. and Eckhoff, P. A.: 2014, Dropout and re-enrollment: implications for epidemiological projections of treatment programs, *AIDS* **28 (Suppl 1)**, pp. S47–S59.

Knittel, A. K., Riolo, R. L. and Snow, R. C.: 2011, Development and evaluation of an agent-based model of sexual partnership, *Adaptive Behavior* **pp. 1-26**.

Kohler, T. A., Gumerman, G. J. and Reynolds, R. G.: 2005, Simulating ancient societies, *Scientific American Journal* **293(1)**, pp. 77–84.

Konstant, T. L., Rangasami, J., Stacey, M. J., Stewart, M. L. and Nogoduka, C.: 2015, Estimating the Number of Sex Workers in South Africa: Rapid Population Size Estimation, *AIDS* **19**, pp. S3–S15.

Kretzschmar, M. and Morris, M.: 1996, Measures of concurrency in networks and the spread of infectious disease, *Mathematical Biosciences* **133(2)**, pp. 165–195.

Kurka, P.: 1997, Languages, Equicontinuity and Attractors in Cellular Automata, *Dynamis Systems* **17**, pp. 229–254.

Kwobah, C. M., Mwangi, A. W., Koech, K. K., Simiyu, G. N. and Siika, A. M.: 2012, Factors Associated with First-Line Antiretroviral Therapy Failure amongst HIV-Infected African Patients: A case-Control Study, *World Journal of AIDS* **2**, pp. 271–278.

Lane, T., Raymond, H. F., Dladla, S., Rasethe, J., McFarland, W. and McIntyre, J.: 2011, High HIV prevalence among men who have sex with men in Soweto, South Africa: results from the Soweto Men's Study, *AIDS Behaviour* **15(3)**, pp. 626–634.

Lavreys, L., Baeten, J. M., Overbaugh, J., Panteleeff, D. D., Chohan, B. H., Richardson, B. A., Mandaliya, K., Ndinya-Achola, J. O. and Kreiss, J. K.: 2002, Virus Load during Primary Human Immunodeficiency Virus (HIV) Type 1 Infection Is Related to the Severity of Acute HIV Illness in Kenyan Women, *HIV/AIDS* **35**, pp. 77–81.

Lawn, S. D., Myer, L., Bekker, L. and Wood, R.: 2006, CD4 cell count recovery among HIV-infected patients with very advanced immunodeficiency commencing antiretroviral treatment in sub-Saharan Africa, *BMC Infectious Diseases* **6:59**, pp. 1–8.

Leclerc-Madlala, S.: 2008, Age disparate and intergenerational sex in Southern Africa: The dynamics of hypervulnerability, *AIDS* **22**, pp. S17–S25.

Lee, P. K., Kieffer, T. L., Siliciano, R. F. and Nettles, R. E.: 2006, HIV-1 viral load blips are of limited clinical significance, *Journal of Antimicrobial Chemotherapy* **57**, pp. 803–805.

Leslie, W. D. and Brunham, R. C.: 1990, The dynamics of HIV spread: a computer simulation model, *Computers and Biomedical Research* **23**, pp. 380–401.

Lewis, K. G. and Moon, S.: 1997, Always single and single aging women: A qualitative study, *Journal of Marital and Family Therapy* **23**, pp. 115–134.

Lichtenstein, B., Desmond, R. A. and Schwebke, J. R.: 2008, Partnership Concurrency Status and Condom Use among Women Diagnosed with T. vaginalis, *Womens Health Issues* **18(5)**, pp. 369–374.

Lofstedt, P., Ghilagaber, G., Shusheng, L. and Johansson, A.: 2005, Changes in marriage age and first birth interval in Huaning Country, Yunnan province, PR China, *The Southeast Asian journal of tropical medicine and public health* **36 No. 5**, pp. 1329–1338.

Lomi, A. and Larsen, E. R.: 2001, *Dynamics of organisations: computational modeling and organization theories*, AAAI Press/MIT Press.

Longini, I. M. J. and Halloran, S. D. M. E.: 1996, Measuring vaccine efficacy for both susceptibility to infection and reduction in infectiousness for prophylactic HIV-1 vaccines, *J. Acquired Immune Deficiency Human Retrovirol* **13**, pp. 440–447.

Louch, H.: 2000, Personal network intergration: trasitivity and homophily in strong-tie relations, *Social Networks* **22**, pp. 45–64.

Luchters, S., Chersich, F., Rinyiru, A., Barasa, M. S., King'ola, N., Mandaliya, K., Bosire, W., Wambugu, S., Mwarogo, P. and Temmerman, M.: 2008, Impact of five years of peer-mediated ninterventions on sexual behaviour and sexually transmitted infections among female sex workers in Mombasa Kenya, *BMC Public Health* **8:143**.

Lurie, M. N., Williams, B. G., Zuma, K., Mkaya-Mwamburi, D., Garnett, G. P., Sweat, M. D., Gittelsohn, J. and Karim, S. S. A.: 2003a, The impact of Migration on HIV-1 Transmission in South Africa, *Sexually transmitted Diseases* **30**, pp. 149–156.

Lurie, M. N., Williams, B. G., Zuma, K., Mkaya-Mwamburi, D., Garnett, G. P., Sweat, M. D., Gittelsohn, J. and Karim, S. S. A.: 2003b, Who infects whom? HIV-1 concordance and discordance among migrant and non-migrant couples in South Africa, *AIDS* **17**, pp. 2245–2252.

Macal, C. M. and North, M. J.: 2006, Tutorial on Agent-Based Modeling and Simulation Part 2: How to model with agents, *Proceedings of the 2006 Winter Simulation Conference* .

Mah, T. L. and Halperin, D. T.: 2010a, Concurrent Sexual Partnerships and the HIV Epidemics in Africa: Evidence to Move Forward, *AIDS Behaviour* **14**, pp. 11–16.

Mah, T. L. and Halperin, D. T.: 2010b, The Evidence for the Role of Concurrent Partnerships in Africa's Epidemics: A Response to Lurie and Rosenthal, *AIDS and Behavior* **14**, pp. 25–28.

Maria, A.: 1997, Introduction to Discrete-Event System Simulation, *Prentice Hall* pp. 7–13.

Marston, M., Zaba, B., Salomon, J. A., Brahmbhatt, H. and Bagenda, D.: 2005, Estimating the Net Effect of HIV on Child Mortality in African Populations Affected by Generalized HIV Epidemics, *Journal of Acquired Immune Deficiency Syndrome* **38, Number 2**, pp. 219–227.

Mascio, M. D., Markowitz, M., Louie, M., Hogan, C., Hurley, A., Chung, C., Ho, D. D. and Perelson, A. S.: 2003, Viral Blip Dynamics during Highly Active Antiretroviral Therapy, *Journal of Virology* **77 No. 22**, pp. 12165–12172.

May, M., Boulle, A., Phiri, S., Messou, E., Myer, L., Woodf, R., Keiser, O., Sterne, J. A. C., Dabis, F. and Egger, M.: 2010, Prognosis of patients with HIV-1 infection starting antiretroviral therapy in sub-Saharan Africa: a collaborative analysis of scale-up programmes, *The Lancet* **376 Issue 9739**, pp. 449–457.

Maynard, S. J.: 1982, *Evolution and Theory of Games*, Cambridge University Press, New York.

McGrath, N., Richter, L. and Newell, M. L.: 2013, Sexual risk after HIV diagnosis: a comparison of pre-ART individuals with CD4>500 cells/μl and ART-eligible individuals in a HIV treatment and care programme in rural KwaZulu-Natal, South Africa, *Journal of the International AIDS Society* **16(1)**, p. 18048.

McKendrick, A. G.: 1926, Applications of mathematics to medical problems, *Proc. Edin. Math. Soc* **14**, pp. 98–130.

McPherson, M., Smith-Lovin, L. and Cook, J. M.: 2001, Birds of a Feather: Homophily in Social Networks, *Annual Review of Sociology* **27**, pp. 415–444.

Medical male circumcision media and information hub: 2015, MMC Programme in South Africa. Available from: http://www.mmcinfo.co.za/partners.

Mei, S., Sloot, P. M., Quax, R., Zhu, Y. and Wang, W.: 2010, Complex Agent Networks explaining the HIV epidemic among homosexual men in Amersterdam, *Mathematics and Computers in Simulation* **80(5)**, pp. 1018–1030.

Miller, C., Ketlhapile, M., Rybasack-Smith, H. and Rosen, S.: 2010, Why are antiretroviral treatment patients lost to follow-up? A qualitative study from South Africa, *Tropical Medicine and International Health* **15 Suppl. 1**, pp. 48–54.

Miller, H. G., Turner, C. F. and Moses, L. E.: 1990, *AIDS The Second Decade*, National Academy Press, Washington, D. C.

Moore, R. D. and Keruly, J. C.: 2007, CD4+ Cell Count 6 Years after Commencement of Highly Active Antiretroviral Therapy in PPerson with Strained Virologic Suppression, *HIV/AIDS* **44**, pp. –446.

Morgan, D., Mahe, C., Mayanja, B. and Whitworth, J. A. G.: 2002, Progression to symptomatic disease in people infected with HIV-1 in rural Uganda: prospective cohort study, *British Medical Journal* **324**, pp. 193–197.

Morison, L., Weiss, H. A., Buve, A., Carael, M., Abega, S.-C., Kaona, F., Kanhonou, L., Chege, J. and Hayes, R. J.: 2001, Commercial sex and the spread of HIV in four cities in sub-Saharan Africa, *AIDS* **15 Suppl 4**, pp. S61–S69.

Morris, K.: 2001, Policy and People Treating HIV in South Africa a tale of two systems, *Lancet* **Vol. 357, No.9263**.

Morris, M. and Kretzschmar, M.: 1995, Concurrent Partnerships and transmission dynamics in networks, *Social Networks* **17**, pp. 299–318.

Morris, W. L., DePaulo, B. M., Hertel, J. and Taylor, L. C.: 2008, *Singulism: Another problem than has no name: Prejudice, stereotypes, and discrimination against singles.*, Nova Science, Hauppauge, NY.

Moultrie, T. A., Sayi, T. S. and Timaeus, I. M.: 2012, Birth intervals, postponement and fertility ddecline in Africa: A new type of transition, *A Journal of Demography* **66:3**, pp. 241–258.

Mukandavire, Z., Chiyaka, C., Magombedze, G., Masuka, G. and Malunguza, N. J.: 2009, Assessing the effects of homosexuals and bisexuals on the intrinsic dynamics of HIV/AIDS in heterosexual settings, *Mathematical and Computer Modelling* **49**, pp. 1869–1882.

Mukandavire, Z., Malunguza, N. J. and Chiyaka, C.: 2010, HIV/AIDS model assessing the effects of gender-inequality affecting women in African heterosexual settings, *International Journal of Biomathematics* **3**, pp. 1–25.

Myatt, M.: 2012, How do we estimate case load for pregnant and lactating women 6 months postpartum in a given time period, Electronic. Available from: http://www.cmamforum.org/Pool/Resources/FAQ2b-Estimating-caseloadPLW-Myatt-June-2012.pdf.

Myer, L., Carter, R. J., Katyal, M., Toro, P., El-Sadr, W. M. and Abrams, E. J.: 2010, Impact of Antiretroviral Therapy on Incidence of Pregnancy among HIV-Infected Women in Sub-Saharan Africa: A Cohort Study, *PLOS Medicine* **7(2)**, p. e1000229.

NAPHSIS: 2012, Statistical Measures and Definitions. Dowloaded on 05/06/2013. Available from: https://naphsis-web.sharepoint.com/Pages/StatisticalMeasuresandDefinitions.aspx.

National Treasury: 2014, Budget 2014 Highlights. Available from: http://www.treasury.gov.za/documents.

Ndlovu, N.: 2009, Out of stock = out of life, Mail & Guardian Online. Available from: http://www.mg.co.za/article/2009-03-05-out-of-stock-life.

Neumann, J. V.: 1966, Theory of Self-Reproducing Automata, *University of Illinois Press, Urbana and London* .

news24: Downloaded 31 july 2015, Spike in SA divorce rate, Online. Available from: http://www.news24.com/SouthAfrica/News/Spike-in-SA-divorce-rate-20131103.

Nishiura, H., Yanai, H., Yoshiyama, T. and Kakehashi, M.: 2004, Simple Approximate Backcaluculation Method Applied to Estimate HIV Prevalence in Japan, *Journal of Infectious Deiseases* **57**, pp. 133–135.

Njeuhmeli, E., Forsythe, S., Reed, J., Opuni, M., Bollinger, L., Heard, N., Castor, D., Stover, J., Farley, T., Menon, V. and Hankins, C.: 2011, Voluntary Medical Male Circumcision: Modeling the Impact and Cost of Expanding Male Circumcision for HIV Prevention in Eastern and Southern Africa, *PLoS Med* **8(11)**, pp. 1–15.

North, M. J. and Macal, C. M.: 2007, *Managing Business Complexity: Discovering Strategic Solutions with Agent-Based Modeling and Simulation*, Oxford university Press, New York.

Odell, J., Parunak, H. V. D., Fleischer, M. and Brueckner, S.: 2003, Modeling Agents and Their Environment, *F Giunchiglia et al. (eds), Agent Oriented Software Engineering VII* **Lecture Notes in Computer Science 2585**, pp. 16–31.

Orcutt, G.: 1957, A new type of socio-economic system, *Review of Economics and Statistics* **58**, pp. 773–797.

Orroth, K. K., Freeman, E. E., Bakker, R., Buve, A., Glynn, J. R., Boily, M. C., White, R. G., Habbema, J. D. and Hayes, R. J.: 2007, Understanding the differences between contrasting HIV epidemics in east and west Africa: results from a simulation model of the Four Cities Study, *Sexually Transmitted Diseases* **83 Supplementary 1**, pp. i5–16.

O.Shisana and Simbayi, L. C.: 2002, Nelson Mandela/HSRC Study of HIV/AIDS. Available from: http://www.hsrc.ac.za/en/research-data/view/66.

Overy, N.: 2011, In the Face of Crisis: The Treatment Action Campaign Fights Government Inertia with Budget Advocacy and Litigation, *International Budget Partnership* **Study No 7**, pp. 1–14.

Palamuleni, M. E.: 2010, Recent Marriage patterns in South Africa 1996-2007, *Bangladesh e-Journal of Sociology* **7 Number 1**, pp. 47–70.

Palella, F. J., Kathleen, J. M. D., Delaney, M., Anne, M. S., Moorman, A. C. and et al.: 1998, Declining morbidity and mortality among patients with advanced human immunodeficiency virus infection, *Journal of Medicine* **338(13)**, pp. 853–860.

Parker, W., Makhubele, B., Ntlabati, P. and Connolly, C.: 2007, *Concurrent sexual partnerships amongst young adults in South Africa*, Centre for AIDS Development, Research and Evaluation (CADRE). Available from: http://jhhesa.org/sites/default/files/CADRE%20MCP%20study%20final%20version_0.pdf.

Peberdy, S., Crush, J. and Msibi, N.: 2004, Migrants in the city of Johannesburg, *Southern African Migration Project* . Available from: http://www.joburg-archive.co.za/corporate_planning/migrants.pdf.

Peltzer, K., Nqeketo, A., Petros, G. and Kanta, X.: 2008, Traditional circumcision during manhood initiation rituals in the Eastern Cape, South Africa: a pre-post intervention evaluation, *BMC Public Health* pp. 1–15.

Perez, L. and Dragicevic, S.: 2009, An Agent-based Approach for Modelling Dynamics of Contagious Disease Spread, *International Journal of Health Geographics* **8**, p. 50.

Perrin, D., Ruskin, H. J. and Crane, M.: 2008, An Agent-Based Approach to Immune Modelling: Priming Individual Response, *World Academy of Science, Engineering and Technology* **17**, pp. 80–86.

Pesavento, U.: 1995, An implementation of von Neumann's self-reproducing machine.

Pettifor, A. E., Maesham, D. M., Rees, H. V. and Padian, N. S.: 2004, Sexual power and HIV risk, South Africa, *Emerging Infectious Diseases* **10**, pp. 1996–2204.

Posel, D. and Rudwick, S.: 2013, Changing patterns of marriage and cohabitation in South Africa, *Acta Juridica* **13**, pp. 169–180.

Quinn, T. C.: 1994, Population migration and the spread of types1 and 2 human immunodeficiency viruses, *Proc. Natl. Acad. Sci. USA* **91**, pp. 2407–2414.

Ramashwar, S.: 2012, Remarriage, HIV Infection Linked Among Women In Sub--Saharan Africa, *International Perspectives on Sexual and Reproductive Health* **38**, pp. 113–114.

Ramerini, M.: 2010, The Dutch in South Africa 1652-1795 1802-1806, Electronic. Available from: http://colonialvoyage.com/SouthAfrica.html.

Ramjee, G., Gouws, E., Dyke, E. V., Williams, B. and Karim, S. A.: 2002, Herpes simplex virus type II infection is a risk factor for HIV seroconversion, *In Medical*

Research Council Policy Brief, Durban, South Africa **3**. Available from: http://www.mrc.ac.za/policybriefs/simplexherpesbook.pdf.

Rao, A. S. R. S. and Kakehashi, R.: 2005, Incubation-Time Distribution in Back-Calculation Applied to HIV/AIDS Data in India, *Mathematical Biosciences and Engineering* **2(2)**, pp. 263–277.

Rauner, M. S.: 2005, Use of Discrete-Event Simulation to evaluate strategies for the Prevention of Mother-to-Child Transmission of HIV in Developing Countries, *Journal of Operational Research Society* **56**, pp. 222–223.

Rech, D., Spyrelis, A., Frade, S., Perry, L., Farrell, M., Fertziger, R., Toledo, C., Castor, D., Njeuhmeli, E., Loykissoonlal, D. and Bertrand, J. T.: 2014, Implications of the Fast-Evolving Scale-Up of Adult Voluntary Medical Male Circumcision for Quality of Services in South Africa, *PLoS One* **9(5)**, pp. 1–10.

Rees, A.: 1997, *Consumer Health USA*, The Oryx Press, Phoenix, Arizona.

Renaud-Thery, F., Duncombe, C., Kerr, S., Thierry, S. and Perriens, J.: 2010, Adult antiretroviral therapy in resource limited settings: a systematic review of first-line failure and attrition rates, *In 17th Conference on Retroviruses and Opportunistic Infections* .

Rhee, A.: 2006, An Agent-based approach to HIV/AIDS modelling: A case study of Papua New Guinea, *Master of Science thesis, Massachusetts Institute of Technology* .

Rhodes, C. and Anderson, R. M.: 1996, Persistence and dynamics in lattice models of epidemic spread, *Journal of Theoretical Biology* **180**, pp. 125–133.

Rhodes, C. J. and Anderson, R. M.: 1997, Epidemic thresholds and vaccination in a lattice model of disease spread, *Theoretical Population Biology* **52**, pp. 101–118.

Richter, M.: 2003, Traditional Medicines and Traditional Healers in South Africa, *Discussion paper prepared for the Treatment Action Campaign and AIDS Law Project* .

Richter, M., Chersich, M., Temmerman, M. and Luchters, S.: 2013, Characteristics, sexual behaviour and risk factor of female, male and transgender sex workers in south Africa, *South African Medical Journal* **103 No. 4**, pp. 246–251.

Richter, M., Luchters, S., Ndlovu, D., Temmerman, M. and Chersich, M. F.: 2012, Female sex work and international sport events - no major changes in demand or supply of paid sex during the 2010 Soccer World Cup: a cross-sectional study, *BMC Public Health* **12**, pp. 763–775.

Robertson, D. L., Anderson, J. P., Bradac, J. A., Carr, J. K., Foley, B. and et. al.: 2000, HIV-1 Nomenclature Proposal, *Science* **288**, pp. 55–65.

Robin, R. and Alessandra, B.: 2007, Realising their rights? Self-assessed community needs in 30 settlements in South Africa. Available from: www.economicswebinstitute.org/essays/communityneeds.htm.

Rosen, S., Fox, M. P. and Gill, C. J.: 2007, Patient Retention in Antiretroviral Therapy Programs in Sub-Saharan Africa: A Systematic Review, *Ploss Med* **4(10)**, pp. 1691–1701.

Rosenberg, P. S.: 2006, Backcalculation models of age-specific HIV incidence rates, *Statistics in Medicine* **13**, pp. 1975–1990.

Ross, R.: 1911, *The prevention of Malaria*, E. P. Dutton & Company, New York.

Rothenberg, R. B., Long, D. M., Sterk, C. E., Pach, A., Poterat, J. J., Muth, S., Baldwin, J. A. and III, R. T. T.: 2000, The Atlanta Urban Networks Study: a bluprint for endemic transmission, *AIDS* **14**, pp. 2191–2200.

Rottingen, J. A., Cameron, D. W. and Garnett, G. P.: 2001, A systematic review of the epidemiologic interactions between classic sexually transmitted diseases and HIV: how much really is known?, *Sexually Transmitted Diseases* **28**, pp. 579–597.

Rule, S. and Mncwango, B.: 2006, *Rights of wrongs? An explanation of moral values*, HSRC Press, Chapter 12, pp. 252–276.

SADC Secretariat: 2008, Regional Economic Integration: A Strategy for Poverty Eradication Towards Sustainable Development, *SADC International Conference on Poverty & Development*.

SADHS: 2003, South African Demographic and Health survey, *Department of Health* . Available from: https://dhsprogram.com/pubs/pdf/FR206/FR206.pdf.

SAHO: 2010a, People of South Africa, Electronic. Available from: http://www.sahistory.org.za/article/people-south-africa-ndebele.

SAHO: 2010b, South Africa and its Culture. Available from: http://www.sahistory.org.za/topic/defining-culture-heritage-and-identity.

Samuelson, D. A. and Macal, C. M.: 2006, Agent-Based Simulation Comes of Age, *Institute for Operations Research and the Management Sciences* **33(4)**, pp. 34–38.

Santos, R. M. and Coutinho, S.: 2001, Dynamics of HIV Infection: A Cellular Automata Approach, *Physical Review Letters* **87**, 168102: pp. 1–4.

Sawers, L. and Stillwaggon, E.: 2010, Concurrent Sexual partnerships do not explain the HIV epidemics in Africa: a systematic review of the evidence, *Journal of the International AIDS Society* **13**, pp. 1–23.

Schelling, T. C.: 1978, *Micromotives and Macrobehaviour*, W. W. Norton, New York.

Schmid, G. P., Buve, A., Mugyenyi, P., Garnett, G. P., Hayes, R. J., Williams, B. G., Calleja, J. G., Cock, K. M. D., Whitworth, J. A., Kapiga, S. H., Ghys, P. D., Hankins, C., Zaba, B., Heimer, R. and Boerma, J. T.: 2004, Transmission of HIV-1 infection in sub-Saharan Africa and effect of elimination of unsafe injections, *Lancert* **363(9407)**, pp. 482–488.

Scorgie, F., Chersich, F., Ntaganira, I., Gerbase, A., Lule, F. and Lo, Y.-R.: 2012, Socio-demographic characteristics and behavioral risk factor of female sex workers in sub-Saharan Africa: a systematic review., *AIDS Behaviour* **16(4)**, pp. 920–933.

Selikow, T., Zulu, B. and Cedras, E.: 2004, "We have our own special language'. Language sexuality and HIV/AIDS: A case study of youth in an urban township in South Africa., *African Health Sciences* **4(2)**, pp. 102–108.

Sharp, E. A. and Ganong, L.: 2011, "I'm a Loser, I'm Not Married, Let's Just All Look at Me": Ever-Single Women's Perceptions of Their Social Environment, *Journal of Familiy Issues* **32**, pp. 956–979.

Shelton, J. D., Halperin, D. T., Nantulya, V., Potts, M., Gayle, H. D. and Holmes, K. K.: 2004, Partner reduction is crucial for balanced ABC approach to HIV prevention, *British Medical Journal* **328**, pp. 891–893.

Sherman, R. and Steyn, M.: 2009, *E-racing the line: South African interracial relationships: Yesterday and today*, Human Sciences Research Council, South Africa.

Shisana, O. and Simbayi, L.: 2002, Nelson Mandela HSRC Study of HIV/AIDS: Full Report South African national HIV prevalence, behavioural risks and mass media. Household survey 2002. Available from: http://www.hsrc.ac.za/en/research-data/view/66.

Simao, J. and Todd, P.: 2003, Emergent Patterns of Mate Choice in Human Populations, *Artificial Life* **9**, pp. 403–417.

Simao, J. and Todd, P. M.: 2002, Modeling mate choice in monogamous mating systems with courtship, *Adaptive Behavior* **10**, pp. 1–24.

Simelela, N. P. and Venter, W. D. F.: 2014, A brief history of South Africa's response to AIDS, *South African Medical Journal* **104**, pp.249–251.

Simon, H.: 1957, *Administrative behaviour : A study of decision-making processes in administrative organisation*, Macmillan Press, New York.

Smith, R. J. and Blower, S. M.: 2004, Could disease-modifying HIV vaccines cause population level perversity?, *Lancet Infectious Diseases* **4**, pp. 636–639.

South African Government Information: 2009, *Key facts of the National Communication Survey on HIV/AIDS, 2009*, South African Government Information. Available from: http://www.politicsweb.co.za/news-and-analysis/nc-survey-on-hivaids-the-key-facts.

South African History Online (SAHO): 2010, People of South Africa, Online. accessed on 17 August 2010. Available from: http://www.sahistory.org.za/article/people-south-africa-ndebele.

South African National AIDS Council (SANAC): 2013, *National Strategic Plan for HIV Prevention, Care and Treatment fof Sex Workers*, South African National AIDS Council. Available from: http://www.sanac.org.za/resources/cat_view/7-publications/9-reports.

Statistics South Africa (StatsSA): 2010, *Mid-year population estimates, 2010*, Statistics South Africa. Available from: http://www.statssa.gov.za/publications/P0302/P03022010.pdf.

StatsSA: 2002, *Mid-year estimates 2002*, Statistics South Africa. Available from: http://www.statssa.gov.za/publications/P0302/P03022002.pdf.

StatsSA: 2003, *South African Demographic and Health Survey SADHS 2003*. Available from: https://dhsprogram.com/pubs/pdf/FR206/FR206.pdf.

StatsSA: 2004, *Census 2001: Primary tables South Africa Census 1996 and 2001 compared*, Statistics South Africa. Available from: http://www.statssa.gov.za/?page_id=5107.

StatsSA: 2010a, *Marriages and divorces*, Statistics South Africa. Available from: http://www.statssa.gov.za/publications/P0307/P03072010.pdf.

StatsSA: 2010b, *Mid-year population estimates, 2010*, Statistics South Africa. Available from: http://www.statssa.gov.za/publications/P0302/P03022010.pdf.

StatsSA: 2011, *Gender statistics in South Africa, 2011.* Available from: http://www.statssa.gov.za/publications/Report-03-10-05/Report-03-10-052011.pdf.

StatsSA: 2012, *Marriages and divorces*, Statistics South Africa. Available from: http://www.statssa.gov.za/publications/P0307/P03072011.pdf.

StatsSA: 2013, *Mid-year population estimates*, Statistics South Africa. Available from: http://www.statssa.gov.za/publications/P0302/P03022013.pdf.

Sternberg, R. J.: 1986, A Triangular Theory of Love, *Psychological Review* **93**, pp. 119 – 135.

Stover, J.: 2004, Projecting the demographic consequences of adult HIV prevalence trends: the Spectrum Projection Package., *Sex Transm Infect* **80**, pp. i14–i18.

Stover, J., Brown, T. and Marston, M.: 2012, Updates to the Spectrum/Estimation and Projection Package (EPP) model to estimate HIV trends for adults and children., *Sex Transm Infect* **88**, pp. i11–i16.

Suiming, P., William, L. and Huang, Y.: 2011, Clients of Female Sex Workers: A population-Based Survey of China., *Journal of Infectious Diseases* **204 (Suppl 5)**, pp. S1211–S1217.

Sumodhee, C., Hsieh, J., Sun, C. T. and Huang, C. Y.: 2005, Impact of Social Behaviors on HIV epidemic: A computer Simulation View, *Proceedings of the 2005 International Conference on Computational Intelligence for Modelling, Control and Automation,* pp. 550–556.

Swanepoel, P.: 2005, Stemming the HIV/AIDS epidemic in South Africa: Are our HIV campaigns failing us?, *Communicatio* **31:1**, pp. 61–93.

Tan, W. Y.: 2000, *STOCHASTIC MODELING of AIDS EPIDEMIOLOGY and HIV PATHOGENESIS*, World Scientific Publishing, Singapore.

Tawfik, A. Y. and Farag, R.: 2008, Modeling the Spread of Preventable Diseases: Social Culture and Epidemiology, *IFIP International Federation for Information Processing; Artificial Intelligence and Practice II; Max Bramer; (Boston: Springer)* **276**, pp. 277–286.

Tay, J. C. and Jhavar, A.: 2005, A complex adaptive framework for immune system simulation, *Proceedings of the 2005 ACM Symposium on Applied Computing (SAC'05), Santa Fe, New Mexico.* pp. 158–164.

Teweldemedhin, E., Marwala, T. and Mueller, C.: 2004, Agent-based Modelling: A case study in HIV epidemic, *Proceedings of the fourth international conference on Hybrid Intelligent Systems* .

Timaeus, I. M. and Moultrie, A.: 2008, On postponement and birth Intervals, *Population and Development Review* .

Tobian, A. A., Serwadda, D., Quinn, T. C., Kigozi, G., Gravitt, P. E., Laeyendecker, O., Charvat, B., Ssempijja, V., Riedesel, M., Oliver, A. E., Moulton, R. G., Chen, M. Z., Reynolds, S. J., Waver, M. J. and Gray, R. H.: 2009, Male circumcision for the prevention of HSV-2 and HPV infections and syphilis., **360(13)**, 1298–309.

Todd, J., Glynn, J. R., Marston, M. and et al.: 2007, Time from HIV seroconversion to death: a collaborative analysis of eight studies in six low and middle-income countries before highly active antiretroviral therapy, *AIDS* **Suppl 6**, pp. S55–63.

Torpey, K., Mandala, J., Kasonde, P., Bryan-Mofya, G., Bweupe, M., Mukundu, J., Zimba, C., Mwale, C., Lumano, H. and Welsh, M.: 2012, Analysis of HIV Early Infant Diagnosis Data to Estimate Rates of Perinatal HIV Transmission in Zambia, *PLoS One* **7(8)**, p. e42859.

Treatment Action Campaign (TAC): 2001, Treatment Action Campaign: An overview. Available from: http://www.tac.org.za/Documents/Other/tachist.pdf.

Ueda, H., Iwaya, Y., Abe, T. and Kinoshita, T.: 2004, A cellular automata model considering diversity associated with HIV infection, *Artificial Life and Robotics* **10**, pp. 73–76.

UNAIDS: 2001, Regional Workshop on Situation Analysis of Sex Work in West and Central Africa. Available from: http://www.who.int/hiv/topics/vct/sw_toolkit/workshop_on_situation_analysis_sex_work.pdf.

UNAIDS: 2010, Methods for estimating HIV incidence. Available from: http://www.unaids.org/sites/default/files/media_asset/epi_alert_1stqtr2010_en_0.pdf.

UNAIDS: 2013, AIDSinfo Epidemiological Status. Available from: http://aidsinfo.unaids.org/.

UNAIDS/WHO: 2009, 2009 AIDS epidemic update. Available from: http://data.unaids.org/pub/Report/2009/JC1700_Epi_Update_2009_en.pdf.

Van der Ploeg, P. B., Van Vliet, C., Vlas, S. J. D., Ndinya-Achola, J. O., Fransen, L., Oortmarssen, G. J. V. and Habbema, J. D. F.: 1998, STDSIM: A Microsimulation Model for Decision Support in STD Control, *Interfaces* **28 No. 3**, pp. 84–100.

Van Der Vliet, V.: 2004, South Africa divided against AIDS: A crisis of leadership, *In K. Kauffman & D. Lindauer (eds) AIDS and South Africa: The Social Expression of a Pandemic, London, Palgrave Macmillan* pp. pp. 48–96.

van Vliet, C., Meester, E. I., Korenromp, E. L., Singer, B., Bakker, R. and Habbema, J. D. F.: 2001, Focusing strategies of condom use against HIV in different behavioural settings: an evaluation based on a simulation model, *Bulletin of the World Health Organization* **79(5)**, pp. 442–454.

Venkatachalam, S. and Mikler, A. R.: 2005, Towards Computational Epidemiology: Using Stochastic Cellular Automata in modeling spread of diseases, *Proceedings of the International Conference on Innovative Internet Community Systems* .

Vergne, L., Malonga-Mouellet, G., Mistoul, I., Mavoungou, R., Mansaray, H., Peeters, M. and Delaporte, E.: 2002, Resistance to antiretroviral treatment in Garbon: need for implementation of guidelines on antiretroviral therapy use and HIV-1 drug resistance monitoring in developing countries, *Journal of Acquired Immune Deficiency Syndrome* **29**, pp. 165–168.

Vernazza, P. L., Eron, J. J., Fiscus, S. A. and Cohen, M. S.: 1999, Sexual transmission of HIV: infectiousness and prevention, *AIDS* **13**, pp. 155–166.

Waver, M. J., Gray, R. H., Sewankambo, N. K. and et. al.: 2005, Rates of HIV-1 Transmission per Coital Act, by Stage of HIV-1 Infection, in Rakai, Uganda, *Journal of Infectious Diseases* **191**, pp. 1403–1409.

Wayne, N.: 1982, *Applied Life Data Analysis*, John Wiley & Sons, Inc., New York.

Weiss, H. A., Buve, A., Robinson, N. J., Dyck, E. V., Kahindo, M. and et al.: 2001, The epidemiology of HSV-2 infection and its association with HIV infection in four urban African populations, *AIDS* **15 (suppl)**, pp. S97–S108.

Weiss, H. A., Thomas, S. L., Munabi, S. K. and Hayes, R. J.: 2006, Male circumcision and risk of syphilis, chancroid, and genital herpes: a systematic review and meta-analysis.

Weller, S. C. and Davis-Beaty, K.: 2002, Condom effectiveness in reducing heterosexual HIV transmission, *Cochrane Database Systematic Reviews 2002* **Issue 1**, CD003255.

Wellings, K., Collumbien, M., Slaymaker, E., Singh, S., Zoe, H., Patel, D. and Bajos, N.: 2006, Sexual behaviour in context: a global perspective, *Lancert* **368**, pp. 1706–1728.

White, S. H., del Rey, A. M. and Sanchez, G. R.: 2007, Modelling epidemics using cellular automata, *Applied Mathematics and Computation* **186**, pp. 193–202.

WHO: 2003a, Expert group stresses that unsafe sex is primary mode of transmission of HIV in Africa. Available from: http://www.who.int/mediacentre/news/statements/2003/statement5/en/.

WHO: 2003b, Scaling up antiretroviral therapy in resource-limited settings: Threatment guidelines for a public health approach. Available from: http://www.who.int/3by5/publications/documents/arv_guidelines/en/.

WHO: 2005, Interim WHO Clinical Staging of HIV/AIDS and HIV/AIDS case Definition for Surveillance. Available from: http://www.who.int/entity/hiv/pub/guidelines/clinicalstaging.pdf?ua=1.

WHO: 2007, 2007 Tuberculosis facts. Available from: http://www.who.int/tb/publications/2007/factsheet_2007.pdf.

WHO: 2009, World Health Statistics 2009. Available from: http://www.who.int/gho/publications/world_health_statistics/EN_WHS09_Full.pdf.

WHO: 2010, Facts at a glance. Available from: http://www.who.int/tb/publications/factsheets/en/.

WHO: 2014, HIV/AIDS key facts, Electonically. Available from: http://www.who.int/mediacentre/factsheets.

WHO: May 2015, Consolidated strategic information guidelines for HIV in the health sector. Available from: http://who.int/hiv/pub/guidelines/strategic-information-guidelines/en/.

Williams, B. G., Korenromp, E. L., Gouws, E., Schmid, G. P., Auvert, B. and Dye, C.: 2006, HIV infection, antiretroviral therapy, and CD4+ cell count distributions in African populations, *Journal of Infectious Diseases* **194(10)**, pp. 1450–1458.

Williams, B., Gilgen, D., Campbell, C., Taljaard, D. and MacPhail, C.: 2000, The Natural History of HIV/AIDS in South Africa: A biomedical and social survey in Carletonville, *Technical report*, Council for Scientific and Industrial Research

(CSIR). Available from: http://eprints.lse.ac.uk/20498/1/The_natural_history_of_HIV-AIDS_in_South_Africa.pdf.

Williams, M.: 1999, *Science and Scocial Science: An introduction*, Psychology Press, London, New York.

Wilson, B. and Smallwood, S.: 2008, Age differences at marriage and divorce, *Office for National Statistics* **Summer 2008**, pp. 17–25.

Wojcicki, J. M. and Malala, J.: 2001, Condom use, power and HIV/AIDS risk: sex-workers bargain for survival in Hillbrow/Joubert Park/Berea, Johannesburg, *Social Science & Medicine* **53**, pp. 99–121.

Wolfram, S.: 1984, Universality and Complexity in Cellular Automata, *Physica 10D* pp. 1–35.

Wooldridge, M.: 2002, *An Introduction to Multi-Agent Systems*, John Wiley and Sons Limited, United Kingdom, West Sussex.

Worobey, M., Gemmel, M., Teuwen, D. E., Haselkorn, T., Keunstman, K., Bunce, M., Muyembe, J., Kabongo, J. M., Kalengayi, R. M., Marck, E. V., Gilbert, M. T. P. and Wolinsky, S. M.: 2008, Direct evidence of extensive diversity of HIV-1 in Kinshasa by 1960, *Nature* **455**, pp. 661–664.

Wrzus, C., Hanel, M., Wagner, J. and Neyer, F. J.: 2012, Social Network Changes and Life Events Across the Lifespan: A Meta-Analysis, *Phychological Bulletin* **139(1)**, pp. 53–80.

Wu, H. and Tan, W. Y.: 2000, Modelling the HIV Epidemic: A state-Space Approach, *Mathematical and Computer Modelling* **32**, pp. 197–215.

Wuensche, A.: 1999, Classifying Cellular Automata Automatically, *Complexity* **4(3)**, pp. 47–66.

Xiang, L., Zheng, W. and Xiang, C.: 2009, Modelling Immune System: Principles, Models, Analysis and Perspectives, *Journal of Bionic Engineering* **6**, pp. 77–85.

Xuan, H., Xu, L. and Li, L.: 2009, A CA-based epidemic model for HIV/AIDS transmission with heterogeneity, *Ann. oper. Res* **168**, pp. 81–99.

Young, P. H.: 1998, *Individual Strategy and Social Structure: An Evolutionary Theory of Institutions*, Princeton University Press, New Jersey.

Index