Supplemental Digital Content - Appendix 1

1. Approach

We developed a behaviourally-complex, dynamic, mathematical model of heterosexual HIV transmission using a compartmental, deterministic framework. We used the model to generate 1,000 **synthetic epidemics** that were driven by commercial sex work (CSW), and based on the best available data from each of West/Central Africa (WCA). These simulations were used to determine the maximum epidemic size of each epidemic and to estimate the population attributable fraction (PAF) of SW to cumulative new HIV infections acquired in the total population.

To ensure that the simulated synthetic epidemics were plausible, we comprehensively reviewed and extracted behavioral (including condom-use), HIV and HSV-2 prevalence data for sex work and other sexual partnerships in WCA. Because most HIV programmes are implemented at the province or state level (usually with adult population size >250,000-500,000), we extracted data at the sub national level where available to more adequately capture heterogeneity between locales. In the Appendix, we first describe the data sources and syntheses for parameters specific to WCA. We then describe the model development and parameterization. We differentiate SW from transactional sex, where the transactional sex refers to financially-motivated partnerships defined as 'sex in exchange for gifts/goods but not money' from any study or 'sex in exchange for gifts/goods or money' from general population surveys. It has been suggested that 'sex in exchange for gifts/goods or money' from general population surveys may be conflating non-commercial, financially motivated partnerships (with smaller partner change rates) with commercial sex (which usually have large partner change rates) [1-3]. Thus, to be as specific as possible when extracting data on sex work, we categorized data on 'sex in exchange for gifts/goods or money' from general population surveys as data on transactional sex.

2. Data Syntheses: Parameters and HIV prevalence data for model constraints

We performed a 3-stage, comprehensive data syntheses to extract parameter values in the two main domains (biological [such as male circumcision and HSV-2 prevalence]; sexual behaviour). Wherever possible, the data or estimates were extracted at the sub national level. The first stage involved an expansion of a systematic review conducted previously and described in Box A1 [4]. Stage 1 was performed to obtain data on sexual behaviour within commercial sex, HSV-2 and HIV prevalence on FSWs from 1985 onwards. The second stage involved extraction of raw data from the demographic health surveys (DHS [5]) to obtain sexual behaviour data on non-commercial partnerships. The third part involved a grey literature search from the UNAIDS country reports for data on overall HIV prevalence across provinces/states and for reports on ‘non-commercial’ multiple partnerships, supplemented by drawing from published systematic reviews of parameters relevant non-commercial partnerships and populations. Tables A.1-A.3 show the parameters extracted from the above steps. Parameters which we assumed were not region-specific (such as the biological transmission probability of HIV per sex act, HIV progression, and population growth rates) were drawn from the literature.

Stage 1: Expanded review on commercial and transactional sex data

We previously systematically reviewed FSW/client population size and HIV prevalence in Sub-Saharan Africa from 2002 onwards [4]. For this study, we expanded the systematic review to more widely define the range of plausible and measured parameter values and FSW HIV prevalence reported from empirical studies of commercial sex. We searched Medline, EMBASE, PsycInfo, and Scopus, for peer-reviewed publications from January 1, 1985 to October 31, 2013, using the following terms in all fields: (“sex work* OR “commercial sex*” OR “paid sex*” OR prostitute* OR client*” or “transact* sex”) AND “(Afric* or [name of each of the 24 WCA countries, Box A.1]. A grey literature search was also conducted and included bibliographic search of reports, grey literature publication database searches, and searching previously published systematic reviews. The details of the grey literature search are described elsewhere [4]. We also contacted the primary authors of reports identified in the bibliographic search of the grey literature (including, but not restricted to, the UNGASS Country Progress Reports [6], and the World Bank West Africa Synthesis [7]) to obtain the source records if they could not be obtained from the grey or peer-review search.

Box A.1. Search terms for electronic database.

Search terms used in Scopus
ALL("sex work*" OR "prostitut*" OR "paid sex*" OR "commercial sex*" OR "client" OR “transact*”) AND ALL("afric*" OR "angola" OR "benin" OR "burkina faso" OR "Cameroon" OR "Cameroun" OR "Cape Verde" OR "Cabo Verde" OR "Central African Republic" OR "Republique Centrafricaine" OR "Chad" OR "Tchad" OR "Congo" OR "ivory coast" OR "Cote d'Ivoire" OR "Gabon" OR "Gabonaise" OR "Gambia" OR "Ghana" OR "Guinea" OR "Guinee" OR "Guinea-Bissau" OR " Guinee-Bissau" OR "Namibia" OR "Niger" OR "Nigeria" OR "Sao Tome and Principe" OR "Senegal" OR "Sierra Leone" OR "Liberia" OR "Mali" OR "Mauritan*" OR "Togo" OR "Togolaise")

We included all published studies and grey literature with data on HIV prevalence in FSWs or clients of FSWs (irrespective of the denominator) as long as the prevalence was determined via biological sampling (and not self-reported HIV status). For sexual behaviour data, we included studies on FSWs and women classified as engaging in non-commercial transactional sex (for transactional sex partnership parameters), and studies on clients. A total of 7,436 unique records were identified, of which 2,113 were assessed at the full-text stage, and 493 sources (including the 213 sources summarized from the previous review[4]) provided HIV prevalence data on FSWs and/or behavioural data on commercial sex as reported by FSWs and/or clients. We extracted the following data to inform model parameters:

- FSW population size (% of adult females) based on non-survey methods of enumerating FSWs
- Proportion reporting transactional sex (exchange of money and/or gifts in exchange for sex) (females, males excluding 'clients' identified by the indirect method or who report sex with FSWs)
- mean or median number of client encounters (visits) per unit time (day, week, or month, as provided) and % are with repeat/regular clients (FSWs only)
- mean or median number of FSW encounters (visits) per unit time (day, week, or month, as provided) and % that are with repeat/regular FSWs (clients only)
- % of clients who visit same FSW regularly
- % of FSWs who have repeat clients
- Number of repeat visits to same FSW per unit time (clients only)
- mean or median number of non-commercial casual partners in the provided unit of time (FSWs, clients)
- % of with main (spouse or other long-term) partner in the last year (FSWs, clients)
- condom-use (at last sex or 'always' over the provided period of time) by partnership type (occasional client, any client, regular client, or any non-commercial partner [including spouse])
- HSV-2 prevalence (clients, FSWs)
- Duration in sex work (median, mean) (FSWs, clients)
- HIV-prevalence among FSWs

Stage 2: Non-commercial sex data from demographic health surveys

The second stage involved extraction of sexual behaviour data on the 'general population' across SSA, including those involved in non-commercial multiple partnerships – main, casual, or non-commercial but financially-motivated (transactional). We extracted raw data from the DHS for WCA countries (a total of 27 surveys) for every survey round from which sexual behaviour data were available. We extracted data by sub-region (province or state, as defined by the survey team) and used the sampling weights provided. Because we used the point estimates (and not the variance) for the model inputs and cross-checks, we did not adjust for potential clustering resulting from how some surveys sampled households and neighbourhoods. We extracted the following DHS data to inform model parameters:

- Mean number of sex acts / year in a main partnership defined by the respondent as spousal, cohabitating, or as girlfriend/boyfriend/lover (reported by sexually active males and females for the last 3 partners)
- Mean number of sex acts / year in a non-main partnership (reported by sexually active males and females for the last 3 partners, and excluding partnerships defined as those with an FSW)
- Mean number of main partners in the last year among those with ≥1 main partner (reported by sexually active males and females)
- Proportion who report >1 non-main partner in the last year (denominator = sexually active males, females)
- Proportion of those with ≤1 non-main partners who report ≥1 main partner in the last year (denominator = sexually active males, females), stratified by age-group (>24 and ≤24 years of age)
- Proportion of those with >1 non-main partner, who report ≥1 main partner in the last year (denominator = sexually active males, females), stratified by (>24 and ≤24 years of age)
- Mean number of non-main partners in the last year among those who report >1 non-main partners in the last year [excluding partners referred to as FSWs] (reported by sexually active males, and females who did not report paid sex in the last year)
- Ratio of mean number of non-main partners reported by the top decile of those with >1 non-main partners in the last year, to the bottom 90% of those with >1 non-main partners in the last year (sexually active males, females; excluding partners referred to as FSWs and excluding female respondents who reported paid sex in the last year)
- Proportion who used a male condom at last sex by partner type (main, non-main, commercial) and by year of the survey (denominator = sexually active males and females who reported ≥1 of any of a main, non-main, or commercial partnership in the last year)
- Proportion with >1 non-main partners reporting transactional sex (exchange of money and/or gifts for sex [excluding sex with FSWs]) in the last year

- Proportion of females between 15-24 years of age who had sex at least one male partner >10 years older in the last year
- Overall HIV prevalence among sexually active adults by sub national region (as specified in the DHS)
- HIV prevalence among women between 15-24 years of age by sub national region (as specified in the DHS)

Stage 3: UNAIDS reports and published systematic reviews for remaining non-commercial sex parameters

We reviewed the UNAIDS country reports (2004, 2008, 2010, and 2012) from WCA to extract HIV prevalence data by sub national region, including surveillance data from antenatal clinics (ANC), by year of data collection from 1990 onwards. We reviewed published systematic reviews for data on HSV-2 in the general and non-commercial high-risk groups (those with multiple partners or attending STI clinics) [8-10].

Table A1. Biological parameters

Data inputs for parameter range				Model Input Range
Definition	**Model assumption**	**Sources**	**Notes**	
% of males circumcised	Stable over time	DHS	Most recent DHS (after 2002); self-reported	30-98
HSV-2 prevalence among low-risk females (%)	Stable over time	Published systematic reviews [8-10]	Low-risk excludes FSWs and other high-risk females (>1 partner in last year[1])	13-26
Ratio of HSV-2 prevalence among females vs. males (all risk-groups)	Stable over time	Published systematic reviews [8-10]	Estimated using the same province/stage wherever possible	1.5-5.6
Ratio of HSV-2 prevalence among FSWs vs. low-risk females	Stable over time	Systematic review	Estimated using the same province/stage wherever possible	1.1-4.4
Ratio of HSV-2 prevalence among >24 years vs. those ≤24 years of age	Stable over time	Published systematic reviews [8-10]	Estimated using the same province/stage wherever possible	1.3-7.8
Ratio of HSV-2 prevalence among non-commercial high-risk women/men to low-risk women	Stable over time Same for clients (no HSV-2 data on clients)	Published systematic reviews [8-10]	Estimated using the same province/stage wherever possible; High-risk refers to >1 partner in last year[1]	1.3-2.8

WCA (West and Central Africa); DHS (demographic health surveys [5]) [1]or sexually transmitted infection (STI) clinic attendees

[1] HSV-2 prevalence shown, not ratio

Table A2. Sexual behaviour parameters for casual, transactional, and main partnerships

Data inputs for parameter range			Input Range
Definition	**Model assumption**	**Source**	
# of casual partners/year	Assigned to males who have >1 casual sex partner/year (MP group); estimated for females to balance casual partnerships	DHS: Mean number of sex acts / year in a non-main partnership (reported by sexually active males and females for the last 3 partners, and excluding partnerships defined as those with an FSW)	2-4.9
Ratio, casual partners/year in the top decile vs. bottom 90%	Used to estimate the number of casual/partners per year in the low-frequency and high-frequency MP group in the model (Section 4.2.3)	DHS: Ratio of mean number of non-main partners reported by the top decile of those with >1 non-main partners in the last year, to the bottom 90% of those with >1 non-main partners in the last year (sexually active males, females; excluding partners referred to as FSWs and excluding female respondents who reported paid sex in the last year)	1.5-13.3
% of males with >1 casual partners/year	Used to define the % of males who enter the MP class; the same fraction of clients are assumed to engage in casual sex	DHS: % of females aged 15–49 who have had sexual intercourse with >1 non-main partner in the last 12 months (denominator = sexually active in last 1 year)	8-32
Ratio of females to males who enter the MP class	The same fraction of FSWs are assumed to engage in casual sex	DHS: % of males aged 15–49 who have had sexual intercourse with more than one non-main partner in the last 12 months (denominator = sexually active in last 1 year)	0.01-0.47
% of young females with partners >10 y older	Translated to % of a young female' casual, transactional or main partnerships that formed with a male >10 years older than her	DHS: % of females between 15-24 years of age who had sex at least one male partner >10 years older in the last year	0--56

MP (multiple partnership group; FSW (female sex worker); DHS (demographic health surveys [5])

[1] shown as % of females with >1 casual partners/year

Table A2 continued. Sexual behaviour parameters for casual, transactional, and main partnerships

Data inputs for parameter range			Input Range
Definition	**Model assumption**	**Source**	
# of sex acts/year in a casual partnership		DHS	8.3-26
# of sex acts/year in a main partnership		DHS	12-88
# of sex acts/year in a transactional partnership		Studies reporting TS [2,11-16]. Because few data available, input range drawn from # casual sex acts/year	8.3-26
# of main partners/year	Assigned to males; estimated for females to balance main partnerships	DHS	1.12-1.83
% of males engaged in TS in the last year	Applied to the MP groups and to the client groups	DHS: % with >1 non-main partners reporting exchange of money and/or gifts for sex (excluding sex with FSWs) in the last year	1-21
% of females engaged in TS in the last year	Applied to the MP groups and to the FSW groups	DHS: % with >1 non-main partners reporting exchange of money and/or gifts for sex in the last year	8-13
Ratio of young to older female engagement in TS	Applied to the MP, FSW, and client groups	DHS and studies reporting TS [2,11-16]	1.5-7.9

MP (multiple partnership group); FSW (female sex worker); TS (Transactional sex is defined as non-commercial sex where money/gifts or other gifts are exchanged but where studies do not refer to females as FSWs or to males as clients, excludes males and females who report exchange of sex for money only [or 'paid sex']); DHS (demographic health surveys [5])

Table A2 continued. Sexual behaviour parameters for casual, transactional, and main partnerships

Data inputs for parameter range			Input Range
Definition	**Model assumption**	**Source**	
% of low-risk males with main partners in the last year	Applied to the always low-activity and the former MP and former client groups	DHS: % of those with 0 non-main partners who report ≥1 main partner in the last year (denominator = sexually active males), age 15-49	66-91
% of high-risk males with main partners in the last year	Same estimate applied across the MP and client risk-groups	DHS and client surveys	13-79
% low-risk females with main partners in the last year	Applied to the always low-activity and the former MP and former FSW groups	DHS: % of those with 0 non-main partners who report ≥1 main partner in the last year (denominator = sexually active females), age 15-49	71-97
% of high-risk females with main partners in the last year	Same estimate applied across the MP and FSW risk-groups	DHS and FSW surveys	2-75
Ratio of the fraction of young to older males who have main partnerships	Applied to all risk-groups	DHS and client surveys; averaged across risk-groups	0.04-0.31
Ratio of the fraction of young to older females who have main partnerships	Applied to all risk-groups	DHS and FSW surveys; averaged across risk-groups	0.33-0.87

MP (multiple partnership group); FSW (female sex worker); DHS (demographic health surveys [5])

Table A3 Sexual behaviour parameters for commercial sex partnerships

Data inputs for parameter range			Input Range
Definition	**Model assumption**	**Source**	
FSW population size (% of adult females currently engaged in sex work)	% of females who could enter sex work (which is then multiplied by the rate of entering sex work)	Systematic review; restricted to non-survey enumeration	0.1-4.3
Fraction of FSW or clients who are engaged in high-volume sex work	Probability of entering the high-volume FSW or client activity classes, if entering sex work	Systematic review	1-50
Ratio of commercial sex partners/year between high- to low-volume FSWs or clients	Used to estimate number of client encounters/year among FSWs; and number of FSW encounters/year among clients	Systematic review	1.12-30
Number of client encounters or visits per year per FSW	Used to generate the client population size (or fraction of males who could become clients)	Systematic review	37-2652
% of client encounters that are with repeat clients	Used to generate the client population size (or fraction of males who could become clients)	Systematic review	20-50
Fraction of FSW visits that are with regular FSWs	Used to generate the client population size (or fraction of males who could become clients)	Systematic review	0.2-0.6

MP (multiple partnership group); FSW (female sex worker)

Table A3 continued. Sexual behaviour parameters for commercial partnerships

Data inputs for parameter range			Input Range
Definition	**Model assumption**	**Source**	
# of sex acts in an occasional commercial partnership	Assumed to be 1 per partnership		N/A
# of sex acts in a repeat/regular commercial partnership	Used to generate the client population size (or fraction of males who could become clients)	Systematic review	4.6-52
% of FSWs who have repeat clients	Used to generate the client population size (or fraction of males who could become clients)	Systematic review	52-69
Duration of sex work among females (years)	Assumed to be independent of age	Systematic review	0.6-7.9
Duration of time spent paying for sex among males (years)	Assumed to be independent of age	Systematic review	1-15

MP (multiple partnership group); FSW (female sex worker)

3. Model Development

We developed a dynamic, compartmental, deterministic model of heterosexual HIV transmission to reflect heterogeneity in sexual behaviour. The compartments represent 'states' of different health and/or sexual activity and demographic status. The goal was to allow enough behavioural heterogeneity to answer the research question but stay aligned with the granularity of available data. Thus, to prevent additional complexity in the model (and thus, to avoid another layer of complexity to the research question at this stage) We did not include HIV treatment. The model is defined by a set of coupled ordinary differential equations and numerically solved with a four-stage Runge-Kutta algorithm (time-step = 0.02 years). The model and solver were coded in C++ programming language. Analyses and graphics were conducted in R version 3.1.2. A schematic representation of the model is shown in Figure A1. The list of demographic state variables is shown in Table A4. There are two sexes (*i*), seven activity-groups (*j*), and two age-groups (*k*).

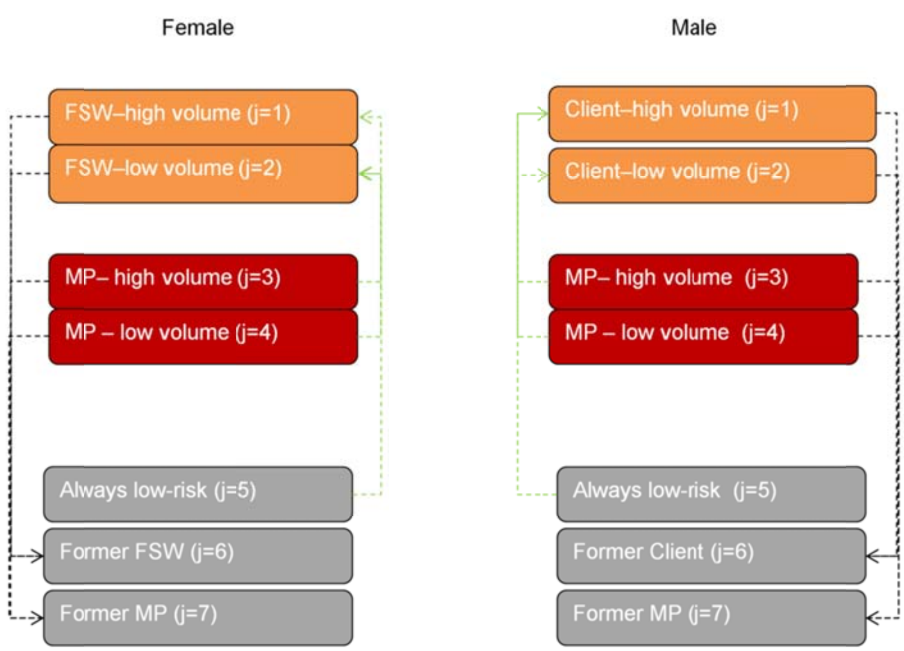

Figure A1. Schematic of the activity-classes in the model. The dashed arrows represent turn-over in the risk-groups. Former FSW, former clients, and former MP individuals have the same behaviour as the always low-risk group (grey). As individuals enter the sexually-active population, they first enter groups j=3,4,5 (entry arrows not shown). FSW (female sex worker); MP (multiple partnership group).

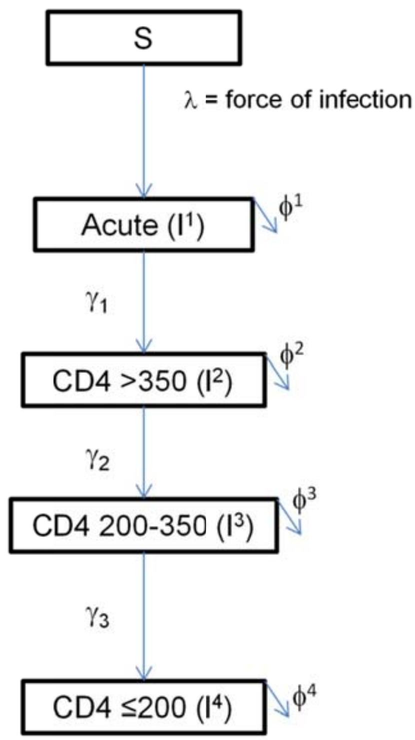

Figure A2. Biological structure of the HIV transmission model. Transitions for HIV progression are given by γ while HIV-attributable mortality is given by ϕ. Births, baseline mortality and cessation of sexual activity are not shown.

Table A4. Demographic state variables

Demographic State variables	Index
Sex	
Male	*i*=1
Female	*i*=2
Activity group (high-activity)	
High-volume sex work	*j*=1
Low-volume sex work	*j*=2
High-frequency multiple partnership (MP) group	*j*=3
Low-frequency multiple partnership (MP) group	*j*=4
Activity group (low-activity)	
Always low-activity	*j*=5
Formerly engaged in sex work	*j*=6
Formerly engaged in multiple partnerships (MP)	*j*=7
Age	
Young (<24 years of age)	*k*=1
Older (≥24 years of age)	*k*=2
Biological State Variables	**Label**
Susceptible to HIV	S
Acute-stage HIV	I^1
HIV infected, CD4 >350 cells/mm^3	I^2
HIV infected, CD4 200-350 cells/mm^3	I^3
CD4 ≤200 cells/mm^3	I^4

3.1 Demographic transitions. Upon start of sexual activity, males and females enter one of three activity classes ($j = 3,4,5$) as young adults (*k*=1): the high- or low-frequency multiple partnership (MP) or low-activity classes. Individuals enter sex work (as FSWs or clients) from the always low-risk and MP groups at rate dependent on the fraction likely to enter sex work and the inverse of the duration in sex work. Entry into sex work is assumed be to be independent of age. Ageing to the k=2 age-group is an exponential process where individuals spend an average of 10 years in the k=1 age-group unless they leave the model population as a result of age-specific baseline mortality $\Gamma_{k=1}$. After an average duration of time in a higher-activity class ($j = 1,2,3,4$) individuals "retire" into their respective low-activity class ($j = 6,7$), at rates given by ε_{ij}. Duration in sex work or time spent in the MP activity-classes is assumed to be independent of age. Individuals in k=2 age-group then exit the population at cessation of sexual activity or baseline mortality, together given by one parameter μ_{ijk}. To stabilize the relative size of subgroups before introducing HIV the model is run with a 100-year burn in period, and checked to ensure <0.01% variation in the relative proportion of individuals in each activity- and age-group. HIV infection is then seeded with 1 infectious individual each activity-class of the younger age-group (*k*=1) in the seed year. The infectious stage of the seed is randomly selected for each simulation.

3.2 Biologic transitions (Figure A2). Individuals are susceptible (S) upon start of sexual activity, and become infected with HIV (acute stage, I^1) with a force of infection (HIV incidence per S) dependent on partnership type, partner change rate, and HIV prevalence of the partners. Individuals then progress (at rates γ) through a total of z stages of untreated HIV (I^2, I^3, I^4) reflecting the following: CD4 >350 cells/μL, CD4 between 200-350 cells/μL, and CD4 ≤200 cells/μL respectively. Each stage is associated with a different transmission probability.

Co-infection with HSV-2 is included at a stable prevalence. HSV-2 is assumed to increase HIV infectiousness and susceptibility, per sex-act. Baseline male circumcision is included and assumed to remain stable over time.

3.3 Sexual partnerships. The model includes 5 partnership types (*pt*), each with its own number of sex acts/year and level of condom-use: occasional commercial (*pt=1*), regular/repeat commercial (*pt=2*), transactional (*pt=3*), casual (*pt=4*), and main (*pt=5*). Depending on whether individuals engage in a given type of partnership, they incur a force of infection from each of these partnerships. Partnership formation and dissolution is instantaneous, and therefore this model does not explicitly take into account duration of partnerships. Individuals within each activity and age-group have a specific probability of forming a partnership of each type, given by ψ_{ijk}^{pt}.

Table A5. Features of each partnership type, and parameters by region

Activity class	Occasional commercial *pt=1*	Repeat commercial *pt=2*	*pt* Transactional *pt=1*	Casual *pt=1*	Main *pt=1*
j=1	$\psi = 1$	Table A3	Table A2	Table A2	Table A2
j=2	$\psi = 1$	Table A3	Table A2	Table A2	Table A2
j=3	$\psi = 0$	$\psi = 0$	Table A2	1	Table A2
j=4	$\psi = 0$	$\psi = 0$	Table A2	1	Table A2
j=5,6,7	$\psi = 0$	$\psi = 0$	$\psi = 0$	$\psi = 0$	Table A2

3.4. Key assumptions about sexual activity. We assumed that sexual behaviour does not differ by HIV stage, which our data from India suggest is likely the case among FSWs [17]. Individuals leave this system (or population under study) upon cessation of all sexual activity (while in *k*=2), baseline mortality (Γ_k), or HIV-attributable mortality (ϕ^Z). Because HIV-attributable mortality can result in large reductions in the relative size of high-activity groups, we assumed that individuals from low-activity groups replace high-activity individuals who died from HIV at a ratio that ranges from 0.8:1 to 1:1. The extent to which the replacement HIV-attributable deaths (in high-risk groups) are required in a model remains uncertain. Modelling studies of non-commercial sex suggest that replacement would have little influence on endemic HIV prevalence [18]. However, models which included sex work (and very high contact-rates with relatively shorter duration of high-risk activity) suggest replacement may be important for HIV persistence [19-22]. There are little empiric data on what happens to the size of sex work communities due to HIV-attributable mortality, with few data on FSW size data from different time points for the same province/state [4]. We operationalized replacement as direct entry from HIV-stages proportional to the number in each HIV-stage. To replace FSW and clients, individuals came from the always low-risk and MP groups. To replace HIV deaths in the MP group, individuals came from the always low-risk groups.

3.5. Model equations: state variables and demographic transitions

The state variables are given by:

$$\frac{dS_{ijk}}{dt} = \theta_{ijk}^{S} + \omega_{ijk} - \left(\mu_{ijk} + \varepsilon_{ij} + \alpha_k - \Gamma_k\right)S_{ijk} - \lambda_{ijk}S_{ijk} \quad (1)$$

$$\frac{dI_{ijk}^{1}}{dt} = \theta_{ijk}^{1} + \delta_{ijk}^{1} - \left(\mu_{ijk} + \varepsilon_{ij} + \alpha_k + \phi^1 + \gamma^1 - \Gamma_k\right)I_{ijk}^{1} + \lambda_{ijk}S_{ijk} \quad (2)$$

$$\frac{dI_{ijk}^{z}}{dt} = \theta_{ijk}^{Z} + \delta_{ijk}^{z} - \left(\mu_{ijk} + \varepsilon_{ij} + \alpha_k + \phi^z + \gamma^z - \Gamma_k\right)I_{ij}^{z} + \gamma^{z-1}I_{ijk}^{z-1}\ ;\ z = 2,3,4 \quad (3)$$

The size of each subgroup is given by:

$$N_{ijk} = S_{ijk} + \sum_{z=1}^{4} I_{ijk}^{z} \quad (4)$$

The following describes entry into the different activity-classes (ω_{ijk}).

Upon start of sexual activity, individuals enter the *k=1* age-group as MP or always low-risk:

$$\omega_{ijk} = \left(\begin{matrix} \zeta_{ij1}N_i^{tot}f_{ij} \\ 0 \end{matrix}\middle| \begin{matrix} j = 3,4,5;\ k = 1 \\ j = 3,4,5;\ k = 2 \end{matrix}\right) \quad (5)$$

Where,

$N_i^{tot} = N_i^{seed}(1 + pr)$ after HIV is seeded into the population in the seed year, and *pr* = population growth rate (assumed to be the same for males and females). ζ_{ij1} is the inverse of the duration of time spent in the j class (Table 4.8), and f_{ij} is the fraction of the population that enters class j at onset of sexual activity.

Individuals enter sex work from the MP and always low-risk classes:

$$\omega_{ijk} = q\_sw_j \sum_{j'=3}^{5} \tau_{ij'} * S_{ij'k}\ ;\ j = 1,2 \quad (6)$$

Where $\tau_{ij'}$ is the rate of entering sex work from class j'

$$\tau_{ij'} = \Omega_{ij'k} * \varepsilon_{ij} ; j' = 3,4,5 ; \; j = 1,2 \tag{7}$$

And $\tau_{ij'} = 0; \; j' = 1,2,6,7$

Where, $\Omega_{ij'k}$ is the relative fraction of the population in class j' that will enter sex work (FSW or client). $\Omega_{ij'k}$ is generated by multiplying initial FSW or client population size with the fraction that enters sex work from the MP class versus the always low-activity class (Table 4.8).

Individuals enter the former sex work and former MP classes from high-activity classes:

$$\omega_{ijk} = \begin{pmatrix} \sum_{j'=1}^{2} \varepsilon_{ij'} * S_{ij'k} & \Big| j = 6 \\ \sum_{j'=3}^{4} \varepsilon_{ij'} * S_{ij'k} & \Big| j = 7 \end{pmatrix} \tag{8}$$

The rate of movement from high-activity to former sex work (FSW/client) and former MP classes among HIV-infected individuals is given by:

$$\delta_{ijk}^{z} = \begin{pmatrix} 0 & \Big| j = 1,2,3,4 \\ \sum_{j'=1}^{2} \varepsilon_{ij'} * I_{ij'k}^{z} & \Big| j = 6, \; j' = 1,2 \\ \sum_{j'=3}^{4} \varepsilon_{ij'} * I_{ij'k}^{z} & \Big| j = 7, \; j' = 3,4 \end{pmatrix} ; \; z = 1,2,3,4 \tag{9}$$

While the rate of entering sex work among HIV-infected individuals is given by:

$$\varrho_{ijk}^{z} = q\_sw_j \sum_{j'=3}^{j'=5} \tau_{ij'} * I_{ij'k}^{z} ; \; j = 1,2 \tag{10}$$

Individuals age out of k=1 a rate of α_k and into k=2 at a rate of

$$\theta_{ijk}^{S} = \begin{pmatrix} \alpha_1 * S_{ij1} & \Big| k = 2 \\ 0 & \Big| k = 1 \end{pmatrix} \tag{11}$$

$$\theta_{ijk}^{Z} = \begin{pmatrix} \alpha_1 * I_{ij1}^{Z} & \Big| k = 2 \\ 0 & \Big| k = 1 \end{pmatrix} \tag{12}$$

Untreated HIV progression into lower CD4 categories is represented by the parameter γ^z, where $\gamma^4 = 0$. The parameter is derived by using empirical estimates of the duration of time spent in each CD4 category, which account for underlying and HIV-attributable mortality:

$$\gamma^z = \frac{1}{dur^z} - \phi^z; z = 1,2,3 \tag{13}$$

3.*6 Model equations: force of infection*

Here one's own activity and age category is denoted *j*, and *k*, respectively, and those of members of the opposite gender are distinguished with a prime (*j'* and *k'*).

Because the sexual activity classes $j = 5{,}6{,}7$ have the same sexual behaviour properties, they form one pool *of currently low-activity* individuals. Thus, We group them together for partnership allocation and mixing, herein denoted as $j = l$

$$S_{ilk} = \sum_{j=5}^{7} S_{ijk} \tag{14}$$

$$N_{ilk} = \sum_{j=5}^{7} N_{ijk} \tag{15}$$

$$I_{ilk}^{z} = \sum_{j=5}^{7} I_{ijk}^{z} \tag{16}$$

The force of infection per susceptible individual is given by:

$$\lambda_{ijk} = \sum_{pt=1}^{5} \sum_{k'=1}^{2} \sum_{j'=1}^{7} \rho_{ii'jj'kk'}^{pt} \left(\frac{\sum_{z=1}^{4} \left[I_{i'j'k'}^{z} \beta_{ii'jj'kk'}^{z,pt} \right]}{N_{i'j'k'}} \right), i \neq i' \tag{17}$$

Where $\beta_{ii'jj'kk'}^{z,pt}$ is the per-partnership transmission rate of HIV from infected individuals in sex *i'* to opposite sex *i*, when the infected partner is in activity-class *j'* and age-class *k'* and HIV stage *z*, and the partnership is of type *pt*. The pattern of contacts for each *pt* is defined through a matrix determining the age and activity group-specific rates of partnership formation with the age and activity groups of the opposite sex.

$\rho_{ii'jj'kk'}^{pt}$ is the number of partnerships formed with individuals of the opposite sex by age and activity group. This number is calculated by distributing the total number of partnerships that are allocated to individuals in each sex, activity, and age-group C_{ijk}^{pt} multiplied by ψ_{ijk}^{pt}, the probability that individuals in sex *i*, class *j*, and age *k* engage in partnerships of type *pt*.

The mixing element $\rho_{ii'jj'kk'}^{pt}$ is given by [23,24]:

$$\rho_{ii'jj'kk'}^{pt} = C_{ijk}^{pt} \psi_{ijk}^{pt} \left[(1 - \varphi^{pt}) \sigma_{jj'} + \varphi^{pt} \left(\frac{N_{i'j'k'} C_{i'j'k'}^{pt} \psi_{i'j'k'}^{pt}}{\sum_{j'}^{l} N_{i'j'k'} C_{i'j'k'}^{pt} \psi_{i'j'k'}^{pt}} \right) \right] \Delta_{ikk'}^{pt} \tag{18}$$

Where, $j = 1,2,3,4, l; j^{'} = 1,2,3,4, l;\ i \neq i$

Where $\sigma_{jj'}$ is the identity matrix. This pattern of mixing by activity-class ranges from assortative ('like-with-like', $\varphi^{pt} = 0$) to proportional ($\varphi^{pt} = 1$), and the pattern of mixing by age is determined by $\Delta^{pt}_{ikk'}$ which is the fraction of a *k*-aged individual's partnerships that are formed with individuals of age-group *k'*.

We assume that for commercial sex (*pt=1*, *pt=2*), there is no age-preference and age-mixing is proportional to the number of partnerships of type pt on offer by individuals of age *k'*.

$$\Delta^{pt}_{ikk'} = \frac{\sum^{l}_{j'} N_{i'j'k'} C^{pt}_{i'j'k'} \psi^{pt}_{i'j'k'}}{\sum^{2}_{k'=1} \sum^{l}_{j'} N_{i'j'k'} C^{pt}_{i'j'k'} \psi^{pt}_{i'j'k'}}\ ; i \neq i, pt = 1,2 \qquad (19)$$

For all other partnerships (casual, transactional, and main), We assume that older females do not form partnerships with younger males (and thus younger males do not form partnerships with older females) [25]. We translated the DHS estimates of the % of young women reporting at least 1 partner >10 years older, into Δ^{pt}_{212} for $pt = 3,4,5$. Although these are not the best data to estimate the parameter Δ^{pt}_{212}, they were the only DHS data available (i.e. data on the fraction of sexual partners >10 years older were not available from the DHS). Accordingly, the fraction of young female (k=1) partnerships that are formed with young males is given by:

$$\Delta^{pt}_{211} = 1 - \Delta^{pt}_{212} \qquad (20)$$

And so for males:

$$\Delta^{pt}_{1kk'} = \Delta^{pt}_{2k'k} \qquad (21)$$

At every time-step, the mixing elements $\rho^{pt}_{ii'jj'kk'}$ are constrained such that the total number of partnerships of type *pt* formed by males *j,k* with females *j',k'* must equal the total number of partnerships of type *pt* formed by females *j',k'* with males *j,k*.

$$N_{1jk} \rho^{pt}_{12jj'kk'} = N_{2j'k'} \rho^{pt}_{21j'jk'k} \qquad (22)$$

This condition is set from time=0. Thus, we set the proportion of males who are clients – i.e. Ω_{1jk} where j=1 and j=2 from the FSW client encounter data. $C^{1}_{21k}, C^{2}_{21k}, C^{1}_{22k}, and\ C^{2}_{22k}$ are calculated from the annual client encounters per FSW, % of FSWs who have repeat clients, % of client encounters that are repeat encounters (repeat clients), number of sex acts within a regular commercial partnership per year, and ratio of client encounters between high-volume and low-volume FSWs. We then use the estimates of the average number of FSW visits/client, ratio of FSW visits between high-volume and low-volume FSWs, and the % of clients who visit an FSW repeatedly to estimate the proportion of males who are clients. For the casual sex, we use size of the MP group among males and females (based on the data) and the average number of casual partners/year among males, to set the average number of casual partners/year among female MP groups. For transactional sex, we do the same but use the average number of transactional partners/year among females to set the average number of transactional partners among males. For main partnerships, we use the average number of main partners/year among males to set the number of main partners/year among females.

During the model run, if equation 4.22 does not hold, $\rho^{pt}_{12jj'kk'}$ and $\rho^{pt}_{21j'jk'k}$ are adjusted as per Garnett *et al* (denoted with *)[23]:

$$D^{pt} = \frac{N_{1jk}\rho^{pt}_{12jj'kk'}}{N_{2j'k'}\rho^{pt}_{21j'jk'k}} \tag{23}$$

$$\left(\rho^{pt}_{12jj'kk'}\right)^{*} = \rho^{pt}_{12jj'kk'}\,(D^{pt})^{-(1-\chi)} \tag{24}$$

$$\left(\rho^{pt}_{21j'jk'k}\right)^{*} = \rho^{pt}_{21j'jk'k}\,(D^{pt})^{(\chi)} \tag{25}$$

Where, χ determines whether the demand for sexual partnerships of males ($0.5 < \chi \leq 1$) or females ($0 \leq \chi < 0.5$) is the strongest determinant of the pattern of partnership formation. For this analyses, we fixed $\chi = 0.5$.

The per-partnership transmission probability of HIV is given by the following:

$$\beta^{z,pt}_{ii'jj'kk'} = \sum_{permut=1}^{16} factor_{permut}\,\left(1 - \left[1 - \left(\mathrm{cofactor_{permut}}\mathrm{B}^{\mathrm{z}}_{\mathrm{ijk}}\right)\right]^{sa_{pt}}\right) \tag{26}$$

$factor_{permut}$ and $\mathrm{cofactor_{permut}}$ are given by 16 permutations of the following possible combinations:

Table A6. Combinations influencing $\beta^{z,pt}_{ii'jj'kk'}$

Factor influencing β	$factor_{permut}$	$\mathbf{cofactor_{permut}}$
Condom-use in each partnership type	Λ^{pt}	$(1 - efficacy_{condom})$if $\Lambda^{pt} > 0$
	$(1 - \Lambda^{pt})$	1
HSV-2 prevalence in one's partner and oneself	$(\varsigma_{ijk})(\varsigma_{i'j'k'})$	$rr_s rr_i$
	$(\varsigma_{ijk})(1 - \varsigma_{i'j'k'})$	rr_s
	$(1 - \varsigma_{ijk})(1 - \varsigma_{i'j'k'})$	1
	$(1 - \varsigma_{ijk})(\varsigma_{i'j'k'})$	rr_i
Male circumcision (only applies to *i=1*):	$pmc_{i=1}$	$(1 - efficacy_{mc})\ if\ pmc_{i=1} > 0$
	$(1 - pmc_{i=1})$	1

The prevalence of HSV-2 is given by ς_{ij}, which can increase the relative risk of HIV infectiousness (rr_i) or HIV susceptibility (rr_s) per sex-act.

For condom-use, we assumed a linear increase in condom-use from zero in the seed year to $Y_{condom\_year\_1}$, which ranged from 1985-2002. The corresponding level of condom-use by partnership type at this point type was drawn from the range in the data shown in Table A7 . We then assumed that condom-use could vary in how it increased to the levels achieved by 2006-2008 ($Y_{condom\_year\_2}$). The latter condom-use level was also drawn from the corresponding range in the data per region, and assumed to saturate at this level by time = $Y_{condom\_year\_2}$. The increase in condom-use from $Y_{condom\_year\_1}$ to $Y_{condom\_year\_2}$ could take any shape and rate under a generalized logistic function, where the growth rate is varied between 0.1 and 0.5, and the time of maximum growth varies between the first third of the time-period to the last quarter of the time-period. If the sampled level of condom-use in $Y_{condom\_year\_2}$ was < $Y_{condom\_year\_1}$, then the lower of the two values was assumed and held constant from $Y_{condom\_year\_1}$ onwards. We fixed condom-use in main partnerships at 10% from $Y_{condom\_year\_1}$ onwards.

Table A7. Condom-use parameters

Data inputs for parameter range		Input Range
Definition	**Source**	**WCA**
Proportion of occasional commercial partnerships where condoms are used ($Y_{condom\_year\_1}$)	Systematic review	0.2-0.98
Proportion of occasional commercial partnerships where condoms are used ($Y_{condom\_year\_2}$)	Systematic review	0.23-0.99
Ratio of condom-use during repeat/regular commercial sex vs. occasional commercial sex	Systematic review; estimated wherever data from the same study was available	0.16-0.98
Proportion of casual partnerships where condoms are used ($Y_{condom\_year\_1}$)	DHS	0.09-0.48
Proportion of casual partnerships where condoms are used ($Y_{condom\_year\_2}$)	DHS	0.02-0.48
Proportion of transactional partnerships where condoms are used ($Y_{condom\_year\_1}$)	Systematic review; there were few data [2,11-16], so we used the same range as for casual sex	0.09-0.48
Proportion of transactional partnerships where condoms are used ($Y_{condom\_year\_2}$)	Systematic review; there were few data [2,11-16], so we used the same range as for casual sex	0.02-0.48

MP (multiple partnership group, see Section 4.2.3); FSW (female sex worker); WCA (West/Central Africa)

Table 4.8. Parameter Values and Descriptions

Symbol	Parameter/variable descriptor	Value or Range	Varied or Fixed by region
Subscripts and superscripts			
pt	Type of partnership	1=regular commercial 2=occasional commercial 3=transactional 4=casual 5=main	N/A
Transition rates and related parameters			
Seed Year	1 HIV infection seeded into each activity class of k=1	1975-1985	Varied
N_i^{tot}	Total starting population (15-49 years of age) in each gender (the initial population in the seed year)	250,000	Fixed
pr	Annual crude birth rate [26]. Rate assumed to remain unchanged and taken as the average across SSA from the last 20 years.	0.024	Fixed
$\varepsilon_{21}, \varepsilon_{22}$	Per-capita rate derived from the inverse of duration in sex work among FSWs, used for rate of entering and exiting sex work	1/duration of sex work (Table 4.3)	Varied
$\varepsilon_{11}, \varepsilon_{12}$	Per-capita rate derived from the inverse of duration in sex work among clients, used for rate of entering and exiting sex work	1/duration of paid sex among clients (Table 4.3)	Varied
$\varepsilon_{i3}, \varepsilon_{i4}$	Per-capita rate derived from the inverse of duration in MP class, used for exiting MP class	1/10	Fixed
$\varepsilon_{i5}, \varepsilon_{i6}, \varepsilon_{i7}$	Currently low-activity class	0	Fixed
ζ_{i3} ζ_{i4}	Rate of entering into the multiple partnerships class (per-capita, per year) after onset of sexual activity	1/10	Fixed
ζ_{i5}	Rate of entering into the low activity class (per-capita, per year)	1/35	Fixed
ζ_{ij}	Sex work, former sex work, and former MP groups	$\zeta_{ij} = 0; j = 1,2,6,7$	Fixed
α_k	Rate of transitioning from k=1 to k=2	$\alpha_1 = 0.1$ $\alpha_2 = 0$	Fixed
f_{ij}	Fraction of individuals who enter the MP class: $f_{i3} = 0.1 * (proportion\ > 1\ non - main\ partners/year)$ $f_{i4} = 0.9 * (proportion\ > 1\ non - main\ partners/year)$ $f_{i4} = 1 - \sum_{j=3}^{4} f_{ij}$ High-frequency MP are fixed at the highest-decile as drawn from the DHS data	Table 4.2	Varied
q_sw_1	Fraction of individuals in sex work (FSWs or clients) or who are high-volume (j=1). Thus, $q\_sw_2 = 1 - q\_sw_1$	Table A3	Varied
Ω_{ijk}	Fraction in i,j,k who will enter sex work $\Omega_{ijk} = 0; j = 1,2,6,7$ $\Omega_{ijk} = 0.75; j = 3,4$ $\Omega_{ijk} = 0.25; j = 5$	Table A3	Fixed
μ_{ijk}	Rate of ceasing to be sexually active (per-capita, per year) in the older age-group k=2 That is, $\mu_{ij1} = 0$ Parameters were confined such that $\mu_{ijk} \geq 0$	j=1,2,3,4; $\mu_{ij1} = 0$ j=5; $\mu_{ij1} = 1/(35 - 10)$ j=6; μ_{ij1} = 1/(25-duration of sex work or paid sex) j=7; μ_{ij1} = 1/(25-duration of time spent in MP class)	N/A
$\gamma^z = \left(\frac{1}{dur^z}\right) - \phi^z$	Rate of progression from HIV stage z to stage z+1 (per-capita per year) Nb: z=4; 0	N/A	N/A
dur^z	Average duration of time (years) spent in each HIV stage, z, before progression to stage z+1 or dying due to HIV-attributable mortality.	z=1; 0.21[27] z=2; 4.8 [28,29] z=3; 3.7 [28,29]	Fixed

ϕ^z	HIV-attributable mortality rate (per-capita per year)	z=1; 0 z=2; 5% [12] z=3; 10.4% [28] z=4; 50% [28]	Fixed
Γ_k	Baseline per-capita mortality/year among <24 year old age-group, taken as average from the SSA using last decadal data[26]	$\Gamma_1 = 0.0001$ $\Gamma_2 = 0$	Fixed
Other parameters			
φ^{pt}	Mixing from assortative (0) to proportional (1), and independently sampled for each partnership type		Varied
sa_{pt}	Number of sex acts per year within each partnership type	Tables A2-A3	Varied
C_{ijk}^{pt}	Yearly partner change rate for each type of partnership	Tables A2-A3	Varied
ψ_{ijk}^{pt}	Probability of an individual from ijk forms a partnership of type pt	Tables A2-A3	Varied
Δ_{212}^{pt}	Fraction of a young females' partners who are older males.	For pt= 3,4, and 5 only, given in Table A2	Varied
pmc	Proportion of males that are circumcised	Table A1	Varied
$efficacy_{mc}$	Efficacy of male circumcision in reducing HIV susceptibility among HIV-negative males	0.6 [30,31]	Fixed
β_{12}^2	Probability of transmission per sex act from female to male, when the female partner is not virally suppressed (during asymptomatic, CD4>350, stage).	0.00043 – 0.00065 [32-34]	Varied
$\beta_{21jj'kk'}^2 = rr_{ftoM} * \beta_{12jj'kk'}^2$	Probability of transmission per sex act from female to male, when the female partner is not virally suppressed (during asymptomatic, CD4>350, stage). Does not depend on age,	rr_{ftoM} = 1-1.5 [32,33]	Varied
$\beta_{ii'jj'kk'}^z = rr\_z\beta_{ii'jj'kk'}^2$	Relative increase in per-act transmission probability Acute (z=1) Asymptomatic (z=2) Pre-AIDS, 200-350 cells/mm^3 (z=3) AIDS or <200 cells/mm^3 (z=4)	rr_1=5-13 [32,35] rr_2=1 rr_3=1.9 [32,35] rr_4=5-19 [32,35]	rr_1 and rr_4 varied, others fixed
rr^s	Relative increase in HIV susceptibility due to a concomitant HSV-2 and/or genital ulcer disease. Per sex act (while shedding). 20% of HSV-2 seropositive individuals are assumed to be shedding at any time	2.0 [36-40]	Fixed
rr^i	Relative increase in HIV infectivity due to a concomitant HSV-2 and/or genital ulcer disease. Per sex act (while shedding). 20% of HSV-2 seropositive individuals are assumed to be shedding at any time.	2.0 [33,40,41]	Fixed
$efficacy_{condom}$	Efficacy of condoms in reducing HIV transmission per sex act.	85% [33]	Fixed
Λ_{pt}	Condom coverage by partnership type pt	Figure A4-A5, Table A7	Varied
$Y_{condom\_year\_1}$	Year that condom-use increases via a sigmoidal function	1991-2000	Varied
$Y_{condom\_year\_2}$	Year that condom-use is assumed to saturate and stay constant thereafter (using the latest data from the surveys)	2005-2008	Varied

3.7 Sampling parameters and plausibility checks

We used Latin hyper-cube sampling with a uniform distribution of the parameter range for each region due to the large number of parameters. As much as possible, correlations between parameter values were accounted for by using ratios and relative risks (such as with HSV-2 prevalence and contact rates within specific risk-groups). Generating relative risks and ratios was governed by data availability for the same province/state or within the same source (publication or survey).

To ensure we sampled enough parameter sets where there was no sex work (to mimic locales where the data might truly suggest there is no commercial sex work), we set 15% of sampled parameter sets to have zero FSWs (and thus, values of zero for all sex work parameters). This was also done to ensure that We did not bias the study towards all synthetic epidemics including some (even if very small networks of) sex work.

We conducted plausibility checks to ensure the following:

1) The relative size of risk-groups remained relatively stable; i.e. that they did not vary by more than 15% of their value at the start of the epidemic (HIV seeding).
2) Client population size would not exceed 35% of the male population. This was based on the largest sub-national estimate using the indirect method of estimating client population size from Chapter 2.
3) The total population did not exceed a 5% annual growth rate [26].
4) Each type of partnership balanced at every time point, and that the adjusted $\left(\rho_{12jj'kk'}^{pt}\right)^{*}$ and $\left(\rho_{21j'jk'k}^{pt}\right)^{*}$ did not produce C_{ijk}^{pt} estimates that were more than 15% of their initial value when ψ_{ijk}^{pt} was held at its initial value. That is, we checked that the balancing of partnerships did not produce large changes in the partner change rates of a given partnership type in each activity-class.
5) FSW incidence would not exceed 50% in the first two years of seeding HIV. This was based on pre-2002 HIV incidence measurements of 10-30% per year [42]. These empirical estimates were measured among women who had already been in sex work for >2 years, and estimated after 1994, We used 50% as my upper bound for feasibility checks.
6) An epidemic established when all condom-use was set to zero from the start of the epidemic. That is, each synthetic epidemic satisfied the following condition in the absence of condom-use: total

HIV incidence exceeded 1 per 1000 people per year (as per Granich *et al* working definition for local elimination [43]) at 50 years from HIV seeding.

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