The various subsystems of the PHOENIX framework have been presented in the previous chapter. Although the overall position of the Fertility Subsystem, the component that simulates the total number of births, and its interactions with other subsystems is given, a detailed description is still lacking. The aggregate, non-age-specific Bongaarts approach is described conceptually and mathematically in this chapter using the PSIR mechanism. This description is based partly on earlier publications (Van Vianen et al., 1994, Hutter et al., 1996, Niessen and Hilderink, 1997). The differences between these reports and the description here will be explicitly indicated in this chapter. In addition to the aggregate approach, an age-specific and multistate modelling approach will also be described and applied. With the use of these three methods to give a broad spectrum of fertility modelling, approaches should enable a description of the fertility transition in all its facets.
4.1 INTRODUCTION

The existing approaches to fertility modelling provide a wide range of possibilities to model fertility change. These approaches can be best characterized by the level of aggregation and the data requirements. One approach is the Bongaarts and Potter approach, where no specification of age for proximate determinants is made. The inclusion of an age-dimension for the specific determinants refines this approach. However, the resulting indices corresponding with the proximate determinants are not observable real-world variables. The validation of such an approach is therefore difficult. In order to simulate variables that can be measured, multistate fertility modelling is adopted, in which events like marriage, getting pregnant and giving births are explicitly included in the model. The disadvantage of this approach is the detailed data requirement.

In Section 4.2, the context of fertility change will be described, laying the basis for Bongaarts and Potter’s non-age-specific modelling approach, which is described in Section 4.3. The application of the age-specific and the multistate approaches will be considered in Sections 4.4 and 4.5, respectively.

4.2 FERTILITY CHANGE

Although fertility change is viewed as the outcome of a dynamic system consisting of interdependent processes, fertility dynamics at the population level represents the outcome of childbearing by individual women. To get a better understanding of fertility dynamics at a population level, the reproductive life span of women will be focused on.

Figure 4.1 shows the major events in the reproductive life span and the factors affecting the rate of childbearing. The potential reproductive period starts at menarche, i.e. the year the first menstruation in a woman’s life takes place. There is considerable variation in the menarche age, for example, due to differences in nutrition levels. Childbearing is usually limited to women living in a stable sexual union. Marriage is used to refer to all these stable sexual unions and is, in practice, the actual starting point of a woman’s reproductive years. Until the menopause, married women can be considered at risk of childbearing. The rate of childbearing is inversely related to the duration of the birth interval. The length of the birth interval is determined by the following three components (Bongaarts and Potter, 1983):

1. The postpartum infecundability interval. After a birth, the normal pattern of ovulation and menstruation is absent for 1.5-2 months. Breastfeeding can prolong this period.
2. Waiting time to conception. The length of this period is largely determined by the frequency of intercourse and can be prolonged by the use of contraceptives.
3. A full-term pregnancy of nine months.
The birth interval is extended in the cases of intrauterine death, or a spontaneous or induced abortion.

Each of the fertility-influencing factors has a particular locus of effect in one of the biological phases in a woman's reproductive life span or birth interval. In past and ongoing demographic research in various parts of the world, two types of variables that influence fertility are distinguished:

- intermediate variables or proximate determinants of fertility, which affect fertility directly; and
- indirect variables, which affect fertility through the intermediate variables.

Proximate determinants are defined as 'the biological and behavioural factors through which social, economic and environmental variables affect fertility. The principal characteristic of a proximate determinant is its direct influence on fertility' (Bongaarts and Potter, 1983 pp. 1-2). The indirect variables capture the effects of social, economic and political contexts in which women have children. The two types of variables are generally associated with the models introduced by Davis and Blake (1956) and Bongaarts and Potter (1983), which have guided fertility research in developing countries for many years. One of the fundamentals of this approach is the distinction of seven proximate determinants:

1. Age at marriage (and marital disruption);
2. Onset of permanent sterility;
3. Postpartum infecundability;
4. Natural fecundability (or frequency of intercourse);
5. Use and effectiveness of contraception;
6. Spontaneous intrauterine mortality;
7. Induced abortion.

Each of these seven proximate determinants has a direct effect on fertility and together they determine the level of fertility. The proximate determinant 'age at marriage' refers to the extent to which women are exposed to regular intercourse. The concept of marriage also includes consensual unions and cohabitation. Postpartum infecundability is due to breastfeeding and culturally motivated postpartum abstinence. The use and effectiveness of contraception, and induced abortion, measure the prevalence of deliberate marital fertility control, while the other factors determine natural marital fertility. A distinction is made between the total fecundity (TF), natural fertility (NF), total marital fertility (TM), total fertility rate (TFR) and wanted fertility (WF).

A significant observation in fertility studies is that observed fertility is well below its theoretical maximum because of fertility-inhibiting factors. The theoretical maximum fertility of a woman is 35 births not counting multiple births. This theoretical maximum is based on a reproductive life span of age 15 to 50 and the absence of all biological and behavioural constraints. If the constraints, waiting time to conception, risk of intrauterine mortality and the onset of permanent sterility are taken into account, the average potential fertility is about 15.3 children per woman, with minor variations between human sub-populations (Bongaarts and Potter, 1983). This potential fertility is referred to as the total fecundity (TF). No population has even come close to this theoretical level of fertility.

Natural fertility (NF) is fertility in the absence of deliberate fertility control. The concept of natural fertility was developed by Henry (1961) to highlight the key role of breastfeeding and postpartum abstinence in lengthening birth intervals and reducing the rate of reproduction. Knodel notices that the definition of natural fertility is surrounded by a grey area of circumstances represented by stopping behaviour, practised without the intention of limiting family size but 'can safely be used to characterize most populations prior to the modern decline of fertility' (Knodel, 1983, p. 64). The absence of deliberate fertility control by means of contraception and induced abortion does not imply a univocal fixed level of natural fertility. There is a wide variation in natural fertility rates and the levels are considerably lower than the theoretical maximum. The NF ranges from 3.7 among the historical population of the Thezels Saint Sernin to 9.5 among the historical population of the Hutterites (Bongaarts and Potter, 1983). Table 4.1 gives the observed ranges of the proximate determinants of natural fertility. The model standard in Table 4.1 corresponds with a total fertility rate of 7 (a reproductive life span of 17.5 years and a 2.5-year period per birth, including a gestation period of 0.75 year). The minimum and maximum values of the TFR corresponding with these ranges are 2.9 and 17.3 children per woman, respectively. The question of present validity of registered ranges will be further discussed in the next section ‘Fertility modelling approach’.
The total marital fertility (TM) is the fertility level of married women. The combination of TM with absence of any birth control results in the total natural marital fertility. Empirical evidence demonstrates the latter to be relatively invariant, showing a very similar decline with age regardless of the overall level (Bongaarts and Potter, 1983).

The actual level of a population's fertility is represented by the total fertility rate (TFR), which reflects the number of births that a woman would have at the end of her reproductive life span if current age-specific fertility rates prevailed. The TFR is a summary measure and indicates an expected number of children a woman to have whereas the completed fertility rate the representation is of the actual number of children born per woman by the end of their childbearing years. And finally, wanted fertility (WF) represents the number of children a woman desires or wants. The definitions of WF are subjected to lack of clarity or reflect only a small part of the underlying mechanisms and will, if appropriate, be discussed in the following sections.

### 4.3 FERTILITY MODELLING APPROACH

Bongaarts and Potter (1983) developed an aggregate fertility model in which four of the most important proximate determinants are included: age at marriage, contraceptive use, induced abortion and postpartum infecundability. Bongaarts and Potter quantified the reducing effect of these four proximate determinants. The resulting total fertility rate (TFR) reflects the inhibiting effects of these four proximate determinants. Figure 4.2 shows the different fertility levels associated with the proximate determinants. Excluding the effect of postponement of marriage, fertility will increase to the total marital fertility rate (TM). If the effects of contraception and abortion are removed, fertility will increase to the total natural fertility rate (TN), while removing the effects of postpartum infecundability causes fertility to rise to the total fecundity rate (TF). The level of TF is relatively invariant and measures the combined effects of the remaining proximate determinants: natural fecundability, spontaneous intrauterine mortality and permanent sterility (Bongaarts, 1984).
4.3.1 Introduction

The model of Bongaarts and Potter has two weaknesses. Firstly, the model represents a static approach, since it only reflects the values of the TFR and the proximate determinants at a given moment in time and does not include any time dimension. The essentiality of the time dimension in the fertility transition impels an adaptation of this static approach. The second weakness is the absence of feedbacks. Feedbacks have to be included to take responses into account. In spite of these weaknesses, however, this model is used as starting point for the PHOENIX fertility modelling approach. Some improvements and refinements will be made. The PSIR approach is used to extend and structure the modelling approach into a more dynamic model including feedbacks. Figure 4.3 shows the framework of the fertility module as a simplified PSIR diagram.

The determinants of fertility are considered in the Pressure subsystem. Pressure variables have their effect on the State subsystem in which fertility determinants like age at marriage and contraceptive use are included. The Impact subsystem reflects the overall fertility levels, which are used to determine the number of births. In the Response subsystem, macro responses like family planning programmes initiated by governments and micro responses like individual fertility preferences are included. In the following sections, the fertility model of PHOENIX will be explained using the PSIR approach.

4.3.2 Fertility Pressure System

One of the most important factors affecting the fertility transition is modernization. 'Modernization may be defined as a transformation in economic, social, and political organization and in human personality observed in a growing number of nations since the mid-eighteenth cen-
Modernization can be represented by many aspects like public health and medical care, education, urbanization, introduction of new goods, mass media and income per capita (Easterlin, 1983). In order to be able to use the concept of modernization in the fertility model, modernization is represented by the level of the human development index (HDI) (UNDP, 1990, 1994, 1995, 1996). The three dimensions used in the HDI (income, life expectancy and education) can be easily identified with facets of modernization. The HDI is highly correlated with the level of fertility although development alone is insufficient to account for observed variations and social interaction should be taken into account (Bongaarts and Cotts Watkins, 1996). The use of an index in the simulation model is not ideal since the value of the index itself is not directly observable. The HDI is only a composite made up of three components. On the other hand, the quantitative unravelling of the modernization aspects and their specific effect on fertility behaviour is lacking.

For the economic component the gross domestic product (GDP) per capita is taken as a proxy of income. The valuation of a national economy is usually done by the calculation of the GDP, which represents the value of the produced goods and services in a particular country. To be able to compare these GDP series in time a deflator is used to take the inflation of money into account. The GDP value is therefore recalculated compared to a reference year (the year 1995 has been
chosen). To be able to compare these GDP series among countries, they can all be recalculated to 1995 US dollars using international exchange rates. These exchange rates reflect the price on international markets of one currency in terms of another but are also affected by capital transactions, speculation and traded services and can therefore be misleading (World Bank, 1997a). In PHOENIX, it is more relevant to look at the value of a dollar within a region or country. This approach, which includes such a correction, is referred to as purchasing power parity (PPP) or real GDP (World Bank, 1997a, Heston and Summers, 1991). In PHOENIX, the GDP expressed in purchasing power parity 1995 US$ (denoted as 1995 PPP$) is included as an exogenous variable.

The life expectancy at birth is taken as an exponent of the mortality level. Life expectancy is derived from the total age-specific mortality rates, which are simulated in the mortality module. The third dimension, education level, can be seen as the representation of the social component. With respect to fertility behaviour, female literacy is more dominant than male literacy. A study by Ainsworth (1996) among 14 SubSaharan countries concluded that 'women's schooling exerts a much larger negative effect on fertility than does men's schooling'. Therefore female literacy instead of adult literacy is used in the PHOENIX fertility model for the HDI composition. The HDI is calculated according to UNDP (1996) and will be further discussed in Chapter 6.

4.3.3 Fertility State System: proximate determinants

The state system considers the inhibiting effects of the proximate determinants on the fertility level. The total fecundity (TF) or maximum total fertility is generally considered to amount to 15.3 children per woman and is a theoretical biological maximum average that has been derived from assumptions about coital frequency, probability of conception and length of postpartum amenorrhoea (Van Vianen et al., 1994). The four proximate determinants included in the fertility model are:

1. The index of marriage (C_m). This index represents the fraction of the reproductive period lost due to postponement of marriage. It is based on the average age of women at marriage or the formation of a stable sexual union. The C_m includes a correction factor for the fraction of women of age 50 who had never been married.
2. The index of use and effects of contraceptives (C_c). This index represents the effects of the period lost for reproduction due to deliberate fertility control via contraceptives. This index varies inversely with the prevalence and effectiveness of the different contraceptive methods practised by couples. The use of contraceptives is bound by an upper limit. This upper limit accounts for the women not using contraceptives because of wanting a pregnancy, having a pregnancy or having had a pregnancy very recently.
3. The index of abortion (C_a). This index accounts for the loss of the reproductive life span due to induced abortion. The average number of induced abortions per woman at the end of her reproductive life span is combined with the reproductive life span loss due to these abortions.
4. The index of postpartum infecundity (C_i). This index is defined as the fraction of the reproductive life span, which is lost for reproduction due to breast feeding and culturally motivated abstinence.
The four proximate determinants listed above all range between one and zero; the smaller the value the greater the reducing effect. They are extensively described by Bongaarts and Potter (1983). In the following sections the most relevant aspects of the four indexes will be summarized. Some of Bongaarts and Potter's definitions and assumptions require adaptation or refinement in order to be used in the PHOENIX model. The linkage of the four proximate determinants with the process of modernization, as part of the Pressure System, will be focussed on. The dynamic modelling of contraceptive use is another important improvement yet to be elaborated.

**Index of marriage (C_m)**

Although menarche marks the start of the potential reproductive life span of a woman, the age at marriage will be taken as the starting point of the actual reproductive life span. For sake of convenience, the definition of marriage includes all stable sexual unions. The importance of the timing and prevalence of marriage on fertility is obvious. In Japan, for example, the age at marriage of 27 is considered the most important factor in the decline of fertility (Klitsch, 1994). Table 4.2 gives an overview of the mean age of females at marriage.

The index of marriage, C_m, represents the reducing effect on marital fertility due to postponement of marriage and is determined by the proportion of women currently married. Since married women in central childbearing ages contribute more to the overall TFR, the proportion of married women is weighted by the age-specific marital fertility. Bongaarts and Potter considered extramarital fertility to be very small and neglected it. The original equation by Bongaarts and Potter is:

\[
C_m = \frac{\sum m(a) \times g(a)}{\sum g(a)}
\]

where \(m(a)\) is the age-specific proportion of women currently in a stable sexual union, and \(g(a)\) is the age-specific marital fertility rate.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>India</td>
<td>17.7</td>
<td>18.7</td>
<td>18.7</td>
</tr>
<tr>
<td>China</td>
<td>NA</td>
<td>22.4</td>
<td>22.4</td>
</tr>
<tr>
<td>East Africa</td>
<td>20.8</td>
<td>20.2</td>
<td>21.8</td>
</tr>
<tr>
<td>Mexico</td>
<td>21.2</td>
<td>20.6</td>
<td></td>
</tr>
<tr>
<td>Japan</td>
<td>24.7</td>
<td>25.1</td>
<td>26.9</td>
</tr>
<tr>
<td>North America</td>
<td>21.8</td>
<td>23.2</td>
<td>24.3</td>
</tr>
<tr>
<td>Western Europe</td>
<td>22.3</td>
<td>24.1</td>
<td>24.1</td>
</tr>
<tr>
<td>Netherlands</td>
<td>23.7</td>
<td>24.5</td>
<td>28.0</td>
</tr>
<tr>
<td>World</td>
<td>21.5</td>
<td>22.3</td>
<td>23.0</td>
</tr>
</tbody>
</table>

Source: UN, 1994
Since in the fertility model of PHOENIX an age dimension is lacking, this relation had to be revised. Therefore the reducing effect of postponement of marriage is estimated on the basis of the average age of a woman at marriage. The modelled relation was initially assumed to be a linear function of the average age at marriage (Van Vianen et al., 1994):

\[ C_m(t) = \text{Ult}_{\text{married}} \times \frac{49 - \text{Avg}_{\text{marriage}}(t)}{35} \]  

(4.2)

where \( \text{Ult}_{\text{married}} \) is the proportion of women ultimately marrying, \( \text{Avg}_{\text{marriage}} \) is average age at marriage of females; 49 is the age at the last childbirth before menopause and 35 is length of the reproductive interval (15 to 49 years). In this approach marital disruption is ignored.

Although the concept of marriage is already extended to living in a stable union, it still does not indicate what it is supposed to indicate, namely the consummation of marriage. Stover (1998) even suggests the substitution of \( C_m \) by a sexual activity indicator, which is suggested as a more direct measure of exposure to pregnancy. Since hardly any data exist on the consummation of marriage and sexual activity, the observed data on marriage will be used, although data are not unambiguous and reliability can be questioned. For example, child marriages in India continue to be practised (Srinivasan, 1991). Due to the lack of reliable data the reducing effect of marriage is hard to estimate but the reducing effect of postponement of marriage seems to be higher than assumed in equation 4.2 at a younger marriage age. On the other hand, it is plausible that at a higher average age at marriage the effect will be weaker due to a better thought-out timing of pregnancy. Hence, the equation for the calculation of \( C_m \) is improved by using a logarithmic function instead of a linear one. Based on regression between historical data of the value of \( C_m \) and average age of marriage, the following equation is obtained:

\[ C_m(t) = \text{Ult}_{\text{married}} \times \left[ 3.37 - 0.88 \times \ln(\text{Avg}_{\text{marriage}}(t)) \right] \quad R^2 = 0.78 \]  

(4.3)

where \( \text{Ult}_{\text{married}} \) represents the proportion of women married at the age of 50 and \( \text{Avg}_{\text{marriage}} \) is average age at marriage of females.

Although Bongaarts and Potter ignored extra-marital fertility, it has become increasingly relevant. Especially in the developed regions, the proportion of births born outside marriage is high (European Union 23.3%, 1996; USA 31%, 1993; Canada 28%, 1995) (Eurostat, 1997). These figures force the inclusion of a correction factor on the average age at marriage. The equation for \( C_m \), which is applied in PHOENIX, finally becomes:

\[ C_m(t) = \text{Ult}_{\text{married}} \times \left[ 3.37 - 0.88 \times \ln(\text{Marital correction}(t) \times \text{Avg}_{\text{marriage}}(t)) \right] \]  

(4.4)

where \( \text{Marital correction} \) is the correction factor on the average age at marriage to take extra marital fertility into account. A value of 1 implies no correction, while a smaller value corresponds with higher extra marital fertility.
In the TARGETS1.0 version, the proportion ultimately married was originally assumed to be 0.90 (Tietze and Bongaarts, 1975). As the data in the following table demonstrate, the value of 0.94 is more accurate. The historical percentage of married women at age 50 shows only minor variation in time (see Table 4.3) and is therefore assumed to be constant, although other observations report a tripling of the percentage of women ultimately not married in some countries. For example, in Japan a 4% to 12% increase in women expected to never marry was observed between 1973 and 1990 (Klitsch, 1994).

The possible determinants of the timing and prevalence of marriage show a large diversity (see Table 4.2). In India, the age at marriage depends highly on cultural factors like religion and caste (Audinarayana and Rajasree, 1995). However, modernization, expressed in terms of literacy level, and proportion in labour force, non-agricultural in combination with per capita income, is also found to be an important predictor for age at marriage in India (Audinarayana, 1985). In Senegal, the cultural factors are found to have little influence on the delay of the age at marriage; this age is largely determined by economic factors like employment and housing (Antoine et al., 1995). In general, there seems to be a negative relationship between levels of mortality, (female) education and income, and timing of marriage (Smith, 1983, Uchida et al., 1992), but employment opportunities, costs of childrearing and disenchantment with marriage are also mentioned (Klitsch, 1994). In general, the age at marriage is low at low levels of development. Urbanization is also recognized as being an important factor for the age at marriage. However, ‘efforts to account for urban-rural differences by controlling for population characteristics such as levels of schooling do reduce observed urban-rural differences are reduced, but rarely eliminate them entirely’ (Smith, 1983, p. 499). These findings justify the assumption of a relationship between average age at marriage and the human development index (HDI). Cross-country analysis in Figure 4.4 demonstrates this relationship to be fairly weak, at least for the 1994 values. Noteworthy in this figure are some absolute high actual values of age (above 29), and some relative high values for low levels of HDI (0.2 - 0.4), which are mainly observed in SubSaharan countries. The latter can be assigned to regional and ethnic differences. Further examination of time-series analysis is required to determine if age at marriage shows structural variation.

### Table 4.3 Percentage of females married at age 50 for selected regions and countries

<table>
<thead>
<tr>
<th>Region</th>
<th>1970</th>
<th>1980</th>
<th>1994</th>
</tr>
</thead>
<tbody>
<tr>
<td>India</td>
<td>99.6</td>
<td>99.6</td>
<td>99.6</td>
</tr>
<tr>
<td>China</td>
<td>NA</td>
<td>99.8</td>
<td>99.8</td>
</tr>
<tr>
<td>East Africa</td>
<td>95.5</td>
<td>96.9</td>
<td>96.8</td>
</tr>
<tr>
<td>Mexico</td>
<td>92.5</td>
<td>92.9</td>
<td>92.9</td>
</tr>
<tr>
<td>Japan</td>
<td>96.7</td>
<td>95.6</td>
<td>95.6</td>
</tr>
<tr>
<td>North America</td>
<td>93.6</td>
<td>94.7</td>
<td>94.8</td>
</tr>
<tr>
<td>Western Europe</td>
<td>90.1</td>
<td>92.1</td>
<td>92.1</td>
</tr>
<tr>
<td>Netherlands</td>
<td>95.5</td>
<td>93.2</td>
<td>93.2</td>
</tr>
<tr>
<td>World</td>
<td>91.9</td>
<td>94.2</td>
<td>94.1</td>
</tr>
</tbody>
</table>

Source: UN, 1994
The relationship used in the simulation model for calculating the average age at marriage is based on these 1994 data. Two additional conditions are included: (i) that women marry at an average age of 15 when social development is extremely low (HDI = 0); and (ii) that age at marriage is postponed to an assumed maximum of 27.5 years when education and employment become established (HDI = 1). The associated equation for the average age of marriage for women then becomes:

\[
\text{Avg}_{\text{marriage}}(t) = \text{Marriage age}_{\text{max}} - 12.5 \times \exp(-2.5 \times \text{HDI}(t)^2)
\]  

where \(\text{Marriage age}_{\text{max}}\) is 27.5 years and \(\text{HDI}\) is the human development index. A range of 15-27.5 years for the average age of marriage is obtained using this function; this is the observed range of population averages. These values may have to be adapted for specific situations as in India (average ages at marriage of around 13 between 1900 and 1941) and the Netherlands (current average age of 30 years), which are outside this range.

**Index of contraception (\(C_c\))**

Once a stable sexual union is formed, a woman may be considered as a potential childbearer. Conception can be deliberately postponed by the use of birth control methods. The index of contraception, \(C_c\), measures the fraction of the reproductive life span, which is lost for reproduction due to deliberate fertility control via contraceptives. In other words, it reflects the length of waiting time to conception that is specifically prolonged due to contraceptive use with the reproductive life span. Bongaarts and Potter (1983) estimate \(C_c\) as follows:

\[
C_c(t) = 1 - 1.08 \times \text{CPR}(t) \times \text{Eff}_{\text{avg}}(t)
\]  

Figure 4.4 Human development index (HDI) and average age of females at the first marriage for 1994. (Source: UN, 1994, UNDP, 1997).
where CPR or contraceptive prevalence rate is the proportion of married women currently using contraception and Effavg is the average effectiveness of contraceptive use. The coefficient 1.08 represents an adjustment for the fact that women (couples) do not use contraception if they know or believe that they are sterile.

During the fertility transition, this index is the most important determinant of fertility decline. The other proximate determinants have only a modest effect. In general, a CPR of 75% is needed to achieve replacement level fertility (Bongaarts, 1986). In the following sections the level of contraceptive use, the various contraceptive methods and their effectiveness are described.

Contraceptive use: a diffusion process

The use of contraceptives seems to be established in all developed countries with level of CPR around 75%. Although not all developed countries have reached this level yet, a strong increase in CPR has been observed in the last decades. In most societies, family limitation was practised first among elite groups and then adopted by society at large (Rodriguez and Aravena, 1991). The fertility decline due to contraceptive use is best described by a process of diffusion of innovation (Retherford and Palmore, 1983, Montgomery and Casterline, 1993, Rosero-Bixby and Casterline, 1993, Rodriguez and Aravena, 1991). Diffusion of innovation is defined as 'the process by which an innovation is communicated through certain channels over time among members of a societal system' (Rogers, 1983, p. 10). Diffusion models are widely used to analyze the spread of innovations like new technologies, products, practices or ideas. The essence of the diffusion process is the spreading of these innovations from one group (consisting of one or more individuals) to another group. The use of (new) methods of contraceptives can also be considered as a process spreading from one group to another.

The classical mathematical model of diffusion is presented to obtain an applicable and appropriate representation of the diffusion process of birth control; the model will be extended towards a more complex representation (Keyfitz, 1985, Rosero-Bixby and Casterline, 1993). The representation of the simplest form of a diffusion process is as follows:

$$\frac{dP(t)}{dt} = a \times (L - P(t))$$  \hspace{1cm} (4.7)

where $L$ is the maximum number of adopters of the diffusion process, $P(t)$ is the number of adopters at time $t$, and $a$ is the constant coefficient of diffusion determining the fraction of potential users influenced to adopt the new method. With the increase of users over time, the $P(t)$ will converge to the upper-limit $L$ and the potential users $(L-P)$ to zero. This process is referred to as an external source-gains process.

Diffusion can also be regarded as an internal source-gains or contagion process. The spreading then depends on the fraction already using contraceptives, influencing the potential users. The equation is as follows:
where coefficient $h$ represents the constant person-to-person spreading of information. The combination of both the external and internal source gains results in a mixed-influence diffusion model:

\[
\frac{dP(t)}{dt} = a \times (L - P(t)) + h \times P(t) \times (L - P(t))
\] (4.9)

The diffusion process of contraceptive use can be regarded as a multi-level process, in which the macro-structure of norms and the information channels embedded in reference groups set the parameters for decisions at the individual level (Montgomery and Casterline, 1993). Retherford (1983) distinguishes three levels of birth control diffusion: local interpersonal networks, network of family planning and related services and an international level consisting of international agencies and private organizations.

In PHOENIX, the use of contraceptives is described in terms of a mixed-influence model, in which the different macro and micro levels can be incorporated. For reasons of simplification it is assumed that the diffusion process takes place in a social heterogeneous group although various social characteristics like geographical distance and social economic status could be distinguished (Montgomery and Casterline, 1993).

Two aspects characterize the diffusion process, the onset and the rate. The onset of the diffusion process is determined by the external source gain of the mixed diffusion process. This component describes contraceptive use, which is not the result of interaction with other users but of individuals who become aware of their desire for birth control. The steps leading to a woman's decision to apply a birth control method generally include the stages of awareness, evaluation, trial, and, finally, adoption of the innovation. On the basis of data from 28 WFS countries, Tsui (1985) found that 29% of the women who are aware of contraceptive methods will finally adopt them. In PHOENIX, 29% of the CPR level is determined by individual awareness. Coale and Cotts Watkins (1986) found that once the CPR passed a threshold of 20%, the irreversible spreading of contraceptive use starts.

The moment the threshold value of 20% is exceeded, the moment the interaction component of the diffusion process is initiated. The interaction component of the diffusion process can be seen as the distribution of the different methods among the population, depending on the proportion of the population already using contraceptives and of the potential users, as well as the rate of this distribution. The rate of diffusion depends on the social structure of the system in which the innovation takes place. The logistic equation for simulating the interaction component of CPR as a classical diffusion process is:
where $k$ is a constant related to time of incipience of the fertility transition and $\text{Diffusion}_{\text{rate}}$ is the rate of the spreading among the population.

The equation originally proposed by Hutter (1996) had to be improved slightly because it incorporated an unintentional and incorrect upper CPR level of 100%. An additional variable $\text{CPR}_{\text{max}}$ as upper CPR level is introduced, taking into account the proportion of women who will not use contraceptives because they are pregnant, or are trying to get pregnant and those who are sterile.

In PHOENIX, the following equation is used to describe CPR as a mixed diffusion process:

$$\text{CPR}(t) = \text{CPR}_{t_0} + 0.29 \times \text{Awareness}_{\text{ind}}(t) + \frac{(\text{CPR}_{\text{max}}(t) - \text{CPR}_{t_0}) - 0.29 \times \text{Awareness}_{\text{ind}}(t)}{1 + \text{EXP}(2.093 - \text{Diffusion}_{\text{rate}} \times (t - t_{\text{threshold}}))}$$

(4.11)

where $\text{CPR}_{t_0}$ represents the initial level of CPR in 1950, $\text{Awareness}_{\text{ind}}$ the level awareness of an individual to control her fertility, $\text{Diffusion}_{\text{rate}}$ the rate of diffusion and $t_{\text{threshold}}$ the year in which the threshold value of 20% is reached.

The external component of the diffusion process is represented by the individual awareness ($\text{Awareness}_{\text{ind}}$). This awareness factor can hardly be related to any observable data. The equation used for calculating the individual awareness is based on Hutter et al and assumes a relationship with human development (HDI), family planning efforts and mass communication:

$$\text{Awareness}_{\text{ind}}(t) = \text{HDI}(t)^{1 - \text{Family planning}(t)} \times (1 - \text{Mass communication}(t))$$

(4.12)

where HDI is the human development index and Family planning and Mass communication are the efforts of specific population policies. With this relationship the $\text{Awareness}_{\text{ind}}$ is dominated by the HDI. An HDI level of 1 corresponds with maximum awareness and a level of 0 with no awareness, irrespective of the values of family planning and mass communication. An HDI value between 0 and 1 can be increased as well by family planning as mass communication, both ranging from 0 to 1 (value 1 not included). This external component determines when the threshold value of the diffusion process is reached and when the interaction component actually starts.

Based on CPR data of 15 developing countries, Rodriguez and Aravena (1991) found a diffusion rate of 0.0707 per year. However, these analyses are based on the assumption of a high CPR-upper level of 85%. In PHOENIX, the CPR-upper level is assumed to be 75%, which reflects current observations in developed countries. This assumption implies a higher diffusion rate.
Equation 4.12 does not account for preference for a son. Ignoring the son preference effect was already revealed by the India application (Hutter et al., 1996). On a highly aggregated global level this effect is rather small but it can have an effect that is not negligible in countries like India, Pakistan, Bangladesh, China and South Korea. This effect becomes more evident with a rise in contraceptive prevalence and a decline in fertility level (Nag, 1991). According to Hutter the CPR\(_{\text{max}}\) is related to an upper limit of CPR, which can be reduced by 10% due to the effect of son preference:

\[
\text{CPR}_{\text{max}}(t) = \text{Upper CPR} - 0.1 \times \text{Son preference function(HDI}(t))
\]  

(4.13)

where Upper CPR is the exogenously determined maximum level of CPR which can be reached if there is no son preference. Son preference function reflects the effect of son preference determined by the level of HDI. The son preference function ranges from 0 to 0.9 and reaches its maximum when the HDI is around 0.5-0.6. This function is obviously only non-zero for countries where son preference is observed.

Although the simulation of contraceptive use by a classical mixed diffusion process proved to be useful, Rosero-Bixby and Casterline (1993) noticed several restrictions and omissions of this approach. One of the shortcomings is the assumption that coefficients like Diffusion rate are constant in time. This assumption is hard to maintain in a context of rapid socio-economic development and changes in (means of) communication and may result in serious specification errors if these effects are ignored (Rosero-Bixby and Casterline, 1993). The diffusion rate could, for example, be related to unmet need, reflecting contraceptive practice as the link between intentions and fertility (Westoff, 1990), but also related to Mass communication policy. Exposure to media information on family planning was also found to have a positive influence on contraceptive behaviour, as in Ghana (Olaleye and Bankole, 1994), Thailand and India (Tamil Nadu). In first instance, the CPR will be simulated by the equations as described above. Options for further refinements and improvements will be studied in the discussion of the results.

Distribution of contraceptive mix

Many methods of contraceptive use exist e.g. male sterilization, female sterilization, Intra Uterine Device (IUD), pill, condom, injectables, female barrier methods, spermicides, primary rhythm and withdrawal. The prevalence of contraceptive methods varies considerably by region. Worldwide, sterilization is the most important method, especially in Latin America and Asia. In China, sterilization accounts for more than 40% of all contraceptive methods. On the other hand, in China as well as in India the oral pill accounts for less than 3% of all methods. In the more developed countries the pill is an important method. Remarkable is the contribution withdrawal makes in almost 20% of the more developed countries. This genuinely traditional European method remains important in parts of Eastern and southern Europe, although it is being rapidly displaced by modern methods (Weinberger, 1991). In Table 4.4, contraceptive methods are shown for some countries and regions.
For the fertility model these methods are grouped based on the availability of data, relevance of distinction with respect to effectiveness and irreversibility (sterilization). This grouping resulted in the following four categories of contraceptive methods: Sterilization, IUD, Pill and Others (including condoms, diaphragms). Although breastfeeding can be seen as a method of birth control by increasing birth intervals, its reducing effect is not included in the index of contraception but is incorporated in the infecundability index.

Effectiveness of contraceptives
To simulate the reducing effect of the use of contraceptives on fertility the effectiveness of the different kind of methods have to be considered. This effectiveness can be reflected in various measures, the three basic of which are (Bongaarts and Potter, 1983):

- Theoretical effectiveness
- Use effectiveness
- Extended use effectiveness

The standard measure of effectiveness is the proportion reduction in the monthly probability of conception due to use of contraception among fecundable women. The average use-effectiveness depends on the particular mix of methods and on the level of human development, in particular of education. Use-effectiveness is specified for each contraceptive method. The effectiveness of sterilization and IUD are based on Bongaarts and Potter (1983, p. 84) and kept constant in time. The use-effectiveness levels of the Pill and Other can be affected by human behaviour. Educated women are supposed to learn about and use contraceptives more effectively (Ainsworth, 1996). In the simulation model, this association is reflected by a linear relationship of the use-effectiveness with the level of development represented by the HDI. A variation in effectiveness only applies to the two methods Pill and Other. For these methods a lower and upper level are defined and the actual level of effectiveness is then determined by the HDI. For the Pill, 85% and 99% (1980 USA level) are taken as lower and upper limit for the use-effectiveness. The lower and upper limit

<table>
<thead>
<tr>
<th>Country</th>
<th>All methods</th>
<th>Sterilization (female/male)</th>
<th>Condom</th>
<th>IUD</th>
<th>Oral (supply*/non-supply**)</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>India (1992)</td>
<td>41</td>
<td>27/3.4</td>
<td>2.4</td>
<td>1.9</td>
<td>1.2</td>
<td>4.3</td>
</tr>
<tr>
<td>China (1992)</td>
<td>77</td>
<td>41</td>
<td>2</td>
<td>30</td>
<td>2.7</td>
<td>1</td>
</tr>
<tr>
<td>Asia</td>
<td>58</td>
<td>23/6</td>
<td>3</td>
<td>16</td>
<td>4</td>
<td>1/5</td>
</tr>
<tr>
<td>Africa</td>
<td>18</td>
<td>1.0/0.1</td>
<td>1</td>
<td>45</td>
<td>6</td>
<td>2/4</td>
</tr>
<tr>
<td>Latin America</td>
<td>58</td>
<td>21/1</td>
<td>2</td>
<td>7</td>
<td>16</td>
<td>2/9</td>
</tr>
<tr>
<td>Developed Countries</td>
<td>72</td>
<td>8/4</td>
<td>14</td>
<td>6</td>
<td>16</td>
<td>2/22</td>
</tr>
</tbody>
</table>

* Includes injectables, female barrier methods and spermicides
** Includes primary rhythm and withdrawal


Table 4.4 Contraceptive methods (%) for selected countries and regions, in 1994
for the Other category are 50% and 80%. The other two methods, Sterilization and IUD, are assumed to have a constant effectiveness of 1.0 and 0.85, respectively. There may be a decline in failure risk with advanced age. However, coital frequency and the woman's intention can elucidate these differences. Use effectiveness is therefore assumed to be independent of the age of the woman. The increase in use effectiveness because of more experience with a method is not taken into account. The resulting equations are:

\[
\text{Effectiveness method}_{(t)} = \begin{cases} 
1.0 & \text{if } i = \text{Sterilization} \\
0.95 & \text{if } i = \text{IUD} \\
0.85 + 0.14 \times \text{HDI}_{(t)} & \text{if } i = \text{Pill} \\
0.5 + 0.3 \times \text{HDI}_{(t)} & \text{if } i = \text{Other} 
\end{cases} 
\] (4.14)

The average use effectiveness of all four contraceptive methods is calculated as follows:

\[
\text{Eff}_{\text{avg}} (t) = \sum_{i=1}^{4} \text{Effectiveness method}_{(t)} \times \text{Share method}_{(t)} 
\] (4.15)

where Effectiveness method is the effectiveness of method \(i\) in equation 4.14, with \(i\) is Sterilization, IUD, Pill or Other. The Share method represents the distribution of these methods.

**Index of abortion (\(C_a\))**

The index of abortion, \(C_a\), represents the fraction of the reproductive life span of a woman lost due to induced abortion. The calculation of the \(C_a\) is based on the average number of abortions a woman has or will have combined with the period of lost reproductivity attached to the occurrence of an abortion. It is rather difficult to estimate the effect of abortions due to the unreliability of the data in countries where induced abortion is prohibited or restricted. Abortion is legal under some circumstances in nearly all countries of the world: 98% of countries with 96% of world's population recognize a threat to mother's life as a legal basis for terminating a pregnancy (UNFPA, 1997). Every year, approximately 75 million pregnancies are unwanted of which 50 million are terminated (WHO, 1998) compared to a total of 160 million live births. The UNFPA (1997) reports the number of legal abortions to be 25 million which results in 50% illegally performed abortions. The distinction between legal and illegal abortions is relates to whether an abortion is done under safe or unsafe conditions and with that it influences the level of maternal mortality (See maternal mortality in the chapter on mortality). There are several measurements in which the level of abortion is reported. The abortion rate (AR) is the number of abortions in a given period related to the size of a population or female population. The total abortion rate (TA, also known as prevalence rate) is defined as the average number of induced abortions per women at the end of her reproductive years if abortion rates remain at prevailing levels throughout the reproductive period. The third measure is the abortion ratio, expressed in number of abortions per live birth, deliveries or pregnancies. In Table 4.5 shows an overview of these three measures for selected countries.
Bongaarts and Potter used the TA for the calculation of the abortion index, \( C_a \). The equation used by Bongaarts is:

\[
C_a(t) = \frac{TFR(t)}{TFR(t) + \text{Abortion}_{\text{factor}}(t) \times TA(t)}
\]

\[
= \frac{1}{1 + \text{Abortion}_{\text{factor}}(t) \times \frac{TA(t)}{TFR(t)}}.
\]  

(4.16)

where TA is the total abortion rate and \( \text{Abortion}_{\text{factor}} \) a correction factor, which is introduced because the fraction of reproductive life span lost is considerably less than in the case of a live birth. In the case of abortion, the gestational period is much less than nine months and the post abortion interval is not lengthened by breastfeeding or abstinence. Bongaarts and Potter relate this factor to the practice of contraception. In absence of contraception, each abortion averts 0.4 births only, while moderately effective contraception averts about 0.8 births. The following equation is used by Bongaarts (1983) for the \( \text{Abortion}_{\text{factor}} \):

\[
\text{Abortion}_{\text{factor}}(t) = 0.4 \times (1 + CPR(t)).
\]

(4.17)

However, it is assumed that most women who have an abortion do not have access to (effective) contraceptives. A more accurate estimate of the \( \text{Abortion}_{\text{factor}} \) would therefore be the ratio of the reproductive time lost per abortion to the length of the birth interval in absence of contraception Bongaarts (1983, p. 85). The equation used in PHOENIX is:

---

Table 4.5 Number of abortions, abortion rate (AR) per 1000 women aged 15-45, abortion ratio per 100 known pregnancies and total abortion rate per 1000 women for selected countries

<table>
<thead>
<tr>
<th>Country (year)</th>
<th>Number of abortions (x1000)</th>
<th>Abortion rate (AR)</th>
<th>Abortion ratio</th>
<th>Total abortion rate (TA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia (1988)</td>
<td>63.2</td>
<td>16.6</td>
<td>20.4</td>
<td>484</td>
</tr>
<tr>
<td>Canada (1987)</td>
<td>63.6</td>
<td>10.2</td>
<td>14.7</td>
<td>299</td>
</tr>
<tr>
<td>Czechoslovakia (1987)</td>
<td>156.6</td>
<td>46.7</td>
<td>42.2</td>
<td>1400</td>
</tr>
<tr>
<td>England and Wales (1987)</td>
<td>156.2</td>
<td>14.2</td>
<td>18.6</td>
<td>413</td>
</tr>
<tr>
<td>Netherlands (1986)</td>
<td>18.3</td>
<td>5.3</td>
<td>9.0</td>
<td>155</td>
</tr>
<tr>
<td>New Zealand (1987)</td>
<td>8.8</td>
<td>11.4</td>
<td>13.6</td>
<td>323</td>
</tr>
<tr>
<td>Singapore (1987)</td>
<td>21.2</td>
<td>30.1</td>
<td>32.7</td>
<td>840</td>
</tr>
<tr>
<td>Sweden (1987)</td>
<td>34.7</td>
<td>19.8</td>
<td>24.9</td>
<td>600</td>
</tr>
<tr>
<td>USA (1985)</td>
<td>1588.6</td>
<td>28.0</td>
<td>29.7</td>
<td>797</td>
</tr>
<tr>
<td>India (1980s)</td>
<td>6000</td>
<td>41.4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>China (1983)</td>
<td>14370</td>
<td>60.2</td>
<td>-</td>
<td>3370</td>
</tr>
<tr>
<td>Brazil (1986)</td>
<td>1400</td>
<td>38.1</td>
<td>30.8</td>
<td>-</td>
</tr>
<tr>
<td>Mexico (1987)</td>
<td>533</td>
<td>23.3</td>
<td>17.1</td>
<td>800</td>
</tr>
</tbody>
</table>

where 14 is the average length of the interval for an induced abortion, i.e. 7.5 months of waiting time to conception, 2 months added because of intrauterine mortality, 3 months of gestation before abortion and a minimum period of 1.5 months due to postpartum anovulation. The latter depends on postpartum abstinence and breastfeeding and is reflected by the \( p_{\text{infecundability}} \). The longer the period of postpartum infecundability, the smaller is the relative reducing effect of an abortion. This average period in months of postpartum infecundability will be further discussed in the section on index of postpartum infecundability.

The determination of the total abortion rate used in equation 4.16 requires elucidation of the underlying mechanisms of the occurrence of abortion. Abortion can be related to contraceptive use, desired family size and legal aspects of abortion. Bongaarts and Potter ignored abortion in all societies in which it has not been legalized, corresponding with value 1 for \( C_a \). This omission is exemplified in the case of urban Latin America where half of all pregnancies are reported to end in illegal abortion (Singh and Wulf, 1994).

At early levels of modernization, desired family size will be large and consequently there is little need for contraception and abortion. With declining levels of desired fertility the need to control fertility will rise and manifest itself in a rising demand for contraception and abortion, at high levels of contraceptive prevalence the knowledge and availability of contraception will be so good that the need for abortion will decline (Ketting and van Praag, 1983). Tietze and Bongaarts (1975) concluded that it would be 'unlikely to reach a low level of fertility without the use of induced abortion, legal or illegal. A total abortion rate (TA) of about 1000 per 1000 women is a plausible minimum for countries with moderately effective contraception and a TA of 200 per 1000 women for countries with highly effective contraception.' Another conclusion is that 'more widespread and more effective use of contraception reduces the need for abortion; however, abortion is not likely to disappear at the levels of contraceptive effectiveness currently attained and unattained' (Tietze and Bongaarts, 1975). Based on these findings it is assumed that abortion will never disappear completely, since it is used when contraception fails. Techniques are also likely to be developed to make abortion safer. Another factor determining whether an abortion is performed safely or unsafely is the legalization of abortion. The effect of legislation of abortion on the number of abortions is unambiguous. The liberal position of the Netherlands on the voluntary termination of pregnancy matches the lowest reported annual abortion rate of 5.3 per 1000 women. On the other hand, restrictive laws do not stop women from seeking abortion. The accessibility of family planning services and the provision of emergency contraception as well as universal sex education at school influence a country's abortion rate to a much greater extent (Van Look and Von Hertzen, 1993). The following equation reflects the abortion ratio (AR) (Van Vianen et al., 1994):

\[
\text{Abortion}_{\text{factor}}(t) = \frac{14}{18.5 + p_{\text{infecundability}}(t)}
\] (4.18)

where 14 is the average length of the interval for an induced abortion, i.e. 7.5 months of waiting time to conception, 2 months added because of intrauterine mortality, 3 months of gestation before abortion and a minimum period of 1.5 months due to postpartum anovulation. The latter depends on postpartum abstinence and breastfeeding and is reflected by the \( p_{\text{infecundability}} \). The longer the period of postpartum infecundability, the smaller is the relative reducing effect of an abortion. This average period in months of postpartum infecundability will be further discussed in the section on index of postpartum infecundability.
\[ \dot{A}R(t) = 1 - \exp(-1.6 \times CPR(t) + CPR(t)^2 + 0.9 \times CPR(t)^3). \] (4.19)

where AR is the abortion ratio expressed in number of abortions per live births, CPR is the contraceptive prevalence rate. The coefficients are estimated on the basis of data provided by Ketting and Van Praag (1983).

Since there is no age-structure assumed, the total abortion rate (TA) is equal to the product of the TFR and the abortion ratio (AR) and thus:

\[ C_a(t) = \frac{1}{1 + \text{Abortion factor}(t) \times AR(t)}. \] (4.20)

**Index of postpartum infecundability (C_i)**

The index of postpartum infecundability, C_i, represents the period lost for reproduction due to breastfeeding or culturally motivated abstinence. This period of breastfeeding and abstinence is referred to as postpartum infecundability. The period of postpartum infecundability 'does not influence the duration of the reproductive years but its effect operates entirely through modification of the birth interval' (Bongaarts and Potter, 1983, p. 86). The index of postpartum infecundability is estimated by the ratio of the average birth interval where breastfeeding and abstinence are absent, and the length of a birth interval, which includes a period of postpartum infecundability.

In a situation without any breastfeeding and abstinence, the average birth interval amounts about 20 months, i.e. the sum of the waiting time to conception is assumed to be 7.5 months, 2 months of spontaneous intrauterine mortality, 9 months of a full term pregnancy and a minimum period of 1.5 months postpartum anovulation. The first three components are assumed to be constant and account for 18.5 months. The fourth factor, the 1.5 months of anovulation, can be prolonged by breastfeeding and by culturally motivated abstinence. Since parity and birth intervals are not included in the model, the reducing effect is expressed in the fraction of fertile life span lost for reproduction. The equation for calculation of the C_i is given by Bongaarts:

\[ C_i(t) = \frac{20}{18.5 + \text{ppinfecundability}(t)}. \] (4.21)

where 20 is the average minimum birth interval in months as a combination of the constant 18.5 months with a 1.5 months minimum of ppinfecundability, the period of postpartum infecundability. In this case, the corresponding value for C_i is 1, implying no reducing effect on fertility. Bongaarts estimated the range of this period (ppinfecundability) at 3 to 24 months, corresponding with C_i values of 0.93 and 0.47.
The component expressing the period of breastfeeding and abstinence still has to be included in postpartum infecundability. This component varies in time. Due to the introduction of western lifestyles, urbanization, employment of women (i.e. labour participation) outside the home and high levels of education, a rapid erosion of traditional patterns such as breastfeeding and the custom of abstinence was observed, resulting in a decrease of postpartum infecundability (Nag, 1983). Breastfeeding is also studied in the context of birth control and, because of the beneficial effect of birth spacing is stimulated by family planning programmes. Millman (1993), however, finds the effect of promoting birth spacing as contraception method on the tendency to breastfeed to be ambiguous.

Most of the developed countries are already situated at the lower level of three months of postpartum infecundability, while in countries like Bangladesh (18.61 months in 1975) and Indonesia (16.16 months in 1976) this level is high (Jain and Bongaarts, 1981). More recent observations in the 1980s indicate a period of 8.1 months in China (Liang Qimin, 1993), 5.7 months in India (Hutter et al., 1996) and 7.5 months in Mexico (ENFES, 1987). An increase of (female) education, income, the level of health services and survival status of children has a negative effect on the duration of breastfeeding. Availability of powdered milk, which can be related to the level of health services combined with the income, is also mentioned. These three socio-economic dimensions to determine the period of postpartum infecundability correspond with the components of the HDI. Besides these socio-economic aspects, the cultural dimension can be of equal importance. In some societies these reducing socio-economic effects are dominated or at least weakened by a strong culturally determined pattern of breastfeeding and postpartum abstinence. In some parts of western African countries abstinence periods up to three years have been observed. Spousal separation due to labour migration is partly accountable for these long periods of abstinence (Bongaarts et al., 1984). The cultural dimension is not easily identified and measured but can have a strong effect on the length, and for this reason, is included as an exogenous variable determining the strength of the HDI influence. Urbanization and female labour force participation are other influential factors but are not included in the model.

The resulting equation used for postpartum infecundability is assumed to be inversely logistic and derived out of data on duration of postpartum infecundability (Bongaarts and Potter, 1983, table 4.2) in relation to estimated historical levels of HDI:

\[
pp_{\text{infecundability}}(t) = pp_{\text{max}} - \frac{pp_{\text{max}} - pp_{\text{min}}}{1 + 12.7 \times \text{EXP}( - 7.8 \times \text{HDI}(t) \times \text{Cultural factor}(t))} \tag{4.22}
\]

where \( pp_{\text{min}} \) and \( pp_{\text{max}} \) are assumed to be 3 and 24 months. The Cultural factor is included as multiplier and represents the cultural dimension. Figure 4.5 shows the assumed logistic relationship between the HDI and the period of amennorhoea when the cultural factor equals 1.
4.3.4 Fertility Impact System

The Impact system reflects the impacts of the variables of the state subsystem. These impacts consist of the overall fertility levels, which are used to determine the number of births. Therefore, the total fertility rate (TFR), representing the number of children a woman has received at the end of her fertile period is calculated. In the fertility module this period is assumed to take place from the age 15 to 49. The TFR is determined by the combined reducing effect of the four proximate determinants on the maximum total fertility. The equation is:

\[ TFR(t) = C_m(t) \times C_c(t) \times C_a(t) \times C_i(t) \times TF \]  

where \( C_m \), \( C_c \), \( C_a \), and \( C_i \) are the indexes for respective factors marriage, contraception, abortion and postpartum infecundability, and \( TF \) is the average population maximum total fertility of 15.3 children per woman. The next step is the calculation of the number of births. The yearly number of births is derived from the TFR.

Downscaling the TFR to ASFR

One of the improvements of PHOENIX compared to the fertility model of TARGETS1.0 is the division of the women aged 15 to 49 into five-year age groups. Instead of calculating the number of births directly from the TFR, age-specific fertility patterns are taken into account. The TFR is therefore broken down into age-specific fertility rates (ASFR). The options for distribution of the TFR to these ASFR can be classified into empirically based method of the U.S. Census Bureau and the use of the gamma-distribution function. These two methods for translating the total fertility rate into five-year age-specific fertility rates will be described.
On the basis of analysis of empirical data, the U.S. Census Bureau provides patterns of age-specific fertility rates for a given total fertility rate (U.S. Census Bureau, 1997). These analyses result in an estimation of age-specific fertility rates corresponding to total fertility rate. For a TFR ranging from 1 to 8 children per woman, this relationship provides the age-specific fertility rates for the seven age groups of fertile women (see Figure 4.6) and is used to translate the simulated overall TFR into ASFR. Although this relation is an average and does not cover some of the fertility patterns which are considered to be exceptional like China and India it serves well as an age breakdown of the TFR.

Another possibility for the decomposing of the TFR into the ASFR is the use of a gamma distribution. A gamma distribution is often used to describe the age-specific fertility patterns (Hoen et al., 1981, Keilman and Manting, 1987). This function is a skewed distribution, increasing rapidly to a maximum and decreasing more slowly afterwards. The equation for the age-specific fertility rates is:

\[
\text{ASFR}(y) = \frac{TFR \cdot \lambda^p \times y^{p-1} \times e^{-y\lambda}}{\Gamma(p)}
\]  \hspace{1cm} (4.24)

where TFR is the total fertility rate, \( \lambda \) and \( p \) are parameters, \( y \) is time since the start of the fertility process, generally assumed to be the age of 15 (hence \( y \) is current age minus 15), and the gamma function is:

\[
\Gamma(p) = \int_0^\infty \text{EXP}(-y) \times y^{p-1} dy
\]  \hspace{1cm} (4.25)
Although this distribution can fit the fertility schedules very well, the used parameters $\lambda$ and $p$ themselves have no sensible direct demographic interpretations (Hoem et al., 1981). However, they can be related to indicators of the fertility schedule, $\lambda$ equals $\mu / \sigma^2$ and $p$ equals $\mu^2 / \sigma^2 - \lambda \mu$ where $\mu$ is the mean age of the fertility schedule and $\sigma^2$ the variance of the schedule (Hutter et al., 1996). Due to the lack of an interpretable linkage with model variables, the parameters of the gamma distribution will be exogenously set.

**Births**

The two methods, as described in the previous section, result in the age-specific fertility rates (ASFR). The resulting ASFRs may be multiplied by the total number of women in each five-year age group between 15 and 49 years, to obtain the number of births. The total annual number of births is:

$$\text{Total births}(t) = \sum_i \text{ASFR}_i(t) \times \text{Women}_i(t)$$

(4.26)

where ASFR$_i$ represents the age-specific fertility rate in children per woman over five-year age groups $i$ (15-20, 20-25, ..., 30-45, 45-50 year) and Women$_i$ is the number of women in the age groups.

To calculate the number of births by sex, the total births are multiplied with a sex ratio at birth, defined as the ratio between the number of boys and the number of girls born.

$$\text{Births}_{\text{boys}}(t) = \text{Total births}(t) \times \frac{\text{Sex ratio}(t)}{1 + \text{Sex ratio}(t)}$$

$$\text{Births}_{\text{girls}}(t) = \text{Total births}(t) \times \frac{1}{1 + \text{Sex ratio}(t)}$$

(4.27)

where Sex ratio is the sex ratio at birth. The resulting number of births by sex is used as input in the accounting equation 3.1.

Although the primary sex ratio of conceptions is not known, it appears that considerably more males are conceived than females since the sex ratios of abortions is 1.6 (Thatcher, 1989). The registered values of the sex ratio at birth are normally around 1.05, which implies that 51.2% of the children born are boys. The sex ratio can be influenced by the practice of sex-selective abortion. Sex preferences revealed by sex pre-selection and prenatal sex determination, which may result in sex-selective abortion, can have a significant effect on sex ratios. This phenomenon can be observed in China where in some particular provinces like Guangxi and Zhejiang sex ratios of 1.17 are registered although underreporting of female births is identified as a contributive factor (Gu and Roy, 1995). This Chinese sex ratio can become more and more biased against daughters due to the one-child policy (Judson, 1994).
In the first half of the 20th century the sex ratio increased as a result from better prenatal care but in the past few decades a decline is observed in the sex ratio for the industrialized countries (Møller, 1996, Davis et al., 1998, Allan et al., 1997, Marcus et al., 1998). Recognized causes like age of father, reproduction techniques like in-vitro fertilization (Thatcher, 1989) and a stressful pregnancy are not fully conclusive for this trend. Møller (1996) identifies hormonally induced ovulation associated with an excess of female births but also identifies a relation with environmental factors with toxic properties. Such an relation is also found in Italy where the effect of high dioxin exposure is strongly associated with a shift in sex ratios of only 26 boys to 48 girls (Mocarelli et al., 1996).

Although most changes in sex ratios are small, it can have significant long-term implications for a population (Walter, 1974). Nevertheless, the underlying causalities are insubstantial and the sex ratios at birth are therefore not related to other variables but are taken exogenously. Reported sex ratios at birth will be used in the simulation model. The sensitivity of this assumption will be analyzed. In Table 4.6, an overview is given of sex ratios at births for some countries.

### Population momentum

The introduction of birth control does not immediately result in an immediately stop of population increase for two reasons. First, the diffusion of awareness and contraceptive use takes time. Second, the age structure of an increasing population is relatively weighted towards the young and consequently favours further increase. Even if fertility declined immediately to a replacement level of about 2.1 children per woman, the population would continue to grow as a result of the relatively young age structure of the population at the onset of fertility decline. If fertility remained at replacement level, growth would level off and the population would tend to stabilize. The ratio between the ultimate stable population and the population at the onset of immediate fertility decline is referred to as the momentum of population growth (Bongaarts, 1994b). The following equation of Keyfitz (1985) is used to calculate the population momentum:

\[
\text{Momentum}(t) = \frac{\text{Total births}(t)}{\text{Population}(t)} \times \text{LE}(t) \times \frac{\text{TFR}(t) \times \text{Survival}_{\text{childbearing}}(t)}{1 + \text{Sex ratio}(t)}
\]

### Table 4.6 Sex ratio at birth for selected countries

<table>
<thead>
<tr>
<th>Year</th>
<th>South Korea</th>
<th>China</th>
<th>Netherlands</th>
</tr>
</thead>
<tbody>
<tr>
<td>1950</td>
<td>NA</td>
<td>NA</td>
<td>1.066</td>
</tr>
<tr>
<td>1960</td>
<td>NA</td>
<td>NA</td>
<td>1.056</td>
</tr>
<tr>
<td>1970</td>
<td>NA</td>
<td>NA</td>
<td>1.049</td>
</tr>
<tr>
<td>1980</td>
<td>1.039*</td>
<td>1.074*</td>
<td>1.052</td>
</tr>
<tr>
<td>1990</td>
<td>1.169</td>
<td>1.09, 1.147*</td>
<td>1.053</td>
</tr>
<tr>
<td>1995</td>
<td>1.145</td>
<td>1.11</td>
<td>1.050</td>
</tr>
<tr>
<td>1996</td>
<td>NA</td>
<td>NA</td>
<td>1.061</td>
</tr>
</tbody>
</table>

Source: IDB, 1997 * Gu and Roy, 1995
Where $LE$ is the life expectancy at birth and $\text{Survival}_{\text{childbearing}}$ is the probability of survival to mean age at childbearing obtained out of age specific mortality rates in the population submodel.

### 4.3.5 Fertility Response System

The last component of the PSIR mechanism is the response subsystem. In this subsystem, macro responses of institutions and micro responses of individuals are taken into account. The micro and macro responses are mostly initiated by feedbacks from the Impact system. The responses influence the variables in the pressure and state subsystem. In this section, the responses and the underlying processes are described.

Through history, there has been a concern for the possible negative effects of population growth on social and economic development. This awareness was already recognized by Malthus who described the discrepancy between the geometrical growth of the population and the arithmetically growth of natural resources like food supply. As a response to this discrepancy, attempts are made to level out these different growth paths. Obviously, the focus will be on the response aiming at the reduction of population growth since the interlinkage with natural resources is modelled exogenous. This response is the outcome of a complex system of behaviour and decision making with all kinds of inter- and intra-dependencies between individuals, governments and all kinds of other institutions. It is not the presumption of this study to suggest that the underlying process of decision making is understood well enough. For example the use of contraceptives is an outcome of a decision based on specific situations, comparisons and other micro and macro influences. In order to keep the response system simple and transparent, a distinction is made between processes taking place on a macro level and on a micro level. The responses on the micro level are partly taken into account by including the association of the level of development with various individual responses like use of contraceptives and the period of postpartum infecundability. In addition to the effect of development, the reproductive behaviour of individuals may be influenced by policy actions, like birth control policies, family and welfare programmes (Greenhalgh and Bongaarts, 1987, Khan, 1992). Most of the possible effects on the micro level are already described in the State System. The consequences of family planning and unmet need on contraceptive use, or abortion legislation on abortion have been included in the relationships determining the proximate determinants. The derivation of these factors is described in this section.

**Micro responses: Wanted fertility and unmet need**

In many developing countries fertility would decline if women were to fully implement their reproductive preferences. The difference between these preferences and the actual observed fertility level indicates a potential for fertility change. Fertility is principally determined by the desire for children. Contraceptive access (or cost) or family planning effort is not a dominant or even a major factor in determining fertility differences (Pritchett, 1994). The reproductive preference is commonly measured in terms of the average desired family size. However, the preferred family size is considered as a commonly used measurement (Lightbourne, 1985). Rationalization plays an
important part: in the case of ‘unwanted’ births, women might claim that they were wanted, and thus create an upward adjustment in desired family size. Non-numerical responses such as ‘it is up to God’ might shift the bias downwards. Moreover, women might express a desire to have a certain number of children, but nevertheless stop the reproductive process at an earlier stage due to social, economic or other circumstances or to health conditions (Bongaarts et al., 1990). Complicating factors like infant and child mortality, sex preferences, involuntary limitation of fertility and changes in the timing of childbearing play a role. When respondents are asked about the family size they desire, they are very likely to answer in terms of surviving children, and are thus take the dead children into account. Moreover, such questions focus on the total desired number of children: no differentiation for the sex of the children being made (Bongaarts, 1990). As a complicating factor, sex preference is of special importance in countries like India, Pakistan and Bangladesh (Nag, 1991).

Given such biases and the complicating effects of various factors, family size preferences have been used to produce an indirect and improved estimate of wanted fertility (Westoff, 1981, Lightbourne, 1985). The wanted total fertility rate (WTFR) is estimated by calculating the total fertility rate, excluding unwanted births. Westoff (1981) found that the prevention of all unwanted births would reduce marital fertility by one-quarter to one-third. The WTFR thus reflects the number of babies an average woman will give birth to, assuming that all of her births are wanted, and that there is no change, either in reproductive motivation or in the proximate determinants of fertility during her reproductive lifetime (Lightbourne, 1985, p. 34). Westoff (1981) and Lightbourne (1985) based their estimates of wanted fertility on WFS data, whereas Bongaarts (1990) used DHS data. Table 4.7 shows the levels of observed fertility and wanted fertility for various countries. Lightbourne assumes that the wanted fertility is always lower than the total fertility (Lightbourne, 1985). This assumption holds when taken from a historical perspective but should be used carefully for future developments. Reduced fecundity, for example due to further postponement of first pregnancy can undermine this assumption. The effects of subfertility can already be observed in some developed countries (Greenhall and Vessey, 1990).

Bongaarts classifies the various countries according to the ratio of unwanted fertility to TFR. He concludes that the great majority of babies are wanted births at the onset of the fertility transition, as suggested by the data. During the early phases of transition wanted fertility declines, but the ability to control fertility is limited and the proportion of unwanted fertility rises. At the end of transition, people are better equipped to control fertility and thus to implement their reproductive preferences: the proportion and number of unwanted births decline (Bongaarts, 1990, p. 499). Having studied WFS and DHS data, Bongaarts (1992) found a significant decline in wanted fertility as human development increased. One of the underlying motivations is the supply of children as a source of labour. The demand for children for labour changes with the shift from traditional societies, associated with relative low income and education levels, to industrialized societies, associated with high income and education levels. The influence of other factors, like children as old-age security and as insurance against economic risks, is also reduced with an
increased income. Besides these aspects, the survival of children to adulthood is of influence on fertility behaviour (Bongaarts and Menken, 1983). It is clear that the three dimensions of the HDI can again serve as approximates for the level of WTFR. Furthermore, the level of WTFR is also affected by the effort of policy to promote family planning. The third factor modifying the level of WTFR is sex preferences. On a world aggregation level the effect of these preferences is not relevant, but these preferences can have a significant effect at a regional scale and are therefore included in the model. The sex preference is based on the level of HDI (Hutter et al., 1996). The level of WTFR is determined by the combination of these three factors using the following equation:

\[
WTFR(t) = 7.63 - 6.1 \times HDI(t) - 1.2 \times \text{Family planning efforts}(t) \\
+ \text{Son preference function}(HDI(t))
\]  

where WTFR is the wanted total fertility rate and HDI the human development index; Family planning efforts reflect the policy actions on family planning programmes (see next section) and Son preference function is given in equation 4.13.

To arrive at the fertility level of the wanted total fertility rate, the use of contraceptive methods has to be increased. The discrepancy between the current CPR level and the CPR level corresponding with the level of WTFR is referred to as unmet need for contraception. The presence of an unmet need was already noticed in surveys in the 1960s, which indicated that a substantial proportion of

<table>
<thead>
<tr>
<th>Country</th>
<th>Natural fertility</th>
<th>Observed fertility</th>
<th>Wanted fertility</th>
<th>Wanted fertility as % of observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thailand</td>
<td>6.7</td>
<td>2.2</td>
<td>2.0</td>
<td>91%</td>
</tr>
<tr>
<td>Sri Lanka</td>
<td>7.1</td>
<td>2.7</td>
<td>2.2</td>
<td>81%</td>
</tr>
<tr>
<td>Indonesia</td>
<td>5.5</td>
<td>3.0</td>
<td>2.6</td>
<td>87%</td>
</tr>
<tr>
<td>Trinidad</td>
<td>5.7</td>
<td>3.0</td>
<td>2.2</td>
<td>73%</td>
</tr>
<tr>
<td>Colombia</td>
<td>8.5</td>
<td>3.1</td>
<td>2.0</td>
<td>65%</td>
</tr>
<tr>
<td>Brazil</td>
<td>9.1</td>
<td>3.3</td>
<td>2.2</td>
<td>67%</td>
</tr>
<tr>
<td>Dominican Republic</td>
<td>7.6</td>
<td>3.6</td>
<td>2.5</td>
<td>69%</td>
</tr>
<tr>
<td>Peru</td>
<td>7.0</td>
<td>4.0</td>
<td>2.1</td>
<td>53%</td>
</tr>
<tr>
<td>Tunisia</td>
<td>8.8</td>
<td>4.1</td>
<td>2.9</td>
<td>71%</td>
</tr>
<tr>
<td>Ecuador</td>
<td>7.7</td>
<td>4.3</td>
<td>2.4</td>
<td>56%</td>
</tr>
<tr>
<td>Morocco</td>
<td>7.2</td>
<td>4.6</td>
<td>3.2</td>
<td>70%</td>
</tr>
<tr>
<td>Zimbabwe</td>
<td>7.5</td>
<td>5.2</td>
<td>4.3</td>
<td>83%</td>
</tr>
<tr>
<td>Ghana</td>
<td>7.0</td>
<td>6.4</td>
<td>5.4</td>
<td>84%</td>
</tr>
<tr>
<td>Kenya</td>
<td>8.2</td>
<td>6.4</td>
<td>4.3</td>
<td>67%</td>
</tr>
<tr>
<td>Senegal</td>
<td>6.8</td>
<td>6.5</td>
<td>5.7</td>
<td>88%</td>
</tr>
<tr>
<td>Burundi</td>
<td>7.0</td>
<td>6.7</td>
<td>5.6</td>
<td>84%</td>
</tr>
<tr>
<td>Liberia</td>
<td>7.3</td>
<td>6.9</td>
<td>6.0</td>
<td>87%</td>
</tr>
<tr>
<td>Mali</td>
<td>7.8</td>
<td>7.6</td>
<td>7.0</td>
<td>92%</td>
</tr>
</tbody>
</table>

Source: Bongaarts, 1992)
women who wanted to stop childbearing were not practising contraception. Contraception is used either to postpone or to terminate fertility. Likewise, an unmet need can be divided into spacing and limiting components (Westoff and Ochoa, 1991). However, in this non-age specific approach only the total fertility level is simulated and parity is not taken into account. Due to the absence of parity, these components can not be modelled explicitly. An overview of the causes of unmet need for contraception is given in Table 4.8, which confirms the assumed underlying causes of WTFR in equation 4.29.

The CPR is frequently viewed as the single most important determinant of fertility. Analyses of the correlation between the CPR and the TFR can be used to derive unmet need. Unmet need is defined here as the discrepancy between the current CPR and the wanted CPR (WCPR), which is the CPR that corresponds with the WTFR. The estimation of this WCPR is derived from the relationship between CPR and TFR. In the database of fertility around 1990 (based on Robey (1992) and Ross (1993) the following correlation ($R^2 = 0.91$) between TFR and CPR is obtained (Van Vianen et al., 1994):

\[ \text{TFR}(t) = 7.5 - 6.6 \times \text{CPR}(t) \]  \hspace{1cm} (4.30)

This finding justifies concentrating on contraceptive prevalence as the basic variable. The equation may be used to estimate the change in contraceptive prevalence that is associated with a given change in the TFR. Using equation 4.30 we arrive at:

\[ \text{CPR}(t) = \frac{7.5 - \text{TFR}(t)}{6.6} \]  \hspace{1cm} (4.31)
The equation above is used for estimation of the wanted CPR (WCPR):

$$WCPR(t) = \frac{7.5 - WTFR(t)}{6.6}$$ (4.32)

To arrive at the unmet need, the value of WCPR is compared with the actual level of the CPR. The difference between these two levels is used as a proximate for the unmet need. Thus,

$$Unmet\ need(t) = WCPR(t) - CPR(t)$$ (4.33)

**Macro responses: Policy awareness**

On a macro level, governments or other institutions, like the United Nations, may stimulate population policies to reduce the population growth. Since 1950, many countries have adopted official policy options, most of them involving the implementation of family planning programmes. The reassurance of the acceptability of these programmes was supported by the fertility surveys in the 1960s, which found that many women wanted to limit family size or space births but did not practise contraception (Bongaarts, 1994b). Along with the progress of human development, these policy actions had an important role in the decline of fertility. Before action is taken, awareness that the population size is going to be worrisome has to grow. For example, discrepancies between the rates of population growth and economic growth could induce a response from governments; this is called policy awareness. If the discrepancy between the two is great, i.e. when population growth cannot be supported by economic growth, governments can be expected to respond by developing population policies. To this end, policy awareness is approximated using the following equation:

$$Policy\ awareness(t) = \frac{Average\ population\ growth_{ten\ year}(t)}{Average\ GDP\ growth_{ten\ year}(t)}$$ (4.34)

where $Average\ GDP\ growth_{ten\ year}$ is the growth of gross domestic product in 1995 PPP$ and $Average\ population\ growth_{ten\ year}$ the growth of the total population, both averaged over a period of 10 years. This period is an assumption included to avoid too great fluctuations.

Both unmet need and policy awareness determine priority of population policy and the level of political and financial efforts to achieve this goal. An exogenously determined priority is included in addition to these two factors. This reflects an autonomous policy, which cannot be directly explained by changed demographic or economic aspects. Several options exist in formulating policies aimed at reducing population growth. Bongaarts distinguishes three broad policy options (Bongaarts, 1994b):

1. Reduction in the number of unwanted pregnancies;
2. Reduction in the demand for large families through investments in human development;
3. Addressing population momentum.
The policy measures implemented to fulfil these targets are family planning programmes, stimulation of human development by improvements in the education system, improving the status of women, modern mass communication systems, and legislation for age at marriage and abortion. The nature and effects of some of these policy options on fertility behaviour are difficult to determine.

PHOENIX distinguishes the following policy options: family planning, mass communication, and education and abortion legislation. The first three policy options are operationalized through policy spearheads. These spearheads are considered as the relative effort in a particular policy area. In the model, a population policy consists of the relative distribution of efforts over these three spearheads. For instance, a value of 0 for family planning implies that there are no efforts to influence fertility behaviour through family planning programmes. Besides these three spearheads, governments can devise an abortion policy determining the legislation for total, partial or no prohibition of abortion.

4.4 AGE-SPECIFIC FERTILITY MODELLING APPROACH

The modelling approach of fertility as described in the previous sections has resulted in a comprehensive tool to simulate the fertility transition. Using the PSIR mechanism, influenced by socio-economic pressure variables like human development, the four proximate determinants in the State system determine the overall fertility patterns. The focus of this approach was to gain insight in the fertility transition over time by studying the underlying components. Using this focus, the second dimension of time, the age of women, is somewhat disregarded. Bongaarts and Potter (1983, p. 114) briefly describe an application of the modelling approach, in which an age dimension is included. This section will further elaborate, improve and extend this application. Firstly, a comparison is made of both approaches. The mathematical description of most important adapted equations is then given. This finally results in the calculation of the age-specific fertility rates, the ASFRs.

4.4.1 Introduction

In the fertility approach, as described in Section 4.3, the proximate determinants are calculated for the whole cohort of women aged 15-50. This results in the TFR. In Section 4.3.4, the Fertility Impact System, the TFR is converted into age-specific fertility rates (ASFR) using an age-distribution function given by the U.S. Census Bureau or a gamma distribution. The resulting ASFRs are calculated for the five-year age groups. An improvement of this modelling approach is the incorporation of the age dimension, which is not restricted to the Impact System but is also applied in the state subsystem. According to one of the applications described by Bongaarts and Potter (1983, p. 114) all four indexes and the TF (see equation 4.23) will be determined for each five-year age cohort of fertile women (15-50 year). These four age-specific counterparts of the prox-
Mating determinants can be related to socio-economic variables using the same methodology as the non-age-specific approach. In Figure 4.7, a graphical overview is given of the age-specific adaptations of first approach to arrive at an age-specific approach.

Most of the extensions of the age dimension are applied to variables of the State system. The Pressure and the Response variables are not distinguished by age. Therefore the description of the age-specific approach is restricted to the age-specific proximate determinants and does not correspond to the PSIR representation, which was used for the aggregate approach. Most of the equations used in the age-specific approach can be derived in a straightforward manner using the equations of previous aggregate fertility approach. The corresponding equation of the aggregate approach will be referred to. The age-specific equations are characterized by an initial capital 'A' to denote age, the age subscript is omitted for reasons of convenience.

### 4.4.2 Age-specific index of marriage (ACₘ)

Age is especially relevant for the index of marriage. This index used to be based on the average age of marriage (see equation 4.4), which serves as a starting point for a woman's reproductive life span. In the aggregate approach, the effect of the postponement of marriage is described by an increase in the average at marriage. In the ASFR approach, the reducing effect of marital fertility due to postponement of marriage is determined by the proportion of currently married fertility among females in the five-year age groups. Table 4.9 shows the time-series of the percentage of married women by age.
In PHOENIX, the age-specific index of marriage is directly derived from the proportion of married women but has to be corrected for extramarital fertility. The equation is:

\[
\text{AC}_{m}(t) = \text{Amarried}(t) + \text{Amarital}_{\text{correction}}(t) \times (1 - \text{Amarried}(t))
\]

where \text{Amarried} is the age-specific proportion of women currently married or in a stable union and \text{Amarital}_{\text{correction}} is the age-specific correction factor for births occurring outside marriage.

In PHOENIX, the proportion married (Amarried) is simulated on the basis of a function of the level of HDI. In Figure 4.8, the assumed marriage pattern for the age groups is shown for various values of the HDI. The distribution over the age groups is revised for the percentage ultimately married. The effect of divorce and widowhood is also ignored in the ASFR-model although it could be incorporated in this approach.

### 4.4.3 Age-specific index of contraception (AC\_c)

The use of contraception is suitable for applying the age dimension. The timing of contraceptive use within marriage and the type of birth control method are highly related to the age of women. The age-specific index for contraception (AC\_c) becomes:

\[
\text{AC}_{c}(t) = 1 - \text{Afecund}(t) \times \text{ACPR}(t) \times \text{Aeff}_{\text{avg}}(t)
\]
where Afecund is the age-specific correction for women or couples not using contraceptives if they know or believe they are sterile; ACPR is the proportion of contraception users among married women with the corresponding effectiveness $A_{eff}$avg. This equation corresponds with equation 4.6. In PHOENIX, the ACPR is not calculated for each age group separately but derived from the overall CPR level, which was simulated by a mixed diffusion process (equation 4.11). Bongaarts uses the standard age pattern of CPR as shown in Table 4.10, which corresponds with an overall CPR level of 0.322. For higher or lower CPR values, this standard age pattern is proportionally inflated or deflated to arrive at the ACPR values. However, this assumption is not valid for currently observed CPR levels of around 75%. Instead, a quadratic function is used for downscaling the CPR to ACPR. This function is derived from the age pattern in Table 4.10, under the additional condition that a CPR value of zero corresponds with zero values for ACPR and a value of 1 corresponds with 1. This results in the following equation:

$$\text{ACPR}(t) = k \times \text{CPR}(t) + l \times \text{CPR}(t)^2.$$  \hspace{1cm} (4.37)

Table 4.10 Age pattern of proportion of contraceptive users among married women (ACPR) and correction for couples/women who know or believe they are sterile (Afecund)

<table>
<thead>
<tr>
<th>Age group</th>
<th>ACPR</th>
<th>Afecund</th>
</tr>
</thead>
<tbody>
<tr>
<td>15-20</td>
<td>0.194</td>
<td>1.0</td>
</tr>
<tr>
<td>20-25</td>
<td>0.295</td>
<td>1.02</td>
</tr>
<tr>
<td>25-30</td>
<td>0.375</td>
<td>1.031</td>
</tr>
<tr>
<td>30-35</td>
<td>0.423</td>
<td>1.042</td>
</tr>
<tr>
<td>35-40</td>
<td>0.418</td>
<td>1.124</td>
</tr>
<tr>
<td>40-45</td>
<td>0.335</td>
<td>1.33</td>
</tr>
<tr>
<td>45-50</td>
<td>0.211</td>
<td>2.083</td>
</tr>
</tbody>
</table>

Source: Bongaarts and Potter, 1983

Figure 4.8 Pattern of marriage related to the human development index (HDI).
where ACPR represents the age-specific proportion of married women using contraception, and \( k \) and \( l \) are age-specific constants fulfilling the conditions for the quadratic equation mentioned above.

The type of contraceptive method a couple uses depends on the wife’s age. Sterilization is a suitable method for couples convinced they want no more children. In 1973, the average age of the wife among sterilized couples in the USA was 35.4 years, compared with 26.8 years for women taking the pill and 29.9 years for women using IUD (Nortman, 1980). Age-specific weights are introduced to take this correlation between age and the contraception method into account. For example, sterilization is practised more in the last phase of the reproductive life span. To take these effects into account, age- and method-specific weights are introduced. These weights are used to calculate the age-specific contraceptive prevalence by the four methods Sterilization, IUD, Pill and Other, using the equation:

\[
\text{ACPR}_{\text{method}}(t) = \text{ACPR}(t) \times \text{Aweight}_{\text{method}}. \tag{4.38}
\]

where \( \text{Aweight}_{\text{method}} \) represents the distribution of ACPR over the four contraceptive methods and seven age groups.

And the corresponding average effectiveness is then:

\[
\text{AC}_i(t) = \sum \text{ACPR}_i(t) \times \text{Effectiveness}_{\text{method},i}(t) \tag{4.39}
\]

where \( \text{ACPR}_i \) represents the age-specific prevalence of these methods and \( \text{Effectiveness}_{\text{method},i} \) is the effectiveness of method \( i \), where \( i \) is Sterilization, IUD, Pill or Other. The \( \text{Effectiveness}_{\text{method},i} \) is equal to equation 4.14 and is assumed to be independent of age.

### 4.4.4 Age-specific index of abortion (AC\(_a\))

Although the occurrence of induced abortion can be allocated to lack of access to or failure of contraception, it is hard to analyze if the assumed relation with CPR is appropriate. Nevertheless, the same approach of the aggregate fertility model is followed. The age-specific abortion index (AC\(_a\)) is as follows:

\[
\text{AC}_a(t) = \frac{1}{1 + \text{Abortion}_{\text{factor}}(t) \times \text{AAR}(t)} \tag{4.40}
\]

where \( \text{Abortion}_{\text{factor}} \) is defined by equation 4.18, the AAR is the induced abortion ratio expressed in annual number of abortions per live births by age of the mother. The \( \text{Abortion}_{\text{factor}} \) is assumed to be independent of age although the waiting time to conception is shortest for younger women and becomes longer with age (Stover, 1998).
To compensate for the lack of data the AAR equation below is assumed to be similar to equation 4.19:

$$\hat{\text{AAR}}(t) = 1 - \exp \left( -1.6 \times \text{ACPR}(t) + \text{ACPR}(t)^2 + 0.9 \times \text{ACPR}(t)^3 \right).$$

(4.41)

where ACPR is the age-specific level of contraceptive prevalence rate.

### 4.4.5 Age-specific index of postpartum infecundability (AC_i)

The fourth age-specific proximate determinant is the loss of reproductive life span due to postpartum infecundability and abstinence. Observations in China show the length of postpartum infecundability to increase with age (Liang Qimin, 1993). Social-cultural factors such as coital frequency and biological factors such as decline in fecundability and increase in foetal wastage with age can affect the period of post-partum infecundability (Rahman and Menken, 1993). The effect of mother's age on the duration of breastfeeding and abstinence is small (Jain and Bongaarts, 1981, Rahman and Menken, 1993). In PHOENIX, the length of the period of post-partum infecundability is assumed to be independent of the mother's age. When distinguishing for age, the period of post partum infecundability does not necessary fall within the defined age groups but can also affect the following age group. This effect is ignored. The equation used to calculate the age-specific index for infecundability (AC_i) is equal to equation 4.21.

### 4.4.6 Age-specific fertility rates (ASFR)

The most substantial age-specific equation is the calculation of the ASFR by multiplying the proximate determinants and the fecundity rates. The equation for ASFR is comparable to equation 4.23.

$$\text{ASFR}(t) = AC_m(t) \times AC_c(t) \times AC_a(t) \times AC_i(t) \times AF.$$  

(4.42)

where AC_m, AC_c, AC_a and AC_i represent the age-specific indices of marriage, contraception, abortion and post partum infecundability, respectively. The AF represents the age-specific interpretation of the maximum total fertility of 15.3 children per woman. In Table 4.11, the AF values in births per 1000 women are displayed for the seven age groups. For example, the number of 511 births per 1000 women aged 15-19 means that a woman gives birth to a maximum of 0.511 children per year between 15 and 20 years, implying a maximum of 2.555 children (5 × 0.511) for this age group. Summation over all age groups results in 15.3 children.

The age-specific method is completed with the equation of ASFR. The number of births, required in the population subsystem can be derived by multiplying the ASFRs by the number of women in the corresponding age groups. For the purposes of presentation and calibration, the total fertility rate (TFR) can be easily obtained as a summation of the ASFRs, taking into account the five-year size of the age groups.
4.5 MULTISTATE FERTILITY MODELLING APPROACH (MSFM)

In the first modelling approach to describe fertility behaviour, the proximate determinants are calculated without specifying the woman’s age. In the second approach, the four proximate determinants are simulated separately for all seven age groups of women. These two approaches act as a generic tool to describe the fertility transition in a broad spectrum. The non-age-specific approach describes fertility behaviour at a high aggregation level. If necessary, this modelling approach can be further refined by distinguishing among the five-year age groups of women aged 15-50. Nevertheless, this more detailed approach has limitations. With the completion of the fertility transition, very low fertility levels are reached. These low levels correspond with a situation in which children are well-planned and timing is becoming one of the crucial factors. With these changes of fertility perceptions, most of the relevant events in the reproductive life span can take place within a period of five years, the size of an age group in the age-specific approach. Instead of further refinement of these age groups, a different approach is advocated. Based on the fertility modelling approach of Bonsel and Van der Maas (1994) and Zeng Yi (1991), a multistate modelling approach is applied. This third approach to simulate fertility behaviour is restricted to an alternative approach of the State and Impact subsystem of the PSIR mechanism and can therefore be easily incorporated in and compared to the previous approaches. The multistate approach will be introduced, compared with and related to the first two approaches the following sections. The systems specification of the MSFM is also given.

4.5.1 Introduction

The Bongaarts and Potter approaches, both non-age and age-specific, can fall short in describing fertility behaviour of populations that have completed the fertility transition. In this post-transitional stage of the fertility transition, the four proximate determinants are not always sufficient for appropriately describing changes in fertility behaviour. The period of the post-partum infecundability remains at a level of three months and shows hardly any variation. In PHOENIX, this is reflected by the assumption that the length of that period is related to the level of HDI. For the developed coun-

<table>
<thead>
<tr>
<th>Age group</th>
<th>AF (in births per 1000 women)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15-20</td>
<td>511</td>
</tr>
<tr>
<td>20-25</td>
<td>682</td>
</tr>
<tr>
<td>25-30</td>
<td>641</td>
</tr>
<tr>
<td>30-35</td>
<td>549</td>
</tr>
<tr>
<td>35-40</td>
<td>414</td>
</tr>
<tr>
<td>40-45</td>
<td>205</td>
</tr>
<tr>
<td>45-50</td>
<td>59</td>
</tr>
</tbody>
</table>

Source: Bongaarts and Potter, 1983
tries the components of HDI, income, literacy and life expectancy do not vary much and remain close to their maximum levels. Consequently, they will hardly cause any variation in the period of postpartum infecundability. The effect of abortion on fertility levels shows a similar stabilization. Abortion is related to the overall CPR level, which has (almost) reached the upper limit of around 75-80% in all the countries completing the fertility transition. Finally, the index of marriage is the only remaining factor, with which some of the variations in fertility levels can be explained.

Another more plausible explanation of variations in fertility level is due to the assumed age-specific breakdown of the overall CPR level to the age-specific being not fully valid for countries in the post-transition phase. The use of contraceptives is probably highly negatively correlated with the event of marriage. The proximate determinants of contraceptive use and age at marriage are assumed to be independent in the previous approaches. Contraceptive use shows that after the start of the internal diffusion process, an autonomous increase up to the upper level is reached, while the age at marriage is determined by the level of HDI. Well-timed use of contraception (for spacing as well as for limitation of births) related to age at marriage is beyond the scope of the previous approaches. Although the latter is also liable to criticism since marriage, a formal event clearly marked in time and officially registered, has become less relevant, being partly substituted by the formation of stable relationships; this is reflected in the observed extra-marital fertility. The underlying mechanism of extra-marital fertility was excluded in the previous approaches.

To overcome the limitations of the first two approaches, fertility behaviour will be described by an alternative approach. Instead of the proximate determinants modelled, the reproductive life span of a woman is considered. To this end, the states and events related to reproduction, as described in Figure 4.1, are used as a starting point, commencing with menarche at the assumed age of 15 and ending in the menopause at age 50. The specification in systems terms leads to a multistate–multi-episode model.

4.5.2 Specification of the MSFM

The reproductive life span of women, as represented in Figure 4.1, includes the most important events related to a woman's reproductive life span. In the MSFM, the consummation of marriage is substituted by sexually active couples/women exposed to pregnancy, with or without an explicit pregnancy wish, the latter also implicitly including the discontinued use of contraception. Linking this use of contraception with consummation of marriage assumes full awareness of and access to contraceptives. To distinguish the major states in the MSFM, the following classification of women is used:

- Women not pregnant subdivided into:
  - Women who do not want to be pregnant;
  - Women who want to be pregnant; and
  - Women who just had a pregnancy ended by an abortion or by a birth.
- Women who are pregnant.
This classification results in the following six states: no pregnancy wanted, pregnancy wanted, pregnancy (by month) and, post-abortion state and postpartum state as two representatives of pregnancy outcomes. Another important extension is distinguishing the parity of a woman. Besides the five-year age groups, women of age 15-50 are further distinguished according to parity class (no children, 1, 2, 3 and 4 or more children). Gravidity i.e. the number of pregnancies, is not explicitly recorded.

Most of the available data like duration of pregnancy and probability of conception are registered on a monthly basis. One month is therefore assumed to be a simulation time-step in the MSFM. The process of ageing, derived out of the one-year survival rates as simulated in the population module, is taken into account for all the reproductive states. Figure 4.9 provides a graphical representation of all states and events of the MSFM.

All the states included in the MSFM will be defined in the following sections.

**No pregnancy wanted state**
No pregnancy wanted state includes women who are not living in a stable sexual union or those who are living in a stable union but who do not have a pregnancy wish. All women start in this state at age 15 and can leave it by means of two events. The first event is represented by the formation of a stable union in combination with the generation of a pregnancy wish. There are hardly
any data available on this first event. This probability will therefore be used for calibration purposes and is estimated on basis of the MSFM outcomes. The second event is becoming pregnant without an explicit pregnancy wish, for example, due to failure of a contraceptive method. This event can be directly related to the use-effectiveness, which is already calculated for the proximate determinant of contraception. One of the advantages of the MSFM is that postponement of childbirth can be taken into account with the distinction of the no pregnancy wanted state and the exit of this state by represented by the pregnancy wanted factor. This allows the analyses of, for example, further postponement of first birth or the effect of spacing.

**Pregnancy wanted state**

When women have left the no pregnancy wanted state because of a pregnancy wish, they will go to the pregnancy wanted state. This state represents women not using any form of contraception and living in a stable sexual union trying to conceive. The length of this state is determined by the period of waiting time to conception. The event of conception, which marks a change of states, is related to the monthly chance of conception, which is better known as the monthly fecundity rate (MFR) (Tietze and Bongaarts, 1975). There have been several studies estimating the MFR. Tietze and Bongaarts (1975) used a MFR starting from zero chance at age 12 and increasing linearly to 0.2 at age 20. This value of 0.2 applies to the age of 35 and decreases linearly to zero at age 48. Van Noord-Zaadstra (1991) observed a decrease in MFR already occurring above the age of 30. Due to the decrease of MFR, postponement of a pregnancy wish could have consequences for achieving the level of wanted total fertility.

**Pregnancy state (by month)**

A woman can get pregnant as a result of a successful attempt in the case of an existing pregnancy wish or due to failure of contraceptive use, landing in the pregnancy state. The pregnancy state is distinguished by a nine-month period, each three months forming a pregnancy trimester. The entry into the first month is determined by the event of conception, the moment of which gives rise to some difficulties. Of 1000 conceptions, 728 reach implantation, 568 are clinically recognized and only 500 result in a live birth (Kline et al., 1989). There are two competing pregnancy outcomes: abortion, both spontaneous and induced, and delivery. Although neonatal conditions related with survival are not included in the model either, they could easily be linked to pregnancy outcomes like length of gestation period. Birth outcomes are not related to any pregnancy characteristics although birth weight, and the corresponding survival, highly correlate with the period of gestation.

The maternal age has an effect on fecundity and generation of a pregnancy wish. The relation of age to, for example, with multiple births and congenital defects has proven to be important but is less relevant in the context of PHOENIX and therefore not taken into account.

**Post-abortion state**

The induced abortion probabilities, based on the current level of ACPR, are applied to the first three months of pregnancy. In the MSFM, spontaneous abortions are also accounted for using the
U-shaped age pattern of foetal mortality (Nortman, 1974). After an abortion a woman enters the post-abortion state without increment of parity. The length of this period is derived from the estimates of index of abortion. For the duration of this state only the period of abstinence after an abortion has to be included: it is assumed to be equal to the postpartum abstinence period. The assumption is made that women go to the pregnancy wanted state after the post-abortion state.

**Postpartum state**

Giving birth after a pregnancy which lasted four to nine months, is the event by which a woman leaves the pregnancy state and always enters the postpartum state. With this event the woman’s parity is increased by one. The births of women of parity 4+ are accounted for, even though their parity is not increased. Multiple births are ignored since their number is small, showing only small variations (e.g. in the Netherlands multiple births increased from 10 to 14 per 1000 live births in the period 1900-1985 (Bonsel and Van der Maas, 1994). The monthly probability for leaving the postpartum state is inversely proportional to the length of the postpartum infecundability period and is determined by the HDI level (see section ‘Index of postpartum infecundability’). After this period, women end up in the no pregnancy wanted state.

4.6 CONCLUSION

The Bongaarts and Potter aggregate approach to describe fertility levels provides a generic method to describe fertility behaviour by making use of four of the most important proximate determinants. The proximate determinants provide insight into the underlying factors of influence on the fertility levels instead of the limited consideration of the overall total fertility rate. This approach has two weaknesses: its static character and the lack of feedbacks. The model was made dynamic by linking the proximate determinants with the HDI and representing the use of contraceptive by a diffusion process. The modelling of responses, like unmet need and the various policy options in combination with policy awareness takes care of the feedbacks. The PSIR approach enabled structuring and positioning of the dynamic process. The inclusion of the age dimension in the proximate determinants results in a further refinement. However, describing fertility behaviour by the inhibiting effect of the proximate determinants has restrictions. Due to conceptual limitations, like consummation of marriage combined with the use of contraceptives, and calibration limitations, an alternative modelling approach is explored. Calibration limitations arise because the four indices are only derivatives of underlying processes so that the indices themselves cannot be measured. The alternative modelling approach refers to the multistate–multi-episode fertility model describing fertility behaviour as an outcome of events in a woman’s life. These processes are more affiliated with real world states and events. On the other hand this modelling approach leans on an elaborated collection of data, resulting in limited application possibilities. The application of all three approaches is described in Chapter 7.