Vienna Yearbook of Population Research 2018 (Vol. 16), pp. 37–53

Education and demography: a review of world population and human capital in the 21st century

Philip Rees*

Abstract

This discussion piece is an extended review of the work on projecting the world's population and human capital by country conducted by the Wittgenstein Centre (WIC). The project was led by Wolfgang Lutz, and its outcomes were published by Oxford University Press in a book that appeared in 2014. Using statistics from the book and elsewhere, this article starts with an overview of the development of educational attainment. The role that education plays in the WIC2014 model is identified. Definitions of 'multi-dimensional', 'multi-state', and 'micro-simulation' are offered, and are used to characterise the model. A thumbnail sketch of the main methods used in the projections is given. The final section sets out a possible agenda for the future development of the WIC2014 model. This review is intended to help readers tackle the more than 1,000 pages of argument and analysis in the book, which represents a major contribution to demographic research in the 21st century.

1 Introduction

This article is a discussion of the role of education in demography, and focuses specifically on efforts by Wolfgang Lutz and his team to add education as a fourth dimension to demographic projection models, after place, age, and sex. In this piece, I review a very important publication produced by the Wittgenstein Centre, *World Population and Human Capital in the* 21st *Century* (Lutz et al. 2014a). Lutz and his colleagues estimated the educational composition of the population for countries across the globe, and linked their findings to two drivers of population change: namely, fertility and mortality. It has been shown that fertility levels are highest among women with the lowest educational levels, and decrease systematically with increasing educational attainment (Basten et al. 2014; Fuchs and Goujon 2014). This phenomenon is embedded in demographic transition theory (Caldwell 1976)

* Philip Rees, Professor Emeritus, School of Geography, University of Leeds, Leeds LS2 9JT, UK
Email: p.h.rees@leeds.ac.uk

DOI: 10.1553/populationyearbook2018s037

and in theories of the role of human capital in economic development (Becker 1962; Becker et al. 1990). When this relationship is included in population models for countries of the world, the projected population numbers are found to be lower than they are in the equivalent forecasts carried out by the UN. There is also evidence that education affects mortality. As people who are better educated tend to live longer and with less disability than their lower educated counterparts, the populations of countries with relatively high educational levels are likely to experience additional population ageing. This trend is already being observed in countries with highly educated populations.

In Lutz et al. (2014a), projections were linked to scenarios (Shared Socioeconomic Pathways, or SSPs) used by climate change researchers in order to assess the impact of future populations on greenhouse gas emissions, and the impact of climate change on the welfare of affected populations. Recently, the Lutz team has carried out new world scenario projections in which they have aligned their assumptions as directly as possible with the United Nation's Sustainable Development Goals (2015–2030) that are likely to affect the demographic components of change (Abel et al. 2016). These projections have a message for international and national policy-makers: namely, that if you achieve these goals, then the world population is likely to grow more slowly than was forecasted in the medium scenario of the Lutz et al. (2014a) projections or in the World Population Prospects of the United Nations (UN 2015a; UN 2015b).

The final component of demographic change that has been shown to be influenced by education is migration. A systematic gradient of increasing migration activity with increasing educational attainment has been established for internal migration by Bernard and Bell (2018). Bélanger et al. (2017) included education and international migration in a microsimulation model that is under development for projecting the populations of Canada, the European Union (EU28), and the USA. However, the influence of education has not yet been fully incorporated into the migration component of published projections. We know that through international migration, there is a transfer of highly educated individuals to highly developed countries that offer attractive employment opportunities. This form of migration increases the productivity and incomes of the migrants, and results in a substantial flow of remittances from higher to lower income countries. Do both richer and poorer societies benefit from these global talent flows, or is there an imbalance?

The aim of this paper is to share the author's understanding of the contribution of Lutz and his colleagues at the Wittgenstein Centre (WIC) to the topic of the relationship between education and demography. The focus of this discussion piece is on the main model employed in *World Population and Human Capital in the 21st Century*, which we refer to as the WIC2014 model. Section 2 of the paper provides a brief overview of educational development across the world, drawing on some WIC2014 country results. In Section 3, the role of education in demographic change is reviewed. Section 4 situates the WIC2014 model within a typology of demographic projection models. In Section 5, the (almost) impossible task of summarising the essential features of the WIC2014 model is attempted. The paper concludes in Section 6 with suggestions for a continuing research and impact agenda to be undertaken by the WIC team.

2 Overview of educational development across the world

Educational attainment has risen significantly over the past 50 years. While the highly developed countries of Europe and North America had achieved universal literacy by 1965, many countries in other regions of the world had not yet reached this level. By 2016, an estimated 86% of the world's population aged 15 or older were literate. While this finding suggests that substantial progress has been made, it also means that some 750 million people are still illiterate (UNESCO 2017), the bulk of whom are living in southern Asia or Sub-Saharan Africa. However, literacy rates are much higher among the younger (aged 15–24) than among the older (aged 65 or older) people in these regions. The literacy gap between these age groups has, for example, been estimated at 36% in Northern Africa and Western Asia, 47% in Southern Asia, and 39% Sub-Saharan Africa (UNESCO 2017, Table 2). Literacy enables people to acquire skills that are useful in the economy, and to receive and understand messages aimed at improving their health and well-being (e.g. messages about vaccination against dangerous infections). Literacy in a population can also help governments gather information that can be used in preparing social and physical plans. Face-to-face interviews – which are labour-intensive, and are therefore expensive – can be replaced by paper questionnaires that respondents can self-complete. With further technical education and the spread of internet-connected devices, the task of digitising survey or census questionnaires or tax returns can be delegated to respondents or householders (Rees 2018). Lutz (2014) has rightly argued that literacy and universal primary schooling will not provide countries with the human capital (skills, cognitive abilities) necessary for success in the 21st century, and that governments should therefore ensure that their populations have universal upper secondary qualifications and enhanced access to post-secondary education.

Barakat and Durham (2014) have argued that educational attainment levels are likely to continue to improve in most countries over the next 50 years, except when crises (especially civil wars) disrupt a country's progress. Table 1 displays forecasts of educational attainment in the world, and in seven countries with large populations spread across the range of the Human Development Index (UNDP 2018). The WIC2014 projections (Lutz et al. 2014, Appendix II; Barakat and Durham 2014; Goujon et al. 2016) indicate that globally, educational levels will improve markedly and continuously over the next half century. Specifically, the projections show that by 2060, a majority of the world's 25-year-olds will have upper secondary or post-secondary education, and a majority of German and American adults will have post-secondary education. In China, just over half of the population will have upper secondary or post-secondary education, although nearly 40% of the population will have lower secondary education only. Indonesia is expected to perform even

Table 1:
Educational attainment, 2010 and 2060, selected countries

	Population aged 25+, % by highest educational attainment								
		World		Germany		USA		Russian Fed.	
	Education	**2010**	**2060**	**2010**	**2060**	**2010**	**2060**	**2010**	**2060**
	HDI 2017	0.728		0.936		0.924		0.816	
E1	No education	18	5	1	0	1	0	0	0
E2	Incomplete primary	7	2	0	0	1	0	0	0
E3	Primary	19	12	3	1	4	1	4	0
E4	Lower secondary	20	16	16	7	7	4	8	1
E5	Upper secondary	25	37	51	40	52	43	67	68
E6	Post-secondary	14	28	30	52	36	52	21	31
	MYS	7.9	10.99	13.71	14.93	12.86	13.88	10.44	12.05
		China		**Indonesia**		**India**		**Zimbabwe**	
	Education	**2010**	**2060**	**2010**	**2060**	**2010**	**2060**	**2010**	**2060**
	HDI 2017	0.752		0.694		0.640		0.535	
E1	No education	1	1	1	1	39	11	9	0
E2	Incomplete primary	0	0	9	1	8	2	17	1
E3	Primary	28	8	36	14	14	12	19	4
E4	Lower secondary	42	39	16	12	11	12	13	5
E5	Upper secondary	13	27	21	49	18	41	37	76
E6	Post-secondary	7	25	8	23	9	22	6	15
	MYS	7.36	10.38	7.96	11.67	5.53	10.12	9.16	13.30

Note: HDI = Human Development Index, 2017. MYS = mean years of schooling.
Source: UNDP (2018, Table 1); Lutz et al. (2014a, Appendix II).

better, with 72% of the population reaching the upper secondary level. India will have substantially reduced but not eliminated the share of the population left behind with no education, and a majority of the country's population will have upper secondary or post-secondary education. In Zimbabwe, three-quarters of the population will have upper secondary or post-secondary education, provided the persistent economic problems (hyper-inflation, high unemployment, corruption) the country has experienced under the Mugabe regime are resolved.

What has driven these improvements in education? Becker (1962), in a theoretical analysis of investment in human capital (the stock of knowledge and skills acquired through education and training), showed how in-firm investment in on-the-job training produces long-term benefits for the firm and for the worker, provided labour productivity continues to rise. His subsequent work added analysis of the effect of human capital investment on fertility and economic growth (Becker et al. 1990), and on the gender division of labour (Becker 1985). Becker's work on this topic is summarised in his book on human capital (Becker 1993). Parents invest in the education of their children so that the children's future life-time earnings will be higher and their lives will better than they would have been in the absence of such investments. The state invests in education in order to raise the productivity of the national workforce in a competitive world economy. Difficult decisions must be made about how the costs of education are divided between the state (i.e. the taxpayers), the firm/organisation, and the family. While the share of educational costs carried by the state has risen in most countries over time, this share can fall when national and local budgets are under pressure. But productivity also depends on investment in physical capital, and in new technologies in particular. To reap the benefits of these new technologies, education – especially in science, technology, engineering, and mathematics (STEM) – is vital. Crespo Cuaresma (2017) combined the WIC educational attainment forecasts with assumptions about investment in technology to generate projections of income (GDP per capita) under different SSP scenarios for countries of the world. According to these projections, world income in purchasing-power-parity US dollars per annum could rise from \$10.7k in 2017 (The World Bank 2018) to between \$20k (least favourable scenario) and \$100k (most favourable scenario) in 2100.

3 The role of education in population change

Lutz and Skirbekk (2014) set out the basic rationale for including education as a variable in world population projections. Education is an important determinant of fertility, as more educated women tend to have fewer children and to have them later in life, while less educated women tend to have more children and to have them earlier in life. Education is also an important determinant of morbidity (health) and mortality (longevity), as more educated people have higher levels of health and longevity, while less educated people have lower levels of health and longevity. Finally, education is an important determinant of international migration, as more educated people migrate at higher rates across international boundaries than less educated people (Dustmann and Glitz 2011). Education is, of course, not the only determinant of the future age- and sex-specific component rates used in demographic projection models, but it is undoubtedly a crucial factor.

To capture the effects outlined above, educational attainment shares by age and gender are introduced in the WIC2014 model as independently forecast determinants. This is a pretty rare strategy in demographic forecasting models, in which most drivers of change are endogenous. Barakat and Durham (2014) explained their rationale for projecting educational grade shares independently, and described the methods they adopted. Goujon et al. (2016) provided a detailed explanation of the complex process of assembling and harmonising the international and national datasets required for estimating the baseline educational distributions.

4 Multi-dimensional, multi-state, or micro-simulation models?

To implement the projections of the population classified by educational grade, Lutz et al. (2014a) used an expanded version of the cohort-component model. In various papers, this model is described as multi-dimensional or as multi-state. These descriptions are somewhat vague; and this fuzziness has persisted since Land and Rogers (1982) edited *Multidimensional Mathematical Demography,* a volume that featured articles with a mixture of the terms 'multidimensional' and 'multi-state' in the chapter titles. A clarification of the differences between these types of models is proposed here.

Multi-dimensional population models incorporate a variety of population attributes, and use these attributes to influence the component assumptions and generate outputs. Thus, for example, the addition of education to age and sex means that differences in fertility rates by education influence future births. Specifically, based on survey and vital statistics evidence, it is assumed that in most countries, there is a gradient of fertility from high to low among people with low to high educational attainment levels.

Multi-state models classify the population by groups beyond age and sex, and, crucially, allow people to transition between one state and another. Multi-state models were initially used to project population flows between sub-national regions (Rogers 2008). They have since been employed extensively in academic research and in official projection methodology. The use of these models in international contexts lagged behind their use in national or sub-national projections by several decades. Essentially, it was not until a new method was developed by Abel (Abel 2013; Abel and Sander 2014; Sander et al. 2014; Abel 2018) that estimating country-to-country flows from information on migrant stocks (population by country of residence and birth) collected by the United Nations became possible (UN 2017). The WIC 2014 model applies migration transition rates from a single country to the rest of the world, and vice versa. International emigration flows by age and sex are multiplied by the proportions of the origin country's population in each educational grade. The net numbers of international migrants by age and sex are then computed and multiplied by the proportions in each educational grade for each country of destination. It is therefore clear that this projection model is unable to determine whether a country is experiencing a 'brain gain' or a 'brain drain'.

Some educational projection models incorporate state-to-state transitions (Stone 1965; Stone 1971). Lutz et al. (2004) experimented with models using transition rates between educational grades. But in the WIC 2014 projections, future shares of the population by educational grade are used. Goujon et al. (2016, p. 322) clarified this approach as follows:

> "...the reconstruction model that we have developed – presented in more details in Barakat and Durham (2014) – ultimately requires not transition *rates* between attainment at time t and $t + 5$, but the *shares* of different attainment levels at ages 15–19, 20–24, and 25–29 years, conditional on (presumed) final attainment at age 30–34 years or above".

This approach to projecting population levels resembles methods used to estimate healthy life expectancy that added health state prevalence rates to a standard life table (Jagger et al. 2008; Jagger et al. 2014).

A final category of projection model is the micro-simulation model, in which the unit modelled is not the group or the state population, but the individual. Van Imhoff and Post (1998) showed that macro- or micro-projection models can be designed to implement the same processes. They discussed the advantages and disadvantages of each of the two representations. In micro-simulation models, the individual profiles can be extensive, and can include many characteristics that influence the components of population change. For example, Bélanger et al. (2017) have proposed, and are currently working on, a demographic micro-simulation model that uses a variety of survey and census micro-datasets for Canada, the European Union, and the USA. This model, which was developed as part of an EU/IIASA project on population and migration (CEPAM 2018), will, when implemented, enable the prediction of current fertility, mortality, internal migration, and emigration rates by age, sex, educational grade, and other variables, such as place of birth, race/visible minority group, immigration generation, age at immigration, language, and religion. The aim is not to include all such variables in a prediction model, but to use those variables that appear to be significant determinants. It is also necessary to project as many determinants as possible into the future, either within the micro-simulation model or via an external model.

5 The Wittgenstein Centre 2014 model: a reader's summary

Underpinning the WIC2014 model is the concept of demographic metabolism (Lutz 2013; Lutz and Skirbeck 2014), which is the process through which the ageing of successive birth cohorts changes the nature of the population, assuming that each cohort differs from the previous and the following cohorts. If a new but persisting trait is acquired by the young and not by the old, the trait will be transmitted upwards in the age distribution to become more common over time. Educational attainment is such a trait. It is assumed that education is acquired in the early years of life, or up to ages 30-34 in the WIC2014 model. In recent years, successive birth cohorts have been progressing further in the educational process than the preceding cohorts. Thus, even if the typical educational career ends by age 30 to 34, the make-up of the whole population will change as newer cohorts replace older cohorts, or age by age. The main processes that contribute to the changes in the educational composition of the population are cohort replacement and education differentials in fertility, mortality, and international migration. Educational differentials decline in strength through this sequence.

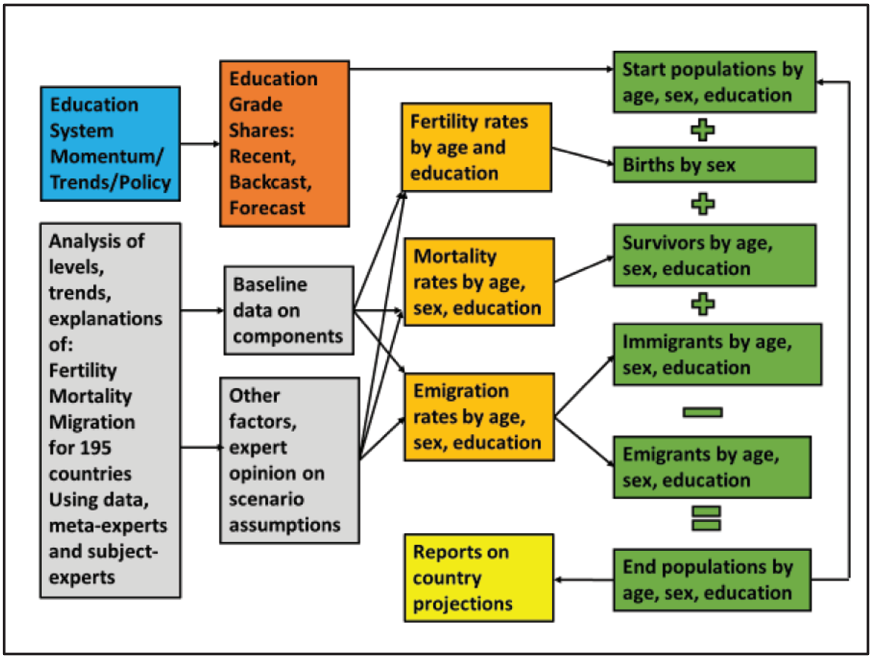
Mortality and fertility rates by educational grade are estimated so that the future numbers are dependent on this additional variable. However, educational composition (attainment rates by ages 30–34, and fixed at ages 35+) is projected independently for each country using a sigmoidal model fitted to past trends of percentages in each grade by age and sex. This is a projection of stock compositions. Transitions between educational grades are inferred from projected stock composition at five-year intervals, with no regression recognised (transitions to a lower grade from a higher grade) because the educational grade is defined as completed education.

The multi-state model is used to project emigration by multiplying the populations of countries by the emigration rates from the origin countries to the destination countries, and summing these rates over all flows to other countries. Immigration is projected by projecting emigration from all other countries to the country in question. For each time interval, a check is made to ensure that when all emigration flows are added to all immigration flows, net international migration worldwide is zero. If it is not zero, the emigration flows are adjusted to be equal to the sum of all immigration flows.

Because of the way net migration is used to estimate the educational composition of immigration flows, immigrants will have the educational composition of the destination country. Thus, the changing educational composition of the population will not influence the projection of total flows. The corollary of this observation, if correct, is that the Wittgenstein model cannot say anything about 'brain gain' (in advanced receiving countries) or 'brain drain' (in many developing and sending countries).

The WIC2014 model is described in Lutz et al. (2014a) using 665 pages of text, followed by 357 pages of results. Here, I offer one reader's understanding of the model through one figure and one table. While these observations are undoubtedly huge simplifications of a highly complex construction, and thus probably contain some errors, they may provide new readers with a useful overview of the model. Figure 1 presents a flow diagram of the WIC2014 model. On the top left-hand side is a box that refers to analyses of educational attainment in all countries, and that provides the knowledge that is employed to estimate educational grade shares by age and sex, and to construct a model for projecting those shares in three educational development scenarios (Barakat and Durham, 2014; Goujon et al. 2016). The projected shares are drawn upon at each five-year time step of the demographic projection model, and are applied to the end populations of countries. Below the education box is a box that refers to the analyses of levels, trends, and explanatory factors for the demographic components (Basten et al. 2014; Fuchs and Goujon 2014; Caselli et al. 2014; Garbero and Pamuk 2014; Sander et al. 2014; KC et al. 2014). These analyses produce baseline estimates of fertility, mortality, and emigration rates by age, sex, and education. The authors produced assumptions for the component rates for the medium scenario (SSP2) of the projections, and for four other SSP scenarios. The boxes on the right side of Figure 1 show the products of populations multiplied by the component rates – namely, births, survivors, immigrants, and emigrants – which cumulate to the end population in each five-year interval. The results of the projections for each country are organised into an elegant two-page spread. The first page shows indicator tables for the medium scenario populations and education shares, and graphs for population sizes

Figure 1:
The structure of the WIC 2014 model of population and human capital



Note: Author's interpretation

by education scenario and population pyramids. The second page presents five tables of populations and associated indicators for SSP scenarios that are also graphed, plus three tables of indicators summarising component assumptions by SSPs and a table of ageing indicators discussed in Scherbov et al. (2014). Table 2 provides more details on the WIC2014 model. The top panel describes the variables and the categories used to describe the country populations. The middle panel provides notes on the data and methods used to prepare the baseline population and components. The third panel summarises the assumptions made for the component rates and for the development of SSP scenarios.

In an epilogue to *World Population and Human Capital in the 21st Century,* Lutz (2014) summarised the work carried out by the Wittgenstein Centre team on the consequences for the future of embedding education in demographic projections. Crespo Cuaresma et al. (2013) showed that without the development of education, the advantage of the population concentrating at working ages will not be realised. Striessnig and Lutz (2013) and Lutz and Striessnig (2014) argued that the optimum fertility rate for European countries is a TFR that is below the replacement level if education and associated productivity are built into the calculations, at least in the medium term. This is because future cohorts will be better educated and more

Table 2:
Summary of the WIC2014 population and human capital projection model

Dimension	Categories	Documentation & sources
Country	171 countries plus 24 countries for which the educational grade distribution was inferred from similar countries. 195 countries with populations > 100,000	KC et al. (2014, p. 436)
Age	5-year ages: 0–4, 5–9 to 100+	UN population estimates
Sex	Male, female	UN population estimates
Education	E1 = no education, E2 = incomplete primary, E3=primary, E4 = lower secondary, E5 = upper secondary, E6 = post-secondary	Barakat and Durham (2014); Goujon et al. (2016)
Component	**Baseline estimates: data and methods**	**Documentation**
Population stock	Multiplying population by projected shares by education grade	KC et al. (2014)
Education	Mainly census data from IPUMS, EUROSTAT, CELADE, NSOs, UNESCO standardised & adjusted	Barakat and Durham (2014); Goujon et al. (2016); KC et al. (2014)
Fertility	Age-specific and total fertility rate series are assembled for low- and high-fertility countries (below and above a 2.1 TFR). Rate ratios are computed for educational grades.	Basten et al. (2014); Fuchs and Goujon (2014); KC et al. 2014
Mortality	Detailed analysis of life expectancy trends in low- and high-mortality countries. Education-specific life tables are developed.	Caselli et al. (2014); Garbero and Pamuk (2014); KC et al. (2014)
International migration	Origin to destination country flows are estimated from UN compiled census tables of population by country of residence and country of birth. Age is estimated by applying model migration schedules. Aggregated to origin country to rest of world flows, and emigration rates are computed.	Abel (2013); Abel and Sander (2014); Sander et al. (2014); KC et al. (2014)

productive. The WIC team has proposed that the more educated populations of the future will be better able to cope with the environmental challenges of climate change (Muttarak and Jiang 2015; Lutz, Muttarak and Striessnig 2014).

**Table 2:
Continued**

Component	Assumptions (medium)	Documentation
Education	Age-specific educational grade shares are moved forward as successive birth cohorts transition to older ages with an S-shaped model for projecting changes in shares.	Barakat and Durham (2014); Goujon et al. (2016); KC et al. 2014
Fertility rates	TFRs are projected using a combination of time series models, meta-expert views, and responses to an online survey by experts.	Basten et al. (2014); Fuchs and Goujon (2014); KC et al. (2014)
Mortality rates	Statistical model and country-specific expert assessments are used with assumptions about convergence to the best current levels. Country-specific factors (e.g. HIV/AIDS) are added.	Caselli et al. (2014); Garbero and Pamuk (2014); KC et al. (2014)
Emigration rates	Emigration rates are applied to origin countries; immigration = emigration from other countries. Educational composition of emigration flows is proportional to the origin country's educational composition. Educational composition of immigration is linked to a destination country's educational distribution. After 2060, emigration and immigration are assumed to converge to zero net international migration by 2100. Meta-expert and expert views are reported but are not built into the assumptions.	Sander et al. (2014); KC et al. (2014)
Alternative scenarios	Educational development under different assumptions. Alignment with Shared Socio-economic Pathways (SSPs) of IPCC.	KC and Lutz (2014)

Note: WIC2014 = Wittgenstein Centre projection model as described in Lutz et al. (2014a).

6 A future agenda

I hope that this review will help more readers come to grips with *World Population and Human Capital in the 21st Century*, and will, as a consequence, agree with me that this volume represents a huge contribution to our knowledge of the likely future of the people on our planet, and can therefore help us in navigating the challenges humanity will face over the rest of the 21st century.

What kind of work on education and demography will Lutz and colleagues turn to next? We discuss in this final section of the paper the following topics: the updating of the projections; efforts to convince international agencies to adopt the innovations of the WIC2014 model; controlled comparisons with alternative models and historical sensitivity tests used to convince the demographic community and agencies; improvements in the international migration component of the projections and links to migration policies; and the embedding of the population and human capital model in a world ecosystem that captures population-environment-economy linkages.

The first challenge is updating. As new data and new trends may have emerged since 2014, the projection's baseline data, and possibly its assumptions, need to be updated. Lutz et al. (2018) have already produced a revision of the WIC2014 results and introduced alternative migration scenarios by level of migration. One feature of the model that will need to be updated in the future is the treatment of education as attainment levels steadily increase; i.e. further differentiation of the types of learning and skills acquired will become necessary, particularly at the upper secondary and post-secondary levels. In the 2018 update for the 28 EU member states, a more detailed set of educational categories has been introduced that distinguishes between three levels of higher education: short post-secondary education, bachelor's degree, and master's degree or higher. Are national educational systems graduating people with the right skills? What is the optimal balance between the fields of science, technology, engineering, and mathematics (STEM) on the one hand, and humanities, arts, and social sciences (HAS) on the other? In addition, more attention should be paid to the quality dimension of education, which is the current focus of UNESCO international research on education (UIS 2017a; UIS 2017b). For example, the UIS (2017b) has found a huge disparity in outcomes at any given grade of education between countries across the world. In Sub-Saharan Africa, 88% of children and adolescents fail to achieve minimum performance levels in reading; while in North America and Europe, this figure is 14%. Thus, the transformation in the educational compositions of developing countries in the WIC projections needs to be accompanied by a quality assessment. Such research would help in further developing the education-specific labour force projections developed for the EU-28 countries by Loichinger and Marois (2018).

The second challenge is to convince international agencies to adopt the two key innovations of the WIC2014 model by adding education and international migration to the dimensions of world projection models. The agencies that might be involved in these efforts include the UN Population Division; the UN Development Programme; the UN Educational, Scientific and Cultural Organisation; the UN World Health Organisation; and the World Bank. Strengthening the argument for adopting the WIC2014 approach will require some additional research. First, historical evaluations of the model are needed. This would entail calibrating the model for one period (e.g. 1985 to 2000) and producing a forecast for a second period (e.g. 2000 to 2015) for which good estimates of the population by educational distribution have been created in the production of WIC2014.

Second, comparisons between the WIC model results and those of international agencies need to be performed by running the projections on software generalised to offer alternative model designs (e.g. no education vs. education included). Currently, comparisons of WIC model results with UN, World Bank, or US Census Bureau projections have focused on differences in the assumptions underlying the outputs (Abel et al. 2016). Studies on country-based sub-national projections have explored the consequences of alternative model designs with the same assumptions (Rogers 1976; van Imhoff et al. 1997; Wilson and Bell 2004; Wilson 2015), while another study has discussed the difficulties of making comparisons between published projections if model design differences are not considered (Rees et al. 2018). A recent systematic review of this question with applications of models of different degrees of complexity and assumptions for India is given in KC et al. (2018). However, Rees et al. (2018) has called such comparisons ‘interpretative’, as they are based on subjective judgements, rather than on ‘controlled’ experiments (e.g. Wilson and Bell 2004).

The WIC2014 model introduces international migration flow estimates produced by Abel and colleagues (Abel 2013, Abel and Sander 2014), while Abel (2018) has extended and improved these estimates. However, the ways in which these flow data are used in the WIC model could be improved.

First, there are survey and census data available on international migration from the destination countries that can be added to immigration-specific rate ratios by educational grade. Bernard and Bell (2018) have derived education rate ratios for internal migration for 56 countries covering 65% of the world’s population by employing International Public Use Microdata Samples (IPUMS) and census data to establish rate ratios that are both crude and controlling for other variables. However, most of the IPUMS datasets lack emigration data by origin country. Population data by country of birth and current residence, which are already used to generate the flow estimates of Abel and colleagues, might be employed to distribute immigrant rate ratios back to the countries of origin.

Second, the flow estimates themselves could be improved by adding the missing migration transitions of new-born survivors, migrants who have died, and new-born migrants who have died, as well as additional repeat and return flows, through assumptions like those employed by Rees and Wilson (1977) in their development of transition-based population accounts. It would also be helpful to clarify whether the WIC model used movement or transition concepts when incorporating international migration (Rees and Willekens 1986).

Third, there is an opportunity to develop a ‘gravity’ model of international migration flows that predicts flows using the population and labour market attributes of the origin and the destination countries, and impedance factors (e.g. distance in transfer costs, distance in language and culture, former coloniser-colonised relations, membership in a federation or a union of states) (Kim and Cohen 2010). Policy (controls on immigration) could be introduced into such a model. This model might be used to explore the transfers of human capital between countries ('brain drain' for developing countries vs. 'brain gain' for developed countries) and the role of 'counter-flows' of international remittances.

My final suggestion for a future agenda would be to take one step further and embed the population and human capital model in a world ecosystem that captures population-environment-economy linkages. In the WIC2014 model, the SSP scenarios are designed to supply alternative future populations for use by climate modellers. How would different climate change scenarios affect the growth and the distribution of the human population? Wittgenstein Centre research has already looked at the ways in which raising educational levels might help populations in adapting to climate change. Work on Population-Development-Environment models has been carried out by the IIASA leg of the WIC tripod (e.g. Lutz 1994).

References

Abel, G. 2013. Estimating global migration flow tables using place of birth data. *Demographic Research* 28(18): 505–546.

Abel, G. 2018. Estimates of global bilateral migration flows by gender between 1960 and 2015. *International Migration Review*. https://journals.sagepub.com/doi/pdf/10.1111/imre.12327, accessed on 10 December 2018.

Abel, G. and N. Sander 2014. Quantifying Global International Migration Flows. *Science* 343: 1520–1522.

Abel, G., B. Barakat, S. KC and W. Lutz. 2016. Meeting the Sustainable Development Goals leads to lower world population growth. *PNAS* 113(5): 14294–14299.

Barakat, B. and R. Durham 2014. Future educational trends. Chapter 8, 397–433 in Lutz et al. 2014.

Basten, S., T. Sobotka and K. Zeman 2014. Future fertility in low fertility countries. Chapter 3, 39–146 in Lutz et al. 2014a.

Becker, G. 1962. Investment in human capital: A theoretical analysis. *Journal of Political Economy* 70(5): Part 2, 9–49.

Becker, G. 1985. Human capital, effort and the sexual division of labor. *Journal of Labor Economics* 3(1): Part 2, S33–S58.

Becker, G. 1993. *Human Capital*. Chicago: University of Chicago Press.

Becker, G. and K. Murphy 1988. The family and the state. *Journal of Law and Economics* 31(1): 1–18.

Becker, G., K. Murphy and R. Tamuna 1990. Human capital, fertility and economic growth. *Journal of Political Economy* 98(5): Part 2, S12–S37.

Bélanger, A., G. Marois and P. Sabourin 2017. Microsimulation for assessing the impact of integration of migrants in Europe. Paper presented at the *Demographic Changes and the Impact of Migration Workshop*, 19–21 April 2017, Joint Research Centre for Advanced Studies, Ispra, Italy.

Bernard, A. and M. Bell 2018. Educational selectivity of internal migrants: A global assessment. *Demographic Research* 39(29): 835–854.

Caldwell, J. 1976. Towards a restatement of demographic transition theory. *Population and Development Review* 2(3/4): 321–366.

Caselli, G., S. Drefahl, C. Wegener-Siegmundt and M. Luy 2014. Future mortality in low mortality countries. Chapter 5, 226–272 in Lutz et al. 2014.

CEPAM 2018. IIASA-JRC Centre for Expertise on Population and Migration. http://www.iiasa.ac.at/web/home/research/researchPrograms/WorldPopulation/Research/Centre_of_Expertise_on_Population_and_Migration.html, accessed on 5 December 2018.

Crespo Cuaresma, J. 2017. Income projections for climate change research: A framework based on human capital dynamics. *Global Environmental Change* 42: 226–236.

Crespo Cuaresma, J., W. Lutz and W. Sanderson 2014. Is the demographic dividend an education dividend? *Demography* 51(1): 299–315.

Dustman, C. and A. Glitz 2011. Migration and education. Norface Migration Discussion Paper No. 2011-11. http://norface-migration.org/publ_uploads/NDP_11_11.pdf, accessed on 10 December 2018.

Fuchs, R. and A. Goujon 2014. Future fertility in high fertility countries. Chapter 4, 147–225 in Lutz et al. 2014a.

Garbero, A. and E. Pamuk 2014. Future mortality in high mortality countries. Chapter 6, 273–332 in Lutz et al. 2014.

Goujon, A. and W. Lutz 2004. Future human capital: population projections by level of education. Chapter 4, pp.121–157 in Lutz et al. 2004a.

Goujon, A., S. KC, M. Speringer, B. Barakat, M. Potančoková, J. Eder, E. Striessnig, R. Bauer and W. Lutz 2016. A harmonized dataset on global educational attainment between 1970 and 2060 – an analytical window into recent trends and future prospects in human capital development. *Journal of Demographic Economics* 82: 315–363.

Jagger, C., C. Gillies, F. Moscone, E. Cambois, H. Van Oyen, W. Nusselder, J-M. Robine, and the EHLEIS team 2008. Inequalities in healthy life years in the 25 countries of the European Union in 2005: a cross-national meta-regression analysis. *Lancet* 372: 2124–2131.

Jagger, C., H. Van Oyen and J-M. Robine, 2014. Health expectancy calculation by the Sullivan method: A practical guide. 4th Edition. Institute for Ageing, Newcastle University. http://www.eurohex.eu/pdf/Sullivan_guide_pre%20final_oct%202014.pdf, accessed on 5 December 2018.

KC, S. and W. Lutz 2014. Alternative scenarios in the context of sustainable development. Chapter 12, 591–627 in Lutz et al. 2014a.

KC, S., M. Potančoková, R. Bauer, A. Goujon and E. Striessnig 2014. Data and methods. Chapter 9, 434–518 in Lutz et al. 2014.

KC, S., M. Wurzer, M. Speringer and W. Lutz 2018. Future population and human capital in heterogeneous India. *Proceedings of the National Academy of Sciences*, 115 (33) 8328–8333; DOI: 10.1073/pnas.1722359115.

Kim, K. and J. Cohen 2010. Determinants of international migration flows to and from industrialized countries: a panel data approach beyond gravity. *International Migration Review* 44(4): 899–932.

Land, K.C. and A. Rogers (eds) 1982. *Multidimensional mathematical demography*. New York: Academic Press.

Loichinger, E. and G. Marois 2018. Education-specific labour force projections for EU-28. Chapter 4, 43–51 in Lutz et al. 2018.

Lutz, W. 2013. Demographic metabolism: A predictive theory of socioeconomic change. *Population and Development Review* 38: 283–301.

Lutz, W. 2014. Epilogue: With education the future looks different. Pp. 628–649 in Lutz et al. 2014a.

Lutz, W. and V. Skirbeck 2014. How education drives demography and knowledge informs projections. Chapter 2, 14–38 in in Lutz et al. 2014a.

Lutz, W., W. Sanderson, and S. Scherbov (eds) 2004. *The end of world population growth in the 21st century: New challenges for human capital formation & sustainable development.* London: Earthscan.

Lutz, W., W. Butz and S. KC (eds) 2014a. *World population and human capital in the twenty-first century.* Oxford: Oxford University Press.

Lutz, W., R. Muttarak and E. Striessnig 2014b. Universal education is key to enhanced climate adaptation. *Science* 346(6213): 1061–1062.

Lutz, W., A. Goujon, S. KC, M. Stonawski and N. Stilianakis (eds) 2018. *Demographic and human capital scenarios for the 21st century: 2018 assessment for 201 countries*. European Commission, Joint Research Centre. Luxembourg: Publications Office of the European Union. DOI: 10.2760/41776.

Muttarak, R. and L. Jiang (eds) 2015. Demographic differential vulnerability to climate-related disasters. *Vienna Yearbook of Population Research* 2015, Special issue, 287pp. Vienna: Austrian Academy of Sciences Press.

O'Neill, B., F. MacKellar and W. Lutz 2007. Population, greenhouse gas emissions, and climate change. Chapter 9, pp. 283–314 in Lutz et al. 2004.

Rees, P. 2018. Lecture (2): Collection of the Census. Lecture given to a delegation from the National Bureau of Statistics of China, Edinburgh, 18 October 2018. Available from the author.

Rees, P. and A. Wilson 1977. *Spatial population analysis*. London: Edward Arnold.

Rees, P. and F. Willekens 1986. Data and accounts. Chapter 2, 19–58 in A. Rogers and F. Willekens (eds) 1986. *Migration and settlement: A multiregional comparative study*. Dordrecht: Reidel.

Rees, P., S. Clark, P. Wohland and M. Kalamandeen 2018. Evaluation of sub-national population projections: A case study for London and the Thames Valley. *Applied Spatial Analysis and Policy.* https://doi.org/10.1007/s12061-018-9270-x, accessed on 10 December 2018.

Rogers, A. 1976. Shrinking large-scale population-projection models by aggregation and decomposition. *Environment and Planning A* 8(5): 515–541.

Rogers, A. 2008. Demographic modeling of the geography of migration and population: A multiregional perspective. *Geographical Analysis* 40: 276–296.

Sander, N., G. Abel and F. Riosmena 2014. The future of international migration. Chapter 7, 333–396 in Lutz et al. 2014.

Scherbov, S., W. Sanderson, S. KC. and W. Lutz, W. 2014. Re-measuring twenty-first century population ageing. Chapter 11, 563–590 in Lutz et al. 2014.

Stone, R. 1965. A model of the educational system. *Minerva* III(2): 172–186.

Stone, R. 1971. *Demographic Accounting and Model Building.* Paris: OECD.

Striessnig, E. and W. Lutz 2013. Can below-replacement fertility be desirable? *Empirica* 40: 409–425.

The World Bank 2018. GDP per capita (current US$). Washington, D.C.: The World Bank. https://data.worldbank.org/indicator/NY.GDP.PCAP.CD, accessed on 5 December 2018.

UIS 2017a. *Literacy rates continue to rise from one generation to the next*. Fact Sheet No.45, September 2017, UIS/FS/2017/LIT/45. Paris: UNESCO Institute for Statistics.

UIS 2017b. *More than one-half of children and adolescents are not learning worldwide*. Fact Sheet No.46, September 2017, UIS/FS/2017/ED/46. Paris: UNESCO Institute for Statistics.

UN 2015a. *World population prospects: The 2015 revision*. Key Findings and Advance Tables. Department of Economic and Social Affairs, Population Division. ESA/P/WP.241. New York: United Nations. https://esa.un.org/unpd/wpp/publications/files/key_findings_wpp_2015.pdf, accessed on 5 December 2018.

UN 2015b. *World population prospects: The 2015 revision*. *Methodology of the United Nations population estimates and projections*. Department of Economic and Social Affairs, Population Division. ESA/P/WP.242. New York: United Nations. https://esa.un.org/unpd/wpp/Publications/Files/WPP2015_Methodology.pdf, accessed on 5 December 2018.

UN 2017. International migrant stock: the 2017 revision. United Nations, Department of Economic and Social Affairs, Population Division. http://www.un.org/en/development/desa/population/migration/data/estimates2/estimates17.shtml, accessed on 5 December 2018.

UNDP 2018. *Human Development Indices and Indicators. 2018 Statistical Update*. United Nations Development Programme, New York. http://hdr.undp.org/sites/default/files/2018_human_development_statistical_update.pdf, accessed on 5 December 2018.

UNESCO 2017. *Accountability in education: meeting our commitments*. Global Education Monitoring Report 2017/18. Paris: United Nations Education, Scientific and Cultural Organisation Publishing.

Van Imhoff, E. and W. Post 1998. Microsimulation methods for population projection. *Population: An English Selection* 10(1): 97–138.

Van Imhoff, E., N. van der Gaag, L. van Wissen and P. Rees 1997. The selection of internal migration models for European regions. *International Journal of Population Geography* 3: 137–159.

Wilson, T. 2015. New evaluations of simple models for small area forecasts. *Population, Space and Place* 21, 335–353.

Wilson, T. and M. Bell 2004. Comparative empirical evaluations of migration models in subnational population projections. *Journal of Population Research* 21(2): 127–160.