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Johan Hauknes

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of researchers

Johan Hauknes
STEP
Storgaten 1
N-0155 Oslo
Norway

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Preface

Modelling mobility of researchers

Policies aimed at the mobility of researchers are an increasingly important element of science, technology and innovation policies. Perhaps the most visible indicator of this is the fact that "Training and mobility of researchers" is the most rapidly growing programme in the European Commission's FRAMEWORK Programme, with a 1994-98 budget of nearly 800 million ecu; this emphasis is also reflected in some national programmes. Interest in researcher mobility should be understood within the context of policies aimed at strengthening the *effects* of research-based knowledge. Mobility is considered important as a consequence of a growing recognition by policy makers that the use of research-based knowledge requires not only access to documented or codified knowledge, but also to tacit knowledges and skills. These tacit skills - uncodified, historically developed and usually localised - are in part a matter of knowing how to interpret, evaluate and transform codified knowledge to forms and contexts facilitating use. Thus the movement of researchers between institutions - and in particular from publicly-supported research insititutions to companies - is a way of enhancing scientific or technological competence which goes considerably further than simply ensuring that companies have access to formal and codified scientific knowledge.

However mobility has a dual aspect. If it enhances the capabilities of recipient institutions, then presumably it has also some inhibiting impact on the 'delivering' institution. This might be particularly the case if research-based knowledge is produced not by individuals but by teams in which interactive learning and collective knowledge-creation is taking place: mobility will disrupt team activities, and thus the effects of mobility will take the form of a more or less complex trade-off between positive benefits accruing to a recipient institution, and negative impacts on the team from which the mobile researcher comes. This paper is in large part an exploration of this trade-off.

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1. The importance of being mobile

From one perspective, mobility of researchers between a research-performing (RP) sector and a research-using (RU) sector is a quantitative phenomenon, being described by the absolute or relative number of researchers moving between the two sectors. But what makes this quantitative phenomenon interesting from a policy point of view is its *qualitative* aspects.

The usual assumption, that researchers possess tacit knowledge as a consequence of their experience as researchers, seems to imply that increased mobility *from* the RP *to* the RU sector, which might be termed first-order mobility, has a direct enhancing effect on the RU actors' ability to use, i.e., to interpret, evaluate and transform, scientific knowledge. Mobility widens the recipient's capabilities with respect to scientific knowledge because it is a carrier of the interpretative and evaluative skills that are conceived as main bottlenecks to effective knowledge transfer.

There is also what we might call second-order mobility, from the RU to the RP sector. This has a more indirect, although not necessarily less important, effect in supplementing the forces driving the continuous, dynamic development of research skills. The indirect effects of this mobility are twofold. It increases the value of the first-order mobility through its effect on the researcher's 'knowledge of scientific knowledge'. Secondly it gives additional weight to 'use-dependent' or *relevance* criteria for making priorities *within* the research establishment, enhancing the effects of priorities based on relevance criteria imposed at a political or strategic level.

These considerations would seem to imply that a specific aim of policy makers should be to stimulate mobility, especially when the usual perception is that the present mobility rate is too low. In this paper we will look at this issue in a stylized way: we regard the research performing sector as consisting of two independent systems - a system of higher education institutions (HEIs), characterized by the dual role of education and research, and a system of public or semi-public[1] research establishments with a research agenda being shaped by criterialegitimated and directed for a substantial part by research-external criteria and valuation. The latter system we term the research institutes system (RIs).

The research laboratories of individual business enterprises are not considered as part of the RP system, unless their services are offered to other enterprises outside the concern of which the enterprise is a part. Likewise joint research ventures and establishments are considered as part of the RU sector. Thus the RP system has a higher visibility, with a higher public awareness. The openness to strategic planning

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[1] Publicity is defined in terms of access, not of ownership. The RI system thus consists of research establishments that may be accessed by groups or categories of 'research users'. This includes includes institutions such as governmental laboratories, HEI-based research and extension centres, autonomous research institutions and institutions organized by industry associations.

Usually there will be close correlation between between publicity in these terms and the degree of public funding of the research activities.

and the substantial fraction of public funding makes the sector susceptible to public initiatives with respect to management, and in particular liable to mobility-enhancing schemes. Thus we would expect to see a connection between an RP-system making up a substantial part of the national research system and the existence of specific mobility schemes.

An RP-like system is found in many countries. If we consider technological research and research directed towards facilitating development of competitive business enterprises, these might include the Norwegian research institutes, the Finnish organization of tehnological research (VTT), the Dutch organization for applied research (TNO), as well as, at least partly, the German Fraunhofer institutes.

On top of the publicly funded component, a sizeable fraction of the research activities in these institutions is funded by private enterprises as research projects and programmes. However it is important to note that this system is *not* part of the private business (enterprise) sector. Even though its main rationale is in terms of its ability to support and enhance innovation in business enterprises, and even though it supplies research services on a commercial basis (and thus faces a marketlike evaluation of institutions in terms of customers' 'willingness to pay', with relevance implicitly understood as some sort of 'willingness to do further business' from business contract partners), there are also non-commercial criteria in play within such institutions.

As a basic rule these institutions are *non*-profit, and often explicitly so. The institutions legitimize themselves in terms of performing *research*, based on the staff members' identification as *researchers*. The success criteria for institutions like these are based on their prime product, usable knowledge, meaning they depend on both an evaluation by peers (in terms of research quality) and by potential users or users' representatives (in terms of market value). This combination of internal and external criteria will, almost with necessity and as consequence of the difference in reference point, lead to a split appraisal of the research institutes utility or 'relevance' for business enterprises, which contributes to explaining the interest in mobility stimulating schemes (MSS) from policy makers. Stimulating mobility rates is proposed and viewed as a way of 'narrowing the gap' between the two systems. The argument is thus that the differing judgment of relevance is a necessary prerequisite for the increased level of attention paid to mobility and mobility rates.

Policies for enhanced mobility imply that roles and goals are imposed on the research institutes which may in part be alien to these institutions' understanding of themselves. The institutions are viewed not only in terms of research performing and knowledge producing institutions, in accordance with internal perceptions of their own role. In addition they are given a role as training and educational institutions to meet needs outside their own four walls. Mobility and its effects are raised from a spin off of traditional activitities to a product category on its own terms.

The attention given to mobility issues by policy makers is in itself a reason to map mobility rates, to analyze mobility as an element in knowledge and technology diffusion and to analyze the effects of mobility in the receiving and delivering end of mobility channels. The work that the present paper is a part of is partly based on such

reasoning. But in addition our work in this field is based on an interest in mapping and understanding the dynamics of technology diffusion.

As technology diffusion is heavily integrated with the flow of tacit knowledge and skills, actual contacts between people, of which the category of researchers is one, ought to be a decisive factor in outcome of diffusion processes. These flows and contacts take many forms, of which actual mobility is but one. To the best of our knowledge there is no literature systematically assessing the different forms of mobility in relation to technology diffusion. [2]

Our point of departure is that the inherent skills base of business enterprises are continually changing and closely dependent on and determined by the tacit knowledges of personnel. This suggests that experienced individuals introduced to this environment may have significant effects on the future development of this base, and through this on the future development of the enterprise.

However at the same time as the receiving firm is supplied with an experienced researcher, the research institution gives one off. This quality reducing effect of researcher mobility is often forgotten in deliberations and policy formulation of MSS, in that the explicit and implicit assumptions that the forms the basis of the policy formulation is forgotten.

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[2] Even a 'classic' in the diffusion literature like E. M. Rogers **Diffusion of Innovations**, The Free Press, New York 1983, does not mention of transfer of individuals as a way of disseminating knowledge. In fact the definition of diffusion given by Rogers, "the process by which an innovation is communicated through certain channels over time" (Rogers, p. 10) excludes physical flow of individuals. Neither of the two social roles *opinion leaders* and *change agents* that he discusses, cfr. chap. 8 and 9, includes the role of a transformation between the two, from a change agent role to an opinion leader.

2. The problem and rationale of a formal model

The reader might object to the starting point of this paper, that simple formal mathematical models have a story to tell, with the assertion that stimulating mobility is a question of giving priority to quality-enhancing effects in the business sector, irrespective of side effects in other sectors. The objective of stimulating a better and more efficient use of scientific knowledge is important in itself, making it legitimate to give it priority as an area where possible side effects are of lesser priority.

We will argue that arguments like these miss some fundamental points. But first let us make some further remarks about the problem, as a way of justifying a modelling approach to analysing it.

The interest in mapping and stimulating mobility patterns is evidently based on two assumptions. The first assumption is that there must be a potential for 'better use', i.e., that the present use of scientific knowledge in business enterprises is deficient in some way. At least a partial way to realize this potential is to make more use of experienced researchers. There must however be a lack of awareness of this potential in the firms. If the awareness had been complete in all respects, the firms would have established a demand, reaching an equilibrium conditioned by the specific labor market. In this equilibrium MSS would be superfluous.

The second assumption, 'explaining' the lack of awareness in business firms, is that the RP system is not 'relevant' enough, i.e., it is not integrated sufficiently with the sectors consisting of its main contract partners and receivers of the prime 'products'.

These assumptions seem to underpin MS schemes, but they have to our knowledge not been exposed to a empirical or logical verfication, and the factual content of the assumptions is left more or less unverified.

But there is no denying the fact that mobility of researchers has a stimulating effect in the economy. On the contrary, as a matter of principle, mobility has such effects. As long as potential employers signal a positive price for the competence of experienced researchers, this shows an expectation of a positive value by the firm. On the other hand enhancing mobility may have devastating effects on the RP system. Everyone would agree that an annual mobility of 50% would quickly destroy a research establishment and break up the 'relevance' pattern. A vanishing mobility rate may have dramatic conserving effects. If we make the reasonable assumption that demand is an increasing function of research experience, the age distribution of the 'mobilized' researchers will be more heavily skewed towards the experienced researcher, relative to the age distribution of the RP system itself.

For reasonable mobility rates we would expect to see such 'brain drain' effects emerging on a longer time scale than the time scale of the quality improvements on the receiving end. In the short run, or considering small 'ad hoc' bursts in mobility rates, it might be appropriate use a static formulation, neglecting brain drain effects, as a *first order approximation*. But if changes in mobility patterns are systematic,

these longer term effects will show up as a reduction in the quality of the primary activity of the RP system, and through this in its 'relevance'.

Striking the balance between two opposing forces is hard. A willingness to change existing mobility patterns has to consider this balance. If one accepts that the present pattern is an outcome of the dynamic properties of the underlying labor markets, it is also evident that this pattern mirrors an 'market-determined' balance between these opposing forces. Unless one is certain that one's own knowledge of potentialities exceeds that of the primary actors, the researchers, their institutions and the business firms, there seems clearly a need for caution in changing this balance. This is especially important if the actual patterns are stable in time and space (which they roughly seem to be, see below).

But in the end one would have to base policy formulation on some kind of conceptual view of how these two antithetical processes (benefits from knowledge transfer and costs of 'team' loss) interact with each other. This is an area where model building and experience with their use have a significant effect. Models have their prime rationale in terms of rigorously exploring the implications of intuitions. That is, models are not intended to explain the world 'as it is', but rather to describe the world 'as it could be' in an idealized setting. What makes models worthwhile is not that they should capture all aspects of real life, but that they include a realistic representation of all or some of the aspects of real life that are considered to be of importance.

Numeric models must be viewed as idealized worlds, or numeric playgrounds. Whether models are good or bad is a question of whether the model incorporates important (but not necessarily complete) aspects which relate it to a 'real life' situation, i.e. to the goals the model is aimed at. The *justification* of the model determines its quality, not its inherent properties (conditioned of course on the truism that the model is logically consistent).

This strikes two related, cautionary notes. If the results of the model are to have any bearing on reality, the results should have a certain robustness against specific model characteristics, avoiding use of model-dependent, model-specific results. The other note is the importance of the traditional qualification in the economics literature of *ceteris paribus*, every model is based on, often implicit, simplifications, implying an unsaid condition of 'other things being equal'.

When the Research Council of Norway establishes, as it recently did, a 15% p.a. target mobility rate from the technologically oriented research institutes, the Council chooses one single number to have validity across technologies, institutions and business sectors. One would expect that such a number would be established through considerations of the underlying dynamics and of optimality conditions for the balance between quality reduction in the RP system. This does not seem to be the case. The target of 15% seems to have been set on the basis of the present mobility and a political signal value in increasing the rate.

This is an instance where numeric models may be of explicit help. As mentioned earlier the intuition behind the targets is based on relatively simple considerations. These considerations seem to be based on one of two conceptual models, or 'mental

images[3]. Any model that incorporates more realistic assumptions than these, at the same level of simplicity, has the potential of giving a better insight into the effects of such targets.

One valid objection to this is that the interindustry and interinstitutional differences are more important than any assumptions of a generalized behaviour and dynamics. But if this is correct, which in principle is open to empirical verification, then the basis for a general target rate vanishes at the same time. We turn now to an anaylsis of a range of formal models of mobility processes and their effects.

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[3]   Policy formulation processes may be understood in terms of a set of mental images, simplified, often tacit, models of the policy object. These mental images are based on a set of simplifying assumptions that makes the (complex) policy object and its interrelations with its environment amenable to policy formulation. The concept of mental images is related to the concept of 'thought forms' described by Aant Elzinga. These ideas will be elaborated in a forthcoming paper.

3. Two Models

3.1 The 'tube' model

What we call the 'tube' model is an extremely simplistic model of researcher mobility. The research institution is composed of $M + 1$ age classes of equal size n. Every researcher stays in the institution for $M + 1$ years, and at the end of the period the whole age class quits and finds occupation in other sectors of the economy. An age class of age 0 replaces the outgoing age class. The probability that any individual researcher quits between the present period and subsequent one identifies this as a 'tube' model and is given by

$$p_i = \begin{cases} 0, & i < M \\ 1, & i = M \end{cases}$$

with the occupation of each non-vanishing age class being $n = N/(M + 1)$. This simple model is thus uniquely determined by two parameters.

The mobility rate is then simply the ratio of the occupation of age class M and the total population N. By construction, the 'tube' model is determined by only two parameters.
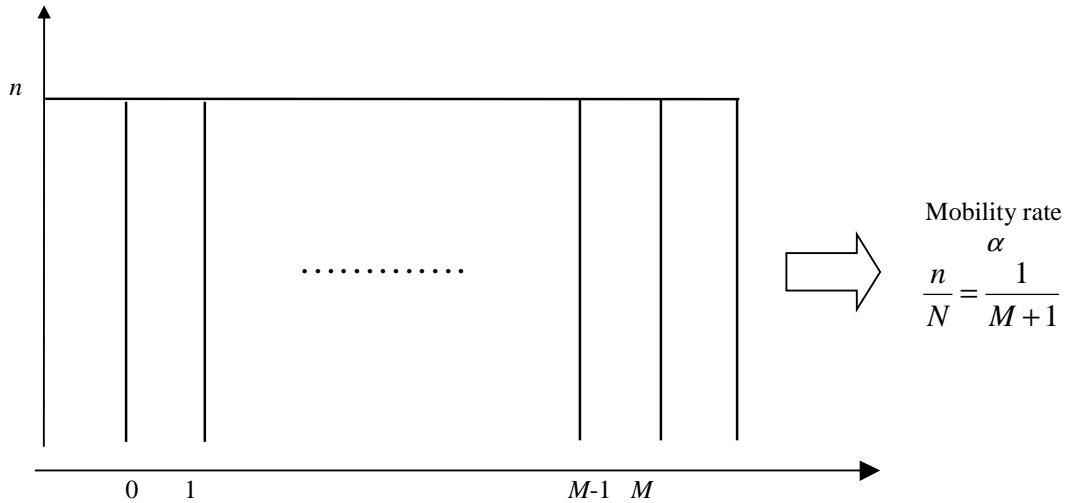

Figure 1. The tube model

3.2 The colinear model

The colinear model is slightly more realistic than the 'tube' model since it includes a non-vanishing probability of mobility in each age class. The model is determined by specifying that the *absolute* mobility out of each age class i, $\Delta n_i (t) \equiv n_{i+1}(t+1) - n_i(t) = \Delta n$, is both time and class independent.

If N is the total and constant population, the model is uniquely specified with two parameters, f.i. N and M,

$$n_i = (M + 1 - i)\Delta n$$

$$\Delta n = \frac{2N}{(M+1)(M+2)}$$

yielding a mobility rate $\alpha = 2/(M+2)$, roughly twice the mobility of the 'tube' model. As with the 'tube' model the outflux is replaced by a constant and equally sized influx into age class 0.

The probability of an individual researcher of age class i leaving the population between the present and subsequent time period is

$$p_i = \frac{\Delta n}{n_i} = \frac{1}{M + 1 - i}$$

Rightly this allows non-vanishing exit rates from all age classes, but with an unrealistic variation. In fact the model may be viewed as constructed to reproduce a predetermined mobility rate, working 'backwards' to individual exit rates. As the previous model, it is determined uniquely by just two parameters.
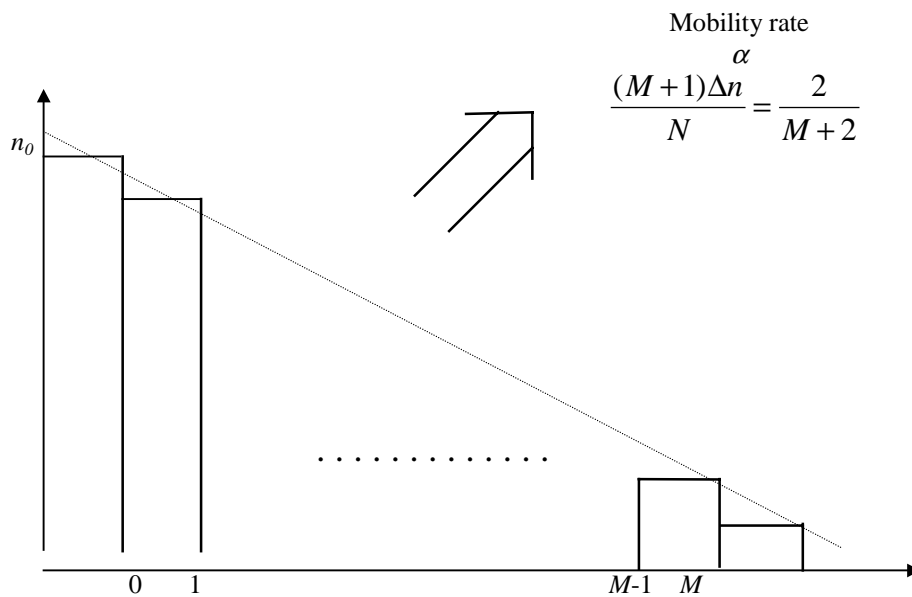

Mobility rate

$$\alpha$$

$$\frac{(M+1)\Delta n}{N} = \frac{2}{M+2}$$

Figure 2. The colinear model
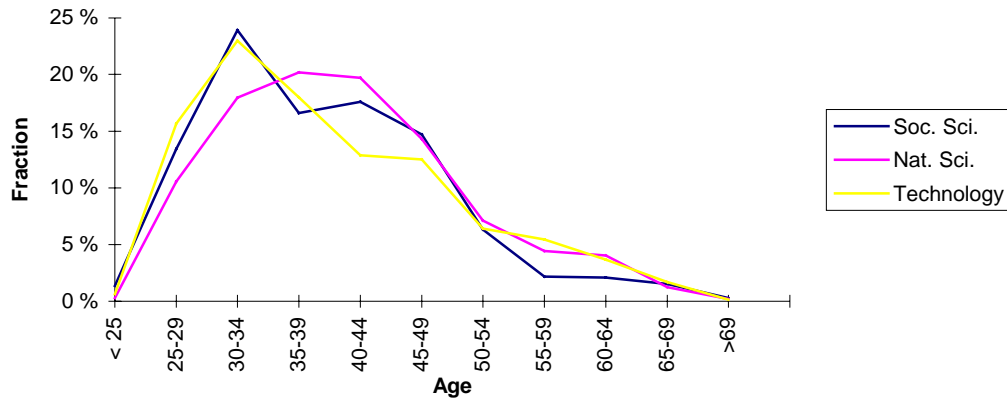
3.3 Age distribution in the RI-system

Figure 3a. Age distribution of personell in the Norwegian research institutes sector 1991. Source: Institute for Studies in Research and Higher Education, Research Personell Register
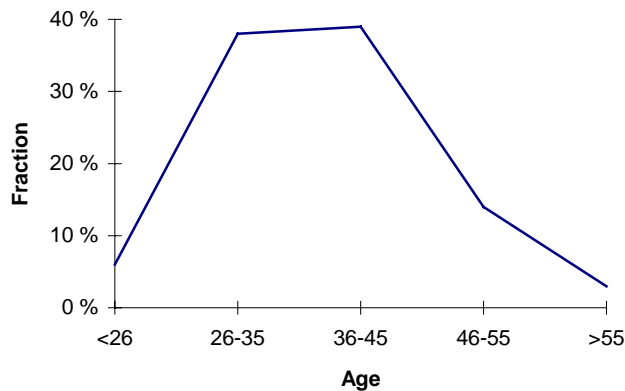

Figure 3b. Age distribution at VTT institutes 1991. Source: VTT, Helsinki

The profile given in the two preceding models may be compared to actual data of the age distribution. The data we use is based on the researcher's physical age and the time since her/his recruitment. The comparability of the data is thus acceptable to the extent that recruitment is peaked around one certain value of physical age or at one given phase of the resarch career. We will come back to this below.

The age distribution of the Norwegian institutes sector in three research fields is given for 1991 in fig. 3. The data, given in 5-year bins, are compared to coarser data, given in 10-year bins, from the Finnish VTT organization, also from 1991.

Three tentative conclusions may be drawn from these data. First, the relative similarity in the age distribution across research fields and countries seems to indicate a configuration that is fairly stable against variations in such parameters. Similarly Norwegian data for the period 1985-91 also seem to indicate a roughly time independent age distribution (see Fig. 4). The last conclusion to be drawn from these data is that the differences between these distributions and the model distributions given above does not support their case.
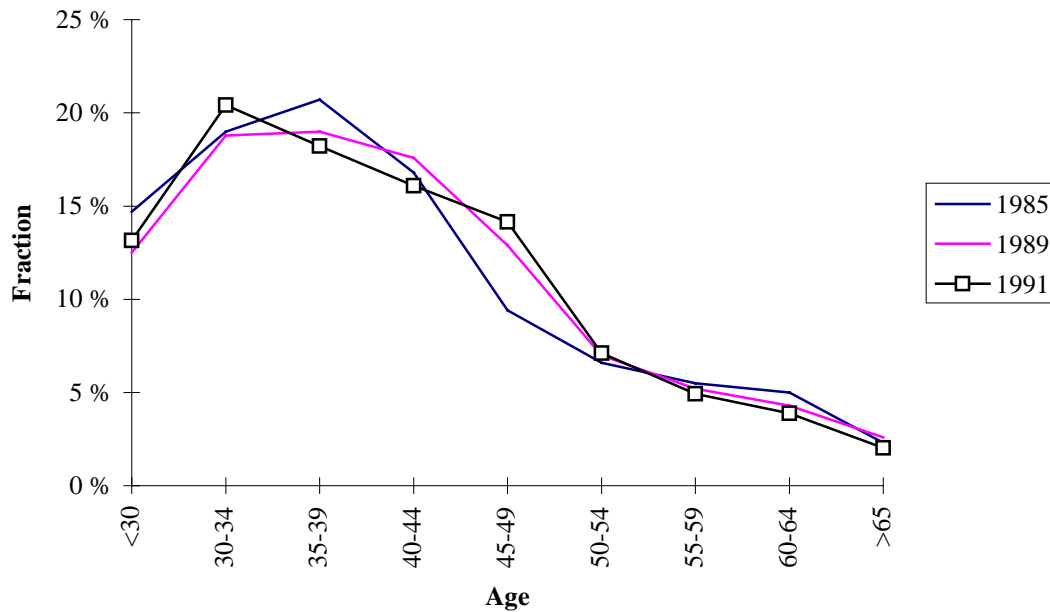
*Figure 4 Age distribution as fraction of the Norwegian R&D personell in the
research institutes sector 1985, 1989 and 1991. Source: Institute of Studies in
Research and Higher Education, Research Personell Register*

3.4 Empirical data for mobility and recruitment

The empirical data that is used in this paper is given and described in H. Wiig and A.
Ekeland, *Forskermobilitet i instituttsektoren*, STEP 1994, except where otherwise
stated.

4. Prerequisites for general models

There are two basic arguments which suggest the importance of a cautionary stance towards models like these, i.e., models that are not based on the underlying dynamics of mobility patterns. The first is that exit rates should form one of the basic building blocks of the model, the other that the model should allow comparisons between different age distributions, whether in ensembles or as a time development.

Realistic models should allow the human factor to come into play. The set of simple models that we consider in this paper is based on two basic assumptions,

P1   Apart from age class, the individual researchers are indistinguishable, we may talk of a representative researcher of age class *i*.

P2   'The human factor' enters the models through two sets of parameters. First each individual researcher has the choice between two alternative states in the next period, to leave or to remain. As a concequence of **P1** the probability for choosing any of these is the same for all members of the same age class, with these probabilities as independent variables. Secondly there is a consideration of the magnitude of substitution through recruitment. The decision of a particular magnitude is independent of any other model parameters.

Furthermore we will assume that the basic model system is large enough to allow for a probabilistic treatment, i.e. that the actual outcome of each transition mirrors the probabilities of the choice of states. This requires that the ratio of 'remainers' to the size in a given age class is equal to the probability of choosing to remain, and similarly for the 'leavers'.

Based on these assumptions we describe a general class of models. These models may be reformulated in terms of transitions between different 'global' states, where the states are described by a set $\{n_i\}$ of occupation numbers and where the transition is a mapping

$$T_t : S_t = \left\{n_i\right\}_t \rightarrow S_{t+1} = \left\{n_i^{'}\right\}_{t+1}$$

The time independent distributions are the fixed points of the mapping T_t . This opens up for a formulation in terms of Markov processes, or random walk. Transition analysis and the present formulation exhibit a large-*N* complementarity[i].

One set of advantages of the present formulation, which at the same time points to its disadvantages, is that it is simple and deterministic. Thus the formulation should be easier to mediate for illustrative and analytical purposes to policy makers. One other advantage of the present quasi-deterministic formulation is that the model is expressed directly in terms of the 'anthropogenic' parameters that determine the time evolution. These parameters are thus directly accessible to exogeneous modifications and interaction with external systems.

The model described below is not yet dynamic, in the sense that dynamic evolution in the model is exogenously determined. An 'endogenization' of the dynamics requires a coupling between the model and the external sectors, ensuring a dynamic determination of exit and recruitment rates.

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[i] Consider a single age class. Then the transition from period t to $t + 1$ is a simple Bernoulli process. If the probabilities for an individual researcher are π_L and π_R for resp. leaving and remaining, the exit rate will be

$$L/N \approx \pi_L$$

in the large-N limit, where L is the number of leavers and N is the total number of members of the age class. The probability that L researchers leave is

$$p_L = \binom{N}{L} \pi_L^L \pi_R^{N-L}$$

with the most probable number of leavers being

$$L_{m.p.} = \left[(N+1)\pi_L \right]$$

The most probable exit rate is then

$$r_L \equiv \frac{L_{m.p.}}{N} = \frac{\left[(N+1)\pi_L \right]}{N} \xrightarrow{N \to \infty} \pi_L$$

In terms of the model parameters in the next chapter, we conclude that we may identify

$$r_{L,i} \sim \pi_{L,i} \sim 1 - e^{-\lambda_i} \sim \lambda_i,$$
$$or \quad \pi_{R,i} \sim e^{-\lambda_i} \sim 1 - \lambda_i$$

5. A general model

We assume a population of individual researchers of 'age' $i \in [0, M]$ for some large M. The parameter i counts the number of periods the individual researcher has spent in the research establishment. Thus i may be considered as a measure of seniority. As we are considering specialized research systems oriented towards applied aspects of specific technological fields or for specific industries, it seems reasonable to assume that *young recruits* taken from HE institutions start out with seniority 0, even though they may have some research experience from their original scientific field. Since shifts in research fields are associated with a significant decline in research productivity in the first 2-3 years after the switch[4], this seems reasonable.

The model is formulated in discrete time t = 0, 1, 2, ..., measuring calendar years from an arbitrarily chosen starting point.

The dynamic assumptions are,

A1   Researchers of age i at time $t \geq 0$ either leaves or transforms to age $i + 1$ in the next period $t + 1$.

A2   Researchers i at time t leaves before the start of the next period with exit rate of change $\lambda_i(t)$.

In addition the population is renewed through recruiting measures,

A3   Between the periods t and $t + 1$ $\delta N(t)$ researchers are recruited. The $\delta N(t)$ has a time-dependent age distribution given by parameters $\{\varphi_i(t)\}$, where $\varphi_i(t)$ is the fraction of the total recruitment $\delta N(t)$ to age class i between the periods (thus $\sum_i \varphi_i(t) = 1$).

These three prescriptions describe a class of models of general validity (in the large-N limit) in terms of $2(M + 1)$ parameters; $M + 1$ exit rates $\lambda_i(t)$, M recruit fractions $\{\varphi_i(t)\}_{i=1}^{M}$ and the total recruitment $\delta N(t)$. These exogeneous parameters determine the dynamics of the model. They are themselves determined by the interaction between the RI system and and other sectors, i.e. they are determined on the different labor markets surrounding the RI system. The general model may be depicted as in fig. 4.

A3 may be simplified, reducing the necessary number of parameters in the model to $M + 2$,

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[4]   A. van Heeringen and P.A. Dijkwel, **The relationships between age, mobility and scientific productivity**, *Scientometrics* **11** (1987) 267 (Part I) and 281 (Part II)

A3'   all recruitment is of individuals with age 0.

Whereas the assumptions **A1 - A3** are quite general, the last simplification of A3 is truly a restricting assumption. The empirical basis for choosing **A3'** is given in paragraph 6. In terms of Norwegian research institutes this accounts for the single largest group of recruits, making up for about 50% of the total recruitment in 1992.
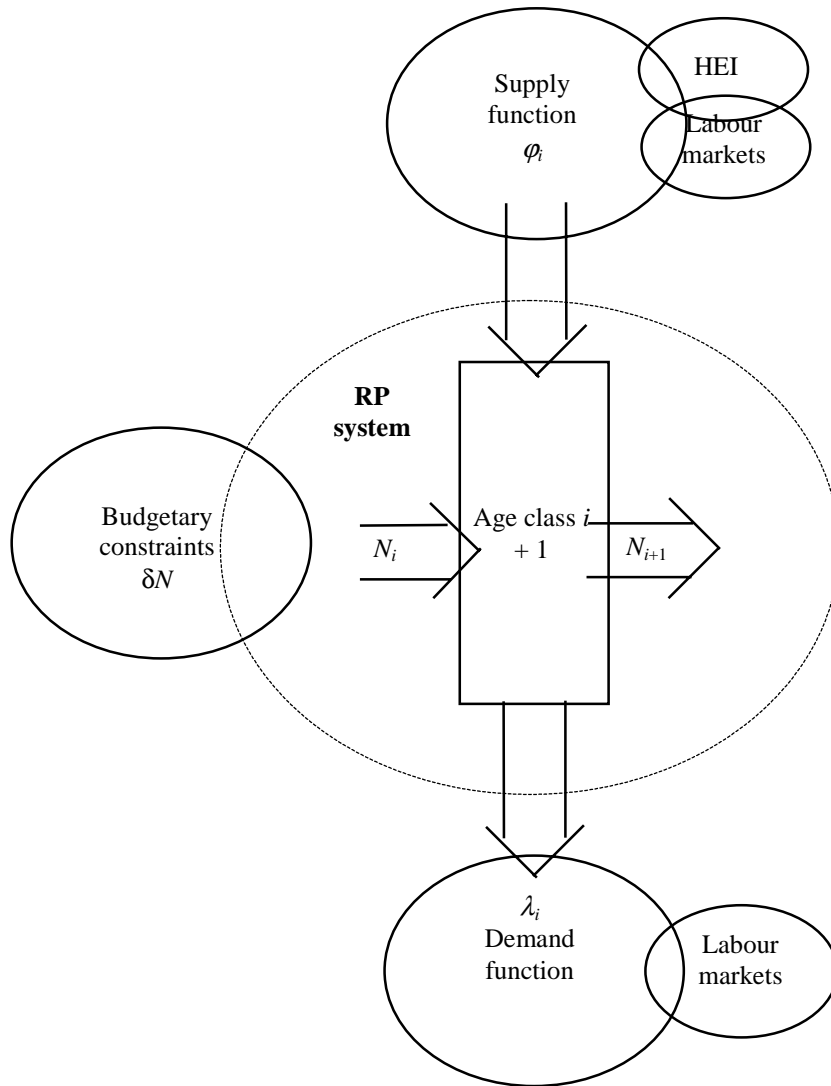

Figure 5. A model of mobility of researchers

The policy formulation programme may be formulated in terms of these general models as a simultaneous maximisation of two quality, or utility, factors. We may describe a quality function

$$\sigma = \sigma(\{N\})$$

of the research system with an implicit dependence on recruitment $\{\varphi\}$ and mobility $\{\lambda\}$, being determined resp. by supply and demand factors. Secondly we may define a quality function

$$\Sigma = \Sigma(\{\lambda\})$$

as measuring the demand for R&D experience and knowledge in the external labour markets. The policy programme thus entails the simultaneous optimisation of

$$\max \sigma \quad \text{and} \quad \max \Sigma$$

It is evident that any maximisation of any single of these will lead to a sub-optimisation, there are f.i. no 'natural' limits to a maximisation of σ, disregarding Σ. The balance is struck between the λ-suppressing and φ-enhancing effects of σ and the λ-enhancing and φ-suppressing (through substitution) effects of Σ.

5.1 The model

The model, when based on **A1**, **A2** and **A3'**[5], may then be expressed as

M1 $\qquad N_i(t+1) = e^{-\lambda_{i-1}(t)} N_{i-1}(t), \quad i \geq 1$ $\qquad\qquad$ (1)

M2 $\qquad N_0(t+1) = \delta N(t) \equiv \sum_{i=0}^{\infty} (1 - e^{-\lambda_i(t)}) N_i(t) + \Delta N(t)$ $\qquad$ (2)

In eq. (2) we have expressed $\delta N(t)$ in terms of the change $\Delta N(t)$ in the total population; $\Delta N(t) = N(t+1) - N(t)$.

We introduce as boundary condition at $t = 0$,

$$N_i(0) = \mu_i, \quad i \geq 0 \qquad\qquad (3)$$

where $\mu_i \geq 0$ are numbers describing the original age distribution.

The *mobility* $\alpha(t)$ between period t and period $t + 1$ is then given by the aggregate exit rate,

$$\alpha(t) \equiv \sum_{i=0}^{\infty} (1 - e^{-\lambda_i(t)}) N_i(t) / N(t) \qquad\qquad (4)$$

5.2 The solution

The simplified (in terms of **A3'**) model[ii] is immediately solved by

$$N_i(t+1) = \begin{cases} e^{-\sum_{l=1}^{t+1} \lambda_{i-l}(t+1-l)} \mu_{i-(t+1)}, & i \geq t+1 \\ e^{-\sum_{l=1}^{i} \lambda_{i-l}(t+1-l)} N_0(t+1-l), & i \leq t \end{cases} \qquad (5)$$

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[5] $\qquad$ If we use **A3**, eqs. (1) and (2) is modified by adding a term $\delta N_i(t) = \varphi_i(t)\delta N(t)$ to eq. (1) and substituting $\delta N_0(t) = \varphi_0(t)\delta N(t)$ for $\delta N(t)$ in eq. (2). The general solution is given in endnote ii)

Thus the age distribution in period t is divided into two categories, the remnants of the original distribution $\{\mu_i\}$, getting older and older, and the new generations that have been recruited during the periods $t > 0$.

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ii   The solution of **A1**, **A2** and **A3** for if $\varphi_i \neq 0, \quad \forall i$ is

$$N_i(t+1) = \begin{cases} e^{-\sum\limits_{l=1}^{t+1} \lambda_{i-l}(t+1-l)} \mu_{i-(t+1)} + \sum\limits_{m=0}^{t} e^{-\sum\limits_{l=1}^{m} \lambda_{i-l}(t+1-l)} \varphi_{i-m}(t-m)\delta N(t-m); & i \geq t+1 \\ \\ \sum\limits_{m=0}^{i} e^{-\sum\limits_{l=1}^{m} \lambda_{i-l}(t+1-l)} \varphi_{i-m}(t-m)\delta N(t-m); & i \leq t \end{cases}$$

Here $N_i(t+1)$ is expressed in terms of the exogenous parameters $\{\mu, \varphi, \lambda, \delta N\}$. Assuming **A3'**, i.e., $\varphi_i = 0$, $i \geq 1$, this simplifies to

$$N_i(t+1) = \begin{cases} e^{-\sum\limits_{1}^{t+1} \lambda_{i-l}(t+1-l)} \mu_{i-(t+1)}; & i \geq t+1 \\ \\ e^{-\sum\limits_{1}^{i} \lambda_{i-l}(t+1-l)} \delta N(t-i); & i \leq t \end{cases}$$

A further simplification is to assume a constant population N, $\delta N(t) = \alpha(t)N$, where $\alpha(t)$ is the mobility rate between periods t and $t+1$.

6. The sustainability index

We will now introduce an index[6] $\sigma(\{N_i(t)\}) \equiv \sigma(t)$ that in some way characterizes the age profile at any time t, giving a measure of the research staff's value or quality, for the research institute or for society. We will assume that this value for any given researcher has a specific functional form. Thus $\sigma(t)$ is a quality function in the sense of section 8.

We will argue that the most important contribution to such a valuation is personal experience, using age as a proxy, and network effects, arising through combinations of pairs, triples, etc. of generations. The value $\sigma(i)$ of a given generation is assumed to be an increasing function of age i. Running through the life cycle of an individual researcher, the value σ should be small at the beginning of a research career, growing significantly through a transition period and then stabilize on a high plateau as the researcher enters a phase of seniority.

The total value of $\sigma\{N_i(t)\}$ arise then through several interactions. First of all each generation has a value on its own term, measuring the experience and value of each generation in itself. Secondly there are terms describing value-enhancing interaction between generations, since the value of generation i is enhanced by the presence of generations $j \neq i$.

Qualitatively we may thus write $\sigma(t)$ as a sum of diagonal terms and crossterms,

$$\sigma(t) = \sigma_d + \sigma_{off}$$
$$= \sum_i \varphi_1(N_i(t))\sigma(i) + \sum_{i \neq j} \varphi_2(N_i(t), N_j(t))\sigma(i,j) + \text{higher order moments}$$

6.1 Diagonal terms

In the formulation above we have assumed that the scale enters multiplicatively. Thus $\sigma(i)$ is a valuation of an individual researcher of age i. The scale dependent phase must then evidently be an increasing function of scale. Hence

$$\varphi_1(N_i) \sim N_i^{\alpha_i}$$

where $\alpha_i = \mathcal{O}(1)$. When i is 'small', there should be positive scale effects, $\alpha_i \geq 1$, as the probability of younger researchers with coinciding research fields increases and 'colearning' effects appear. When i is 'large', there should on the other hand be negative scale effects, $\alpha_i \leq 1$, because of increased probability for 'crowding out' effects of experienced researchers as 'national experts'. The effect of such a scale factor is thus to favor 'large' young generations and 'small' experienced generations.

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[6]   The index is constructed as an analytical tool for comparing different age distributions, and is not intended as presciptive index to evaluate the performance of any single research establishment.

Significant deviations from 'constant returns to scale' should evidently be a large-N effect, that is φ_i should be given by a scale factor α_i close to unity, $\alpha_i = 1 + \delta_i$, with $|\delta_i| << 1$,

$$\varphi_1(N_i) \sim N_i\left[1 + \delta_i \ln N_i + \mathcal{O}(\delta_i^{\,2})\right]$$

Thus if $\delta_i > 0$, the contribution of small generations are suppressed relatively to larger ones, and vice versa if $\delta_i < 0$. Below we will simply put $\alpha = 1$ for all generations, simply for wont of criteria for distinguishing between different possible values. We recognize that we overestimate the contribution of the large generations of the experienced kind, and underestimate the contribution of large, young generations, for reasonably sized generations[7].

We put

$$\varphi_1(N_i) = N_i^{\alpha_i}\rho(N - N_i)$$

where $\rho(N\text{-}N_i)$ is a smeared version of the ϑ-function, cf. fig. 6.
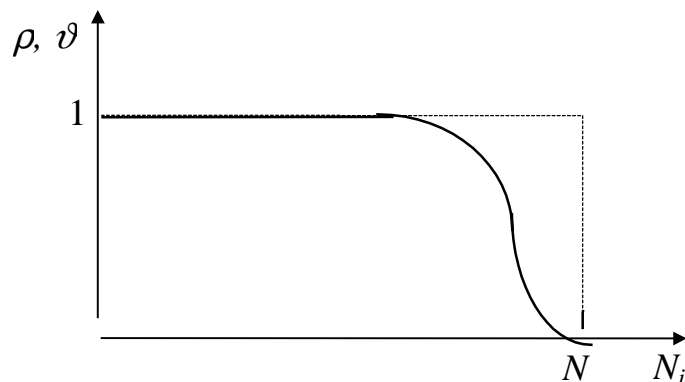

Figure 6. The smearing effect of the quality index for large N_i .
The next step is to see if we can establish a functional form of $\sigma(i)$. Evidently the index $\sigma(i)$ should be a measure of the knowledge of the individual researcher. In terms of research institutions where the main activity is research projects financed by external 'customers', a valuation would be based on the ability of researchers to acquire externally financed projects. Thus one possibility for such a measure would be project acquisition, identified per researcher, measured as some form of degree of self-financing. Even if it should be possible to identify such data, it is an open question if they are meaningful, as project acquisition evidently is more of a 'group' concept than an individualized concept. The fact that a research institution is organized with functional differentiation between the individual members, as research directors, group leaders, senior and junior research personell, illustrates that.

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[7]   That is, we assume that N_i/N is significantly less than unity, as it is unreasonable to assign larger values to configurations with $N_i \sim N$, i.e., with the population concentrated on one generation.

On the other hand we may argue that the valuation should be given more directly in terms of the individual researcher's accumulated knowledge, i.e., as a measure of the researcher's knowledge 'volume', or that part of this volume that is 'relevant'.

We argue that there must be two general characteristics that such a measure must fulfill. The first is that knowledge accumulation is evolutionary; the measure is a continuous function of the accumulation process. The measure should model the aspects of organic growth that characterizes the development of mental concepts.

The other characteristic is tied to the dynamics of the time evolution. The measure's change over time should first of all reflect that the growth of knowledge is conditioned by the present knowledge and the invested time τ in knowledge acquisition,

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\tau} = f(\sigma, \tau)$$

As a zeroth order approximation we will simply put $f^{(0)} = k_0$, the 'velocity' of knowledge acquisistion is a constant. Within limited domains of time this may seem as a reasonable approximation. Letting the time window expand, however, it does not capture a 'learning to learn' effect, that the 'velocity' for small τ should be an increasing function of time.

A first order approximation that captures this is

$$f^{(1)}(\sigma, \tau) = k_0 + k_1 \frac{\sigma(\tau)}{\tau}$$

and we argue that is a suitable form. This takes care of two effects. As a researcher acquires new knowledge, (s)he has expanding possibilities for 'generalising' the knowledge 'volume' in new directions, as well as being exposed to an increasing 'unknown territory'. Another volume dependent learning effect lies in the fact that as (s)he acquires experience with knowledge acquisistion in the research field, the knowledge of potential sources and methods for developing the knowledge get refined. Both of these volume-type terms must therefore be moderated. As the present knowledge volume, measured by $\sigma(\tau)$, increases, new knowledge is harder to get at, requiring increasing resources. We choose to moderate the development with a term proportional to time τ.

For large τ, however, this would lead to a 'velocity' and knowledge value, or volume, that increases without limits. But knowledge is not established once and for all. 'Valuable' knowledge must be rephrased and reformed in light of later acquired knowledge. There are many possible functional forms that could account for such effects. We fix the form by assuming that the rate of change σ due to this effect is proportional to σ and to the rate of change of τ. This may also be seen as a quantification of the common experience that 'the more you know, the more you know that you do not know'. Evidently the term must be negative definite,

$$\frac{\Delta\sigma}{\sigma} \propto -\sigma\frac{\Delta\tau}{\tau}$$

In accord with this the second order approximation becomes

$$\frac{d\sigma}{d\tau} = f^{(2)}(\sigma,\tau) = k_0 + k_1\frac{\sigma(\tau)}{\tau} - k_2\frac{\sigma^2(\tau)}{\tau} \qquad (6)$$

By fixing an arbitrary scale of σ, we may put $k_2 = k_1$.

Since σ measures an external value, we require that $\sigma(0) = 0$, any researcher being recruited at experience age 0 has value 0 for the research institution. Since a shift in research field is related to a significant reduction of research productivity, even for experienced researchers[8], we expect a vanishing 'velocity' at $\tau = 0$, or $k_0 = 0$. Eq. (6) is then simply the logistic differential equation in logarithmic time,

$$\frac{d\sigma(\tau)}{d\tau} = k\frac{\sigma(\tau)}{\tau}\big(1-\sigma(\tau)\big)$$

with solution

$$\sigma(\tau) = \frac{\tau^k}{\tau_0^k + \tau^k} \qquad (7)$$

where τ_0 is a chosen normalization point. For illustrative purposes $\sigma(\tau)$ is drawn in the diagram, fig. 7, with $k = 3$ and $\tau_0 = 5$ years.
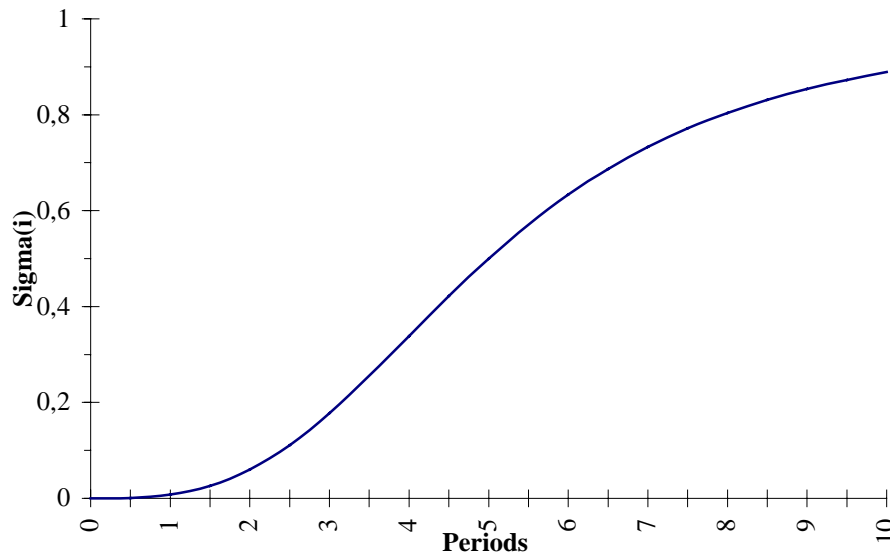

Figure 7. The diagonal quality index $\sigma(i)$

To fix the value of k and τ_0 we would need empirical data describing an index like $\sigma(\tau)$. Even if we choose to use publication data, with its obvious weaknesses as a

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[8]   A. van Heeringen and P.A. Dijkwel, *op.cit.*

'quality index', we are up against difficulties. First of all we should use data for categories of publications relevant to the part of the RP system we consider. Evidently this refers to a major extent to publication categories outside the scope of official publication data bases, like the *Science Citation Index*. In contrast to academic publication, the major channel for publication is through research reports not exposed to peer review.

Even if we could establish these data, their interpretation would not be immediate. The research activity may be unevenly distributed among researchers, with differences between ordinary researchers, group leaders, research directors, etc., that are not possible to relate to their value as researchers for the system/establishment. On the contrary, at least partly it seems a reasonable conjecture that seemingly 'low-productivity' activities are associated with experience and higher value.

A partial answer to this would be to use *accumulated* publication data. Then we encounter the fact that there evidently is a wide distribution in terms of quality or degree of novelty. On the other hand one may reply that the ability to 'sell the same stock twice' should increase the value of the original breakthrough.

One way of reducing the possibility for 'double-counting' is to focus on 'academic publication' by researchers in this system, i.e., peer reviewed publication if such data could be accessible. Since this is a marginal form of publication by these researchers, relative to academic researchers, one risks losing the publication data's representatibility.

But the most important objection to the data that is accessible, at least in principle, is that they are given in terms of cross-section data, and referring to physical age, possibly in combination with other parameters[9]. Thus we require time series, referring to shifts in research fields. At the present stage of this project, it has not been possible to assemble various data sets and discuss futher how these problems could be met. It would be of interest to elaborate these potentialities further in future research projects.

As a proxy for data we will use cross-sectional and global publication data for the academic sector. We will use these data to limit the possibilities for index formulation, with the understanding that it is not possible to pin down any exact values. Hence any assignments of values must be regarded as conjectural.

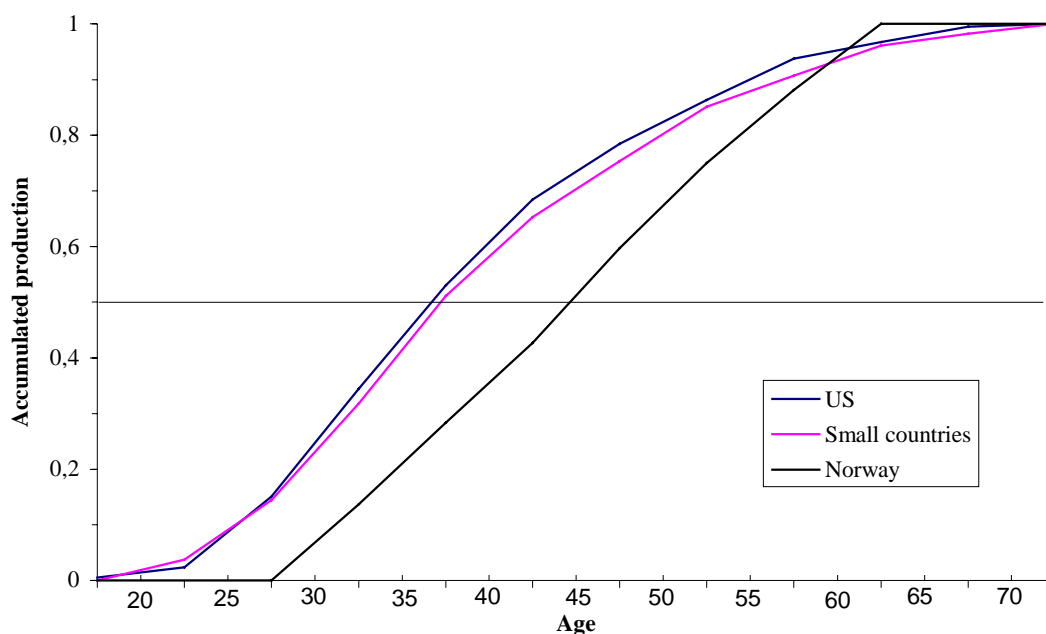[9]   See f.i. S. Kyvik, *Alder og vitenskapelig produktivitet*, TfS **31** (1990) 23

Figure 8a. Age productivity relations. Source: H. Lehmann and S. Kyvik

As part of the ongoing project it has not been possible to assemble data oriented to the specific goals of this project. This would be a necessary ingredient in a continuation of the project. We are therefore limited to use of already available data. Fig. 8 is based on two such datasets, Lehmanns old data from the early 50's and Kyvik's data based on the Norwegian *Universitetsundersøkelsen* of 1981[10]. Whereas Lehmann's data are based on logitudinal data, the Norwegian are crossection data.

The main limitation of the Norwegian data is that they describe the publication activity of academic researchers with a permanent position at HEIs. Thus they do not cover the period of what might be termed the 'rush for tenure', sliding the curve towards the right in the diagram.

Lehmann's data are 40 years old and hence influenced by a manner of publication differing significantly from the present regime. There are essentially two ways in which the situation differs between the early 50's and 40 years later. First the available publication channels have changed considerably. But in addition the size of the research system, and the number of researchers, has had a sustained growth in the whole period. Presumably this has lead to an increased rush for tenure.

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[10] H. Lehmann, *Science Monthly* **78** (1954) 321
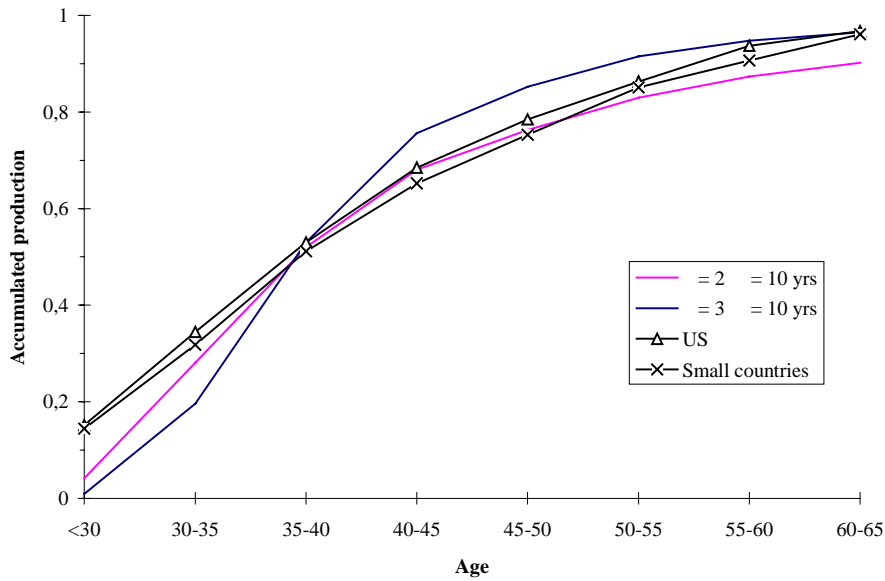S. Kyvik, *Tidsskrift for samfunnsforskning* **31** (1990) 23

Figure 8b

If hypothesis that an increasing fraction of time used in other areas than research with increasing age explains (partly) a decreasing productivity[11], the upper half of the Lehmann and comparative data are shifted to the right (research time is some fraction less than unity of clock time). In terms of the model curves, the Lehmann data are compared in fig. 8b with $k = 2, 3$ and $\tau_0 = 10$ years, assuming that a more formalized research career starts at an age of approx. 28 years.

Without more recent and approppriate data sets we will have to do with data like these. Without a firm foundation we will nevertheless, and in line with the comments made above, claim that the data lend support to the given formulation of the diagonal terms with $k \sim 3$ and $\tau_0 \sim 5$ - 10 years. We will use $k = 3$ and $\tau_0 = 7$ years.

6.2 Off-diagonal terms

The diagonal terms are concerned with each generation of researchers by themselves, apart from the (slight) distributional effect of the smeared ϑ-function $\rho(N-N_i)$, reducing the value, and hence the probability, of a strongly peaked age distribution[12]. Thus the obvious maximization of the diagonal σ-values is to concentrate the population around generations where $\sigma(i) \sim 1$, i.e., in experienced generations.

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[11] S. Kyvik, *op.cit.*, claims that this hypothesis, termed *nyttemaksimeringshypotesen* (hypothesis of utility maximization) by him, is disproved by the Norwegian data from *Universitetsundersøkelsen* of 1981. It is important to note that the limitation to data for academic researchers in permanent positions at HEIs implies a serious sampling bias of the data, especially in 'younger' age groups (age < 40 years), both in terms of age, the 'mean' academic professor with age 35 is of a more productive kind than the 'mean' academic professor of age 55, within any field, and in terms of research fields, as there are significant differences between the 'mean' career development in different disciplines.

[12] The ϑ-function will exclude the possibility of $N_i = N$ for some i. Hence it will force the system into an age distribution where N_i is at most N - 1.

As we saw in section 5 the relative age distribution of the Norwegian research institutes sector is fairly stable over time. We argued there that this must be interpreted as a fairly stable configuration on the labor markets in fig. 4. The fact that disruptive fluctuations do not happen, at least over reasonable time scales, indicates that there is a balance between supply and demand on these labor markets, i.e., they are close to an equilibrium.

The Norwegian research institute sector has had a fairly constant growth of approx. 4% over a 20 years period, as measured through the national R&D statistics[13]. An assumed mobility rate of about 6%, based on Wiig & Ekeland[14], indicates that about 10% of the total research staff in the Norwegian research institutes sector is recruited each year, corresponding to 10-15% of the annual number of awarded degrees at these levels. Thus the balance on these labor markets is robust against changes in demanded volume; by a low demand elasticity.

As figs. 3a and 4 illustrates, the age distribution is given in terms of physical age A, and not in terms of 'experience' level or age class i. There is a simple relation between the two, $A = i + p$, where p is a period measure, being simply the physical age at $i = 0$.

We claim that the qualitative features of the distribution in terms of age parameters mirrors essential characteristics of the conditions for a dynamic research environment. That is, we view the actual age distribution as a pattern emerging on the basis of a local adaptation to the 'rules' of a productive research atmosphere. It should be clear that i is closer to being a 'correct' measure of this effect than the physical age. Hence, the emerging distribution in terms of the age class i expresses these underlying 'rules'.

Evidently this is for the off-diagonal terms in a quality index like $\sigma(\{N_i\})$ to accomplish; the 'collective' features of the age distribution is primarily an effect of inter-generational interaction. At this stage we will simply consider one such term in the two-'point' function $\sigma(i, j)$, based on a supposition that a major characteristic of a productive research environment is the learning effects. We consider the learning effects, both individually and collectively, as a major constituting factor for the research environment.

Interpersonal interaction enhances learning. We gave a partial argument for this when considering intragenerational effects in section 9.1 above in terms of a 'crowding out' and a 'crowding in' effect. It is clear that in addition to this, there are considerable intergenerational effects. These effects spring out of formal and informal networks between researchers and between researchers and external systems. Here we will consider the former kind of networks.

The first network effect we will consider is more or less formalized supervision of junior researchers. A significant part of the learning process of younger generations at this level, is through guidance and instruction from senior personnel. In this

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[13] Norges forskningsråd **FoU-statistikk 1991**, Oslo 1993. The growth refer to the number of researchers with education level ISCED 6 and above.

[14] *Op.cit.*

context, the prime interest being research in technology-oriented research and research in the natural sciences, we find it resonable to use parallels to 'training' of academic researchers. Then we may divide the junior and median phases of a research career in two periods, a basic training, apprentice period of 3-5 years and a 'post doc' period of 3-4 years. At the end of these periods, the researcher is established at a level of tenured positions, i.e., at a senior level.

All through these phases, formal and informal interaction with senior research personell is important for the learning process. As the junior approaches seniority and independence in terms of supervision, the value of the presence of supervisors decreases. This effect will be modelled by,

$$\sigma^1(i,j) = \begin{cases} \sigma, & j = i+7,...,15, & 0 \leq i \leq 4 \\ \frac{1}{2}\sigma, & j = i+7, i+8 & 5 \leq i \leq 7 \end{cases} \tag{8}$$

i.e., instructors are at least 7 year senior. We limit supervising generations to $j = 7, ..., 15$, thereby suppressing the importance of older generations in the diagonal formulation.

The presence of junior researchers and research assistents, enhances the effectivity and efficiency, and hence the 'value' of senior researchers. A considerable part of research work is of a kind that is suitable for experience-gathering for junior researchers, but which is more of routine work for an experienced researcher. At institutions based on contract research, this is of importance both to the individual researcher and to the institution. The presence of junior researchers allows for making efficient use of limited resources like experienced researchers an explicit aim of a contract research instutions, in terms of both project acquisition and performance. This will require an ample supply of junior researchers *qua* research assistents. In addition, as these institutions necessarily must have a high auto-sufficiency in terms of future experienced researchers, the presence of a stock of junior researchers is important to have researchers knowing the 'craft' in the future. This second network effect will also be modelled by eq. (8), by assuming that a simple scaling of the parameter σ includes this effect.

A quality term like this gives preference to age distributions with a significant amount of researchers in the low-*i* classes, with the supervising classes being non-empty. The degree of preference is determined by two factors,

∗   the volume factor $\varphi_2^1(N_i, N_j)$ corresponding to $\sigma^1(i,j)$ and
∗
∗   the relative value between this off-diagonal term and the corresponding diagonal terms.
∗

The volume factor may vary considerably between different research fields. But in accordance with the discussion given above, the term should balance two effects. The value increases for the junior partner as one approaches a single-instructor regime, that is one-to-one or few-to-one relations between juniors and seniors. We will prefer the latter, within the same junior generation; as learning effects of

supervision is evidently enhanced by two or more 'students' on complementary projects under the same instructorship.

To form the volume factor, we first note that it is evidently necessary for the different terms in $\sigma(\{N\})$ to scale by the same factor in global scale transformations ($\{N_i\} \to \{\lambda N_i\}$). Modulo 'large scale' crowding out effects, we may set this exponent (α) to unity. This is an assumption that the scaling of the research institutes system is into an infinite research landscape.

Assuming that the occupation numbers of the 'interacting' levels enter multiplicatively, we may then write

$$\sigma\left(\{N_i\}\right) = \sum_i N_i \sigma(i) + \sum_{i,j} N_i^\beta N_j^{1-\beta} \Theta(N_i, N_j) \sigma^1(i, j) \qquad (9)$$

where $\sigma(i)$ and $\sigma(i, j)$ are given in eqs. (7) and (8), and where $\beta < 1$.

The function $\Theta(N_i, N_j)$ is inserted to restrict the second term to regions in the (N_i, N_j) - plane where the two occupation numbers have a 'quality-enhancing' ratio. The limit ratios are assumed to be

$$\left(\frac{N_j}{N_i}\right)^* \begin{cases} \geq \frac{1}{7} \text{ and } \leq \frac{2}{3}, & i = 0,..,4 \\[2mm] \geq \frac{1}{3} \text{ and } \leq 1, & i = 5,..,7 \end{cases}$$

i.e., there should be 1,5 - 7 junior researchers/research assistent for every supervising researcher (it is evidently counter productive to let the ratio of research assistents to supervisors get large). The 'post doc' to senior researcher ratio should be lower, here it is set to 1:1 - 1:3. For simplicity we express the function $\Theta(N_i, N_j)$ in terms of step-functions,

$$\sigma\left(\{N_i\}\right) = \sum_i N_i \sigma(i) + \sum_{i<5,j} N_i^\beta N_j^{1-\beta} \vartheta(N_j - \tfrac{1}{7} N_i) \vartheta(\tfrac{2}{3} N_i - N_j) \sigma^1(i, j)$$

$$+ \sum_{4<i<8,j} N_i^\beta N_j^{1-\beta} \vartheta(N_j - \tfrac{1}{3} N_i) \vartheta(N_i - N_j) \sigma^1(i, j)$$

To achieve an equal valuation of the two network effects $N_i \leftrightarrow N_j$, we put $\beta = 1/2$.

The relative constrisution of the two terms is determined by the parameter σ in eq. (8). In terms of our argument about the present age distribution, this would imply $\sigma \sim \vartheta(1/2)$ - $\vartheta(1)$. Letting the parameter σ grow the index will be dominated by the intergenerational interactions, letting $\sigma \to 0$ the index is determined by intra-generational effects.

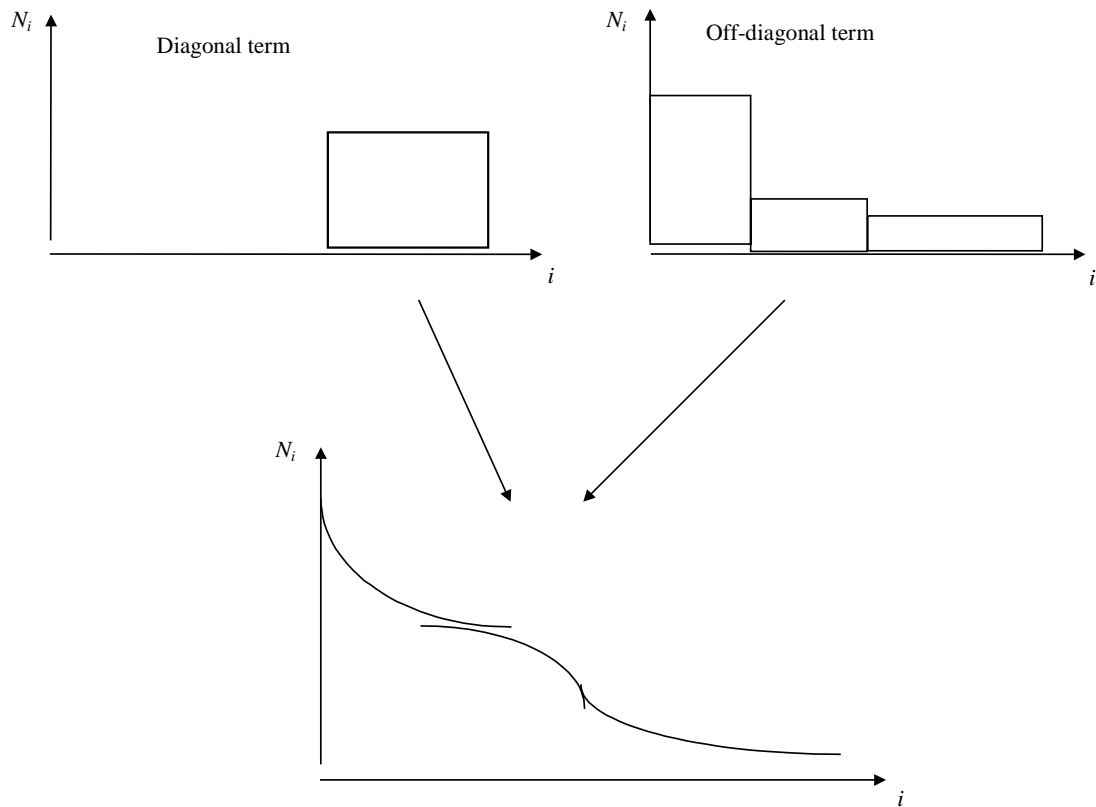*Figure 9. Solving the optimization problem max* σ*({*N*})*

We will not solve this problem here. But evidently we may describe the solution to the problem qualitatively, cfr. fig. 11. We will not solve this problem for an optimal solution, instead we will use the specification to compare different distributions.

The optimization problem

$$\max_{\substack{\sum N_i = N \\ N_i(t) \sim e^{-\lambda_{i-1} N_{i-1}(t-1) + \delta N_i(t)}}} \sigma\left(\{N_i\}\right)$$

is solved in terms of a balance between a 'short term' optimization from the diagonal term and a 'long term' optimization of the off diagonal term.

7. Simplifying the model

As a comparison with the tube and colinear models we will now describe the simplest model[15], a constant population with constant exit rates. We will describe the consequences of these three models for the physical age distribution of the population and the experience level of the researchers leaving the research system. This will lead to a conclusion that the simplest possible exit model gives a better description of empirical data than the two 'fixed' models.

Our first assumtion is

SA1   the overall population is constant.

Hence

$$N(t) = \sum_i N_i(t) \equiv N \tag{10}$$

is constant, and $\Delta N(t) = 0$. This is equivalent to a reformulation of **A3'**,

A3'   Each dying individual is replaced by a new individual the next period with age 0.

Secondly we will assume that

SA2   the exit rate λ is constant both over time and over generations.

I.e.,

$$\lambda_i(t) = \lambda = const.$$

This leads to a constant mobility,

$$\alpha(t) = 1 - e^{-\lambda} \equiv \alpha_C = const.$$

But then the periodic recruitment is also constant, $N_0(t+1) = \alpha_C N = const., \quad t \geq 0$. The solution eq. (5) simplifies similarly

$$N_i(t+1) = \begin{cases} e^{-\lambda(t+1)} \mu_{i-(t+1)}, & i \geq t+1 \\ e^{-i\lambda} \alpha_C N, & i \leq t \end{cases} \tag{11}$$

Thus apart from boundary conditions, we have again a model with only two parameters, as with the 'tube' and colinear models. The advantage of the present

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[15]   It is, of course, possible to express both the tube and the colinear model in terms of a generalized decay model described in section 8 by a simple adjustment of the 'decay' rates λ.

formulation is that it is 'derivable' from a more realistic description, thereby hopefully being 'closer' to reality. The age profile at any time $t > 0$ is then

i)   the cohorts $i > t$ mirroring the age profile at $t = 0$, scaled by $e^{-\lambda(t+1)}$,

ii)   the cohorts $i \leq t$ with a simple exponential as a time independent profile.

The rest of this paper is an intuitive approach to the effects of this model, and a comparison of these effects with the 'tube' and colinear models. In the expressions given below, we have neglected the effect of a finite age of retirement P. The full expressions include adding a P-dependent term proportional to $\exp\{-P\lambda\} \sim .0148$ when $P = 40$ yrs and $\alpha = 10\%$.

7.1   The mean age

The mean age $\tau(t)$ of the population is defined as

$$\tau(t) \equiv \frac{1}{N}\sum_i iN_i(t)$$

yielding

$$\tau(t) = e^{-t\lambda}\tau_0 + \frac{1-e^{t\lambda}}{e^{\lambda}-1}, \quad t \geq 1 \qquad (12)$$

where $\tau_0 = \tau(t=0)$. The mean age increases or decreases in a transitory regime according to whether the mobility is smaller, resp. larger, than $(\tau_0 +1)^{-1}$. The physical age distribution indicates a mean age of about 40 years, corresponding roughly to $\tau_0 \sim 10$. In fig. 10 the evolution of the mean age is given for 10 periods for four values of the mobility with $\tau_0 = 10$. Thus our first conclusion is that we would expect to see a declining mean age when $\alpha >\sim 10\%$.
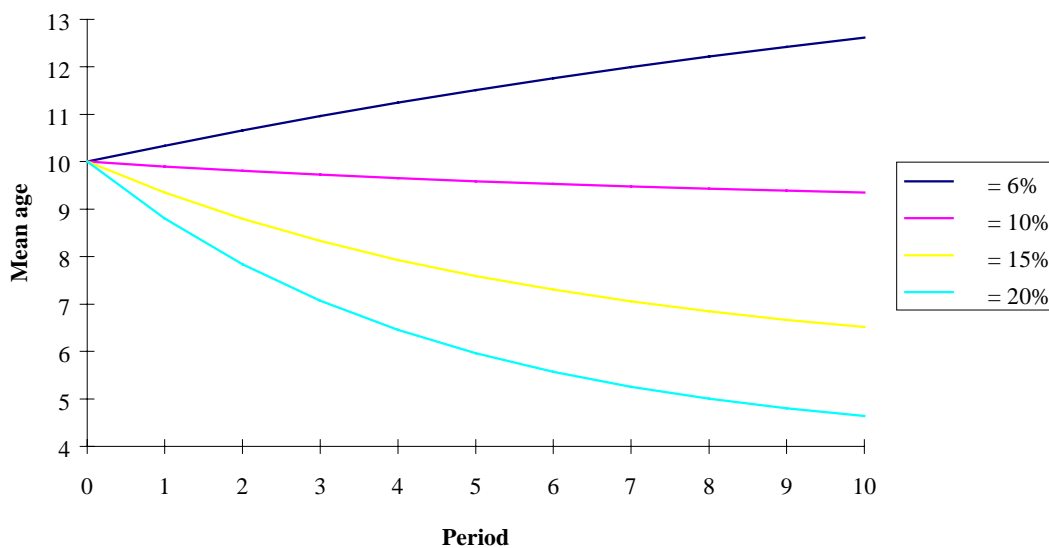

Figure 10. Mean age τ as a function of time. $\alpha = 6\%$ corresponds roughly to the present mobility rate.

Expressing τ in terms of the mobility, we get $\tau_\lambda = f_\alpha$ in the long term, as compared to $\tau_T = f_\alpha/2$ and $\tau_C = 2f_\alpha/3$, where $f_\alpha = (1-\alpha)/\alpha$, resp. for the 'tube' and colinear models.

Similarly we may calculate the mean age of the researchers leaving the population in each period,

$$\rho = \frac{1}{\delta N}\sum_{i\geq 0}(i+1)(n_i - n_{i+1})$$

For all three distributions or models $\rho = 1/\alpha$, but with a different distribution, the 'tube' distribution being a single peak, the colinear a 'white noise' distribution and the λ-distribution being left-skew.

7.2 Expected lifetimes of populations

The second concept we will introduce that characterizes the distribution is the lifetime of a given population. I.e., we ask the question, 'at what time t_δ is a fraction $\delta, 0 < \delta \leq 1$, of the individuals making up the population at time t still present?'

The calculation is simplified by the fact that there is a direct linkage between time t and age i, $i(t) = i(t') + (t - t')$. Thus we have to solve

$$\sum_{i=t_\delta - t}^{\infty} N_i(t_\delta) = \delta\sum_{i=0}^{\infty} N_i(t) = \delta N$$

This yields directly

$$t_\delta - t = -\frac{\ln\delta}{\lambda} = const. \tag{13}$$

The relation is shown in fig. 11 for different mobility rates.

With a mobility rate of ~ 6-8%, 80% of the original population has left after about 20-25 yrs. With a mobility rate of 15%, there is less than 20% of the original population left after 10 yrs. The approximation of a constant mobility rate over age classes affects the actual life times, but the figure should give a better approximation of the realtive effect in life times for changes in the mobility level. Even though this might be considered a crude approximation of reality, there remains the fact that a substantial increase of the mobility rate over the long run, affects the ability to sustain a viable research environment. To what degree this is the case, is a matter of qualitative assessement.
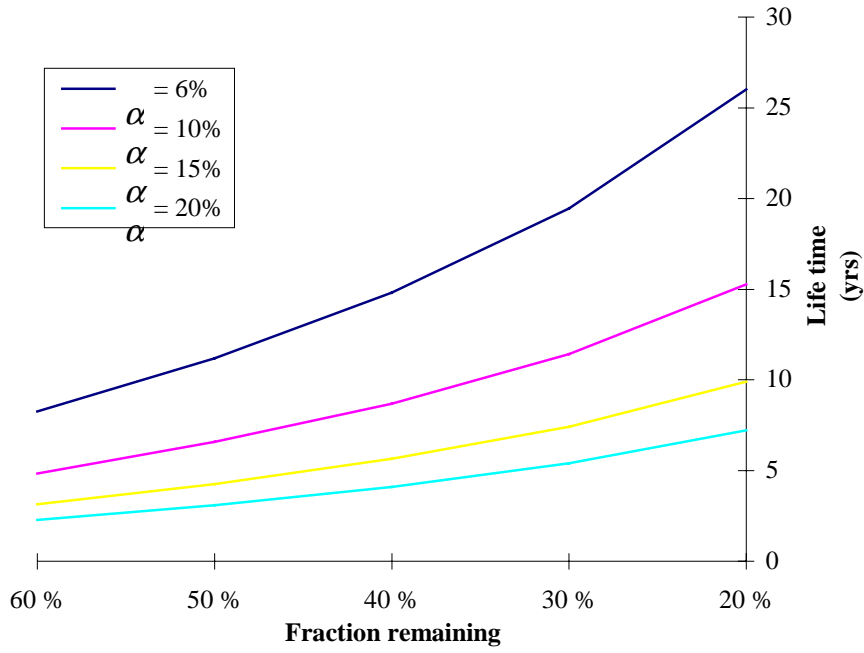
Figure 11. Life time evolution for a given population as a function of mobility rates

8. The age distribution

So far we have described 'age' in terms of the researchers age class i, i.e., in terms of the time passed since (s)he was recruited as a researcher into age class 0. As we saw in section 3 the empirical data are given in terms of a distribution in physical age. Hence we need a translation between the two parameters.

As pointed out this translation is given by $a = i + a_0$, with a_0 being the physical age at $i = 0$. This relation is illustrated in fig. 12. In drawing up fig. 12, we have assumed that a_0 is normally distributed around a mean age $< a>_0$. Even the simple assumptions behind this figure, with all recruitment at $i = 0$ and constant mobility rates generates age distributions giving the qualitative features of fig. 4.

Assuming that the exit rate's dependence of physical age is solely determined by the age class, the time evolution does not change the initial relative age distribution, i.e.,

$$\langle a \rangle_i = \langle a \rangle_0 + i$$
$$\sigma_i = \sigma_0$$

where σ_i is the standard deviation of the age distribution in class i. Then fraction $\nu(a)$ of the total population with physical age a, measured natural numbers, is

$$\nu(a) \equiv \frac{n(a)}{N} = \sum_{i=0}^{'\infty'} \frac{N_i}{N} p_i(a) \tag{14}$$

where

$$p_i(a) = \frac{1}{\sqrt{2\pi}\sigma} \int_{a-<a>_0-i-\frac{1}{2}}^{a-<a>_0-i+\frac{1}{2}} d\alpha \, e^{-\frac{\alpha^2}{2\sigma^2}}$$
$$= p_0(a - i)$$

8.1   The tube model

Since the class distribution is given by a constant population of all levels, $n_i = n = N/(M+1)$, the fraction $\nu_T(a)$ is

$$\nu_T(a) = \frac{1}{M+1} \sum_{i=0}^{\min(M, a-\Lambda)} p_0(a - i)$$

where we have introduced a lower end cutoff Λ in the age distribution. The fraction is calculated in fig. 13 with a mean age $<a>_0 = 28$ yrs[16], standard deviation 2 yrs and lower cutoff 22 yrs.

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[16]   This corresponds roughly to the mean age of Norwegian graduates at the equivalent of a Masters degree. We received data for Norwegian graduates in 1992 from
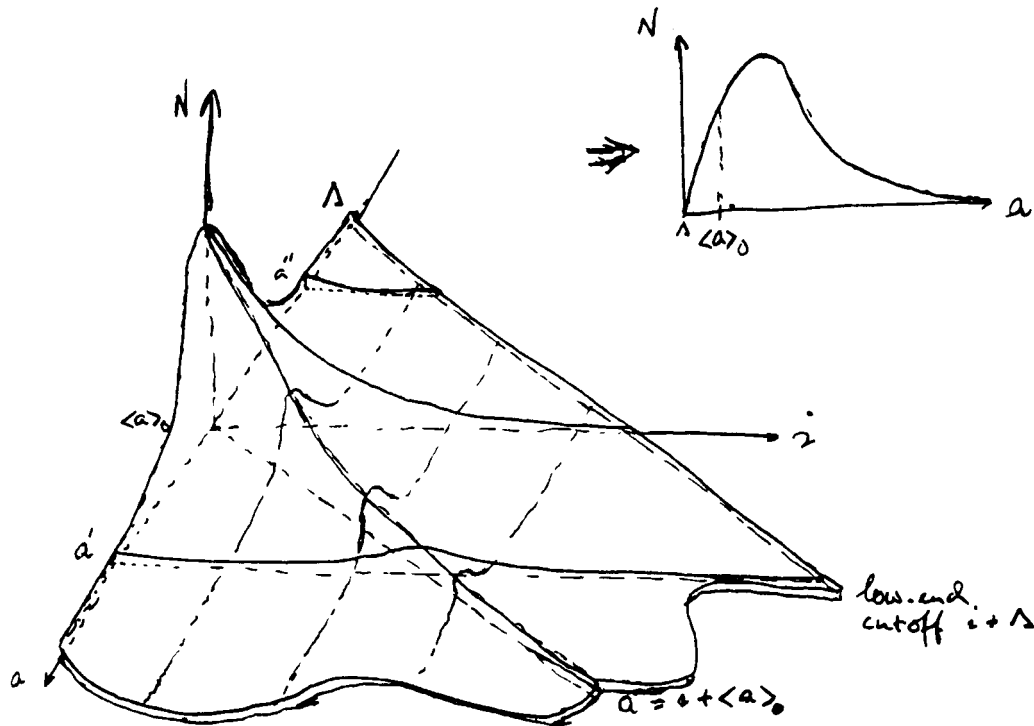
Figure 12. The relation between physcial and experience age, a *and* i. *In the figure*
we have assumed that the recruitment at i = 0 *is normally distributed around*
a mean physical age <a>$_0$. *The integral of the surface along the lines*
parallell to the i-*axis at different physical ages, gives the age distribution.*

The fraction $v_T(a)$ is given for two values of the parameter M, $M = 6$, a value often
incurred in dsicussions concerning the effects of MS schemes, corresponding to a
mobility rate of ~ 15%, and $M = 16$, the value implied by the present mobility rate of
~ 6%. These two curves are compared to personell data for 1991. As is seen in the
figure, with a mobility of about 15%, the tube model would predict that all
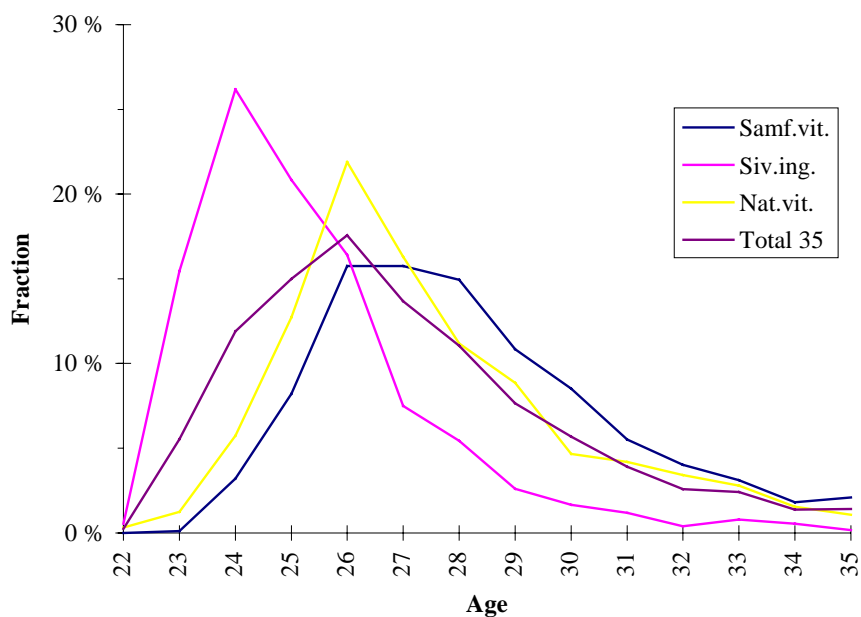researchers are younger than 40 years.

Figure 12b. The age distribution of Norwegian graduates 1992. Source: Institute of Studies in Higher Education and Research, Akademikerregisteret.
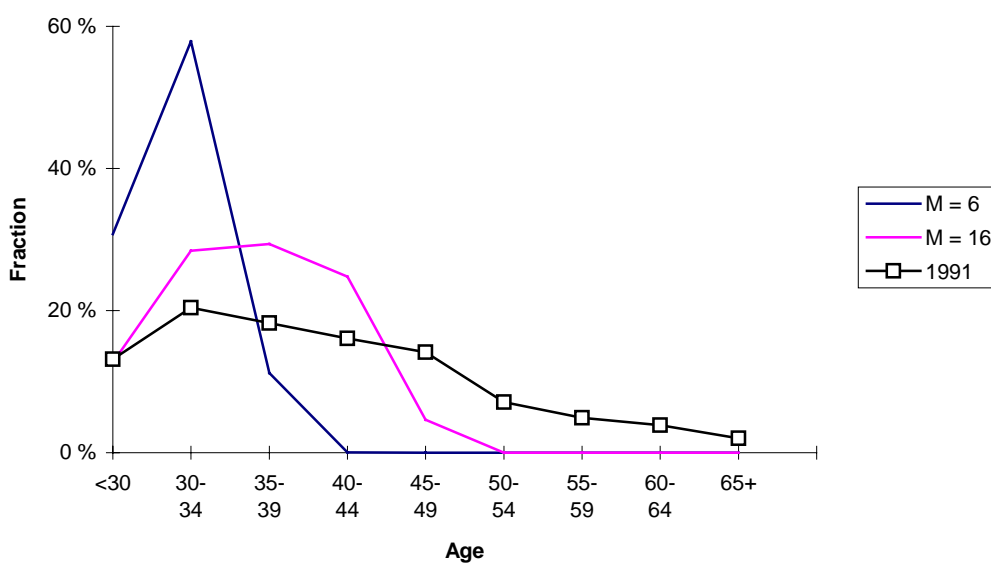

Figure 13. Age distribution in the tube model

8.2 The colinear model

The class distribution of the colinear model is

$$\frac{N_i}{N} = \frac{2}{M+2}(1 - \frac{i}{M+1})$$

giving

$$v_L(a) = \sum_i \frac{N_i}{N} p_0(a - i)$$

$$= \frac{2}{M+2} \sum_i (1 - \frac{i}{M+1}) p_0(a - i)$$

$$= \frac{2}{M+2} \left\{ (M+1)v_T(a) - \frac{1}{M+1} \sum_i i p_0(a - i) \right\}$$

where $v_T(a)$ is the fraction at age a in the tube model, calculated with the same M-value.
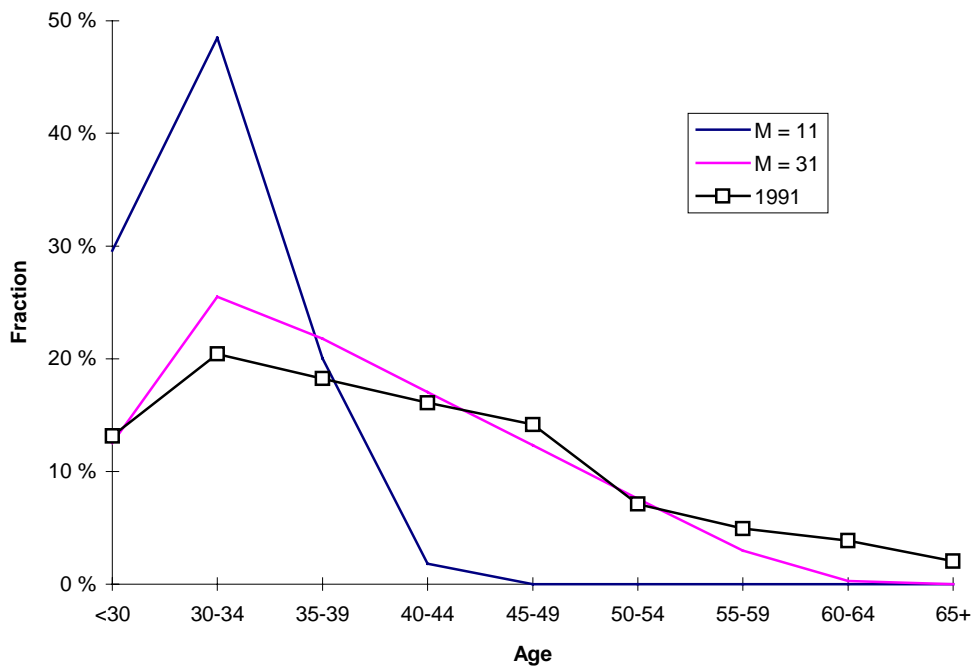

Figure 14. The age distribution of the colinear model

The age distribution is drawn in fig. 14, corresponding to the same mobility rates and based on the same assumptions as in fig. 13. With a span of $M = 31$ years, the model replicates fairly good the actual age distribution, but as is seen from the figure, the M-dependence is strong.

8.3   The constant-λ model

In this model the exit rate λ replaces the span M of the previous models as the adjusted parameter. With an age distribution

$$\frac{N_i}{N} = e^{-i\lambda}\left(1 - e^{-\lambda}\right)$$

the age distribution is

$$v_\lambda(a) = \left(1 - e^{-\lambda}\right)\sum_i e^{-i\lambda} p_0(a - i)$$

$$= \alpha \sum_i (1 - \alpha)^i p_0(a - i)$$

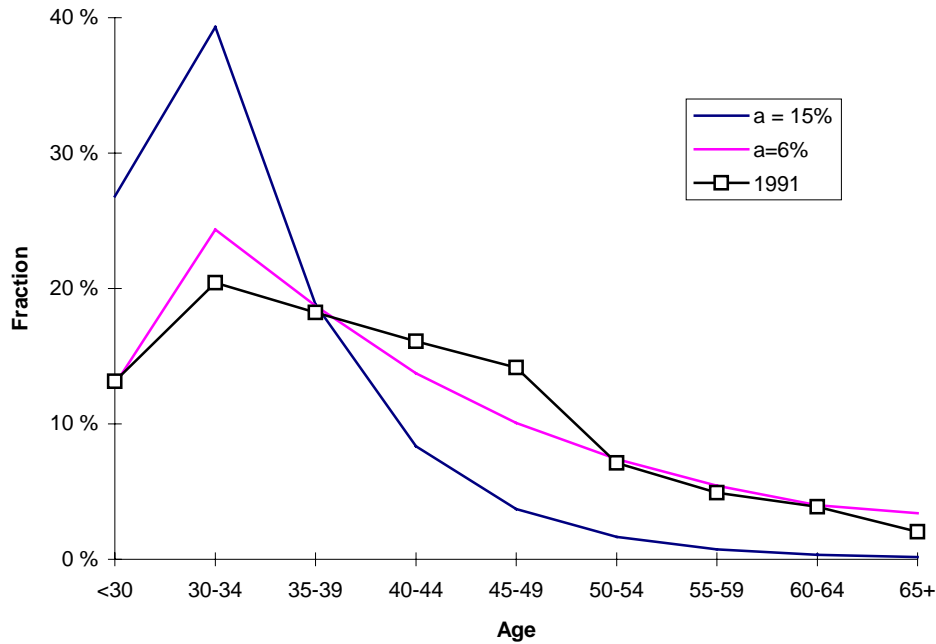and is shown in fig. 15 for the two values of the mobility rate.

Figure 15. Age distribution of the decay model with constant λ

Even with the simple assumptions behind the model, it captures the essential features of the actual age distribution. There are two important factors that may explain the deviations between the $\alpha = 6\%$ model and the 1991-data. Firstly we have assumed λ to be constant across age classes. Fig. 15 would seem to imply a slightly increasing function of i up to $i \sim 10$-15 (yrs), turning into a decrease in later periods.

Secondly the assumption **A3'** of all recruitment at $i = 0$ accounts for about 50% of the actual recruitment, the remaining 50% corresponding to recruitment in older age classes. To illustrate the effect of adding other recruits we may add a recruitment of experienced researchers. This is done in fig. 16, where we have added recruitment to

the $i = 5$ and $i = 10$ age classes respectively in constant population model, retaining the simplicity of the original model. The parameters η and ζ measure the ratio of $i =$ 5 and 10, respecively, to the $i = 0$ recruitment. All curves comply roughly with the 50-50 recruitment profile. The resulting age distributions is compared in fig. 16 to the $\alpha = 6\%$ curve from fig. 14 (η, $\zeta = 0$) and the 1991-data.
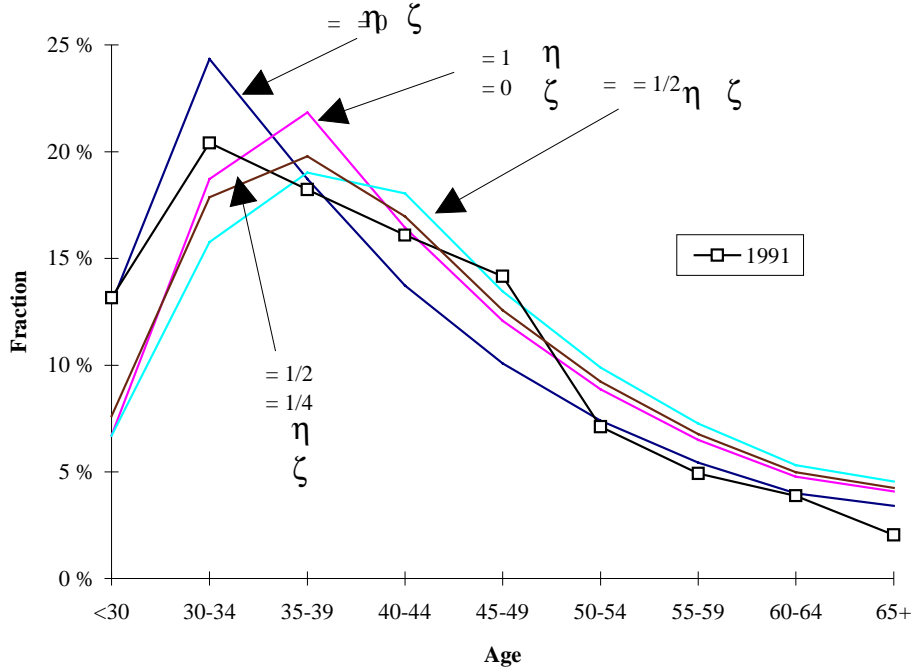

Figure 16. Age distribution recruitment of experienced researchers. Three curves are drawn, for different values of the recruitment ratios, to illustrate the effect of recruiting experienced researchers.

To conclude this section, we draw the curves for the three models corresponding to an annual mobility rate of 6%. The best fit of the constant population models is gained with the constant-λ model, a model also showing a less critical dependence on the mobility rate (cmp. figs. 13-15).
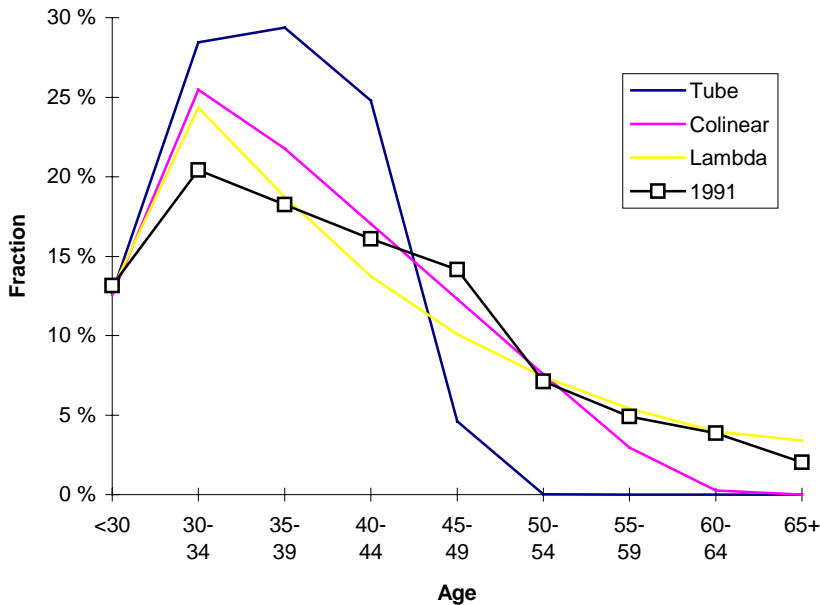

Figure 17. Model age distributions with $\alpha = 6\%$

9. The experience level of leaving researchers

We are interested in considering mobility as a mechanism for transfer of knowledge between a research performing and a research using system. Mobility is thus not interesting in itself: rather it is competence and research skills inherent in each individual 'mobilized' researcher that is of interest. It takes time to build competence and stable networks, it is a considerable difference between a junior researcher leaving after half a year and a senior researcher of 6-10 years experience in terms of both competence and the ability to maintain personal networks.

One way of measuring this effect is to calculate the age class distribution of the researchers leaving the RP system. The experience profile gives the fraction of the 'mobilized' researchers leaving age class i.

Defining l_i as the number of researchers leaving age class i,

$$l_i = n_i - n_{i+1}$$

the experience profile is

$$\frac{l_i}{l} = \frac{l_i}{\alpha N}$$

since, by definition, $l = \sum_i l_i = \alpha N$.

To compare the profile with empirical data, we will group the class distribution in four class categories, 0-2 years, 3-5 years, 6-10 years and 11+ years in accordance with the data given in Wiig & Ekeland[17]. The profile may then be written as a vector $\left(l^0, \quad l^3, \quad l^6, \quad l^{11} \right)$ in an obvious notation and where

$$l^{11} = 1 - \left(l^0 + l^3 + l^6 \right)$$

The profile for the three models, together with empirical data, are drawn in fig. 18.

9.1 The tube model

In the tube model

$$\frac{l_i}{l} = \begin{cases} 0, & i < M \\ 1, & i = M \end{cases}$$

---

[17]   H. Wiig and A. Ekeland, *op.cit.*

by conctruction. With $M = 16$, corresponding to a mobility rate of approx. 6%, the profile vector is (0, 0, 0, 1).

9.2   The colinear model

In the colinear model, the number of researchers leaving each age class is a constant. Hence

$$\frac{l_i}{l} = \frac{1}{M+1}$$

is independent of i. A mobility rate of approx. 6% yields the profile vector $\left(\frac{3}{32}, \; \frac{3}{32}, \; \frac{5}{32}, \; \frac{21}{32}\right)$.

9.3   The constant-λ model

With the constant-λ model, the fraction of researchers leaving each age class is constant. Since the scaling factor is just the mobility rate α,

$$\frac{l_i}{l} = \left(1 - e^{-\lambda}\right)e^{-i\lambda} = \alpha(1 - \alpha)^i$$

Hence, the profile vector is

$$\left(1 - \left(\tfrac{94}{100}\right)^3, \; \left(\tfrac{94}{100}\right)^3 - \left(\tfrac{94}{100}\right)^6, \; \left(\tfrac{94}{100}\right)^6 - \left(\tfrac{94}{100}\right)^{11}, \; \left(\tfrac{94}{100}\right)^{11}\right)$$

with $\alpha = 6\%$.

9.4   Experience profiles

The calculated experience profiles are drawn in fig. 18 together with the empirical data described in section 6. As is seen from the figure, all models overestimate the fraction in the oldest category, with the constant-λ model performing slightly better than the colinear model.
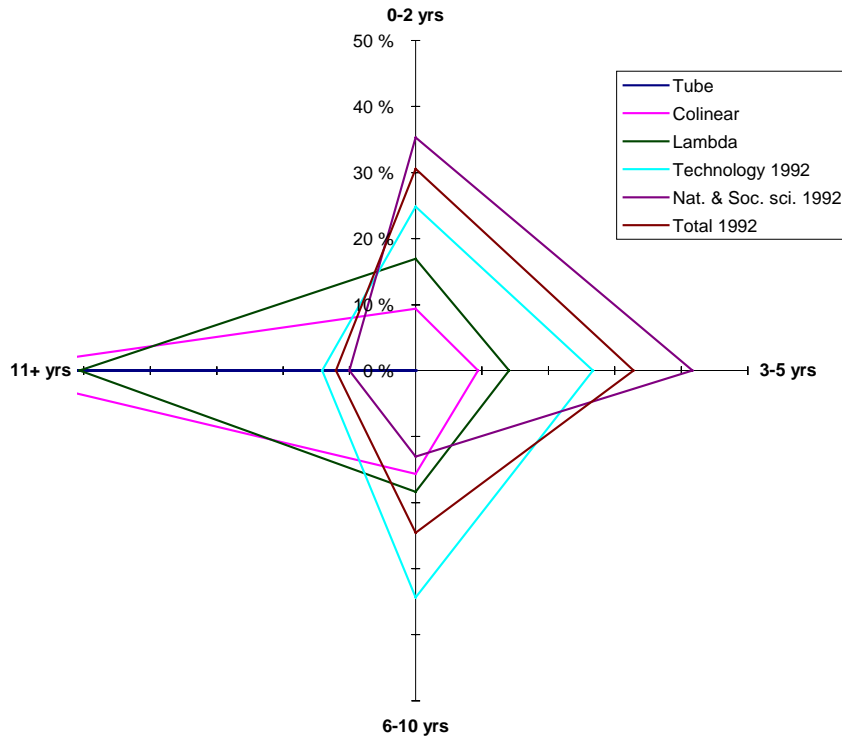
Figure 18. Experience profile of the mobility compared to 1992-data from Wiig & Ekeland

The effect of increasing the exit rate λ for intermediate values of i, in line with what the empirical data indicate would enhance the values of the corresponding profile vector elements. The constant-λ profile would be shifted towards the southeast sector.

In comparing the model calculations with empirical data we have made one implicit assumption; that the time spent in a particular research institute is a measure of the experience level. As indicated by the actual recruitment profile, this is overly simplifying. To account for the fact that the 'real' experience level is higher than the given parameter, the profiles based on empirical data should be shifted in a clockwise rotation from the positive *y*-axis towards the negative *x*-axis.

Modifying the constant-λ model as we did in constructing fig. 16, the profile is shifted even more towards the negative *x*- axis, cfr. fig. 19. Even if allowing growth would shift it back again, this proves that exit rates vary across age classes, even considerably when comparing 'old' (11+ yrs) classes with intermediate (3-5 yrs) ones.
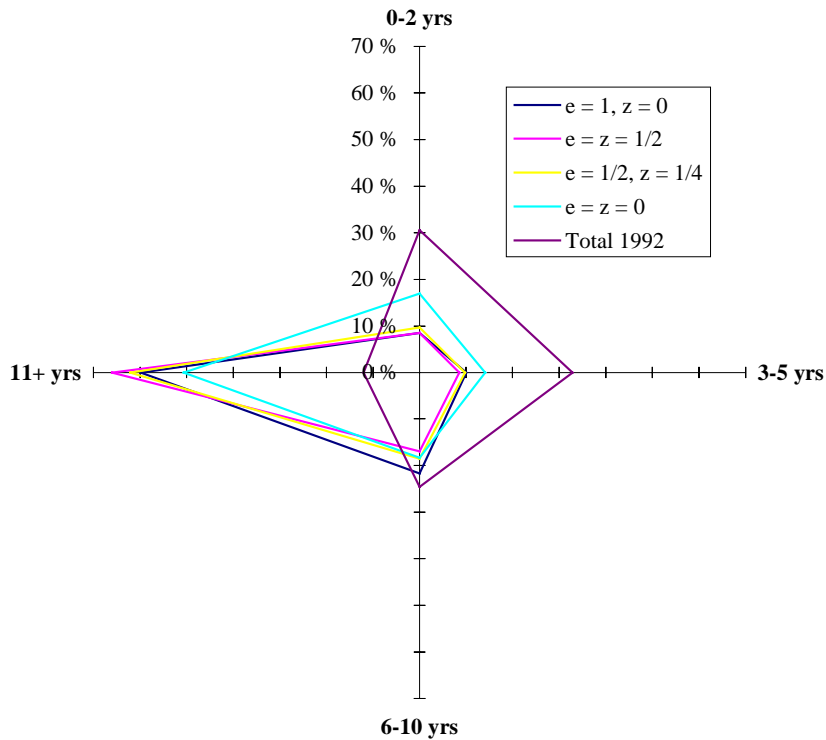
*Figure 19. The effect of recruiting experienced researchers on the experience profile
of 'leavers'. The curves corresponds to the curves in fig. 15.*

It is evidently meaningless to talk of a turnover, or mobility rates, simply in terms of
the mean time span spent in the research institution of the 'leavers'. As shown in
figs. 18 and 19 the experience profile deviates both between models and when
comparing these to empirical data. A measure of one aspect of the skewness of the
distribution, is the difference between the mean and the median age of the profile.
Forming a skewness factor φ as (median age/mean age - 1), $\varphi < 0$ will correspond to
a left skew distribution, and $\varphi > 0$ to a right skew distribution. The factor φ is given
for different values of the mobility rate in the table below.

α	6%	10%	15%	20%
Constant-λ	-0,29	-0,27	-0,25	-0,22
Colinear	+0,03	+0,06	+0,09	+0,13
Tube	0	0	0	0

10. The quality index

In section 9 we described a quality index allowing a comparison between different age distributions. The index as it is constructed in no way incorporates all the effects of intergenerational interactions. Having chosen one set of such interactions, it is not to be expected that the actual age distribution will optimize the index, both because there are interactions beyond those represented, and because there may be dynamics present that is not includeable in an index like $\sigma(\{N_i\})$.

An assumption of an overall validity of $\sigma(\{N_i\})$ implies a temporal development based on rational planning, or with all dynamics being quality enhancing (as measured by the index). Thus a temporal path should be a path towards a quality optimum. An obvious interaction that does not fulfill this is the interaction with the external labor markets. The labor markets determine the exit rates λ as a balance between the individual attractivity of remaining and of alternative positions.

With the expression for the index $\sigma(\{N_i\})$) given in eq. (9), we have calculated the index for different configurations for different parameter choices. With the same assumption as we made in section 11 in constructing the age distribution of the model configurations, we translated the actual age distribution into an (experience) class distribution with a linear interpolation between the 5-yr bins of the data. Thus we could calculate the index also for the empirical age distribution.

The result of these calculations are shown in fig. 20 for two values of the 'coupling constant' σ in eq. (8), $\sigma = 1$ and $\sigma = 1/2$. Whereas the value $\sigma = 1$ emphasises the intergenerational effects, the value $\sigma = 1/2$ puts stronger emphasis on the diagonal valuation.
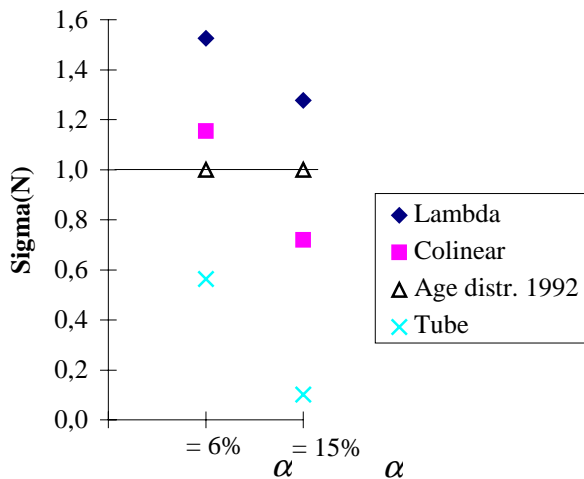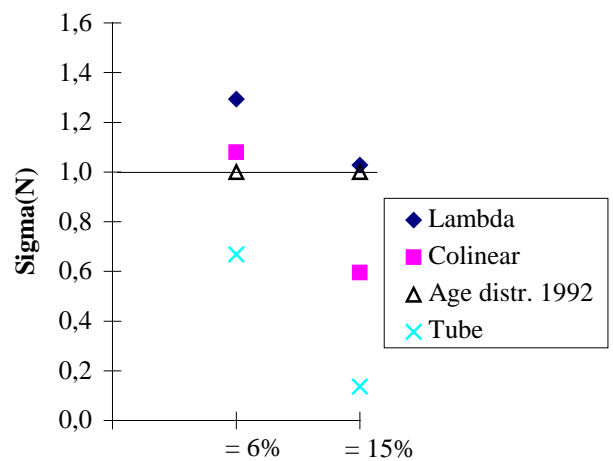

Figure 20.a

Figure 20.b

Figure 20. The index values for the three models for two mobility rates.
. . Figure 20.a. Coupling constant $\sigma = 1$
. . Figure 20.b. Coupling constant $\sigma = 1/2$

The values given are values relative to the 1992 age distribution for two values of the mobility rate, $\alpha = 6\%$ and $\alpha = 15\%$. As is seen directly from the figure, the effect of increasing the mobility is a significant reduction in 'quality' as defined by the index $\sigma(\{N_i\})$).

The intergenerational effect that is included in $\sigma(\{N_i\})$) is a measure of what we consider as a central prerequisite for the survivability of the research environment. Thus it would seem that model calculations like these, indicates that the sustainability of the research environment is seriously affected by increases in the mobility rates, by loosing out on the interaction between senior and lesser experienced personnel.

That the λ-model has a higher σ-value than the 1992 age distribution, indicates that the actual age distribution (or rather the class distribution that is calculated on the basis of this) is not optimal with respect to $\sigma(\{N_i\})$). But on the other hand that the σ-values of the colinear and tube models for a larger mobility rate shows that these distributions will have problems in sustaining a quality level.

The rate of change of σ-values when changing mobility rates from $\alpha = 6\%$ to $\alpha = 15\%$ varies between the models; the colinear and tube model has a significantly more critical α-dependence than the λ-model, with a 40%, resp. 80% decrease compared to the 15-20% decrease of the λ-model. The critical α-dependence underscores that one should be careful in applying these models as basis for 'intuition building' on MS schemes.

11. Concluding remarks

We have constructed a class of deterministic models of intergenerational mobility of researchers and studied the effects of this mobility on different aspects of research system. The goal of this has been twofold, to illustrate the possibility of modelling as basis for considering effects of policy measures in a restricted context, and to point to shortcomings of simple models in terms of their ability to reproduce aspects of 'reality' as warning against drawing far reaching conclusions from model considerations where the basic model loses out on significant aspects of 'reality'.

It is our belief that policy making in all areas makes extensive use of (formal and informal, conscious and inconscious, explicit and implicit) 'conceptual models' as a basis for policy formulation. These models is a representation of reality 'as perceived by the policy maker'. These conceptual models form the backbone of 'guts reactions', of the intuition that is a necessary basis for formulating policies and strategies.

The policy maker's persuasive ability is determined by his or her ability to get other policy makers to accept these models. These models are not static, they are adjusted on the basis of experience both about the lack of 'persuasive value' of the models and of their limitations in representing aspects of reality within the attention sphere of the policy maker. They are furthermore adjusted by extensions of the policy maker's horizon, in terms of acquisition of knowledge and skills. Thus we would expect to observe both models evolving, getting substantially more complex and sophisticated, and what we may term 'model paradigms'.

The quality, in some sense of the word, of the applied policy is therefore closely related to the quality, or relevance, of the models and of the policy maker's use of the models. There is a problem, however, in that the models themselves are seldom brought to the forefront, certainly in an explicit form, and that they rarely are problematized. On the contrary, one often meets the objection that considerations of these models are irrelevant, if not they are utilized completely unconscious.

Any model contains a simplification of reality. Appearances of 'counter-intuitive' behaviour or anomalies is not a problem for reality, but for the conceptual models forming the basis for the intuition. This points to the value in forming models as close to reality as possible, balanced by the economic argument of keeping them simple, of not making them unwieldy because of their complexity.

The underlying thesis behind these comments, is that treating these models explicitly is a fruitful way of exhibiting their value and their limitations. Our starting point was that the area of MS policies is an area where the policy debate is dominated by two extremely simple models, and where the models may be viewed as being constructed solely to treat mobility issues in a taxonomic way. These models have no dynamics attached, they make no pretence of *explaining* mobility patterns. The models have been constructed in a way which deliberately violates significant aspects of reality.

It is immediately clear that a 'totally' relevant model of a complex reality would require a complex model. What we have shown is that moderately loosening up the requirement of relevance gives the opportunity of constructing models that are simple and are usable as a background for policy formulation, as long as the policy maker is aware of the limitations present in the model. At the same time these models offer the possibility of extension towards incorporating dynamics in a manner which is recognizable as a model of real behaviour.

We claim therefore that a conseptualization of 'general purpose', but still simple, models like the constant-λ model offer the possibility of better policy formulation relevant to MS schemes than 'single purpose' models like the tube and colinear models.

Nevertheless, these models must not be confused with reality, they imply simplifications, to some extent gross oversimplifications, of reality. Only by making them explicit can we have any hope of gaining understanding of their usefulness and limitations. By doing this we would also make the political discourse more rational, aiding a better policy formulation and reducing the frequency of counter intuitive behaviour. Though one might wonder whether describing mental images explicitly, destroys their status as mental images.

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STEP-gruppen ble etablert i 1991 for å forsyne beslutningstakere med forskning knyttet til alle sider ved innovasjon og teknologisk endring, med særlig vekt på forholdet mellom innovasjon, økonomisk vekst og de samfunnsmessige omgivelser. Basis for gruppens arbeid er erkjennelsen av at utviklingen innen vitenskap og teknologi er fundamental for økonomisk vekst. Det gjenstår likevel mange uløste problemer omkring hvordan prosessen med vitenskapelig og teknologisk endring forløper, og hvordan denne prosessen får samfunnsmessige og økonomiske konsekvenser. Forståelse av denne prosessen er av stor betydning for utformingen og iverksettelsen av forsknings-, teknologi- og innovasjonspolitikken. Forskningen i STEP-gruppen er derfor sentrert omkring historiske, økonomiske, sosiologiske og organisatoriske spørsmål som er relevante for de brede feltene innovasjonspolitikk og økonomisk vekst.

The STEP-group was established in 1991 to support policy-makers with research on all aspects of innovation and technological change, with particular emphasis on the relationships between innovation, economic growth and the social context. The basis of the group's work is the recognition that science, technology and innovation are fundamental to economic growth; yet there remain many unresolved problems about how the processes of scientific and technological change actually occur, and about how they have social and economic impacts. Resolving such problems is central to the formation and implementation of science, technology and innovation policy. The research of the STEP group centres on historical, economic, social and organisational issues relevant for broad fields of innovation policy and economic growth.