Simulating Growth of the h-Index

Raf Guns
University of Antwerp, IBW, Venusstraat 35, City Campus, 2000 Antwerpen, Belgium. E-mail: raf.guns@ua.ac.be

Ronald Rousseau
KHBO (Association K.U.Leuven), Industrial Sciences and Technology, Zeedijk 101, B-8400 Oostende, Belgium. E-mail: ronald.rousseau@khbo.be

Temporal growth of the h-index in a diachronous cumulative time series is predicted to be linear by Hirsch (2005), whereas other models predict a concave increase. Actual data generally yield a linear growth or S-shaped growth. We study the h-index's growth in computer simulations of the publication-citation process. In most simulations the h-index grows linearly in time. Only occasionally does an S-shape occur, while in our simulations a concave increase is very rare. The latter is often signalled by the occurrence of plateaus—periods of h-index stagnation. Several parameters and their influence on the h-index's growth are determined and discussed.

Introduction

The h-index, proposed by Hirsch (2005), immediately drew a great deal of interest from the informetric community (see, e.g., Bornmann & Daniel, 2007 and references therein). If a scientist's publications are ranked in decreasing order of number of citations, then the h-index is the highest rank such that the first h publications each received h or more citations. Hirsch (2005) primarily intended the h-index to be used for quantifying a scientist's lifetime achievement. Any researcher starts with 0 publications and thus h-index 0. Typically, as the number of publications increases, the number of citations increases as well, leading to an evolution of the h-index. At the scientist's retirement (or any other circumstance that may cause him to stop publishing), the resulting h-index is, according to Hirsch, an adequate reflection of this scientist's lifetime achievement. We note that the h-index can never decrease and that it is constrained by the total number of publications N_p ($h \leq N_p$). Several studies have shown that the h-index can be used for many other types of source-item relationships as well. The h-index has been calculated for journal citations (Braun, Glänzel, & Schubert, 2005; Rousseau, 2006), topics (Banks, 2006; The STIMULATE-6 Group, 2007), and library loans per category (Liu & Rousseau, 2007). In this paper we will, however, mainly use the terminology of publications and citations.

When discussing the evolution of an indicator such as the h-index, it is vital to precisely define which publication and citation years one is considering, since many different types of time series are possible. Using an adaptation of the framework for general impact factors introduced by Frandsen and Rousseau (2005), Liu and Rousseau (2008) provide a generic framework for indicating exactly which time series are being studied, and discuss 10 types of time series.

We will refer to the types by their number in Liu & Rousseau (2008) and characterize them using a p-c matrix consisting of N publication years, from year Y to $Y+N-1$, and M citation years, from year Y to $Y+M-1$ ($N \leq M$). Liang (2006) and Burrell (2007a) study a Type 10 time series, which is a series starting at the most recent publication year $Y+N-1$ and cumulatively looking further back in time. Rousseau (2006) considers the evolution of the h-index of a journal (JASIS), using a Type 1 time series. In this synchronous type, one collects all citations at a fixed moment in time, which gives older volumes more chance to garner citations: Publications in year Y have citations from year Y to year $Y+M-1$, publications in year $Y+1$ have citations from year $Y+1$ to year $Y+M-1$, and so on. Hirsch (2005, 2007) himself has considered the evolution of the h-index in a Type 5 time series. This diachronous cumulative type can be characterized as follows. Assuming that the publication and citation period both start in year Y, the first element is based on citations in year Y to publications in year Y, the second element is based on citations in years Y and $Y+1$ to publications in year Y plus citations in year $Y+1$ to publications in year $Y+1$ and so on.

Regarding the evolution in a Type 5 time series, Hirsch (2005) claims that "one expects that h should increase

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TABLE 1. Illustration that $2h + 1$ citations are needed to achieve a higher h-index.

h-index	Publications, with the number of citations to each				
4	4	4	4	4	0
5	5	5	5	5	5
	h (= 4) additional citations				$h + 1$ (= 5) additional citations

approximately linearly with time," and adds that the slope m of this linear function can be used to compare researchers of different seniority (since the senior scholar has a natural advantage when comparing h). Indeed, a linear increase occurs for Hirsch' baseline model in which a scientist publishes a fixed yearly number p of publications and each paper receives a fixed yearly number c of citations. Burrell's (2007b) stochastic model is more realistic, but makes similar predictions. More importantly, there is empirical evidence that a typical researcher's h-index increases linearly (see, e.g., Egghe, 2008a; Rousseau & Jin, in press). Some examples in the literature (e.g., Anderson, Hankin, & Killworth, 2008) also present an S-shaped curve.

Contrary to Hirsch (2005), we do not consider the prediction of linear increase self-evident, since the number of citations needed to increment the h-index increases each time. Generally, one needs $2h + 1$ extra citations to obtain a higher h-index. Take for example the worst-case example of h-index 4: four publications with four citations each and no other publications with any citations (see Table 1). We then need at least 9 citations to achieve h-index 5.

Consequently, one might intuitively expect the h-index to increase concavely—rapidly during the first few years and then gradually more slowly. Why do our expectations (concave increase) not match empirical observations (linear increase)? In this paper, we try to address this question by investigating the h-index's evolution in different simulations of the publication and citation process.

It should be stressed that, as did Hirsch, we focus on the evolution of the h-index in a diachronous cumulative approach (Type 5). Other types of time series may of course evolve in completely different ways.

Simulating a Scientist's Publications and Citations

More than two decades ago, Leimkuhler (1987) advocated the use of "computational experimentation" and numerical simulations in information science. Nevertheless, even today, this approach is rarely employed in informetric research. Some examples, though, can be found in Bogaert, Rousseau, and van Hecke (2000), Burrell and Rousseau (1995), Efron (2005), Gilbert (1997), and Huber (2002). We have adopted computer simulations as a useful means for testing the influence of a set of parameters on the h-index's increase. In this section, we explain and illustrate our simulation approach.

All simulations are created using the Python programming language (http://www.python.org). Apart from standard Python libraries, we also use the "Hirsch" library we created

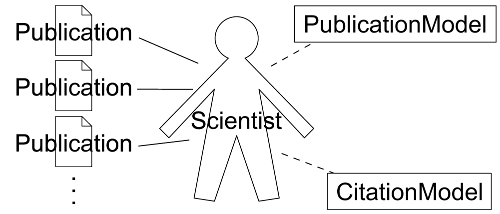

FIG. 1. Schematic representation of the simulation approach.

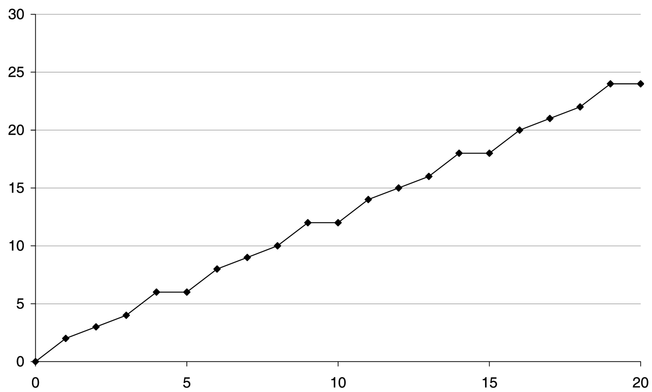

FIG. 2. h-index evolution for baseline model ($p = 3$, $c = 2$).

ourselves. As its name implies, this simple library is used here to calculate the h-index.

Our simulation approach is schematically represented in Figure 1. At the center is a scientist, who has a number of publications (zero or more). Each scientist is also associated with two models, a "PublicationModel" and a "CitationModel." The PublicationModel determines the number of new publications in a given year, the CitationModel determines the number of citations a given publication receives in a given year. This may of course be a different number for different publications and years. Thus, the combined PublicationModel and CitationModel indirectly determine the h-index at a given point in time.

This can be demonstrated using the most basic PublicationModel and CitationModel: "BasePublicationModel" and "BaseCitationModel." These simply return a fixed number of publications or citations, regardless of the year (and of the publication, in the case of a citation number). A combination of a BasePublicationModel and a BaseCitationModel is thus equivalent to Hirsch's baseline model. Figure 2 shows the evolution of the h-index during 20 years if we use a BasePublicationModel (3 publications per year) and a BaseCitationModel (2 citations per year per publication). In Figure 2 and all other similar figures the horizontal axis represents the lifetime of a scientist. This evolution is clearly linear in form. Of course, the baseline model is unrealistic; in the following sections, we will discuss other, more realistic publication and citation models and their influence on the evolution of the h-index. We note, however, that our computer simulation confirms the analytic results of Hirsch's baseline model.

The models upon which these simulations are based are intended to capture specific aspects of the publication and

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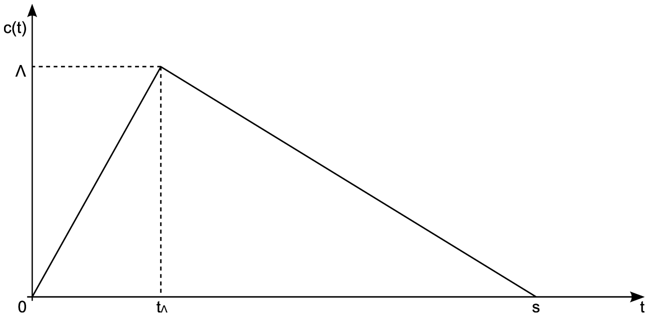

FIG. 3. Peak model (X axis = time t, Y axis = number of citations $c(t)$).

citation process and are generally not applicable to other situations. We therefore do not consider them fit for studying the h-index's evolution in other kinds of source-item relationships such as those hinted at in Egghe (2008b).

Citation Models

In this section, we present a "family" of citation models, which we will refer to as *peak models*. Citations are generally distributed over time according to a certain regularity: The yearly number of citations initially rises quickly until it reaches a peak, and then slowly decreases (see, e.g., Glänzel & Schoepflin, 1995). Peak models as depicted in Figure 3 are a simplification of this general regularity. Triangular peak models are quite close to the more realistic lognormal curves, yet a lot simpler, which is why they were preferred here.

In a peak model, the number of citations per paper increases linearly, reaches a peak, and then decreases linearly to 0. The peak (t_Λ, Λ) with value Λ occurs at time t_Λ. Note that in this model a publication can no longer receive citations after a fixed amount of time, reflecting the obsolescence of the literature in most scientific disciplines. In a peak model, three parameters completely determine the number of citations: the peak time t_Λ, the peak value Λ, and the support s of the citation period, i.e., the time interval in which the number of citations is nonzero. We assume that $0 < t_\Lambda < s$ and $\Lambda > 0$.

In the simplest case, t_Λ, Λ, and s are given numbers, resulting in a *deterministic peak model* (see below). If one or more of these parameters receives its value according to some probability distribution, we get a *nondeterministic peak model*. Two instances of the latter are discussed later, although many more nondeterministic variants can be conceived.

Deterministic Peak Model

In a deterministic peak model, t_Λ, Λ, and s are given numbers. Since each publication has a fixed amount of citations in this model (for a given peak), there is also an upper bound to the h-index: max(h) = tot(c). This is equal to the triangle's area:

$$\text{tot}(c) = \frac{s \times \Lambda}{2} \tag{1}$$

TABLE 2. Default values used for parameters in a deterministic peak model.

Parameter	Default value
t_Λ	3
s	20
Λ	5

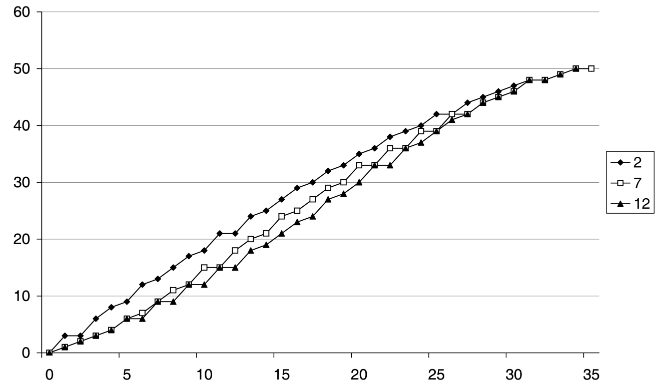

FIG. 4. h-index growth in the deterministic peak model, for values 2, 7 and 12 of peak time t_Λ.

In our simulations the outcome is not always completely exact, because citation scores resulting from the model are rounded to the nearest integer.

We will now look at the influence of these parameters on the h-index growth curve, by varying one parameter and keeping all others fixed at a default value. The default values used are shown in Table 2. In all cases, we are using a constant yearly publication rate $p = 3$. There is no limit on the active lifetime of a scientist.

Variations in t_Λ have no effect on tot(c) (all triangles have the same area), apart from small differences due to rounding. Figure 4 shows the evolution of the h-index for three different values of t_Λ. It can be seen that all three curves converge in Year 35 at max(h) = tot(c) = 50, and stay at this level afterwards. The year in which max(h) is reached can be determined as follows: Since max(h) does not vary with t_Λ, we may just as well consider the case where each year yields an equal amount of citations per publication, equal to $\Lambda/2 = \max(h)/s$. This is not necessarily a natural number. As this simplified case is another example of the baseline model, we can use the approximating formula given in Liu and Rousseau (2008):

$$h_k = \frac{p(k+1)c}{p+c} \tag{2}$$

Proof (reiterated from Liu & Rousseau, 2008). We assume that all publications up to year t_k ($\leq k$) contribute to h_k, a simplification introduced by Hirsch (2005). Then $h_k = t_k p$, where t_k is the solution of $t_k p = (k - t_k + 1)c$, with the requirement that $t_k \leq \min(k, N)$. This results in Equation 2.

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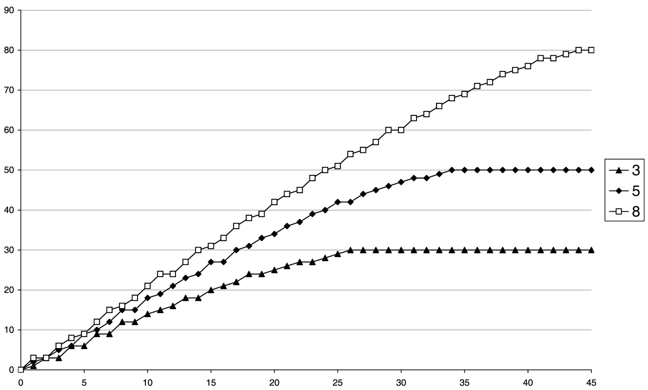

FIG. 5. *h*-index growth in the deterministic peak model, for values 3, 5 and 8 of peak value Λ.

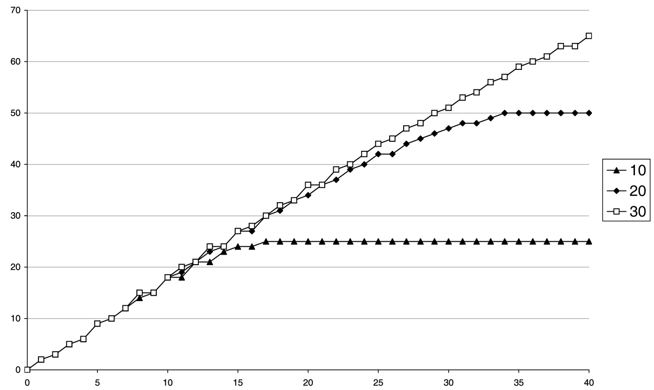

FIG. 6. *h*-index growth in the deterministic peak model, for values 10, 20 and 30 of support *s*.

The year k in which $\max(h)$ is reached can thus be determined as

$$k = \frac{h(p+c)}{pc} - 1 \tag{3}$$

In Equation 3, h is equal to $\max(h) = \text{tot}(c) = s\Lambda/2$ and $c = \Lambda/2$. In other words,

$$k = s\left(\frac{\Lambda}{2p} + 1\right) - 1 \tag{4}$$

For the current case, this results in a reasonable approximation of 35.67.

In general, it seems that the growth rate for smaller values of t_Λ is a bit faster initially, due to the higher number of citations in earlier years. Larger values of t_Λ (e.g., 12 in Figure 4) result in an S-shaped curve. This result is in accordance with other indicators. The number of citations per publication per year evolves in a similar way: slightly concave for small values of t_Λ and S-shaped for large values of t_Λ.

Next, we consider the influence of variations in Λ. As shown in Figure 5, the effect here is much greater: Curves for a higher Λ rise much faster, have larger $\max(h)$ values, and take longer to achieve $\max(h)$. All curves in Figure 5 start out as linear, subsequently become very slightly concave, and then reach $\max(h)$, resulting in a constant "tail."

Variations in s only have an effect on the number of citations in $]t_\Lambda, s[$. As such, their influence on h-index evolution is smaller. In Figure 6, the curves are quite similar up to the point where they reach $\max(h)$. Note that the curve for $s = 30$ has $\max(h) = 75$, which is not yet reached in the interval shown in Figure 6.

In general, we conclude that, employing the deterministic peak model, the h-index increases linearly up to $\max(h)$, even if some minor flattening can be observed before $\max(h)$ is reached. In this model, the peak value Λ is the parameter with the largest influence.

Nondeterministic Peak Models

The deterministic peak model of the preceding section is unrealistic in several ways, one of which being the fact that each publication eventually (s years after its publication) garners the same amount of citations. For this reason we developed two nondeterministic variations of the peak model with a varying number of citations per publication (by varying Λ), which will be discussed in this section.

In accordance with the fact that most informetric features are highly skewed we vary Λ, the height of the top of the citation curve, according to a power law. Of course, this is only a simulation, and we do not claim that this is actually the case. Specifically, Λ is determined as

$$\Lambda = \frac{\min(\Lambda)}{(1-r)^\alpha} \tag{5}$$

where r is a randomly generated number ($0 \leq r < 1$) and $\alpha > 1$. Multiple iterations of this calculation result in an array of different values for Λ, distributed according to a power law with exponent α.

When applying Equation 5, larger values of the random number r (for instance, 0.99) can easily result in values for Λ that are far too large for realistic citation scores—recall that Λ is the number of citations in one year (t_Λ). It therefore seems advisable to rule out such extremely high values. Unfortunately this has a negative impact on the fit between the resulting values and the expected power law. Several techniques were tested; the best results were achieved by multiplying r with a damping factor such that extremely high values can no longer occur. This solution is, however, not perfect.

Constant support. The first nondeterministic peak model varies Λ according to a power law, but keeps s and t_Λ constant for a given scientist. This is represented schematically in Figure 7. This model has four parameters: Apart from t_Λ and s, there is also the minimum peak value $\min(\Lambda)$ and the exponent α of the power law. We will demonstrate the effect of these parameters one by one; the parameters not under scrutiny have the default value shown in Table 3.

Figure 8 illustrates the (not unexpected) major influence of $\min(\Lambda)$, the minimum peak value. It is obvious that this parameter plays a major role from the beginning of the scientist's career. We can also observe a new phenomenon in

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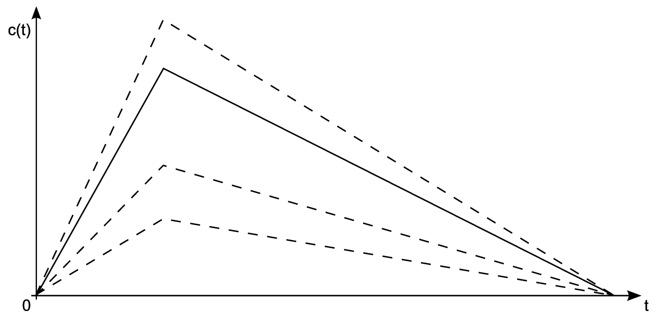

FIG. 7. Nondeterministic peak model with constant s.

TABLE 3. Default values used for parameters in nondeterministic peak model with constant support.

Parameter	Default value
t_Λ	3
s	20
$\min(\Lambda)$	2
α	2

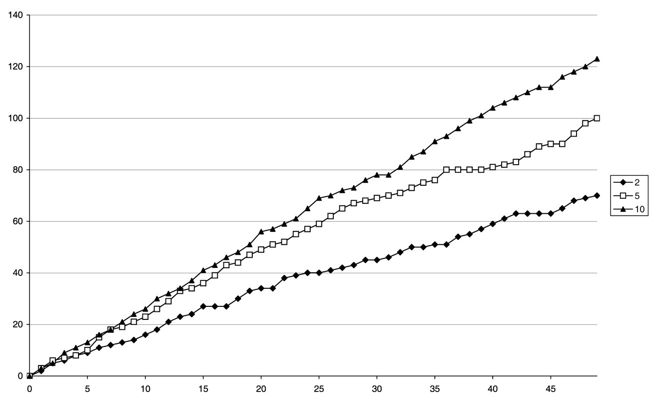

FIG. 8. h-index growth in nondeterministic peak model with constant support, for values 2, 5 and 10 of minimum peak value $\min(\Lambda)$.

this figure (and the following figures), which was much less evident in the deterministic peak model: It sometimes happens that the h-index reaches a plateau—a period of two or more years during which it stagnates. This can be expected, given the h-index's calculation. This phenomenon can also be observed in L. Egghe's and R. Rousseau's personal curves (Egghe, 2008a; Rousseau & Jin, in press).

We illustrate this "plateau effect" with an example, which is completely described in Appendix A. This example is taken from a simulation with a nondeterministic peak model. In the example, the period between years 9 and 11 constitutes a plateau: the h-index is stuck at 11, because the publication at rank 12 receives too few citations. It is thanks to two recent papers, which quickly receive a lot of citations, that the h-index suddenly jumps to 13 in Year 12. This is of course just one possible scenario, but it illustrates the importance of new publications for a steady temporal increase of the h-index in some cases.

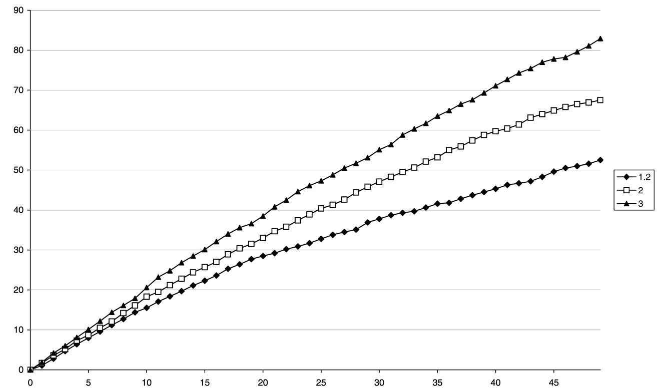

FIG. 9. h-index growth in the nondeterministic peak model with constant support, for values 1.2, 2 and 3 of exponent α (averaged over 10 iterations).

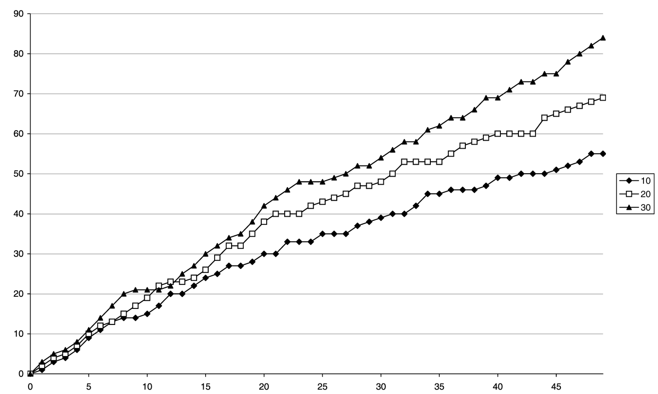

FIG. 10. h-index growth in the nondeterministic peak model with constant support, for values 10, 20 and 30 of support s.

The peak time t_Λ does not influence the h-index's evolution very much. Its effect is similar to that in the deterministic peak model: the h-index initially rises a bit faster for smaller values of t_Λ, sometimes resulting in an S-shaped curve. In the long run, this parameter does not have much of an influence.

Figure 9 illustrates the effect of variations in α. The numbers upon which Figure 9 is based are averages over 10 iterations. Low values of α, such as 1.2, result in a slightly concave curve; higher values of α result in a linear curve. It should be emphasized that this effect is not always visible when considering the results of one iteration. It is also obvious from the figure that higher values of α lead to a faster increase.

The support s (Figure 10) has an effect on the speed of increase as well. The speed differences are partly due to the amount and length of plateaus, with a lower value of s resulting in more and longer plateaus and hence in a slower increase. In some cases, the plateau effect leads to a curve resembling an S-curve.

Constant slope. The second nondeterministic peak model also varies Λ according to a power law, but keeps t_Λ and the slope m of the decreasing part constant for a given scientist. This of course entails that s varies with Λ. The model is

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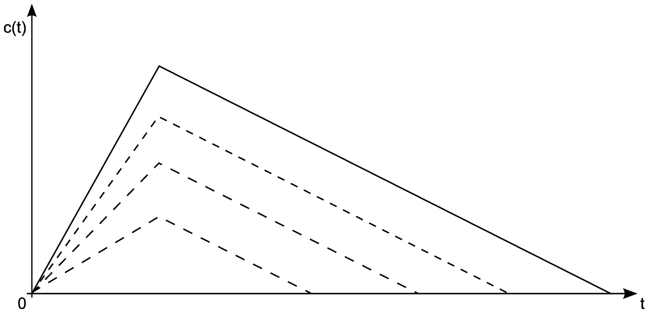

FIG. 11. Nondeterministic peak model with constant slope.

TABLE 4. Default values used for parameters in nondeterministic peak model with constant slope.

Parameter	Default value
t_Λ	3
m	−1.25
$\min(\Lambda)$	2
α	2

represented schematically in Figure 11. Since variations in Λ also affect s, variations in the number of citations are larger in this model than in the first one. One may expect this to have a more profound influence on the h-index and its evolution as well.

The model is determined by the parameters t_Λ, $\min(\Lambda)$, α, and the slope m (< 0). As soon as we know Λ for a given model M, denoted as $\Lambda(M)$, we can also determine $s(M)$ as

$$s(M) = t_\Lambda(M) - \Lambda(M)/m(M) \qquad (6)$$

We will use the default values in Table 4, unless specified otherwise.

Figure 12 illustrates the effect of different slopes: A steeper slope (higher absolute value of m) results in a more concave curve. The influence of the other parameters is comparable to that in the first nondeterministic peak model, but is a bit more pronounced in the case of α, which can be seen in the comparison of Figure 9 and Figure 13.

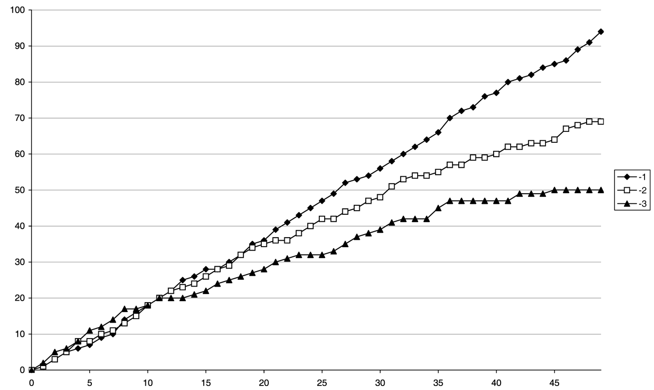

FIG. 12. h-index growth in the nondeterministic peak model with constant slope, for values −1, −2 and −3 of slope m.

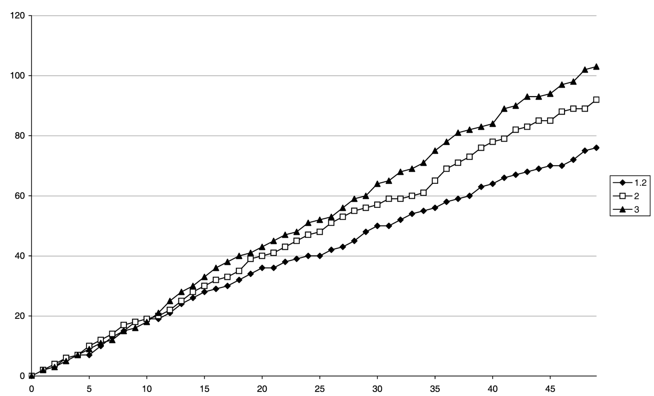

FIG. 13. h-index growth in the nondeterministic peak model with constant slope, for values 1.2, 2 and 3 of exponent α.

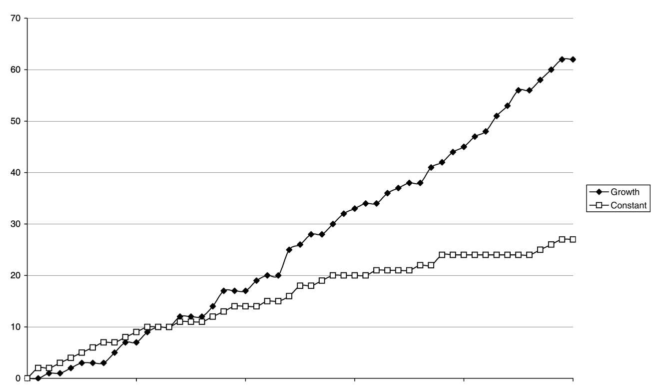

FIG. 14. Comparison of constant number of publications ($p = 2$) and growing number of publications ($b = 1$, $i = 1$, $y = 4$).

Publication Models

So far, we have only considered cases with a constant number of publications per year. We will now consider a more realistic model, in which the number of publications per year slowly increases in time. Indeed, Egghe (2008a) argues that such an increase is a major factor in the h-index's linear increase.

Every y years the annual number of publications is augmented with i. This is a simple linear function:

$$f(t) = \left(\frac{i}{y}\right) t + b \qquad (7)$$

with b the number of publications in the first year.

Even with a very modest increase in number of publications (1 publication extra per 4 years), the effect is quite profound, as can be seen in Figure 14. The h-index sequence associated with a "growth" publication model starts as a convex function, which will eventually lead to an S-shaped curve. The citation model used in Figure 14 is a nondeterministic peak model with constant slope, using all the default values from Table 4.

Conclusions

Numerical simulation is fast and offers possibilities not directly available when one starts from a probabilistic model. When simulations lead to interesting phenomena they may, in a second step, be explained by using a probabilistic model.

The simulations outlined in the present paper are intended to get a feeling for which factors contribute to faster (linear) or slower (concave) growth of the h-index in a publication-citation context. In most cases the lifetime-achievement h-index grows linearly in time. Only occasionally an S-shape occurs, while in our simulations a concave increase is very rare. The deviation with respect to linear growth that occurs most often is the occurrence of plateaus. This means that the h-index does not increase, but stays constant for a while.

There is no single factor that determines the kind of growth curve for the h-index. All factors that positively influence the number of citations also positively influence the speed and linearity of the growth curve. The main factors are

- the height of the peak: Λ in a deterministic model or $\min(\Lambda)$—and, to a smaller extent, α—in a nondeterministic model;
- the citation period length: s or m;
- increase in the number of publications: $\frac{i}{y}$.

The last factor seems especially important: Even small values of $\frac{i}{y} > 0$ trigger a much faster increase. The time when the peak occurs (t_Λ) has, at least theoretically, no effect on the total number of citations for a publication. A later peak time may, however, contribute to an s-shaped curve, due to the low amount of citations in the first few years. These simulation results suggest that h-index growth may also differ between research disciplines.

On a final note, it would be very interesting to compare these simulations with real publication and citation data, but since databases like Web of Science and Scopus do not make Type 5 time series of h-indexes directly available (necessitating a tedious and time-consuming method), such data are only available for a few individuals. Until such data becomes available on a larger scale, it is virtually impossible to accurately compare the models to real-world time series.

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Appendix 1. Example of h-index stagnation in a nondeterministic peak model

Table A1 shows the citation counts during Year 9 up to Year 12 for all 26 publications published between years 1 and 12 (in a simulation with the nondeterministic peak model with

TABLE A1. Citation counts during 4 successive years, illustrating h-index stagnation.

Citation year/Publication ID	9	10	11	12
P1	**442**	**501**	**545**	**574**
P2	**374**	**407**	**429**	**440**
P3	**313**	**330**	**338**	**338**
P4	**249**	**394**	**518**	**622**
P5	**47**	**141**	**223**	**293**
P6	**42**	**46**	**48**	**49**
P7	**22**	**25**	**27**	**28**
P8	**18**	**22**	**25**	**27**
P9	**15**	**45**	**71**	**93**
P10	**15**	**15**	**15**	**15**
P11	**14**	**15**	**15**	**15**
P12	6	7	8	9
P13	5	5	5	5
P14	5	5	5	5
P15	5	5	5	5
P16	3	4	5	5
P17	3	4	5	5
P18	2	3	4	5
P19	0	1	3	5
P20	0	1	3	5
P21		0	5	**15**
P22		0	1	2
P23			0	**19**
P24			0	2
P25				0
P26				0
Resulting *h*	11	11	11	13

constant support). The numbers in bold indicate the publications that are part of the Hirsch core in the given year. Between years 9 and 11, the h-index is stuck at 11, because the publication ranked $h + 1$ (P12) receives only few citations (1 per year in this period). However, two recent papers (P21 published in Year 10 and P23 published in Year 11) quickly receive many citations and help to lift the h-index to 13 in Year 12.

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