Simulating Thomas Kuhn's Scientific Revolutions: The Example of the Paradigm Change from Systems Dynamics to Agent Based Modelling

Georg P. Mueller

Abstract Based on evolutionary game theory, this paper presents a model that allows to reproduce different patterns of change of the main paradigm of a scientific community. One of these patterns is the classical scientific revolution of Thomas Kuhn (The Structure of Scientific Revolutions. University of Chicago Press, Chicago 1962), which completely replaces an old paradigm by a new one. Depending on factors like the acceptance rate of extra-paradigmatic works by the reviewers of scientific journals, there are however also other forms of change, which may e.g. lead to the coexistence of an old and a new paradigm. After analysing the different types of paradigm-changes and the conditions of their occurrence by means of EXCEL based simulation runs, the article explores the applicability of the model to a particular case: the spread of agent based modelling at the expense of the older systems dynamics approach. For the years between 1993 and 2012 the model presented in this article reproduces the observed bibliometric data remarkably well: it thus seems to be empirically confirmed.

Keywords Kuhn's scientific revolutions • Multi-paradigmatic science • Evolutionary game theory • Agent based modelling • Systems dynamics

1 Background and Overview

This chapter refers to the famous book "The Structure of Scientific Revolutions", which Thomas Kuhn published the first time in 1962 (see [1]). The book describes the life cycle of so-called paradigms, which starts with the introduction of new

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G.P. Mueller (✉)
University of Fribourg, Pérolles 90, Fribourg CH-1700, Switzerland
e-mail: Georg.Mueller_Unifr@bluewin.ch

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scientific theories, an agenda of problems to be solved, and methods that are rapidly accepted by the scientific community at the expense of a previously used paradigm. This revolutionary stage is followed by a period of “normal science”, where the problems — i.e. the “puzzles” in Kuhn’s terminology — of the new paradigm are treated and successfully solved by means of its specific methods. At the end, the limitations of the paradigm become more and more visible since many of its remaining “puzzles” turn out to be unsolvable. This is the time, when the scientific community is ready for another scientific revolution by abandoning the existing paradigm in favour of a new one. Thus, science according to Kuhn is a sequence of paradigms, which in the stage of normal science monopolistically dominate the activities of a scientific community.

In spite of its excellent reputation, Kuhn’s book has two major shortcomings: First, it is mainly based on historical examples and thus neglects the institutional framework of contemporary science like peer-reviewing or the publish-or-perish rule for academic careers. Second, Kuhn’s book mainly deals with sequences of mutually exclusive paradigms and thus does not really come to grips with multi-paradigmatic situations, which are so typical for the humanities and social sciences (see [2]). In order to tackle these difficulties, we present in the following sections a simulation model, which is based on game theoretical premises. As proposed by [3], it takes the institutional settings of modern science better into account and offers the possibility to reproduce the coexistence of paradigms.

Obviously there are other simulation models of scientific revolutions (see [4]), the most prominent ones being developed by Sterman [5] and Sterman/Wittenberg [6], who directly refer to Kuhn’s work. Whereas these two authors used a systems dynamics approach (see [7]: Chap. 3), the present chapter is based on evolutionary game theory (see e.g. [8]), which we consider as much more appropriate to the study of competition between paradigms. Moreover, the cited works [5] and [6] of Sterman and Wittenberg are purely theoretical, whereas this paper attempts to corroborate the theoretical simulations with empirical data. The respective analyses in Sect. 4 demonstrate that our model is able to grasp not only the complete replacement of successive paradigms, as described by Kuhn [1], but also the more complex reality of multi-paradigmatic scientific communities. This again is a major advantage over the older model of Sterman/Wittenberg, which seems to explain only the total replacement of an exhausted paradigm by a new one (see [6]: 329, Fig. 7a).

2 A Game Theoretical Model of the Competition Between Paradigms

In its simplest form, evolutionary game theory (see [8], [9]: Chap. 8, [10]) departs from the idea of two randomly interacting species and an associated matrix of $2 \times 2 = 4$ pairs of possible payoffs, which determine the so-called fitness of the two species as well as their reproduction and death rates: the higher the mentioned fitness of the first species as compared to the second, the higher its population growth at the expense of the other.

These basic ideas from theoretical biology have successfully been used for the analysis of dynamic social processes (see e.g. [11–14]). Thus we are going to tackle the modelling of Kuhn's scientific revolutions on the basis of evolutionary game theory. Obviously, the two interacting species are in this case the supporters of the old and the new paradigm, which we describe by:

$$\mathrm{S}_n = \text{Share of the supporters of the } \underline{\text{n}}\text{ew paradigm,} \tag{1a}$$

$$\mathrm{S}_o = 1 - \mathrm{S}_n = \text{Share of the supporters of the } \underline{\text{o}}\text{ld paradigm.} \tag{1b}$$

The arenas where these two "species" encounter are editorial boards of scientific journals, search committees for filling academic posts, or institutions for funding research projects. In each of these arenas academics appear in the role as suppliers and requesters of publication space, posts at universities, or research money. Due to the exclusiveness of their paradigms, interactions in the mentioned arenas are rather hostile for encounters of different paradigms and relatively friendly between representatives of the same paradigm. This has consequences for the academic careers of the requesters, which we are going to analyse in the following paragraph for the case of the submission of articles to scientific journals.

If we assume that the composition of reviewers of journals by paradigm corresponds to the paradigm-orientation of the general population of scientists, it is possible to calculate the total *acceptance rates* A_o *of the old paradigm* and a respective value A_n for the *new paradigm.* Both are the sums of the *acceptance rates* A_i *of intra-paradigmatic* and A_e *of extra-paradigmatic works,* weighted by the population shares S_n and S_o. For reviewers supporting the old paradigm, intra-paradigmatic works are authored by members of the old paradigm and extra-paradigmatic works by supporters of the new one. For reviewers representing the new paradigm, the definitions of intra- and extra-paradigmatic works are just the reverse. Thus, according to Table 1:

$$\mathrm{A}_n = \mathrm{S}_o{*}\,\mathrm{A}_e + \mathrm{S}_n{*}\,\mathrm{A}_i \tag{2a}$$

$$\mathrm{A}_o = \mathrm{S}_o{*}\,\mathrm{A}_i + \mathrm{S}_n{*}\,\mathrm{A}_e \tag{2b}$$

Table 1 The acceptance rates of the old and the new paradigm

		Author's paradigm:	
Reviewer's paradigm:	Share	Old paradigm	New paradigm
Old paradigm	S_o	A_i	A_e
New paradigm	S_n	A_e	A_i
Total acceptance rates of old/new paradigm		$\mathrm{A}_o = \mathrm{S}_o{*}\,\mathrm{A}_i + \mathrm{S}_n{*}\,\mathrm{A}_e$	$\mathrm{A}_n = \mathrm{S}_o{*}\,\mathrm{A}_e + \mathrm{S}_n{*}\,\mathrm{A}_i$

A_i = acceptance rate of intra-paradigmatic articles; A_e = acceptance rate of extra-paradigmatic articles; A_o = acceptance rate of articles based on old paradigm; A_n = acceptance rate of articles based on new paradigm. Source: [22]: Table 1.

Implicitly we are postulating in the formulas (2a) and (2b) that the result of the reviewing process is influenced by the *randomness* of the assignment of reviewers to manuscripts, as demonstrated by [15]. If we assume in addition that there is a publication bias against new ideas (see [16]: p. 71 and [17]: Chap. 3) such that

$$\mathrm{A}_e < \mathrm{A}_i \tag{3}$$

the Eqs. (2a) and (2b) imply that new paradigms have at the *beginning* of their existence a lower acceptance rate A_n than the dominating old paradigm, since in this situation $\mathrm{S}_o \approx 1$ and $\mathrm{S}_n \approx 0$.

At the beginning, however, new paradigms have the advantage of offering to ambitious scientists a lot of easy-to-solve new puzzles such that the *ease of discovery E_n* is at this stage for the *new paradigm* much higher than the *ease of discovery E_o of the old paradigm.* As mentioned by Kuhn (see [1]: Chap. 7), the latter is in its final stage often confronted with insurmountable difficulties in solving its own scientific puzzles. Thus the ease of discovery obviously has consequences for the scientific productivity F_o of the supporters of the old and F_n of the new paradigm, which modify the effects of the initial non-acceptance of the new paradigm in the following way:

$$\mathrm{F}_n = \mathrm{E}_n{*}\,\mathrm{A}_n = \mathrm{E}_n{*}\ (\mathrm{S}_o{*}\,\mathrm{A}_e + \mathrm{S}_n{*}\,\mathrm{A}_i) \tag{4a}$$

$$\mathrm{F}_o = \mathrm{E}_o{*}\,\mathrm{A}_o = \mathrm{E}_o{*}\ (\mathrm{S}_o{*}\,\mathrm{A}_i + \mathrm{S}_n{*}\,\mathrm{A}_e) \tag{4b}$$

Since the above-mentioned productivity in terms of accepted and published papers determines the careers of the respective scientists, we are using in (4a) and (4b) as left-hand-terms the letters F_n and F_o, which stand for the *fitness* of the two groups of scientists. Hence we hypothesise in accordance with the general assumptions of evolutionary game theory (see e.g. [10]: Chap. 3) that the *growth of the supporters of the new paradigm* is

$$\Delta\mathrm{S}_n = \delta * (\mathrm{F}_n - \mathrm{F}_o),\ \text{if}\ 0 < \mathrm{S}_n < 1,\ \text{else}\ \Delta\mathrm{S}_n = 0, \tag{5a}$$

where δ is a constant laps of time. Similarly we assume that the *growth of the supporters of the old paradigm* equals

$$\Delta\mathrm{S}_o = \delta * (\mathrm{F}_o - \mathrm{F}_n),\ \text{if}\ 0 < \mathrm{S}_o < 1,\ \text{else}\ \Delta\mathrm{S}_o = 0. \tag{5b}$$

Both equations are conceptualised in such a way that the shares S_o and S_n do not leave their definition interval [0,1] and always sum up to 1.[1] The changes which they describe are partly due to the transitions of established scholars between paradigms

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[1] From (5a) and (5b) follows $\Delta\mathrm{S}_n = -\Delta\mathrm{S}_o$ such that the sum $\mathrm{S}_n + \mathrm{S}_o$ is *time-invariant* and always yields 1 (see formula (1b)).

and partly to the rational choice of young scientists, who start their careers with the paradigm that promises the more successful professional future.

The advantage of the new paradigm in terms of a higher ease of discovery E_n tends to decrease by the number of newly solved scientific puzzles, which is proportionate to $F_n * S_n$, i.e. the product of the relative size S_n of the population of scientists and its productivity F_n. Similar things hold true for the dynamics of the ease of discovery with the *old* paradigm. Consequently we postulate:

$$\Delta E_n = -\delta * F_n * S_n, \text{ with initial value } E_n = 1 \text{ and } \delta = \text{constant laps of time.} \tag{6a}$$

$$\Delta E_o = -\delta * F_o * S_o, \text{ with initial value } E_o \leq 1 \text{ and } \delta = \text{constant laps of time.} \tag{6b}$$

Hence, after some time, both paradigms are depleted and may be replaced by a third paradigm, which is however not considered in the simulations that follow.

3 Model Simulation

3.1 Introductory Remarks

This section pursues two related goals:

(i) We want to look for an inventory of the different *types of population dynamics* that can be reproduced by the model. Of special interest are on the one hand the empirically observed coexistence of two paradigms and on the other the complete replacement of the old paradigm by a new one, as described by Kuhn [1].

(ii) We attempt to analyse the *determinants* of the mentioned patterns of population-dynamics. Given the limited number of exogenous model parameters, we focus on the acceptance rates of extra-paradigmatic works A_e and the initial ease of discovery E_o by the old paradigm. For reasons of standardisation we set for the start of the simulations the ease of discovery of the new paradigm $E_n = 1$ and the acceptance rate of intra-paradigmatic works $A_i = 1$. This way E_o and A_e become *relative* values, i.e. fractions of the former ones.

In view of the complexity of our model we tackled the goals (i) and (ii) by *simulation* experiments: they allowed to study the effects of parameter changes on the population dynamics of the supporters of the old and the new paradigm in a rather easy way. This method obviously required the translation of the model into a computer program. We used for this purpose an EXCEL spread-sheet with columns being defined as time-dependent variables, like e.g. S_o and S_n and rows representing subsequent time-points with a laps of time $\delta = 0.1$. The rows are linked in such a way that changes of variable-values on one line are propagated to the next, as described by the difference equations (5a, 5b) and (6a, 6b). This process always started under the assumption that between t $=0$ and t $=1$ a new paradigm showed up and lowered the share of the supporters of the old paradigm from an initial de facto monopole $S_o = 1.0$ to $S_o = 0.95$. By simulation of the subsequent population dynamics it was e.g. possible to analyse, under which conditions the new paradigm is crowded out by the old or alternatively further spreads and finally becomes the mainstream of the scientific community.

3.2 Simulated Types of Population Dynamics of Scientists

As a matter of fact, a relatively small number simulation experiments with randomly selected parameter values E_o and A_e show the population dynamics that correspond to the *classical revolutions* described by Kuhn [1]. Figure 1a is an example for these rather rare situations, where the new paradigm immediately attracts a growing number of scientists until it completely replaces the old one.

Much more frequent than the classical "perfect" revolutions are in our simulation experiments the *incomplete* ones, as exemplified by Fig. 1b: the new paradigm immediately starts to grow at the expense of the old. The latter however recovers after some time and leads to a multi-paradigmatic situation, which is often observed in the social sciences. A closer look at Fig. 1b explains this fluctuation in the support for the two paradigms: the rapid start of the new paradigm leads to its early exhaustion and soon lowers its ease of discovery E_n. Between time t=30 and t=100, the E_n of the new paradigm is already smaller than the E_o of the old, which this way gets a chance for a revival (see Fig. 1b). This dynamic of E_o and E_n is in sharp contrast to the classical scientific revolution, depicted in Fig. 1a: here the ease of discovery of the new paradigm is for a much longer time, i.e. until t $=50$, above the old one and thus leads to its complete victory.

In about half of all simulation experiments with randomly selected parameter values E_o and A_e, the change of paradigm is *delayed:* the new paradigm is available, but for some years the old is still vigorous enough to exert monopolistic control of the scientific community. Only after a latent period of further depletion, the old paradigm breaks down and triggers either a *complete* (Fig. 2a) or an *incomplete revolution* (Fig. 2b).

Last but not least there is the rather rare possibility that the outbreak of a scientific revolution is not only temporarily but even infinitely delayed and consequently ends in a *failed revolution.* Hence, from the perspective of evolutionary game theory there are particular conditions (see Sect. 3.3), under which paradigms can be *evolutionarily stable.*

In sum, this model is able to reproduce not only the scientific revolutions of Kuhn [1] but many other phenomena of scientific change like delayed revolutions, where new ideas come too early to be accepted by the scientific community, or incomplete revolutions that lead to multi-paradigmatic science. Thus in view of the last-mentioned category of changes, the model fulfils one of the major goals of this chapter (see Sect. 1).

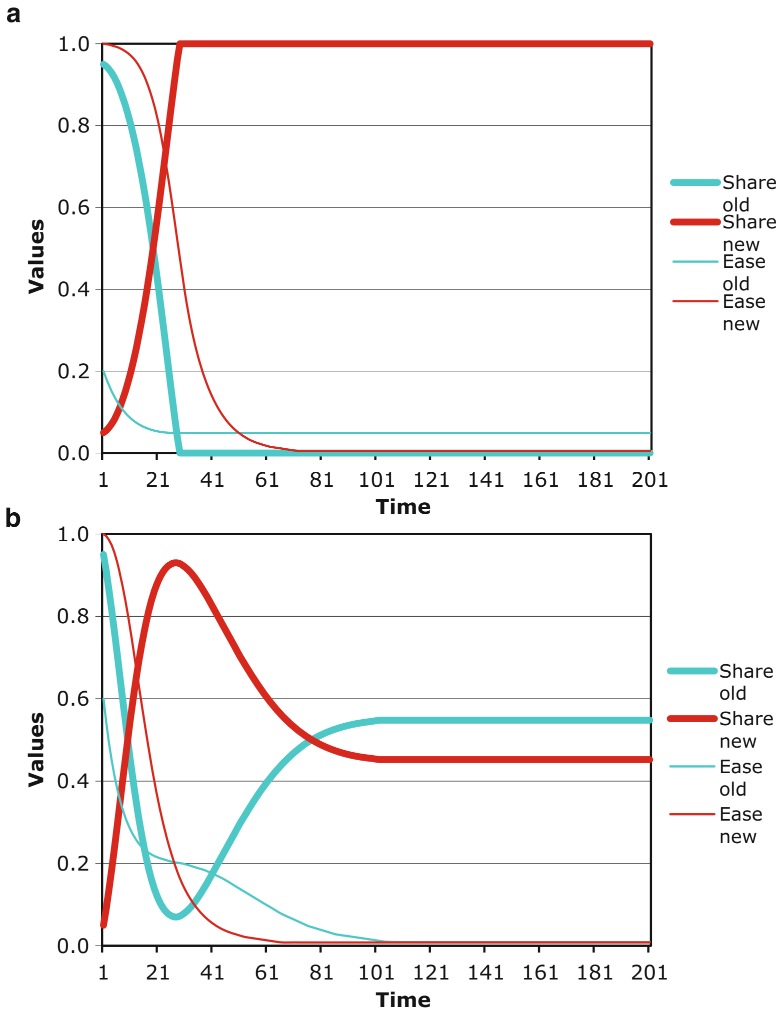

Fig. 1 (**a**) Kuhn's classical revolution: immediate and complete change from the old to a new paradigm (initial parameter values: $E_o = 0.2$, $A_e = 0.2$). (**b**) An incomplete revolution: coexistence of the old and a new paradigm (initial parameter values: $E_o = 0.6$, $A_e = 1.0$)

3.3 The Determinants of the Stability and Long-Term Dominance of Paradigms

The previously encountered types of paradigm-changes differentiate mainly with regard to the following two dimensions:

(i) The *stability of the old paradigm* in the case of the arrival of a new one: it may be *immediately unstable, temporarily stable,* or *permanently stable.* In the first

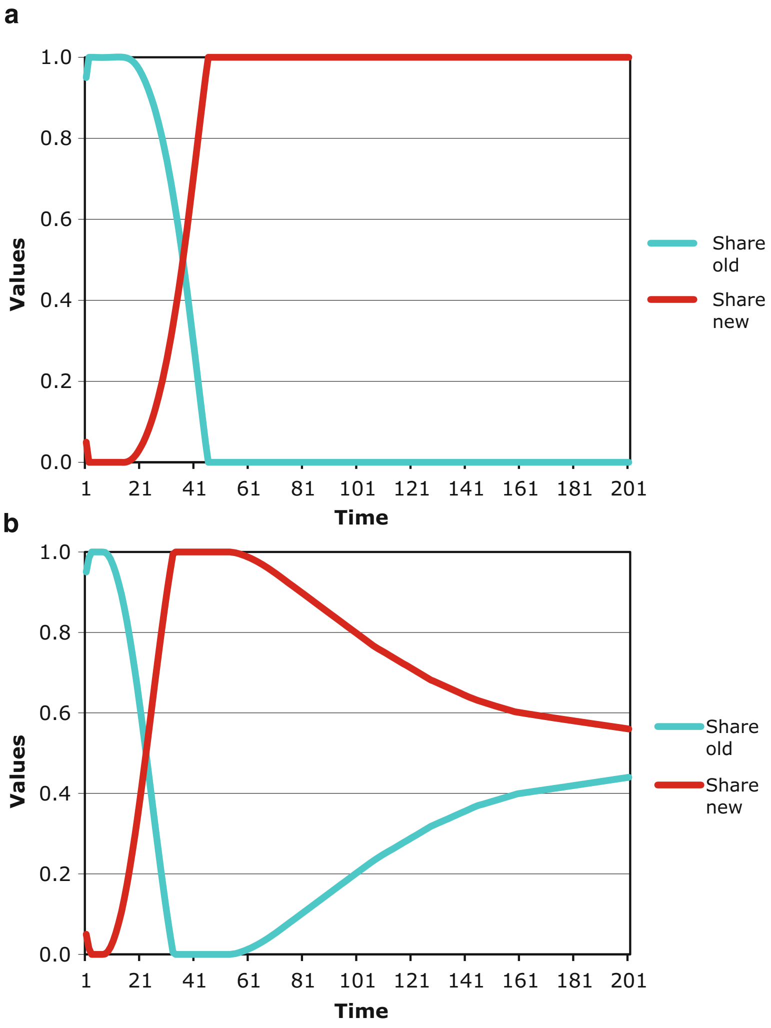

Fig. 2 (**a**) A delayed classical revolution: complete change to a new paradigm (initial parameter values: $E_o = 0.8$, $A_e = 0.2$). (**b**) A delayed incomplete revolution: transition to the coexistence of the old and a new paradigm (initial parameter values: $E_o = 0.9$, $A_e = 0.5$; source: [22]: Fig. 1)

case we expect a classical or an incomplete revolution, in the second delayed changes, and in the third a failed revolution.

(ii) The *paradigm,* which finally *dominates* after the changes induced by the arrival of a new paradigm have fully developed. In the long run the dominating model of science may be the *new paradigm,* the *old paradigm,* or *both paradigms.* The first case corresponds to the effect of a classical revolution, the second of a failed revolution, and the third of an incomplete revolution.

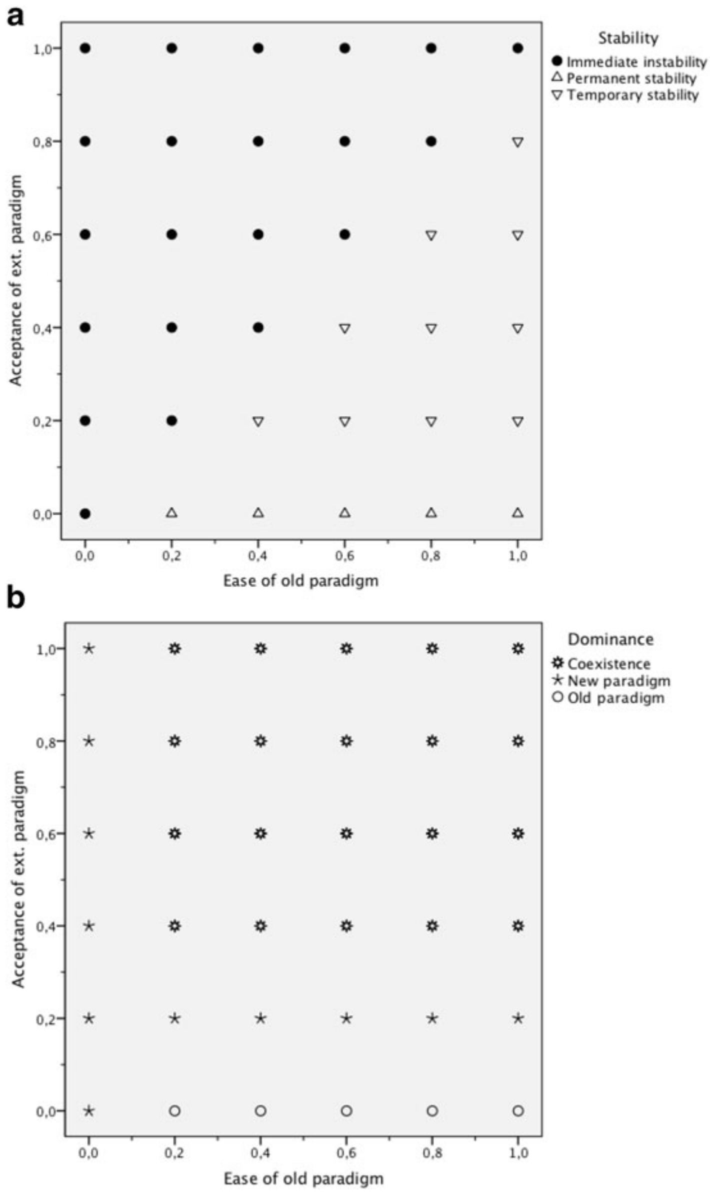

Fig. 3 (**a**) The stability of the old paradigm, by values of A_e and E_o (source: [22]: Fig. 2a). (**b**) Long-term dominance of different paradigms, by values of A_e und E_o (time horizon: 400 units of time; source: [22]: Fig. 2b)

The outcome of the model with regard to both dimensions (i) and (ii) depends on the ease of discovery of the old paradigm E_o and the acceptance of extra-paradigmatic works A_e. Thus we ran the simulation model over a span of 400 units of time with $\delta = 0.1$ and for varying values $E_o = 0., 0.2, 0.4, \ldots, 1$ and $A_e = 0., 0.2, 0.4, \ldots, 1$.[2] The results of these simulations are presented in Fig. 3a, b.

As Fig. 3a demonstrates, scientific revolutions *immediately* break out if $A_e \geq E_o$. Thus, if the reviewers of the old paradigm, who initially have full control of the editorial boards, are too indulgent to new extra-paradigmatic ideas, a change of paradigms is very likely. If $A_e > 0.2$ the revolution remains *incomplete* and leads to a multi-paradigmatic compromise (see Fig. 3b). If $A_e \leq 0.2$, the revolution ends with the dominance of the new paradigm, as described by Kuhn [1] (see Fig. 3b). It is important to note that this kind of a *complete* classical revolution only occurs for a small minority of randomly selected parameter values of A_e and E_o.

Alternatively, if $A_e < E_o$, but $A_e > 0$, the ease of discovery with the old paradigm is too high for an immediate swing from the old to the new paradigm (see Fig. 3a). Nevertheless, after some time the old paradigm is sufficiently depleted and a *delayed revolution* breaks out. For $A_e > 0.2$ it ends again with a compromise between the old and the new paradigm (see Fig. 3b). If $A_e \leq 0.2$, the growth of the supporters of the new paradigm is slower but finally leads to a classical revolution, where the dominance of the scientific field completely shifts from the old to the new paradigm (see Fig. 3b).

Finally, if $A_e = 0$, the supporters of the old paradigm use their initial control of the scientific production to exert a perfect "censorship": no extra-paradigmatic work from the new paradigm is accepted for publication. As Fig. 3a demonstrates, this kind of censorship is an evolutionary stable strategy, which turns the invasion of the field by supporters of the new paradigm into a failure, at least as long as there are any puzzles from the old paradigm left that can be solved by its representatives. In the very moment when E_o reaches the level 0, a classical revolution is immediately triggered, which ends with a complete victory of the new paradigm, as Fig. 3a, b show for $E_o = 0$.

4 An Empirical Test of the Model

4.1 The Explanandum and Its Operationalization

This paper aims at an explanation of the rise and fall of two paradigms of social simulation: systems dynamics simulation (see [7]: Chap. 3) and agent based modelling (ABM) (see [18], [7]: Chap. 8). The former was introduced by Forrester [19] and dominated the simulation literature of the 1970s and 1980s. The latter has

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[2] By definition $A_e = 0$ and $E_o = 0$ are the *lowest* possible values of these two parameters. Similarly, since $A_e \leq A_i = 1$ and $E_o \leq E_n = 1$, A_e and E_o *cannot exceed* the value 1.

its roots in the work of Schelling [20] and spread after 1990 at the expense of the older systems dynamics approach. However, agent based modelling was never able to crowd the other competitive approaches out. According to Table A1 (see Data Appendix), this rise of ABM was rather an incomplete than a complete revolution, and thus resembles Fig. 1b more than Fig. 1a. Hence the case under consideration is an interesting test on whether our model is able to reproduce also the quantitative aspects of an incomplete scientific revolution.

Unfortunately, the shares of scientists S_o and S_n adhering to the *old* and the *new* paradigm are much more difficult to measure than the *shares of their respective publications* P_o *and* P_n, which can easily be extracted from bibliographies. Therefore we tested our model by explaining the publication shares P_o and P_n, which we hypothesise to be the standardised products of the shares of scientists and their fitness related productivity:

$$P_n = (F_n{*}\, S_n) \;/\; (F_n{*}\, S_n + F_o{*}\, S_o) \tag{7a}$$

$$P_o = (F_o{*}\, S_o) \;/\; (F_n{*}\, S_n + F_o{*}\, S_o) \tag{7b}$$

Obviously the shares of the old- and the new-paradigm publications P_o and P_n sum up to 1.[3]

In order to measure P_n, we used the electronic bibliography of Scholar Google [21] as a basic resource that allowed us to count for each year between 1993 and 2012 the *absolute* number of articles with the keyword "agent based" in the title. For measuring P_o we utilised the same bibliography and determined the number of articles with the title-words "system dynamics" or alternatively "system<u>s</u> dynamics". Subsequently we calculated the relative shares P_o and P_n by dividing the number of articles in the old, respectively in the new paradigm through the number of both types of articles. The intermediate and final results of this procedure are presented in the annex in Table A1 (see Data Appendix). The figures are obviously only a rough approximation to reality, with many erroneous omissions and inclusions of articles. Its also important to keep in mind that the data refer not only the social sciences but to any scientific activity covered by Scholar Google, thus e.g. including engineering.

4.2 An Empirical Tests with Preliminary Results

As shown in the previous Figs. 1a and 2b, the dynamics of the model depend very much on the values of its "free" parameters like e.g. the acceptance of extra-paradigmatic works or the ease of discovery with different paradigms. Thus, these parameters have the advantage that they can be used in order to fit the model to

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[3] $P_n + P_o = (F_n{*}S_n) / (F_n{*}S_n + F_o{*}S_o) + (F_o{*}S_o) / (F_n{*}S_n + F_o{*}S_o)$
$= (F_n{*}S_n + F_o{*}S_o) / (F_n{*}S_n + F_o{*}S_o) = 1$

the data. Ideally they should be determined with regression-like statistical methods. However, this is for the present model rather difficult, among others because of the missing time series data for the ease of discovery. Hence the author changed the values of the parameters δ, E_o, and A_e by trial and error, until there was for the whole analysed period between 1993 and 2012 a good correspondence between the outcome of the respective simulation run and the observed shares P_n of publications, referring to the new agent based modelling paradigm. This ad hoc method has yielded the following results:

$$\delta = 0.0191 \tag{8a}$$

$$A_e = 1 \tag{8b}$$

$$S_o = 0.872 \text{ at time } t = 1 \tag{8c}$$

$$E_o = 0.892 \text{ at time } t = 1, \tag{8d}$$

where for reasons of standardisation all simulation-experiments started at time t=1 with the parameter values $A_i = 1$ and $E_n = 1$. The resulting model-fit,[4] defined as the mean difference between the observed and the simulated share of publications equals 0.0041 and thus appears to be quite ok: the simulated trajectory of the publication share P_n is on the average less than half of a per cent away from true share of these publications. This positive evaluation of the model is further corroborated by Fig. 4, which shows a good correspondence between the real and the simulated temporary evolution of P_n, especially with regard to the geometrical properties of the two curves, like e.g. the peaks or the phases of acceleration. However, it has to be kept in mind that a more profound assessment of the model is only possible on the basis of additional examples of paradigm changes, preferably with other types of revolutionary dynamics.

The parameter-estimates (8a) to (8d) are not only useful for a good model fit but also help to understand the modelled processes of science: especially striking in this respect is the estimate $A_e = 1$ (see (8b)),[5] which means that the extra-paradigmatic papers are treated by the journal reviewers in a very similar way as the intra-paradigmatic papers with the same value $A_i = 1$. This is probably due to the fact that the representatives of the new ABM-paradigm had even at the beginning of the simulated period enough opportunities to publish in journals, which were not under control of the older systems dynamics paradigm. Of similar interest as $A_e = 1$ is the strikingly high ease of discovery $E_o = 0.892$ of the old paradigm at the initial time-point t=1. This probably reflects the fact that the systems dynamics paradigm was not really in crisis, when agent based modelling entered the scientific scene. Obviously this is a different situation from the one described by Kuhn

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[4] Model-fit = Square root of (Sum of squares between observed and simulated $P_n/20$) = 0.0041

[5] As explained earlier in Sect. 3.1, $A_e = 1$ is a relative and not an absolute acceptance rate.

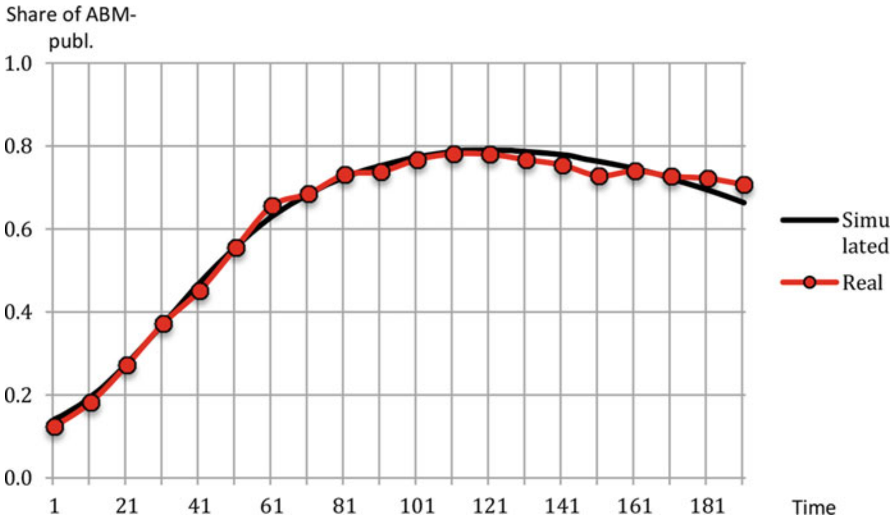

Fig. 4 The temporary evolution of the observed and the simulated share P_n of publications based on agent based modelling (ABM) (Time = 1 ≈ 1993, Time = 11 ≈ 1994, ..., Time = 181 ≈ 2011, Time = 191 ≈ 2012)

[1] at the outbreak of a scientific revolution. Consequently we cannot expect the disappearance of the old paradigm, as suggested by Kuhn, and the coexistence of two paradigms seems to be an intuitively plausible result of the model.

5 Summary and Conclusions

In this chapter we present a model that allows to simulate the classical scientific revolution of Th. Kuhn [1] as well as many other forms of paradigmatic changes like the stable coexistence of an old and a new paradigm. According to Fig. 3b, Kuhn's revolution seems to be a possible but rather *special* event that can only occur if the acceptance A_e of external paradigms is rather *low.* Given the large number of scientific journals, the difference between the intra- and extra-paradigmatic acceptance $A_i = 1$ and A_e is probably often only small. Thus, A_e too is for many cases close to 1 such that Kuhn's revolution becomes according to Fig. 3b a *rare* event. Moreover, due to the mentioned high values of A_e, the old paradigm need not really be depleted in order to enable the *immediate* start a new one: as shown in Fig. 3a, the triggering of this kind of paradigmatic change simply requires that the old paradigm has an ease of discovery $E_o < A_e$. The high acceptance rate A_e of new external paradigms makes this a *likely* event, which leads according to Fig. 3b to *multi-paradigmatic* science — in reality not only with two, but often *several* paradigms coexisting in parallel. Obviously, the model presented in this paper is not made for situations with *more than two* simultaneous paradigms and thus requires in the future an additional modification.

A.1 Data Appendix

Table A.1 Numbers and shares of publications in the agent based modelling paradigm and the systems dynamics paradigm

Year	Sys. dynamics: number	Agent based: number	Both paradigms: number	Agent based: share P_n
1993	183	26	209	0.124
1994	202	45	247	0.182
1995	198	74	272	0.272
1996	247	146	393	0.372
1997	297	244	541	0.451
1998	282	351	633	0.555
1999	285	543	828	0.656
2000	357	775	1132	0.685
2001	366	994	1360	0.731
2002	411	1160	1571	0.738
2003	450	1480	1930	0.767
2004	472	1680	2152	0.781
2005	541	1920	2461	0.780
2006	601	1980	2581	0.767
2007	644	1970	2614	0.754
2008	736	1970	2706	0.728
2009	787	2240	3027	0.740
2010	845	2250	3095	0.727
2011	856	2220	3076	0.722
2012	905	2180	3085	0.707

Source: own calculations, based on [21]

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