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Public funding in the academic field of nanotechnology: a multi-agent based model

Nadine Hoser

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Abstract This paper simulates research networks in nanotechnology in Germany and the US. Agent-based modelling is used to analyse how public third-party funding influences the diffusion of a high technology by four different ways of funding. This diffusion is measured by the emerging number of nanoscientists. Next to the size of the national research systems and the number of scientists, the spread of nanotechnology is measured by interdisciplinarity and the probability of changing one's disciplinary identity. The model is proper for the investigation of other high-technologies. Different ways of funding researchers can, according to the study results, influence the pattern of diffusion of a new technology in academia, in particular in the bigger research system of the US. While results are not significant for Germany, the way of funding researchers has significant effects in the US, with star scientists playing a crucial role for the distribution of public funding.

Keywords High technology · Nanotechnology · Technology diffusion

1 Introduction

The present study contributes to existing literature on scientists' networks and specialties at universities that has not simulated academic networks so far by using

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N. Hoser (✉)
Department of Sociology II, Bamberg University, Bamberg, Germany
e-mail: nadine.hoser@uni-bamberg.de

N. Hoser
DFG-Graduate College "Markets and Social Systems in Europe", Lichtenhaidestr. 11, 96045 Bamberg, Germany

agent-based modelling. The simulation modelling approach is applied to trace the emergence of a new academic specialty, namely nanotechnology, focusing on the influence of public funding. In policies, the assumption most often goes that funding directly leads to innovations and economic growth. Tackling this rather simplistic belief, this paper contributes to a deeper understanding of the complexity of the influence of funding on a fairly new technology and the relationships among technology stakeholders without trying to reproduce all stakeholders and all effective variables. The question is how a new (technological) specialty that is conceived of as an interdisciplinary technology emerges and meets discipline-oriented structures of knowledge production. The formal model draws on general observations that are derived from and validated in empirical research: the role of public funding, the structure and size of research centres, the probability of disciplinary identity change or, in other words, the perseverance of disciplinary structures (see Hagstrom 1970; Abbott 2005), interdisciplinary cooperation as well as the production of graduates from degree programs, such as nano-specific studies, represent relevant modelling factors. The model looks at ideal-type situations in terms of identity change and interdisciplinarity values. It does not represent concrete empirical social cases.

In the model, the institutional and disciplinary development of the academic field of nanoscience is simulated and measured by the number of researchers that are active in nano-scale research. The goal is to compare Germany and the US based on their respective status quo of nanotechnology at universities. The basic question underlying the simulation is: What happens if a new academic field, namely nanotechnology, is being funded by public agencies in different ways among other specialties and disciplines? How does interdisciplinarity influence the spread of nanotechnology? How does the openness of researchers affect its development given the perseverance of disciplinary structures at universities, as widely acknowledged in literature?

A comparison of Germany and the US is relevant because in academic literature the rise of nanotechnology in Germany is surprising. Varieties-of-Capitalism (VoC) literature e.g. cannot adequately explain the development of nanotechnology since its categorization of political economies into liberal and coordinated market economies does not grasp the success of nanotechnology. In general, coordinated market economies are characterized by non-market relations, collaboration, long-term employment strategies, the production of "specific or co-specific assets" as well as durable ties between firms and banks ("patient capital provision predisposes firms to 'incremental innovation' in capital goods industries, machine tools, and equipment of all kinds" (Hancké et al. 2007)). Liberal market economies, by contrast, are marked by "competitive relations", "formal contracting", "fluid labour markets", "stock market capital", "producing 'radical-innovator' firms" and "switchable assets" (Hancké et al. 2007). Nanotechnology must be a special case and deserves further investigation since it does not fit squarely into this VoC categorization. Radical innovations, such as the scanning tunnelling microscope, have occurred in Germany and Switzerland, not, as would be expected by VoC, in the US. This observation incited the present formal model about national cases of nanotechnology asking to what extent different ways of public funding, encountering different structural circumstances, can foster the spread of a new technology in terms of the number of nanoresearchers. This question leads to the following hypotheses that are tested in this paper:

Hypotheses
The null-hypothesis H_0 is: There is no difference in median numbers of nanoresearchers due to public funding strategy [$m_1 = m_2 = m_3 = m_4$].

Alternative Hypothesis H_a: There is a difference in median numbers of nanoresearchers due to public funding strategy [$m_1 \neq m_2 \neq m_3 \neq m_4$].

The paper is structured as follows: First, the methodological procedure and the model description and setup are presented in Sect. 2. The simulation results of Sect. 3 are divided into two foci: normality and network effects as well as an illustration of four steps of simulation models that help understand the procedure of simulation modelling. After a short overview of the results at the end of Sect. 3, the discussion and conclusion sections point to policy implications and strengths and weaknesses of the formal model.

2 Method

Social simulation is used here to generate "artificial" data (Squazzoni 2010), i.e. computer-generated data, to detect and explain social relationships by means of simulated mechanisms. These mechanisms focus on the intended and unintended consequences of individual behaviour for the macro-level rather than on variables that are to be statistically evaluated (Hedström 2008). This is particularly important in the context of public policy as here, the interrelationship of the micro- and macro-level is crucial for decision-making. In the present study, the mechanisms relate to the likelihood of interaction. They include the formation of publicly funded research alliances based on spatial proximity (Pattison and Robins 2002; Schweinberger and Snijders 2003; Blau 1977; Powell et al. 2005), personal acquaintance and relationships (seen as a result of homophily (Blau 1977)),[1] transitivity (also known as clustering (Davis 1970)) in research collaboration and citations as well as the tendency to cite 'star scientists' ('Matthew Effect' (on the unequal distribution of scientific papers see Merton 1968; De Solla Price 1965) and 'Lotka's Law' (Lotka 1926)). 'Lotka's Law' refers to scientists citing 'star scientists' and thus expresses an unequal distribution in science, not only of papers but also of citations. In addition, transitivity (Davis 1970) holds, i.e. indirect relationships with agents acquainted with a specific other agent (node) who can only enter research or reference links (citations) with directly or indirectly known agents. Only when changing their disciplinary identities as a result of the application of the parameter of identity change, agents can merely choose among directly known agents. The latter rule accounts for the fact that a change in identity is influenced by peers. Furthermore, the reproduction of the research networks are modelled by studies producing graduates that follow research interests based on their university education. As a result, nanotechnology diffuses within the network, and thus nanotechnologists emerge who identify themselves as nanotechnologists. A social mechanism, following Hedström, is hence defined as "a constellation of entities

[1] For a current issue on homophily, see the theoretical and methodological discussion on the mechanisms of influence (e.g. by peers) and selection (homophily) and the difficulty of differentiating between the two. A discussion from a statistical-methodological point of view is provided in Steglich et al. (2010)

and activities that are organized such that they regularly bring about a particular type of outcome" (Hedström 2008).

Targets, i.e. "'real-world' phenomena" (Gilbert and Troitzsch 1999a), are to be explained in the model. The main interest is to explore the influence of public funding on research cooperation between researchers, i.e. agents, and on the development of main disciplines and specialties measured in terms of the number of agents that belong to that field of research or graduated from a study program. The main parameters, i.e. factors, are the degrees of interdisciplinarity and the readiness to change disciplinary identities (dubbed here as 'identity-change'). It is examined how funding affects the network of researchers and their collaboration. Basic characteristics from network analysis are adopted, such as spatial proximity (Pattison and Robins 2002; Schweinberger and Snijders 2003; Powell et al. 2005), meaning that knowing each other and having short paths (distances) to other agents increase the probability of entering collaboration, and prestige measured by the number of citations (Jackson 2008), influencing the probability of effecting relationships between researchers. In sum, the model results show how funding can induce network effects in research cooperation and, in general, how social phenomena emerge that are not laid into the model at the beginning of the simulation. Emergence thus "occurs when interactions among objects at one level give rise to different types of objects at another level" (Gilbert and Troitzsch 1999b).

The analysis of significant differences due to the way of distribution for public funding is done by Kruskal-Wallis and Nemenyi tests. One must be aware that these data are artificial and not empirical. Therefore, one must keep in mind technically, significant effects could be obtained by increasing the number of simulation runs. The fact, however, that significant differences between the four funding strategies are already reached by a moderate number of runs, namely 100, indicates that network effects lead to mass effects and significant differences already with a low number of n, with n being the number of simulation runs. A non-parametric test was used because of the violation of the normality assumption of ANOVA, the parametric one-way analysis of variance. Every sample followed a non-linear distribution. To see which funding strategy samples differ significantly from each other in the cases of a significant Kruskal-Wallis result, the post hoc Nemenyi test was used for multiple comparisons, being the non-parametric correspondent for the Tukey test, which is the post hoc test for ANOVA.

2.1 Model description

There are several theoretically based parameter and variable settings delineating a US-American and a German model. The model is based on the different size of the respective national research systems and on literature (see e.g. Jansen et al. 2010). The independent variables are the spending of public money for disciplines and specialties, in particular nanotechnology, and the production of graduates from degree programs that are nano-specific (as often in Germany) or not. The focus on public funding is explained by the largest share that public funding provides for nanoscience and -technology at universities in both countries. The variation and calibration of a discipline-based change of one's (occupational and, more generally, social) identity, the probability for interdisciplinary cooperation and the social mechanisms for the likelihood of interaction provide control variables of the model. The following procedure exemplifies the likelihood of interaction based on spatial proximity describing the emergence of a research link:

```
to est_rs-links
  ask researchers [
    if prob_est_rs-link > random-float 1 [
     ifelse prob_interdis > random-float 1
       [ set pot_link_neighbors ( other researchers with [ ( member? who
       [known_to_me] of myself) and ( not member? who partners ) and
       ( color != [color] of myself )] ) ]
       [ set pot_link_neighbors ( other researchers with [ ( member? who
       [known_to_me] of myself) and ( not member? who partners ) and
       ( color = [color] of myself )] ) ]
     if any? pot_link_neighbors [
       ask pot_link_neighbors [
         set last_distance distance myself
         while [ last_distance = 0 ] [
           set last_distance random-float 1]
         set last_rndm-fac random-float 1
         while [ last_rndm-fac = 0 ] [
           set last_rndm-fac random-float 1] ]
      let max_distance ( max ( [last_distance] of pot_link_neighbors ) )
      let max_rndm-fac ( max ( [last_rndm-fac] of pot_link_neighbors ) )
               let tmp-list []
      ask pot_link_neighbors [
        set link-score ( 10 * ( weight_distance * ( 1 - last_distance /
        max_distance ) + ( 1 - weight_distance ) * ( last_rndm-fac /
        max_rndm-fac )
  ) )
        let counter 0
        while [ counter < link-score ] [
          ; as long as counter < link-score, turtles put their number
          into tmp-list--the bigger link-score, the more numbers the
          turtle puts in the pot & the higher the probability of being
          chosen as link-neighbor,i.e. research partner
          set tmp-list ( sentence tmp-list who )
          set counter ( counter + 1 ) ] ]
     if empty? tmp-list [
       set tmp-list ( list ( [who] of one-of pot_link_neighbors ) ) ]
     let link-neighbor ( researcher ( one-of tmp-list ) )
     create-rs-link-with link-neighbor [
       set color 8 ] ] ] ]

end
```

Being a random-based network model, parameters are varied to simulate real social networks and to generate artificial data. These data are analysed by statistical methods (Kruskal-Wallis and Nemenyi tests) to detect if there are significant differences between the samples for the four funding strategies. These strategies are: the funding of ‘star scientists’, i.e. those with a maximum number of citations, ‘core scientists’, i.e. those who have a maximum number of research alliances, the random funding of 'any scientist' in the research networks, and the funding of 'research programs' in which two coordinators are funded. The basic procedures are as follows:

```
to go
  if ticks > (end-tick - 1) [ stop ]
  fund_nano
  del_links
  update_funders
  est_links
  change_identity
  change_generations
  color_studies
  update_agents
  update_globals
  tick
  do-plots
end
```

See (Electronic Supplemantary Material with Attachments 1 and 2) for all algorithms and procedures of the model.

2.2 Model: setup and agent behaviour

In the setup of the model, agents (96 in Germany, 408 in the US as a proportion of the absolute numbers in the respective countries) are distributed randomly over the number of research centres that are displayed in the grid of the model. The number of agents in both model settings is distributed equally over four scientific disciplines (chemistry, engineering, materials science and physics), which participate in nanotechnology research. This way, there is no bias in the model towards one single discipline. The adoption of nanotechnology as the identity of the researcher can only occur during the simulation when the function 'funding of nanotechnology' is activated in the simulation rounds, namely 1200 rounds per run, as this is a condition for the spread of nanotechnology. The agent behaviour is based on the fact that agents cooperate with and cite whom they know directly or indirectly (see 'transitivity' mentioned above).

Directly known are, first of all, all agents that belong to one research centre. This rule favours intradepartmental research alliances, as cooperation with a spatially close agent is preferred. In addition, an agent knows directly those whom he or she cites or cooperates with and who graduated from the same research centre's study program and stay in the centre. An agent also knows its funding agencies which look for funding partners throughout the existing research centres independently of the research centre they are located in. Since funding agencies are not bound to one research centre, as agents are, funding agencies function as intermediaries between different research centres and their agents. It is via agencies that agents indirectly get to know researchers from other centres. This rule takes into account the importance of spatial proximity highlighting the centrality of research centres for research. The rule further stresses the role of agencies which link research centres and influence the researchers' perceptions with regards to which topics are worth pursing and which are not.

Agents can be influenced in their research content by other agents' disciplines and research by changing their disciplinary affiliation. This affiliation can only change by way of the probability of identity change where agents adopt the identity of one of their funding agencies or one researcher that they know directly. Nanotechnology can spread via funding agencies or via already existing nanoresearchers who are cited or who collaborate in research networks with others. The more nanoresearchers thus exist, the more additional nanotechnologists can emerge. Identity change therefore denotes the self-description of researchers with reference to their identity as a scientist. In addition, agents can be influenced by graduates from degree programs who, at least at the beginning, pursue research that is identical with their study programs. Thus, when researchers cooperate with these graduates and happen to change their identities, already active researchers might be influenced by graduates or vice versa, if graduates change their identities themselves.

2.2.1 National model cases of Germany and the US: similarities and differences

In both national models, the creation of degree programs and the influence of researchers on degree programs is depicted by a constant probability of 'study change' (0.1) ensuring that degree programs do not stay the same but are subject to the influence of researchers who are responsible for lecture content and for their creation in the first place. There is one study/degree program with a particular focus on a single discipline or on nanotechnology for each research centre. Researchers belonging to that research centre influence the content of the study program.

The function 'funding of studies' is only activated in the German model since, due to the relatively recent reforms of the 'Excellence Initiative' (and Bologna), new degree programs in the form of bachelor/master programs as well as doctoral graduate colleges have been created to raise third-party funding:

```
to fund_studies
   if ( funding_studies? = true ) and ( any? studies = true ) [
     ask funders with [ color != blue ] [
       let tmp-links ( count fd-links with [ ( is-study? end2 ) and
       ( end1 = myself ) ] )
       while [ tmp-links < 1 ] [
         update_funders
         let link-neighbor one-of studies
         create-fd-link-to link-neighbor [
           set color [color] of myself ]
         ask link-neighbor [ set color [color] of myself ]
         set tmp-links ( tmp-links + 1 ) ] ] ]

end
```

Thus, public money flows into degree programs as well, in particular into master programs in the natural sciences, the relevant disciplines in the context of nanotechnology (Hüning and Langer 2006). By way of funding, these degree programs are influenced not only by researchers (via the probability for study change) but also by the funding agency itself that gives money due to a particular intention for the content of that program (depicted by the funding link directed to studies).

Table 1 Differences in the national model cases of Germany and the US

Germany	US
96 nanoresearchers, 9 research centres	408 nanoresearchers, 25 research centres
Funding-studies option	No funding-studies option
Higher proportion of public funding goes to nanotechnology (based on public funding figures from 2007)	Lower proportion of public funding goes to nanotechnology (based on public funding figures from 2007)

These reforms have not occurred in the US so that the US model lacks the 'funding studies'-option. One must bear this national distinction in the model setup in mind since it indicates a major difference between Germany and the US from the view of the VoC approach, as pointed to in the introduction. With the focus on institutional education and training systems and specific skills in coordinated market economies like Germany (Streeck and Thelen 2001; Thelen 2004), the 'funding studies'-option applies to Germany. This option includes the establishment of institutional complementarities in the German political economy by providing education in specific skills through nanotechnology study programs. This way, the importance of education and vocational systems in a coordinated market economy is taken into account, whereas a liberal market economy like the US continues to pursue its focus on large national research systems and institutes as well as more general skills acquired in education (Thelen 2004). Table 1 summarizes the respective national setups of Germany and the US:

The main question examined here is: what happens if differing funding strategies for money allocation are applied? To analyse money allocation based on different foci, four possible, logically derived strategies of funding for nanoscience are applied that might turn out to be influential in the diffusion of nanotechnology within the simulated scientific community: funding of 'star scientists', of 'core scientists', of 'research programs', and of 'any scientist'. The funding of nano-'star scientists' is based on the maximum number of citations a researcher has, which increases the chance of being funded.

```
to fund_star_scientists
  let tmp-links n_rs_funded_by_me
  while [ tmp-links < grants_by_funder ] [
    update_funders
    let link-neighbor ( max-one-of ( researchers with [ not member? who
    [rs_funded_by_me] of myself ] ) [n_referencing_me] )
    create-nano-fd-link-to link-neighbor [
      set color [color] of myself ]
      set tmp-links ( tmp-links + 1) ]
end
```

The funding of 'core scientists' depends on the maximum number of a researcher's research links, which increases the chance of being funded. In other words, those who have a maximum number of (outgoing) research links are the first ones to engage in collaboration or to be chosen as co-operators.

```
to fund_core_scientists
  let tmp-links n_rs_funded_by_me
  while [ tmp-links < grants_by_funder ] [
    update_funders
    let link-neighbor ( max-one-of ( researchers with [ not member? who
    [rs_funded_by_me] of myself ] ) [n_partners] )
         create-nano-fd-link-to link-neighbor [
           set color [color] of myself ]
           set tmp-links ( tmp-links + 1) ]

end
```

One might object that prominence in terms of the number of cooperation relationships with other researchers is rather a secondary criterion resulting from high reputation due to citations. Yet, here, the logical possibility of the network to fund researchers with a high number of research links was regarded to be worth of a separate analysis, as it might indicate an additional importance of research alliances for the funding of nanotechnology as opposed to the importance of citations within the network alone. The funding of nano-'research programs' describes the funding of a group of researchers who are already partners and known to each other, such as German 'excellence clusters' or US research groups headed by several PIs, e.g. department/research centre collaboration. Hereby, as long as grants are available, one funding agency supports a maximum of two researchers at a time, one with a maximum number of partners and one of his or her partners. A funding agency cannot fund a researcher who is already receiving a grant from that same agency. With the 'research programs' strategy, public money is distributed over several agents and lessens the influence of a central position that one researcher might obtain within the network in the course of the funding process simulation.

```
to fund_research_programs
  let tmp-links n_rs_funded_by_me
  while [ tmp-links < grants_by_funder ] [
    let link-neighbor ( max-one-of ( researchers with [ not member? who
    [rs_funded_by_me] of myself ] ) [n_partners] )
    let link-neighbor-partners researchers with [ member? who [partners]
    of link-neighbor ]
    if link-neighbor != nobody [
    create-nano-fd-link-to link-neighbor [
      set color [color] of myself ] ]
    set tmp-links ( tmp-links + 1)
    if ( any? link-neighbor-partners ) and ( tmp-links <
    grants_by_funder )
[
       create-nano-fd-link-to one-of link-neighbor-partners with [ not
       member? who [rs_funded_by_me] of myself ] [
       set color [color] of myself ]
       set tmp-links ( tmp-links + 1) ]
   update_funders ]

end
```

The funding of 'any scientist' refers to nanoresearch performed by a single researcher without having a high reputation in nanotechnology, be it with regards to citations or research alliances, but who nevertheless has a chance of obtaining grants by way of submitting proposals.

```
to fund_any_scientist
  let tmp-links n_rs_funded_by_me
  while [ tmp-links < grants_by_funder ] [
    update_funders
    create-nano-fd-link-to one-of researchers with [ not member? who
    [rs_funded_by_me] of myself ] [
           set color [color] of myself ]
           set tmp-links ( tmp-links + 1) ]

end
```

In other words, the structural position within the simulated research network does not have any influence on whether a respective researcher gets funded in the case that the strategy of 'any scientist' is applied. This differentiation between strategies only applies when the procedure 'nanofunding' is activated, which is done here for both cases, Germany and the US, as in both countries nanotechnology is publicly funded. Otherwise, i.e. in a model setting where nanotechnology would not be fostered, research disciplines are funded in a random way. This would be equivalent to the funding type of 'any scientist'.

The two models are true to scale when it comes to the following aspects: the number of agents (96 in Germany (based on Jansen et al. 2010), 408 in the US), research centres, the relation of nanofunding links to all other funding links, which is the proportion of nanofunding in national R&D budgets in 2007 (National Nanotechnology Coordination Office 2010; VDI Technologiezentrum e.V. 2009; National Science Foundation (NSF) 2010; National Science Foundation (NSF) 2008; Bundesministerium für Bildung und Forschung (BMBF) 2009) and, finally, the number of disciplines. These disciplines are related to nanoscience but remain structurally separate from nanotechnology since they merely implement this technology but do not base their identity on that specialty. The disciplines compete for funding links as well.

Other factors and parameters true to scale are: the approximate duration of research projects, i.e. in the model, the duration of research and funding links, and the size of the average research networks that determines the probability for establishing research alliances between simulated researchers (Jansen et al. 2010). Furthermore, one tick (i.e., step of the model runtime) equals one month. This is relevant for the implemented 'renewal' of agents, i.e. the production of a new generation of scientists, because researchers are not doing science perennially but for a limited period of, as in the present model, around 40 years. This is an approximation and means that researchers enter the field at the age of 25 and leave at the age of 65, meaning that they vanish from the nanofield that is simulated. Altogether, the maximum number of ticks is 1200, representing a period of 100 years, i.e. nearly three generations. The empirically-based values for the parameters are recalculated to fit the time unit of months.

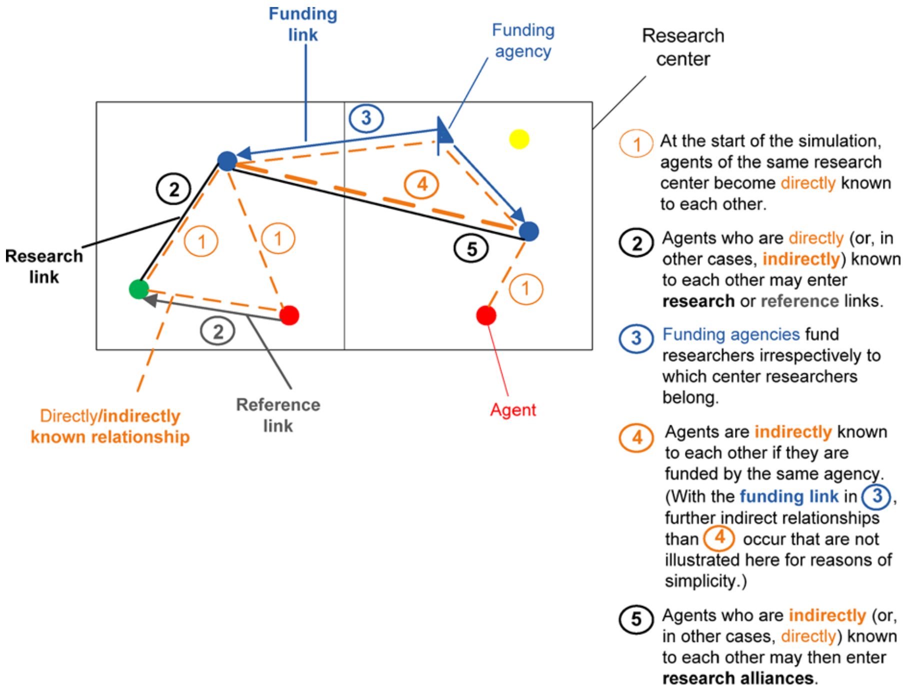

Fig. 1 Typical agent relationship mechanisms; own source

2.2.2 Creation of links: research, reference, and funding links

The basic procedure is the creation of links between researchers from different disciplines and specialties who know each other directly or indirectly through another researcher. There are three types of links: research, reference, and funding links, of which nanofunding links represent a special type. See procedure:

```
to est_links
  est_rs-links
  est_rf-links
  est_fd-links
  est_nano-fd-links
  fund_studies
  fund_nano-studies
end
```

Figure 1 illustrates a possible scenario of agent and agency behaviour by pointing to a number of steps that can occur within a tick.

Research alliances are formed between researchers whereby those who are spatially closer to one another are more probable to engage in collaboration: cooperation with a researcher from the same research centre or from one research centre in the vicinity of this centre occurs more likely than cooperation with someone further away from the research centre. Distance in the present model is a rather abstract measurement, as it solely refers to the distance between researchers in the grid of the model.

Reference links emerge between researchers as well and represent citations. These links are not based on 'spatial proximity' but on the prominence of researchers due to citations that are measured by already extant references that are directed towards a researcher. This means that the more prominent a researcher is, the more probably that researcher is cited by somebody who knows that researcher directly or indirectly (by reading his or her research for example), but not necessarily by somebody who is already a research partner. This observation is similar to Lotka's law (Lotka 1926), whereas in the present case, the simulated mechanism does not denote publications but citations, as was studied by De Solla Price (1965).

An agent can have multiple research, reference and funding links. The number is not limited by an absolute number but by the rule that research and reference links end after a realistic period of time, i.e. probability of deleting a link. The number of research alliances and citations depends on the probabilities for these links in any given simulation round (0.1 and 0.5 respectively). The probability for reference links is higher because a single agent can engage with research alliances less frequently than with citations due to their limited capacity concerning time and money. In each simulation round, a random probability is chosen between zero and one. If these randomly selected probabilities are lower than 0.1 or, in the case of citations, 0.5, a respective link emerges between two agents. Therefore, the number of links varies from one round to another. Concerning funding links, the number of links cannot exceed the budgets that are available for research grants. However, if an agent is already funded in one project by a funding agency, agencies do not give further grants for the same field of research to that particular agent.

Degree centrality for research and reference links are the measure of prominence which is originally based on research collaborations or citations (Mutschke 2010). For reference links, the relative in-degree more precisely measures prominence in the present network. Degree centrality denotes the number of direct neighbours of a node i (here of a specific researcher on a specific position within one of the model's research centres) based on the number of links that connect node i with other nodes. The relative in-degree is central because it implies that reference links are directed towards a 'star scientist', not directed away from a 'star scientist'. A 'star scientist' is a researcher who unites a maximum of citations of their publications (on the introduction of the term 'star scientist' see e.g. Zucker and Darby 2001). Research links, however, are undirected, which means that they can be directed towards or away from a researcher. It remains to be noted that there is no coupled dynamics of reference or research links when taking into account the funding. In each round, i.e. after each 'tick', which is the time unit of the model, a new randomized probability between 0 and 1 determines the establishment of research and reference links. This procedure takes place independently of what has happened in the previous round. It implies that a different type of researcher is more or less probable of being funded dependent on the funding strategy that is used throughout the 100 runs of each of the four samples. Research links in the 'core scientists' strategy denote as much funding as reference links in the 'star scientists' strategy, for example. Just the fact who receives a budget differs due to a higher probability of the occurrence of reference links. In the case of research programs, however, two researchers at a time receive funding and thus the same budget so that, overall, more budget is received for the same research project.

Funding agencies establish directed funding links with researchers who are not already being funded by that particular agency's program or specialty. A funding agency establishes one funding link with one researcher at a time. This is repeated so long as its budget, i.e. the size of its grant, allows. On the other hand, one researcher can have several funders at the same time. Furthermore, directed reference links are established from researchers to other researchers as well as undirected research links among researchers. Funding links always remain the same, i.e. they designate the same amount of money to each researcher. Funding agencies can also fund degree programs but only in the German model to account for the third-party funded bachelor and master degree programs in the sciences that have been established due to the European Bologna reform.

Nanofunding links stand out as a special type of funding because it is of interest here how nanoscience and -technology develop by being funded as a separate program. If the function 'nanofunding?' is activated, then one funding agency funds nanotechnology. Funding agencies in this model can thus fund disciplines and specialties, with nanotechnology being but one example. The funding target depends on the research emphasis the respective agency program has. The funding links namely denote the project content that is funded by the agency.

2.2.3 Variables and parameters

The model is set up in a way to observe what happens when a new sub-discipline, nanotechnology, is funded by public funding agencies and new generations of scientists are reproduced in the form of nano-degree graduates. The observations are based on several parameters and variables but do not constitute empirical values representing observed empirical cases. The following factors are recognized as influential for research collaboration: interdisciplinarity and identity change (referring to the degree of openness to change ones disciplinary/professional identity). Identity change varies in each country setting to check two extreme values of openness, whereas the respective probability of interdisciplinarity takes the value of zero and one (i.e. interdisciplinarity funding yes/no) for each country, also representing two extreme values. An overview of all parameters is given as follows:

- *n_research-centres*: This value indicates the number of research centres that are extant in the respective national setting. The value, which differs for Germany and the US, represents the relative number of nano-related research units attached to universities compared to the total number of research institutes specialized in nanotechnology. Here, the number of researcher centres in the respective countries was calculated (see Jansen et al. 2010 for Germany).
- *n_researchers*: This number depicts the relative number of nanoresearchers in Germany and the US respectively compared to the estimated total number of nanoresearchers as of 2009.
- *n_disciplines*: N_disciplines includes the number of four main disciplines that form the (natural) sciences (Schummer 2007). These are physics, chemistry, materials sciences, and engineering.
- *studies?*: This switch enables the creation of course programs of different specialty and disciplines that produce graduates from the respective specialty or discipline.

- *prob_study-change*: This parameter, kept at a low level of 0.1, assures that nano-degree programs change slowly over time to represent the influence by the creators of courses, course catalogues, whole programs and lectures.
- *prob_identity-change*: This variable represents the probability that researchers change their professional disciplinary identity, adopting two extreme values for openness and thus representing ideal-type conditions. Identities can be nanotechnology or other academic disciplines. Researchers when changing their identity do not adopt a random specialty or discipline but orient themselves towards one of their funding agencies or towards the identity of somebody they already know by virtue of collaboration or citation. See procedure:

```
to change_identity
  ask researchers [
    if prob_identity-change > random-float 1 [
      ifelse prob_innovation > random-float 1
      [ set color one-of color_list ]
      [ if not empty? dir_known_to_me [
          set color [color] of one-of turtles with [ member?
          who ( [dir_known_to_me] of myself ) ] ] ] ] ]
end
```

- *prob_interdis*: This parameter reports if researchers from different disciplines start interdisciplinary research collaboration by choosing randomly a partner of a different discipline or not. The parameter also describes an ideal-type condition of interdisciplinarity representing two extreme values: either no interdisciplinary co-operation is fostered or there is a 100 % probability that a new cooperation is between different disciplines, including nanotechnology.
- *nano-funding?*: This switch (nanofunding: yes or no) tells if nanotechnology as an academic specialty is funded or not. For the analysis here, funding of nanotechnology is always applied, as it is of interest how this specialty develops. See procedure:

```
to fund_nano
  if any? funders with [ color = blue ] [
    if not nano-funding? [ ask funders with [ color = blue ] [ die ]
] ]
  if not any? funders with [ color = blue ] [
    if nano-funding? [
      setup_nano-funders ] ]

end
```

- *funding_strategy*: This variable applies, one at a time, the four strategies of funding ‘core scientists’, ‘star scientists’, ‘any scientist’ or complete ‘research programs’ that have to do with nanotechnology. See the exemplary procedure for ‘star scientists’:

```
to fund_star_scientists
  let tmp-links n_rs_funded_by_me
  while [ tmp-links < grants_by_funder ] [
    update_funders
    let link-neighbor ( max-one-of ( researchers with [ not member?
    who [rs_funded_by_me] of myself ] ) [n_referencing_me] )
    create-nano-fd-link-to link-neighbor [
      set color [color] of myself ]
```

```
        set tmp-links ( tmp-links + 1) ]

  end
```

- *funding_studies?*: This switch (funding studies: yes or no) indicates if degree programs are funded (as in the German model) or not (as in the US model). Studies furthermore adopt the funding agency's thematical or disciplinary focus while they are funded to indicate the changes in study content that go along with external funding and/or accreditation of study programs. See procedure:

```
to fund_studies
   if ( funding_studies? = true ) and ( any? studies = true ) [
     ask funders with [ color != blue ] [
       let tmp-links ( count fd-links with [ ( is-study? end2 ) and (
       end1 = myself ) ] )
       while [ tmp-links < 1 ] [
         update_funders
         let link-neighbor one-of studies
         create-fd-link-to link-neighbor [
           set color [color] of myself ]
         ask link-neighbor [ set color [color] of myself ]
         set tmp-links ( tmp-links + 1 ) ] ] ]

end
```

2.2.4 Simulation setup

Running the model illustrates the development of the field of nanotechnology delineated by the establishment of links. There are two national model setups further constellations with regards to interdisciplinarity, identity change, and funding strategy.

For each of the four funding strategies, 100 simulation runs were conducted, which leads to 2 (two values for identity change, 0.00 and 0.01) * 400 (4 strategies * 100) runs * 2 (two values for interdisciplinarity) for each country. This totals 1,600 runs. Measures of one run are averaged using arithmetic means. Therefore, one receives one mean for one run for the respective model setting. There are 100 values for 'random seed' ranging from 67 to 166. This function is included to ensure that random sample variances are identical, i.e. imply the same variations attributable to random variables ('noise') over the whole 100 runs per funding strategy. Random variables refer to the potential values of an exogenous variable whose value is uncertain. With random seed, these values are kept constant over all runs but they are not reduced to zero. Thus, one can safely say that the observed differences, and similarities, in the model can be traced back to the different types of funding strategies and the different values for identity change and interdisciplinarity, which makes the single runs comparable to each other. This is also crucial for the robustness of the model: One can be confident that the differences observed between the runs are due to the different parameter settings, not to random variables. Thus, there is high reliability in the obtained results based on the parameter settings.

Table 2 Nemenyi test results for US, interdisciplinarity value 0, identity change value 0.01: rank sum differences given for funding strategies; own source

Funding strategy	–	Any scientist	Research programs	Star scientists
–	Rank sums	16,283.0	18,727.0	30,807.5
Core scientists	14,382.5	1,900.5	4,344.5*	16,425.0**
Any scientist	16,283.0	–	2,444.0	14,524.5**
Research programs	18,727.0	–	–	12,080.5**

Significance-level: * 5 % (critical value of 4,254.6), ** 1 % (critical value of 5,202.6)

3 Simulation results: summary and interpretation of the influence of public funding—of results

It is checked if the differences in median numbers of nanoresearchers between the four samples are significantly different or not compared to the funding strategies applied. The first check was done with the Kruskal-Wallis test, a one-way analysis of variance. This analysis checks for variances between and within samples. With the Nemenyi test, it is examined which samples differ significantly from each other. The result for all the German models is that there were no significant differences in sample medians at the 5 % significance level. Therefore, the null-hypothesis H_0 that the expected values in the four groups of funding strategies do not differ is confirmed for the German data.

For the US, significant results were given by the Kruskal-Wallis test for the identity change value of 0.01 with both interdisciplinarity values. With an identity change value of 0.01 and an interdisciplinarity value of 0, the results are strongly significant at the 5 % and 1 % level: the strategy 'star scientists' yields higher medians of the number of nanoresearchers that are significantly different from the strategies of 'core scientists', 'any scientist' and 'research programs' on a 1 % significance-level (see Table 2). The strategy 'research programs' yields a significantly higher number of nanoresearchers compared to 'core scientists' at the 5 % significance-level (see Table 2). With an interdisciplinarity value of 1, the strategy 'star scientists' yields significantly higher numbers of nanoresearchers than all the remaining funding strategies on a 1 % significance level given an identity change value of 0.01 (see Table 3). Therefore, for the US, the null-hypothesis H_0 is rejected for the identity change values of 0.01 and both interdisciplinarity values.

The identity change value of 0, even without implying significant results, brings about very interesting findings for the US: There is a constant output of two nanoresearchers in each run irrespective of the value of interdisciplinarity and a standard deviation of zero and no skewness/kurtosis values available. This forecloses the finding of 1.0 that is given by the Kruskal-Wallis test, meaning that the variance between the four sample values is zero or, in other words, the sample distributions equal each other 100 %. This means, if two researchers are funded as a research alliance, a constant output of nanoresearchers on the macro-level is obtained, but only in the bigger academic system of the US. The finding suggests that if there is no openness of researchers to adopt a new disciplinary identity, even the funding of two researchers at

Table 3 Nemenyi test results for US, interdisciplinarity value 1, identity change value 0.01: rank sum differences given for funding strategies; own source

Funding strategy	–	Any scientist	Research programs	Star scientists
–	Rank sums	15,773.5	17,862.0	31,517.5
Core scientists	15,047.0	726.5	2,815.0	16,470.5**
Any scientist	15,773.5	–	2,088.5	15,744.0**
Research programs	17,862.0	–	–	13,655.5**

Significance-level: * 5 % (critical value of 4,254.6), ** 1 % (critical value of 5,202.6)

a time does not induce dynamic network effects, but leads to a stagnant number of nanoresearchers. In sum, the strategy of ‘star scientists’ still turns out more effective in producing nanoresearchers and yields a significantly higher number of nanoresearchers compared to ‘research programs’, as Tables 2 and 3 show.

Now that the different model settings have been simulated, it is to be noted that the way of public funding distribution that has great interest in promoting innovative technologies has only limited impact in Germany on the creation and fostering of academic disciplines and scientific communities although the numbers of nanoresearchers reach a fairly high level, yet not in a stable way.

In the US, significantly different medians have been yielded with the identity value being 0.01 whereby the medians of nanoresearchers are higher than for Germany (two to 71 compared to 13 to 15). Therefore, asymmetrical distributions, indicated in the non-normal distribution of the data and the large number of outliers, in particular for the US results, suggest the hypothesis that funding strategies alone do not significantly influence the number of nanoscientists. Still, in both countries, the makeup of funding policies seem indeed to be able to influence to some degree the diffusion of a high-technology in terms of the number of researchers that adopt the nano-label. Funding strategies in our model do not support, however, policy directions that assume a positive linear relationship between public spending and the establishment and/or enlargement of an academic specialty, given the non-normal data distribution. As the model is not validated with empirical data, it rather represents a descriptive, yet analytical and abstract model that shows that influence takes place, but not in a linear, causal way.

Overall, it is to be stated here that the US produce a higher number of nanoresearchers than Germany throughout the simulation runs. This, however, is not surprising due to the larger research systems simulated in the US model. In relative numbers, Germany is not highly disadvantaged in spreading nanotechnology when comparing the number of nanoreseachers with the absolute numbers of researchers which is about four times less than the US system. With four times the number of nanoresearchers in Germany, Germany reaches numbers larger than most US output values and close to the maximum value of 71 for the US. This finding from the simulation confirms the observation made on the nanoeducation at universities and thus validates the model that has been created here: In Germany along with a more favourable institutional higher education structure for professional education (Streeck and Thelen 2001), nanotechnology is established more strongly than in the

US in terms of the number of nano-degree programs, just as the number of nanoresearchers in the model is also higher for Germany than for the US. In other words, there is congruence between the empirical observation that Germany is much more 'active' in the creation of nano-degree programs than the US and the simulation result that Germany is more effective in producing higher numbers of nanoresearchers than the US.

3.1 Simulation statistics

After looking at the test results, descriptive statistics are presented, giving an overview on arithmetic means, medians, standard deviations, and skewness. Table 4 compares the spread of the number of researchers in terms of standard statistical measures on all constellations of national cases for the four funding strategy samples. The means and medians refer to the number of nanoresearchers that emerge when nanotechnology is funded by public agencies.

For the German model, the (weighted) *means* of the number of nanoresearchers vary from 12 ('research programs;' interdisciplinarity 0; identity change 0.01) to 15 ('core scientists;' interdisciplinarity 0; identity change 0.0) nanoresearchers. For the US models, the means range from 2.0 for the identity change value of 0.0 in both interdisciplinarity settings and from 7 to 72 nanoresearchers for the identity change value of 0.01. Thus, the means are higher than for the German values. Outliers like the mean value of 72 for the US indicate that extreme numbers rather emerge in the US setting where dynamic effects are more probable due to the greater size of the research system.

The *median* of German nanoresearchers ranges from 9.0 to 14.0 nanoresearchers. The strategy of 'core scientists' and 'star scientists' for values of interdisciplinarity of 1 and identity change of 0 produces the highest median of nanoresearchers, 14.0. The lowest medians of 9.0 have been brought about by 'any scientist' with values of 0 for interdisciplinarity and 0.01 for identity change. The medians for the US samples have a greater range overall: from 2.0 to 72.0 whereby the samples for an identity change value of 0.01 produce higher maximum medians (from 4.0 to 72.0) than the samples for a value of 0.0, which results in the same value for all runs (2.0).

Standard deviation values, measuring statistical variability by using the mean as the central tendency, vary from 4.4 to 8.53 in the German model. With increasing identity change values, standard deviations increase with both interdisciplinarity values but more drastically with an interdisciplinarity value of 0. The US values for standard deviation range from 0 to 60.3. Therefore, standard deviations are more than three times higher than the German means, whereby the deviations are about similar to the means in the case of the US values. The values show a high variation of the data supporting the notion that there are non-linear effects and non-normal distributions.

Skewness greater than 0 implies right-skewed data; a value of 0 would mean that the data are distributed symmetrically. Thus, skewness gives preliminary insights into how the data (the number of nanoresearchers) are distributed. Lack of skewness does imply normality but not alone: data can be symmetrically distributed (having a value of 0 for skewness) but still not be normally distributed, for instance when data mirror each other by forming an inverted parabola. Positive skewness values signify that the

Table 4 Descriptive statistics for four funding strategies and national parameter constellations; own source

Country	Inter-discipli-narity	Identity change value	Funding strategy	Mean	Median	SD	Skewness	Kurtosis
Germany	0	0.0	Core Scientists	13	12	5.12	0.54	0.58
Germany	0	0.0	Star Scientists	14	13	4.61	0.24	−0.46
Germany	0	0.0	Any Scientist	14	13	4.66	0.50	0.58
Germany	0	0.0	Research Programs	14	13	4.77	0.51	−0.37
US	0	0.0	Core Scientists	2	2	0	n/a	n/a
US	0	0.0	Star Scientists	2	2	0	n/a	n/a
US	0	0.0	Any Scientist	2	2	0	n/a	n/a
US	0	0.0	Research Programs	2	2	0	n/a	n/a
Germany	0	0.01	Core Scientists	13	10.0	7.73	1.19	1.37
Germany	0	0.01	Star Scientists	13	10.0	7.42	1.24	2.63
Germany	0	0.01	Any Scientist	14	12.0	7.08	0.60	−0.06
Germany	0	0.01	Research Programs	12	9.0	6.89	0.88	0.15
US	0	0.01	Core Scientists	8	6.0	6.12	3.44	20.69
US	0	0.01	Star Scientists	63	45.0	60.30	1.31	1.42
US	0	0.01	Any Scientist	10	7.0	8.15	1.83	3.59
US	0	0.01	Research Programs	7	4.0	6.74	2.14	4.82
Germany	1	0.0	Core Scientists	15	14.0	4.97	0.74	1.25
Germany	1	0.0	Star Scientists	14	14.0	4.40	0.30	−0.46
Germany	1	0.0	Any Scientist	14	13.0	4.83	0.49	−0.25
Germany	1	0.0	Research Programs	14	13.5	4.78	0.46	0.05
US	1	0.0	Core Scientists	2	2	0	n/a	n/a
US	1	0.0	Star Scientists	2	2	0	n/a	n/a
US	1	0.0	Any Scientist	2	2	0	n/a	n/a
US	1	0.0	Research Programs	2	2	0	n/a	n/a
Germany	1	0.01	Core Scientists	13	11.0	7.13	1.06	1.39
Germany	1	0.01	Star Scientists	14	13.0	7.21	0.59	−0.05
Germany	1	0.01	Any Scientist	14	13.0	8.53	0.80	0.12
Germany	1	0.01	Research Programs	14	12.0	7.71	1.08	1.68
US	1	0.01	Core Scientists	18	10.0	16.84	1.85	4.49
US	1	0.01	Star Scientists	72	72.0	43.57	0.36	−0.72
US	1	0.01	Any Scientist	21	12.5	18.54	1.62	3.18
US	1	0.01	Research Programs	17	10.0	17.50	1.88	3.51

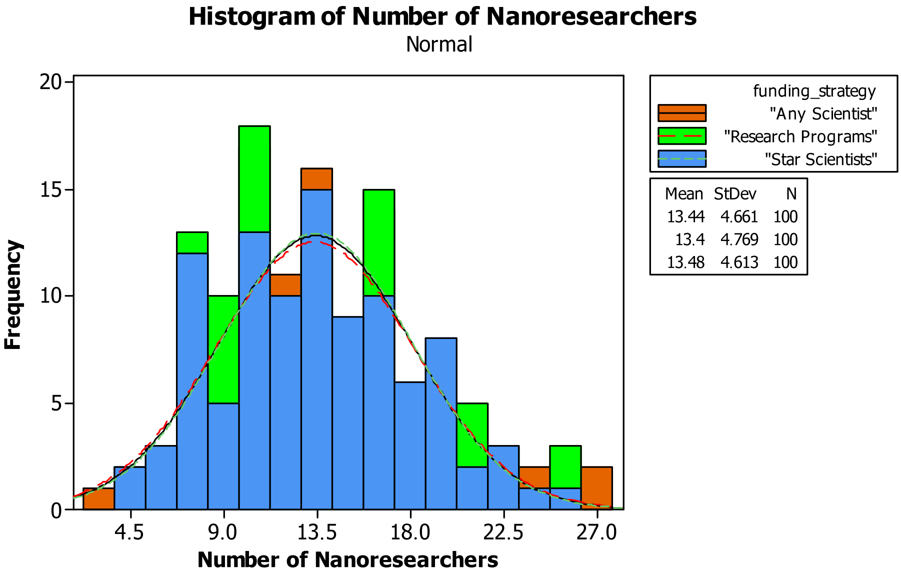

Fig. 2 Histogram for Germany with identity change value 0.00 grouped according to funding strategies; groups compared to normal distribution (see lines); own source

data distributions are right-skewed, i.e., concentrated to the left of the centre of the normal distribution. The distribution 'tail' thus points to the right of the distribution of the collected data. At first glance, one can notice that the US samples are more highly asymmetrically distributed than the German samples. This could mean that in the US, network effects are stronger, as distributions are right-skewed and even less normally distributed. The lowest skewness value is 0.24 for 'star scientists' in the German model with interdisciplinarity and identity change values of 0.0 indicating a very slight right-skewed distribution for this sample. With 3.44, the highest value is obtained by the strategy 'core scientists' in the US model with the identity change value of 0.01 and an interdisciplinarity value of 0 indicating the greatest asymmetry of the right-skewed data in that sample.

Overall, the skewness values differ from 0 and therefore indicate a non-symmetrical distribution. This—next to the high standard deviations and the kurtosis values—suggests network effects that point to non-linear relationships between funding strategy and the number of nanoresearchers that emerge due to public funding of nanotechnology. Figures 2 and 3 illustrate the distribution of selected German sample data in the form of histograms exhibiting the non-normal distributions (with the normal distribution given in coloured lines). The value for interdisciplinarity for the following histograms is always zero, which gives an adequate and insightful overview of how the data are distributed. The bars depict the frequency of the occurrence of the number of nanoresearchers, as shown on the x-axis. The coloured lines show what the distribution would be like if normal distribution was given.

These observations on descriptive statistics, in particular the high values of standard deviation, underline the non-normal distributions of the data, which will be discussed in more detail in the results Sect. 3.

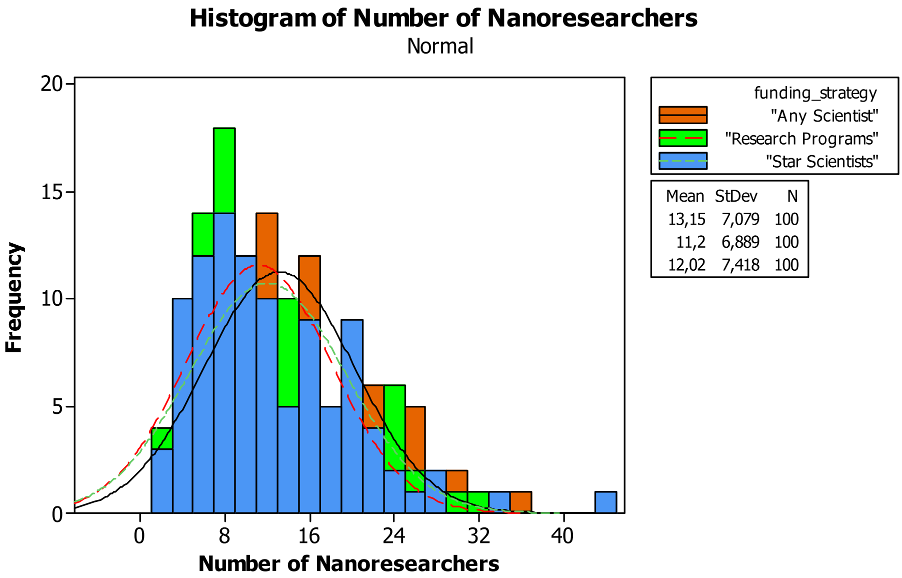

Fig. 3 Histogram for Germany with identity change value 0.01 grouped according to funding strategies; groups compared to normal distribution (see lines); own source

3.2 Normality and network effects

Before turning to the closing section of the simulation results presented above, normality and network effects are discussed shortly. In normality tests, non-normal distribution was confirmed for all samples. The fact that these tests gave a p-value of less than 0.010 for all the model samples alludes to network dynamics that are effective in scientific communities. This observation also explains why nanotechnology, in the model being funded just like any other discipline, can get 'a hold' in the scientific community. Nanotechnology, however, does not become a stable main discipline within the simulation run time that equals 100 years.

A central role is performed by 'star scientists', as the results indicate. The highly referenced scientists ensure knowledge spread, such as in the case of nanoscience and -technology, by being cited by other researchers who are in turn influenced by the knowledge they absorb from other 'star scientists'. This endogenous dynamic process reflects the influence scientists have on research in the form of citations and on the research directions that are taken by other scientists. In the model, this behaviour is reflected by the probability of changing one's discipline and specialty resulting from citing scientists of a different discipline.

One often-mentioned example of non-normal distributions are power-law distributions that are indeed not the only form of distribution found in this study but that are common in network analyses, as the overview article of Cioffi-Revilla (2010) suggests. Moody (2004) found out about clustering in scientific communities and that there is a power-law distribution in social science scientific communities constructed through preferential attachment where "stars will act as 'area authorities' with respect to particular theoretical or empirical claims. . . . However, competition for status within the discipline will likely revolve around stars who generate new ideas at the intersection of different research specialties" (Moody 2004). In other words, there is an inequality in returns on research with 'stars' gaining more prestige and being more attractive collaborators than others. In Moody's case, power-law distribution is consistent with preferential attachment (known as 'Matthew Effect' according to Merton (1968)), but Moody points out that power-law distribution does not always imply preferential attachment. With the funding strategy of 'star scientists', i.e. highly cited researchers, this preferential attachment process is implied.

The results indicate that network effects arise depicting non-linear distributions of the number of nanoresearchers, being the dependent variable, and thus also of the diffusion of nanoresearchers at universities. Non-linearities are regarded as emerging phenomena due to network effects that have already been analysed e.g. in complex markets (Gilbert et al. 2007). Public funding as an independent variable can be assigned only a limited role in fostering the emergence of nanotechnology in academia so that, in future research, a wider range of variables ought to be integrated when examining research networks and the development of new specialties therein.

For the funding strategy of 'star scientists', the only pre-condition was the number of reference links. Dimensions of status, such as awards or the size of acquired third-party funding, were excluded. It was also not measured through a network analysis if the actual 'star scientists' funded are responsible for connecting the network or not (Moody 2004).

Next to 'star scientists' the remaining funding strategies are also non-normally distributed. Therefore, network and mass effects seem persistent over all strategies. This supports the conclusion that non-normal distributions also apply to other conditional variables, not only to star networks. Normal distribution cannot be assumed in these kinds of models and thus prevent using statistical tests that require normal distribution. Whereas for the German model data no pattern could be discerned in their asymmetric distribution, the US data exhibited an exponential distribution of the data.

3.3 Four steps of simulation models

The final simulation results in the form of numbers of nanoresearchers represent analytical results derived from 'abduction' (Squazzoni 2010), not from empirical results by deduction or induction. Thus, they would need to be externally validated with empirical data to be used for inference on populations. Simulation models aim at understanding processes and mechanisms based on the simplicity of the model. They represent a heuristic towards understanding, not a proof of theories via statistically measurable correlations. However, there are certain steps to be adhered to in social simulation models. These are the assumptions, verification, sensitivity analysis and validation (Gilbert and Troitzsch 1999a).

With regards to assumptions for the theoretical conception of the model, main assumptions are, as previously mentioned, spatial proximity and direct personal relations, being the basis for collaboration and self-categorization of researchers in terms of their professional identity (Pattison and Robins 2002; Schweinberger and Snijders 2003; Powell et al. 2005; Blau 1994). The mechanism of spatial proximity has already been confirmed by Hagstrom who found out that

> “[i]nteraction between individuals is a function of the distance between them and the number of personal links that might join them. Most university scientists communicate more with their departmental colleagues than with others, and they are often introduced to the work of scientists in other institutions by their departmental colleagues. Large and high prestige departments might therefore be expected to be centres of communication, and all members of these departments, including those with little personal prestige, might benefit from this position” (Hagstrom 1970).

Another assumption, as already mentioned, is oriented towards ‘Lotka’s law’ (Lotka 1926), whereby the unequal distribution of scientific productivity refers to citations, not papers (De Solla Price 1965). This was implemented into the ‘star scientists’ strategy.

Verification being another step in agent-based modelling controls if the model actually simulates what it is intended to simulate. Naturally, this is an iterative process. A number of runs must be made, and the results must be compared to each other to see if they are expected and realistic. If not, the model must be ‘debugged’, i.e. corrected. To do this, different parameter settings are tested and respective results evaluated and compared (Gilbert and Troitzsch 1999a). An ideal-type model is set up in this study by varying the probabilities for interdisciplinarity taking 0 and 1, which means that either no interdisciplinary collaboration is intended (the parameter value being 0) or that in each run interdisciplinary cooperation takes place (the parameter value being 1). This value influences if research and reference links are created with research from a different or from the same discipline or nanotechnology for that matter. Identity change probabilities are also varied: from 0 (no identity change takes place over 1200 ticks) to 0.01 (value based on the duration of one project assuming that identities are changed every 8.2 years (Jansen et al. 2010)). These values are extreme values to finally test the sensitivity of the model, another step in social simulations, and to establish relationships between the parameters.

A sensitivity analysis checks how ‘sensitive’ the model is to changes in parameter or initial conditions (Gilbert and Troitzsch 1999a). The results presented here are robust because changes in parameter settings, in particular the two values for identity change lying at the realistic extremes of the probability scale, do not lead to a too large “effect of variations in the assumptions on which the model is based” (Gilbert and Troitzsch 1999a). The simulation results per se are representative and reliable because the sample sizes and number of runs (100 for each funding strategy, interdisciplinarity and identity change probability) are large enough and the simulation procedure is objective, i.e. independent of the modeller’s actions. Nevertheless, differences between the parameter settings are to be detected, as the simulation results show.

Validation implies that the simulation is a plausible model for the different strategies of public funding. Validation occurs if empirical results are available and compared to the model results to check if there is a correspondence of the behaviour of the target to the behaviour of the model (Gilbert and Troitzsch 1999a). Structures and budget proportions are empirically validated using data from 2007 to calculate the proportions that national nanobudgets have out of the total German Federal Ministry of Education and Research budget and the National Science Foundation budget.

However, this is not the case for all parameters in the present model. Rather, assumptions and mechanisms are used to simulate social reality, such as the above mentioned 'spatial proximity'. Instead of using numerical empirical data, this model's focus lies on empirical observation asking: what can be observed?

Furthermore, the aim of this model is to understand the mechanisms of four different funding strategies and their effect on the dynamics of the field of nanotechnology. The effect is measured by looking at the spread of the number of nanoresearchers. Hereby, the study takes into account the degree of perseverance of researchers with regards to their disciplinary self-categorization. This is evaluated by looking at the degree of variance due to the effect of public funding and by integrating the effects of interdisciplinarity and the probability for scientists' identity change on the dependent variable, the number of nanoresearchers. The model is thought of as a help to analyse in an explorative way these processes to see what would happen if funding strategies varied, given the initial conditions of size, interdisciplinary, identity change, and funding of studies. Therefore, rather than feeding a list of numerical data into the model, mechanisms and structures have been simulated to compare two different national contexts that differ in their size of research systems, the number of agents, the number of research centres and the proportion of federal grants available for nanotechnology research (see Table 1).

3.4 Overview of results

Overall, the findings illustrate that nanotechnology emerges as a specialty, not as a main discipline. Furthermore, network effects in research collaboration are noticeable. Hereby, 'star scientists', i.e. highly cited and thus prominent researchers, turn out to be crucial in terms of fostering the emergence of a distinctive and a strong specialty at universities. This suggests the still important role of Lotka's Law (Lotka 1926) and, more precisely, of the unequal distribution of citations (De Solla Price 1965).

Going into more detail, one can note further model-specific observations. With the four funding strategies being taken as independent variables for the outcome of the number of nanoresearchers, we get the following results: The data for the US models result in significant differences in the median numbers of nanoresearchers. These median numbers correlate with, but are not caused by, the four different strategies due to the low variance explanation level of the model that includes relatively few variables. The strategies of 'star scientists' in the US model setting with an identity change value of 0.01 and interdisciplinarity values of 0 and 1 turn out to be significantly different from all the remaining strategies on a 1 % significance-level. On a 5 % significance-level, the strategy 'research programs' significantly differs from the number of nanoresearchers of 'core scientists', yet only with an interdisciplinarity value of 0. For Germany, however, the sample medians are not significantly different in all model settings. The reason for the insignificance in the German model is traced back to structural differences with lower number of research centres and researchers in the German higher education and research system.

The US finding suggests that 'star scientists' are most central and, to degrees, influential in the proliferation of nanotechnology. With regards to the control variables, interdisciplinary cooperation does not influence the outcome. However, a relatively high value of identity change, here 0.01, is needed to obtain significantly different results. The Kruskal-Wallis test tells us that for Germany, the numbers do not differ significantly from each other in the context of different funding strategies. This result indicates that the way how public funding is distributed in a research network, here in particular by focussing on 'star scientists' and on 'research programs', is not as influenceable as in the US model setting.

4 Discussion and conclusion

Nanotechnology is used here as an example of a high-technology specialty that has been increasingly financed by national governments since the late 1980s. However, this model, if extended and adapted, is also suited for the study of other specialties that might be of interest for policy research, higher education research or issues of technology diffusion. For instance, the proportion of funding going to nanotechnology that is used in the present case can be changed to the proportion of funding another high-technology under investigation receives or, if the proportion for nanotechnology alters e.g., this parameter can be modified, too.

First, it must be remarked that the presented model is abstract, as it concentrates only on the variables and parameters described above. The paper does not want to test a model on research networks. Rather, the strength of the model lies in the exploration of the complexity of scientific networks and the emergence of a new specialty. Trends can be extrapolated that ought to be singularly examined more deeply in future research. This can be done by an extension of the model setting, by simulating the model using empirical data, such as network analysis data, or by the gathering of further realistic parameter values and data.

Second, emerging phenomena come into play in the form of those funding strategies that yield significantly different numbers of nanoresearchers. Quite interestingly, the strategy of 'star scientists' and, in just one specific case, 'research programs', turn out to be most effective. The 'star scientists' mechanism only considers the maximum of links irrespective of the total number of links. Therefore, it is not important how many citations a researcher receives, but if he or she dominates the citation landscape. Mass effects come into play with regards to the 'research programs' strategy since in that strategy several researchers are funded at once and thus become known to each other, increasing the probability to adopt the nanolabel. The finding that the 'core scientists' strategy has yielded insignificant results can be interpreted in such a way that reputation in terms of citations indeed appears to be a primary criterion with research cooperation being of secondary importance.

Given that Germany yields insignificant differences in sample medians, what is decisive for significant differences is the fact that the network of researchers is larger in the US in terms of the number of research centres and researchers. The larger size and differing institutional structure of the US research system increase the probability to obtain significant differences in the number of nanoresearchers due to different funding strategies. This means that the effect of different strategies can increase in a non-linear and dynamic way and thus significantly alter the number of nanoresearchers due to network effects. This is underlined by the fact that all the data follow a non-normal leptokurtic or platykurtic distribution. Germany's insignificant differences do not mean, however, that there is no model setting that might lead to significantly different sample medians. As the US results imply, network size and the degree of identity change, i.e. openness, play a role when it comes to significant differences.

Based on the fact that no causal relationships can be obtained, other variables that are not included in the abstract model presented here would explain more comprehensively the distribution of the data. Ostensibly, the structural conditions at organizations play a role, namely conditions that create differing opportunities for researchers to implement nanotechnology or not. There is a range of other variables that influence the development of the number of nanoresearchers at research institutes and that might not only correlate with, but present causes for the obtained number of nanoresearchers. These reasons can be departmental and faculty structures that facilitate nanotechnology, laboratory structures, communication networks and interdisciplinary cooperation. Therefore, the formal model presented here is a starting point for more empirically oriented analyses whereby the systematic collection of empirical data constitutes a challenge for future research. The model elucidates structural relationships and ideal-types conditions. It does not reproduce a case from social reality in terms of empirically observed values of identity change and interdisciplinarity since it lacks systematic empirical foundations of network data.

In the case of nanotechnology, the issue of structural differences has to be examined more closely in further research. Hereby, the approach of Blau (1994) seems adequate for addressing the issue not from a micro-sociological view, but from a macro-sociological view: For a change in occupations or other social groups, structural opportunities must be created first so that they can be filled by individuals according to their probabilistic chances to occupy that vacant position. In the networks, too, the bigger a centre, the more positions it can offer for nanoscientists. Given the concept of structural opportunities, one might conjecture in the present case that a larger structure in terms of the number of positions produces a higher number of nanoresearchers. This is true, since the US data show higher output values for the mean numbers of nanoresearchers. The effect of size is crucial for nanotechnology organizations such as firms that tend to be small in numbers and small in size, not counting large companies that integrate nanotechnology as merely one of many technologies. If nanotechnology firms reach a critical threshold, which can be replicated by the formal model, nanotechnology might spread rapidly and reduce uncertainty that comes along with radically innovative technologies and the risk of investment. This is also an issue of further investigation.

Due to the fact that little variance is explained by the examined independent variable of funding strategies, one can conclude for public policy that public funding has limited impact on the creation and fostering of academic disciplines and scientific communities and is, if at all, only correlated with the spread of a high-technology research field. One explanation that is derived from the non-linear distributions in the simulation is based on network effects that emerge due to relational positions of researchers. These effects occur because 'star scientists', 'core scientists' or researchers that either know each other or are spatially near to each other have a higher probability of being cited or being chosen as collaborators. These researchers then obtain a position that is increasingly influential in the make-up of the research network. The effects lead to a dynamic that cannot be explained naturally by public spending or identity change alone and that does not follow a linear distribution (as made evident by the absence of linear relationships between the observed variables). The US yielded significantly different sample medians with an identity value of 0.01. Thus, openness of researchers is central for the spread of nanotechnology and the influence of how funding is distributed. What the US government in short can influence in the model is their choice of funding strategy and, with that, how to produce more nanoresearchers.

Consequently, a range of other variables must be included in future research to give safe and comprehensive answers on the emergence of a research specialty in higher education. Yet, the result complies with another result on the limited influence of government funding, namely in the creation of biotechnology as an industrial sector: there is only very moderate "evidence that governments can orchestrate the construction of science-based industries, such as biotechnology, particularly within coordinated market economies" (Casper 2009), such as Germany is. As made evident in the models, Germany, being a coordinated market economy, has indeed more limited means in creating a stable academic nanocommunity than the US. This is contrary to Etzkowitz's finding on Europe and the US that the US government has fewer means of influence on the development of technology (Etzkowitz 2003). Yet, Etzkowitz observed the influence of governments on technology as a whole and did not focus academia. So, there is a hint that the emergence of a field must be looked at from different angles, be it with a focus on academia, industry or society, which underlines the contribution of this study that concentrates on the university sector.

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Nadine Hoser was a scholar of the DFG-graduate college "Markets and Social Systems in Europe" at Bamberg University, Germany from January 2009 till September 2012. During the academic year 2009–2010, she was a Fulbright scholar at California State University, Chico, USA. She wrote her dissertation

about the organizational field of nanotechnology in Germany and the USA. She completed her B.A. (2007) and M.A. (2008) in Communication and Cultural Management at Zeppelin University, Friedrichshafen, Germany. She has worked and lived in Germany, Kansas, USA, California, USA, and Chile. She does research on higher education, professions, knowledge transfer, innovation and high technologies, nanotechnology and technology diffusion.