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The impact of the autonomy and interdependence of individual researchers on their production of knowledge and its impact: an empirical study of a nanotechnology institute

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This article discusses how to organise and manage research to get the best performance out of researchers in terms of use of their produced knowledge. To this end we extended the strategic positioning theory developed to predict the level of the production of knowledge. The strategic positioning theory considers researchers as agents who reach their goals by collaboration, i.e. by sharing their resources. In this way researchers acknowledge being strategically interdependent with other researchers, while at the same time retaining some autonomy in taking decisions. As it turns out in a test on researchers of an institute for nanotechnology, the higher the interdependence and the better this is aligned with autonomy the higher the impact and citations of their produced knowledge. The theory explains largely the variance of the impact and citations of produced knowledge. It is concluded that researchers need to share resources to be highly performing: research management is advised to stimulate this sharing in combination with a commensurate degree of governance in directing research. Given specific domains and organisational conditions, the theory can serve as a tool in setting research programmes as it gives insight on which settings could and should be created by research managers or policy-makers.

IT GOES WITHOUT SAYING that the organisation of the production of knowledge depends on the goals researchers have for their produced knowledge. One of these goals, and an important one, is the transfer of this knowledge. In this article we will focus on aspects of the transfer of the produced knowledge. Whereas transfer of knowledge is broadly seen as transfer to the society at large, including the general public, industry, the research community also involving teaching, in this article we restrict transfer to the use of knowledge in the research community. Furthermore, it may be emphasised that throughout this article we study the impact of the production of knowledge of individual researchers only. The produced knowledge in terms of number of papers published by individual researchers is the subject of another article (Zalewska-Kurek *et al*, forthcoming).

In the study of knowledge transfer it is often assumed that researchers are amalgamated in the environment and will act as agents of the society, as described in mode2 (Gibbons *et al*, 1994). However, the example of the Genetics Knowledge Parks Initiative implemented by the UK Government (Swan *et al*, 2007) shows that researchers are not necessarily primarily interested in delivering transferable knowledge. In this research programme the UK Government aimed at producing societal, transferable knowledge but failed to consider the individual research goals of the involved researchers. The intention of the government was that the researchers

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would position themselves in mode2 (Gibbons *et al*, 1994), in which transfer is supposed to be of primary interest. But as there were no relevant incentives to do so, these researchers positioned themselves in mode1 (Ziman, 1994), or in other words in an ivory tower, in which transfer of knowledge outside the direct scientific environment is of secondary interest. As a result this programme failed.

Mode2 of Gibbons (1994) and the triple helix (Leydesdorff and Etzkowitz, 1998a,b), presently dominating the discussion on the relation between science and society, have a common flaw: the interest of the researchers involved is not part of these, essentially descriptive, approaches. Applying these approaches to the process of steering scientific programmes is therefore doomed to fail. Another more predictive approach is the principal–agent theory (Guston, 1996; Van der Meulen, 1998). However, this theory cannot be generalised to society, as society would have to be taken as the principal and it is unclear who in society might be the principal.

To overcome such shortcomings we propose to look not only from society to science but also from within the science system towards society, that is, at researchers themselves and how they react to their environment. In this way, we allow both symmetrical and asymmetrical relationships. Obviously, principal–agent theory excludes symmetrical relationships.

In strategic management, researchers realised that discharging the goals and resources of organisations, as done in the outside-in view from the perspective of the industry (Porter, 1985), leads to a homogeneous view on industry and to similar strategies for all its organisations (Barney, 1991). This has been happening in science policy as well. And although there are quite a few voices of recognition raised by researchers that 'one size does not fit all' (e.g. Kuhlmann *et al*, 2007) and about heterogeneity of the science system (e.g. Heimeriks and Vasileiadou, 2008), this topic still receives too little attention.

In our study, we are specifically interested in determinants driving researchers to produce knowledge, that is, in the decisions of individual researchers taken during the process. We therefore direct our focus on the researchers themselves, applying Barney's (1991) idea of looking from the inside of the organisation. And this is possible if we assume that researchers are just like any other organisation directed towards attaining their goals by means of their resources, competencies, etc. Their goals are revealed in their intentions and situations, which we can analyse in studying the production of knowledge (Kurek *et al*, 2007a,b). Situations can include all the resources individual researchers can dispose of, such as skills, instrumentation, and social contacts. Intentions and situations are observable in the decisions researchers make when producing knowledge. These decisions are not taken in isolation from the environment as present in the process of producing knowledge. We will discuss this more extensively below.

Our starting point in developing the theory presented here is that researchers have goals they strive to attain. These goals are to a large extent determined by the science system as such. When joining the scientific community researchers agree on deliverables, such as the production of knowledge. Common goals are, for example, transfer of produced knowledge by educating students or starting spin-off companies. Researchers also have personal goals such as the choice of career type, in science or in industry, etc. To attain these goals researchers make strategic choices: how to get positions in renowned institutes, what to decide on as research topics, where to submit their results, or with whom to work together among their peers.

Collaboration — and we consider competition a driver of collaboration — is one of the most crucial drivers in the process of the production of knowledge. Researchers leverage their resources in their environment. Depending on what they control in-house and what they lack, they seek for collaborators. Empirical studies confirm that collaboration enhances scientific productivity (e.g. Lotka, 1926; Price and Beaver, 1966; Zuckerman, 1967; Pao, 1982; Pravdic and Oluic-Vulovic, 1986; Allison and Long, 1990; Lee and Bozeman, 2005), as this production has been seen to increase with the number of co-authors and joint research projects (Lee and Bozeman, 2005).

Van Raan (1993) propagated citation analysis to measure the use of the produced knowledge and confirmed that there is a correlation between collaboration and received citations. This argument is actually often used by policy-makers in setting research programmes, for example, in mode2 research programmes or in programmes set by the European Union for which collaboration at both a national and international level is a requirement.

The main question to be answered in this research is: Does the strategic positioning of researchers predict their performance?

In order to answer this question we have developed some hypotheses derived from the strategic positioning model and have tested these hypotheses on a sample of researchers working at an institute for nanotechnology.

2. Strategic positioning

The strategic position of an agent, an organisation or an individual is generally defined as the link with other agents, in our case the link between one individual researcher and other researchers. The strategic positioning of researchers in their environment is studied in their strategic relations and how they react to and influence each other. By their environment we mean fellow researchers, the institute, the university, the general public or industry. We study strategic positioning resulting in choices rather than the strategic position as it represents the drivers for researchers'

decisions, whereas the strategic position can be measured only *post hoc*. In this article we limit strategic positioning to all decisions taken in producing knowledge expressed in scientific publications proper.

For an extensive description of the strategic positioning model, the reader is referred to Kurek *et al* (2007a). It assumes researchers in their strategic positioning will behave like temporary integrating or even merging organisations. Following Haspeslagh and Jemison (1991), strategic positioning has two dimensions: the necessity for strategic interdependence and the necessity for organisational autonomy. The basic idea is that the partners have a joint goal and see the necessity to integrate their resources in order to attain this goal. Researchers share their heterogeneous resources such as expertise, skills, facilities, etc. This results in a certain degree of strategic interdependence. In fact access to all different kinds of resources adding to the production of knowledge is the main reason for researchers to work together (Beaver and Rosen, 1978). They also need to govern their resources, research, set research goals, etc. This results in a certain degree of organisational autonomy.

In observing these two dimensions of interdependence and autonomy we should keep in mind that these dimensions should always be interpreted in relation to the goals of researchers. Thus, these degrees are not desired but deemed necessary to attain goals. Researchers are assumed to give up autonomy and accept interdependence if so required to attain these goals.

Combining these two dimensions results in a continuum of modes of strategic positioning in which we can distinguish four ideal–typical positions (Table 1). Mode0 researchers are not in need of control of research, nor are they in need of resources from others in a particular project. Mode1 (ivory tower) researchers have a strong need to direct research but do not need resources from others. Mode2 researchers need resources from others but at the same time they do not need to direct research; such decisions are primarily made by the environment. Mode3 — the research entrepreneur has a strong need for both sharing resources and making decisions regarding research. The research entrepreneur creates demand for his/her scientific products.

This brief description (see further Kurek *et al*, 2007a,b) leads to predicting that the two dimensions of interdependence and autonomy will influence the production and transfer of knowledge.

Table 1. Modes of strategic positioning

		Necessity for organisational autonomy	
		Low	**High**
Necessity for strategic interdependence	**High**	Mode2	Mode3
	Low	Mode0	Mode1

The above considerations then lead to the following hypothesis:

> the more the researcher is both interdependent on his colleagues and autonomous when making research results public and when acquiring scientific information, the more he/she performs in terms of use of his/her knowledge

or:

$P_3 > P_n$, where n = mode0, mode1, mode2.

P stands for performance, to be detailed below.

3. Measurement

We measure the dependent variable of performance and the independent variables: organisational autonomy and strategic interdependence. In this article we want to focus on the resulting impact of the produced knowledge and the citations it receives.

The impact of produced knowledge P_I, called the journal impact factor (JIF) weighed output, is measured as the number of papers published per year by an individual researcher in international, refereed journals multiplied with the impact factor of the journal of publication:

$$P_I = \Sigma_m \, n_m \, (I_F)_m,$$

where n_m is the number of papers published in journal m and $(I_F)_m$ is the impact factor of this journal m.

In this way the impact factor is taken as a measure for the overall impact of knowledge. We measure the strategic positioning of individual researchers to be able to predict how variations in organisational autonomy and strategic interdependence result in variations in the production and impact of knowledge of the same researcher. This means that we are interested in relative variation and not in the absolute level of production. We took whole count as an indicator, but could have used fractional count just as well as both apart from the absolute level should be interchangeable for our purpose. This interchangeability has been confirmed (see Section 5 and Appendix 2, the correlation matrix). The absolute level of production for the fractional count is about 25% of the level for the whole count. We used the ISI impact factor as it is generally being used in university policy and by researchers themselves.

The number of citations received per year and per individual researcher is measured as the number of papers published per year by this individual researcher in international, refereed journals multiplied by the citations received by these individual papers:

$$P_C = \Sigma_n \, nc_n,$$

where c_n is the number of citations received for paper n.

Here, the citations are taken as a measure of the individual impact of the knowledge upon other researchers. Citations are a good measure for the research performance of the group or institute (see Van Raan, 2005). The number of citations is therefore corrected for self-citations at the individual or group level (Van Raan, 1993). P_C will be called the citation impact.

All papers considered were published in refereed journals in 2003 to 2007. All papers of each sampled researcher are taken into account. Citations to these papers are measured from the publication of the paper till November 2009 using Scopus ensuring a time window for citing of at least two years or more (see Moed *et al*, 1995; Van Raan and Van Leeuwen, 1995). Again, as we want to test variations, we have taken this approach to the time window. For accurate absolute measurements an exact time window should be taken.

The independent variables are measured by taking the average of positive or negative indicators (i.e. – or +) for these variables, and are then normalised to the interval (0,1). All questionable assignments are extensively discussed in the research team, resulting in a definite coding scheme. As for these independent variables, we studied decisions taken when producing knowledge, that is, decisions taken in producing publications by the researcher. In producing publications we distinguish between making research results public and acquiring scientific information.

Strategic interdependence is measured as the dependence on colleagues in writing scientific articles and on information sources when acquiring scientific information. More specifically, strategic interdependence is measured in:

- The researcher's dependence on colleagues in writing;
- The dependence on information sources in acquiring scientific information; and
- Dependence on the societal environment.

In the literature, autonomy of researchers is defined as 'freedom from influence of the environment', external pressure, for example, in formulating tasks (Dill, 1958) or 'autonomy to control sufficient resources' (Collin in Whitley, 1984: 12–13), or 'self-governing in deciding about research, research goals and directions' (Kurek *et al*, 2007a). The degree of autonomy 'depends on strategic choices to such factors as location, markets to be served or products to be made' (Aharoni *et al*, 1978). Operationalisation of organisational autonomy in this study includes decisions on:

- The setting of research goals;
- What to write in articles;
- Where to submit articles;
- When the work can be published;
- Which relevant references to include in articles and when acquiring scientific information.

The specific decisions being probed are given in the coding scheme in Appendix 1.

The process of producing knowledge also requires strategic choices of in which journal, and which type, to publish, bearing direct consequences for the impact and the potential for receiving citations.

Strategic interdependence is measured in the researcher's dependence on colleagues in writing, the dependence on information sources in acquiring scientific information and dependence on the societal environment

4. Field study/testing the theory

The theory is tested on researchers sampled from the MESA+ research institute for nanotechnology (University of Twente, 237 full-time equivalents of scientific staff) operating in an international environment. The studied institute is organised in six strategic interdisciplinary research programmes, each combining a number of scientific domains including applied physics, chemistry, biology, biochemistry, electrical engineering, and mathematics. These research programmes are rather homogeneous in terms of their publishing behaviour. The institute is chosen for its competitive environment at national and international levels. The institute has been studied in previous research to analyse the positioning of researchers in their societal environment on the basis of negotiated research contracts (Kurek *et al*, 2007a,b).

To maximise variety we used a random stratified sample of 28 researchers varying in terms of strategic research programmes, and of their scientific (from PhD students to full professors) and managerial positions (group chairmen and scientific directors). One sample candidate was not available, all other candidates cooperated.

The data are gathered from semi-structured interviews supported by management data from the institute. Personal interviewing was chosen as it allows flexibility in asking probing questions about decisions researchers make during the process of making research results public and in acquiring scientific information.

It should be taken into account that we measure individual strategic positioning decisions related to

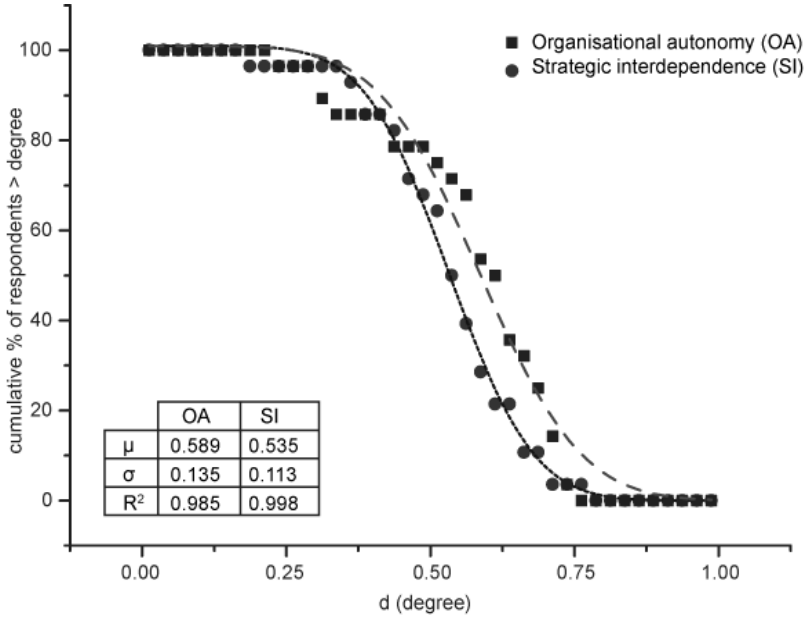

Figure 1. The cumulative distribution of the respondents having strategic interdependence and organisational autonomy higher than degree *d*

individual goals of each researcher, ensuring in this way independent results. Excluding preparation time, each interview took approximately one hour to 90 minutes, sometimes two hours.

5. Results

The distribution of the production of knowledge in the sample shows an exponential decay and fits Lotka's law (1926): about 60% of the researchers in the sample publishes about one article a year (Zalewska-Kurek, 2008).

Figure 1 shows the distributions of the observed interdependence and autonomy, including the mean values μ and standard deviations σ. We use the cumulative distributions showing the percentage of respondents having a degree of either autonomy or interdependence larger than d, running from 100% having a degree larger than 0 to 0% having a degree larger than 0.75. The results show that the researchers have on average a rather high necessity for autonomy (80% of the researchers have a value higher than 50%) in making research results public and acquiring scientific information. As seen in Figure 1 the researchers are highly autonomous and at the same time highly interdependent.

How do these distributions of the dimensions relate to our dependent variables of JIF weighed output P_I or citation impact P_C of knowledge? In Figure 2 we present the observations in the sample. The circles indicate measurements per individual researcher; the larger the circles, the higher the performance. We see that the researchers are predominantly positioned in mode3 and mode1 and that, as in the case of the production of knowledge

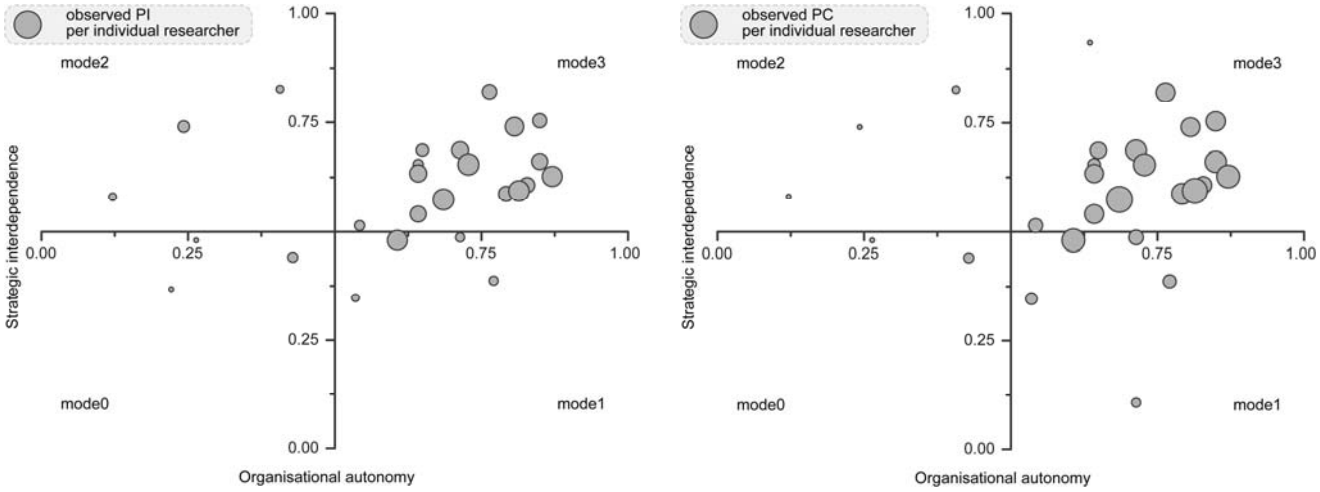

Figure 2. The observed journal impact factor-weighed output of knowledge P_I and citation impact P_C for the modes of strategic positioning

Note: The circles indicate the logarithm of the values of P_I and P_C observed for each individual researcher

(Zalewska-Kurek, 2008, Zalewska-Kurek *et al*, forthcoming), these researchers have the highest performance.

To test the feasibility of the model in predicting the performance P, we performed a linear regression analysis on the collected data:

$$P = b_0 + b_{OA}OA + b_{SI}SI + e$$

where

SI:	strategic interdependence (0,1)
OA:	organisational autonomy (0,1)
b_0:	the intercept;
b_{OA}:	the slope of the independent variable OA;
b_{SI}:	the slope of the independent variable SI;
e:	the error term.
P:	P_I (0, 84) or P_C (0,342)

The values of P_I and P_C indicate the values per year per individual researcher; 84 and 342 are the observed maximum values and give an indication of the intervals analysed.

We took the logarithm of P to overcome estimation problems arising from a bottom effect (censored below) and the extreme skewness of the distributions of this count variable. The coefficients of the regression analyses are given in Table 2. We also introduce the slope representing the relation between interdependence and autonomy. The correlation matrix is given in Appendix 2.

To exclude the possibility that SI and OA are artefacts of experience, we controlled for past performance expressed in rank and experience expressed in the number of years working in science. This added extra explained variance to the predictions, but did not significantly affect the parameters. Strategic decisions are always taken for the situation at hand; this is the reason that we wanted to check if past performance would supersede the parameters of SI and OA. This was not the case. We refrain from reporting the parameters as this would overstretch what is possible with this limited number of observations. Scientific position is not a control factor, as this asymmetrical relation is automatically taken into account in the dimensions of autonomy and interdependence. A higher scientific or management position will lead in the strategic positioning model evidently to higher degrees of interdependence and autonomy.

Table 2. Coefficients for the various measures of performance: JIF weighted output P_I and citation impact P_C

Coefficients	log P_I	log P_C
b_0	–1.82 (0.79)$^+$	–2.73 (0.80)$^+$
b_{OA} (standard error)	2.12 (1.03)*	5.59 (1.00)*
b_{SI} (standard error)	2.72 (1.18)*	1.05 (1.15)
R^2 adj	0.26	0.54
slope ($-b_{OA}/b_{SI}$)	–0.78	–5.32

Notes: $^+$: significant at 5%, tested two-sided
*: significant at 5%, tested one-sided

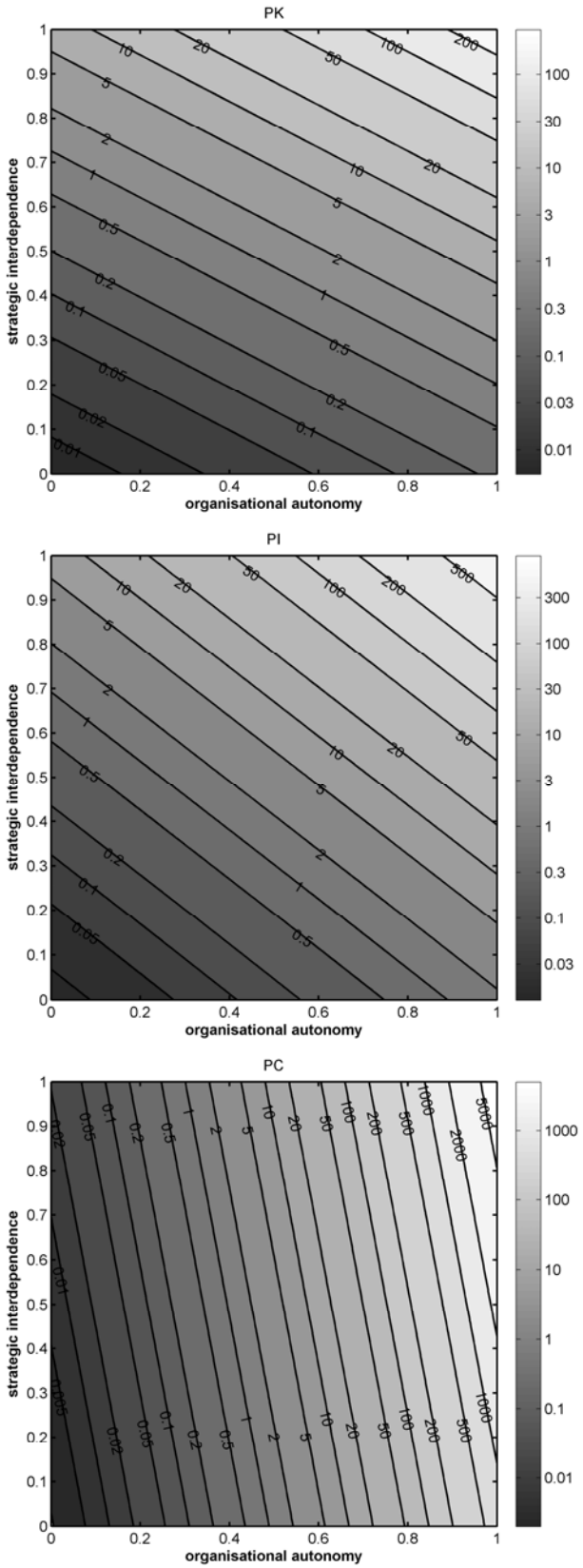

Figure 3. Contour plots of the predicted production of knowledge P_K (no. of papers/year), the JIF weighted output P_I and citation impact P_C as a function of strategic interdependence and organisational autonomy

Note: The absolute values for P_K, P_I and P_c are shown as contour lines and given in the legends

Figure 3 represents the predicted values for the two variables P_I (mean value: 21; standard deviation: 26) and P_C (mean value: 55; standard deviation: 78) as a function of interdependence and autonomy. Also the prediction for the production of knowledge P_K (i.e. number of papers published per year by an individual researcher in international, refereed journals, mean value: 5.7; standard deviation: 6.6; for fractional count P_{Kfract}, i.e. number of papers published per year by an individual researcher in international, refereed journals divided by the number of authors, these numbers are 1.4 and 1.6) is included for discussion reasons.

The contour lines indicate the performance of the researchers in the sample as a function of interdependence and autonomy. As for P_K, we see that P_I and P_C increase exponentially from 0 to large values in the extreme mode3. Furthermore, the performance increases when the necessities for interdependence and autonomy increase simultaneously. In all cases mode3 researchers perform best.

If we have a closer look at how interdependence and autonomy influence the performance (Figure 3), we see characteristic differences in slope between the three variables. For P_K (slope –0.53) and P_I the slopes are larger than –1, the P_I slope coming close to –1, indicating that interdependence is predominant over autonomy for these performance indicators, while for P_C we find a slope much smaller than –1, indicating a very clear predominance of autonomy over interdependence.

In all three cases there needs to be a sufficient degree of autonomy to perform and this degree is increasing in the order: P_K, P_I and P_C. This reflects the fact that the choice for a journal is a deliberate and multifaceted strategic choice. The differences between P_I and P_C reflect differences in the audience: giving citations is an individual judgement of the individual paper by individual researchers, while the impact factor represents a collective and therefore smoothed measure of all researchers publishing in and citing the journal. Where we see that mode3 researchers perform best in all three variables, mode3 researchers are trailed by mode2 researchers for P_K and P_I, but by mode1 researchers for P_C. It may be stressed here that the observations are in all cases based on the full set of papers published by an author during the studied period of five years.

As is the case for P_K (Zalewska-Kurek *et al*, 2008) the results shown in Figure 3 confirm the hypothesis proposed earlier in the text, that the order of performance of the different modes depends on the specific performance indicator.

6. Discussion and conclusions

In this article we discuss how to organise and manage research to get the best performance out of researchers in producing knowledge, and particularly in having this knowledge transferred and used. To deal with and to evaluate research organisations we look at the combined inside-out and outside-in views: at individual researchers with their goals, intentions, and resources positioning in their environment. To this end, we apply the strategic positioning theory (Kurek *et al*, 2007) and test it in nanotechnology. The theory assumes that the necessities for strategic interdependence and organisational autonomy in relations between science and environment affect the performance of researchers. We are able to confirm that the strategic positioning of researchers in their environment affects their performance, in producing knowledge and in transferring knowledge.

The results obtained in the interviews with the researchers generally confirm the theory: next to creating clear observables for the modes of strategic positioning, the theory is able to predict the different aspects of performance. Furthermore, we claim that our results give insight in the conditions for performance. Consequently, these conditions should be considered when establishing collaborations with other researchers as they present a diagnosis of the performance of researchers. Different combinations of the degrees of both strategic interdependence and organisational autonomy result in differences in performance. It has been confirmed that the more researchers are both interdependent and autonomous, the higher their performance will be.

A significant result of this study is that in order to be highly performing, researchers need to share resources with others — collaboration and interaction in science is crucial resulting in enhanced interdependence coupled with commensurate autonomy. Preliminary results for social sciences show a much lower level of interdependence at a higher level of autonomy (Zalewska-Kurek, 2008). This may well be part of the reason that production, impact and citations are observed to be generally lower in these fields. In terms of collaboration, and thus interdependence and autonomy, these fields are seen to be less integrated as a system.

It is well advised to stimulate strategic interdependence between researchers in combination with a reasonably high degree of autonomy of the individuals, as in general researchers will tend to mode1. Stimulating strategic interdependence thus requires management interventions and effort (Zalewska-Kurek, 2008). The relation between interdependence and autonomy as represented by the slope between these two variables has been seen to be a discriminating indicator for performance. In particular, if a high number of received citations is the management objective, autonomy should be optimised without compromising too much on interdependence. Not only does it suffice to choose a prospective strategic research direction, but also research groups should be strategically formed by bringing individuals together resulting in the right combinations of interdependence and autonomy, simultaneously also being commensurate with the research direction.

We have noted that citations are a more direct, individual measure for performance than impact factors as these are collective, intermediate measures smoothed by researchers external to the group or institute. It is therefore more suitable to manage research groups by setting the right conditions for interdependence and autonomy in a way that will lead to receiving more citations rather than demanding publishing in high-impact journals.

This diagnosis of the performance of researchers also allows the drawing of relevant conclusions for policy-makers. The theory can well serve as a tool in setting research programmes as it gives insight on which settings could and should be created by research managers or policy-makers, given the specific domains and organisational conditions. The theory can be used for strategy development of research groups or institutes as it predicts the degree of necessity for both the strategic interdependence and the organisational autonomy the researchers need in order to attain their chosen strategic goals. Adequate strategic positioning in the environment allows researchers to enhance performance in line with the strategy and goals of the group or institute.

Appendix 1. Indicators (–1 = low; +1 = high)

Organisational autonomy

- Choice of research goals
  - Low – others decide what to research
  - High – decides what to research, goals are not given by others (e.g. project leaders, project partners, etc.)
- Choice of a journal
  - Low – others decide where to submit the paper
  - High – decides where to submit the paper
- Writing papers
  - Low – comments on a last draft, I am not involved in the writing process
  - High – writes the paper
- Assessment when the work is ready for publication
  - Low – does not decide when the work is ready to be submitted for a publication (co-authors make this decision)
  - High – decides when the work is ready to be submitted for a publication
- Selecting journals
  - Low – does not decide to which journal the paper to submit (co-authors make this decision)
  - High – decides to which journal to submit the paper
- Deciding to whom to refer
  - Low – co-authors make decisions on the relevant literature to be included in the paper
  - High – decides on the relevant literature to be included in the paper
- Choice when and what information to acquire
  - Low – colleagues influence to search for specific information
  - High – influences others to search for specific information
- Checking for similar publications
  - Low – co-authors check whether similar work has been published
  - High – checks whether similar work has been published
- Deciding what to read
  - Low – others influence in choosing literature
  - High – chooses the literature

Strategic interdependence (SI)

- Re information sources when choosing experiments
  - Low – depends on own collection, internet, etc.
  - High – relies on colleagues
- Re information sources when writing the paper
  - Low – depends on own collection, internet, etc.
  - High –relies on colleagues
- Re information sources when learning about new developments
  - Low – depends on own collection, internet, etc.
  - High – relies on colleagues
- Re co-authors when writing the paper
  - Low – knowledge is not acquired from co-authors
  - High – relies on colleagues
- Re financial resources
  - Low – no external funding is acquired

  High – writes proposals, acquires external funding

Appendix 2. Correlation matrix

	Mean	s.d.	*OA*	*SI*	P_k	P_{kfract}	P_i	P_c
OA	0.59	0.146	1					
SI	0.54	0.128	0.160	1				
P_k	0.48	0.531	0.643	0.305	1			
P_{kfract}	–0.18	0.561	0.526	0.461	0.926	1		
P_i	0.84	0.859	0.431	0.425	0.718	0.853	1	
P_c	1.12	1.113	0.751	0.237	0.782	0.692	0.693	1

Notes: For all dependent parameters P the ^{10}log values are given
OA = organisational autonomy
SI = strategic interdependence
S.d. = standard deviation
All correlations are significant at least at 5% level (2-sided), except SI–OA, SI–P_K, and SI–P_C

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