Measuring the Knowledge Base of an Economy in terms of Triple-Helix Relations among 'Technology, Organization, and Territory'

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ERIM REPORT SERIES *RESEARCH IN MANAGEMENT*	
ERIM Report Series reference number	ERS-2004-034-ORG
Publication	May 2004
Number of pages	35
Email address corresponding author	w.dolfsma@fbk.eur.nl
Address	Erasmus Research Institute of Management (ERIM) Rotterdam School of Management / Rotterdam School of Economics Erasmus Universiteit Rotterdam P.O.Box 1738 3000 DR Rotterdam, The Netherlands Phone: +31 10 408 1182 Fax: +31 10 408 9640 Email: info@erim.eur.nl Internet: www.erim.eur.nl

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BIBLIOGRAPHIC DATA AND CLASSIFICATIONS		
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Library of Congress Classification (LCC)	5001-6182	Business
	5546-5548.6	Office Organization and Management
	HD 38.7	Business Intelligence
Journal of Economic Literature (JEL)	M	Business Administration and Business Economics
	M 10 L 2	Business Administration: general Firm Objectives, Organization and Behaviour
	D 8	Information and Uncertainty
European Business Schools Library Group (EBSLG)	85 A	Business General
	100B 240 B	Organization Theory (general) Information Systems Management
	160 D	Theory of the firm
Gemeenschappelijke Onderwerpsontsluiting (GOO)		
Classification GOO	85.00	Bedrijfskunde, Organisatiekunde: algemeen
	85.05 85.08	Management organisatie: algemeen Organisatiesociologie, organisatiepsychologie
	83.81	Theorie van de onderneming
Keywords GOO	Bedrijfskunde / Bedrijfseconomie	
	Organisatieleer, informatietechnologie, prestatiebeoordeling	
	Kennis, economische systemen, statistische verdeling, technologische ontwikkeling	
Free keywords	Knowledge base, probabilistic entropy, services, medium- and high-tech, triple helix	

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Abstract

The interrelationships among technology, organization, and territory in an economic system have been considered as a 'holy trinity' from the perspective of regional development studies. The mutual information in three dimensions was proposed as an indicator of the surplus value (entropy) in triple-helix configurations. When this probabilistic entropy is negative, the configuration reduces the uncertainty that prevails at the systems level. Data about more than a million Dutch companies were used for testing this indicator. This data contain postal codes (geography), sector codes (proxy of technology), and firm sizes in terms of number of employees (proxy of organization). The knowledge base is mapped at three levels: national (NUTS-1), provincial (NUTS-2), and regional (NUTS-3). The levels can be cross-tabled with the knowledge-intensive sectors and services. The results suggest that medium-tech sectors contribute to the knowledge base of an economy more than high-tech ones. Knowledge-intensive services have an uncoupling effect, but less so at the high-tech end of these services.

Keywords: knowledge base, probabilistic entropy, services, medium- and high-tech, triple helix

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Measuring the Knowledge Base of an Economy in terms of Triple-Helix Relations among 'Technology, Organization, and Territory'

Economists have argued that the economy can be considered as an entropical system (e.g., Georgescu-Roegen, 1971; Khalil, 2004; Khalil & Boulding, 1995; cf. Schumpeter, 1949 [1991]). Probabilistic entropy has been used as statistics mainly in econometrics and in studies of technological innovation (e.g., Theil, 1972; Saviotti, 1996; Frenken & Leydesdorff, 2000). Casson (1997, at p. v) argued that the economy could be considered as 'a system of structured information flow,' but he assumed an institutional (or agent) perspective on the structuration of these information flows.

In this study, we use an information-theoretical perspective and argue that structuration is an effect of the coordination and interaction among industrial structures, geographical constraints, and technological trajectories. As these factors, interact a knowledge base can increasingly be shaped. We submit that the mutual information among the three factors can be used to measure the extent to which the economy has become knowledge-based (Watts & Porter, 2003). Although several authors have used entropy statistics for the measurement, the focus has remained on specific sectors and trajectories (De Gregori, 1986; Alexander, 1996; Frenken, 2000; Watts & Porter, 2003). However, the mutual information in three dimensions can capture structure at the next-order level of a knowledge-based system or regime (Dosi, 1982; Foray & Lundvall, 1996; OECD, 1996).

1. The 'holy trinity' and the 'triple helix'

In his study entitled *The Regional World*, Michael Storper (1997: 26f.) argued that technology, organization, and territory can be considered as a 'holy trinity' for regional development. This trinity should not be studied as an aggregate of the composing elements, but in terms of the relations between and among these elements. These relationships shape regional economics. Storper formulated as follows:

> Regional economics, in particular, and integrated territorial economies in general, will be redefined here as *stocks of relational assets*. […] Technology involves not just the tension between scale and variety, but that between the codifiability or noncodifiability of knowledge; its substantive domain is learning and *becoming*, not just diffusion and deployment. Organizations are knit together, their boundaries defined and changed, and their relations to each other accomplished not simply as input-output relations or linkages, but as untraded interdependencies subject to a high degree of reflexivity. Territorial economies are not only created, in a globalizing world economy, by proximity in input-output relations, but more so by proximity in the untraded or relational dimensions of organizations and technologies. Their principal assets—because scarce and slow to create and imitate—are no longer material, but relational. (Storper, 1997: 28)

Furthermore, Storper argued that this extension of the 'heterodox paradigm' in economics implies a reflexive turn. The 'holy trinity' is to be understood not only as elements in a network, but as the result of the dynamics of these networks shaping new worlds. These worlds emerge as densities of relations that can be developed into a competitive advantage, when and where they materialize by being coupled to the ground in regions (Callon, 1986).

The location of the niche can thus be considered as a dependent variable of the self-organization of the interactions (Bathelt, 2003; Cooke & Leydesdorff, 2005).

In a similar vein, authors using the model of a triple helix of university-industry-government relations have argued for considering the 'overlay' of relations between universities, industries, and governments as emerging from the interactions. The overlay at a meta-level can feed back on the network relations from which it emerged, but as another sub-dynamic. The feedback reshapes the arrangements among the carrying institutions in terms of mutual expectations. Because of this reflexive turn, the interactions can become increasingly knowledge-based.

In the triple helix model, the institutional layer and the overlay operate upon one another in terms of frictions that provide opportunities for innovation both vertically within each of the helices and horizontally among them (Etzkowitz & Leydesdorff, 2000; Leydesdorff & Etzkowitz, 2003). While the institutional arrangements may provide a knowledge infrastructure, the reflexive overlay can be considered as the knowledge base of this economy, albeit to a variable extent. The quality of the knowledge base depends on the locally specific functioning of the interactions in the knowledge infrastructure and on the interface between this infrastructure with its self-organizing dynamics at the (global) systems level. A knowledge base diminishes the uncertainty that prevails in the network, that is, as a structural property of the system.

The correspondence between these two theories is not formal or confined to theorizing, but can be extended to operationalization. Storper (1997: 49), for example, used the following depiction of ‘the economy as a set of intertwined, partially overlapping domains of action’ in terms of recursively overlapping Venn-diagrams:

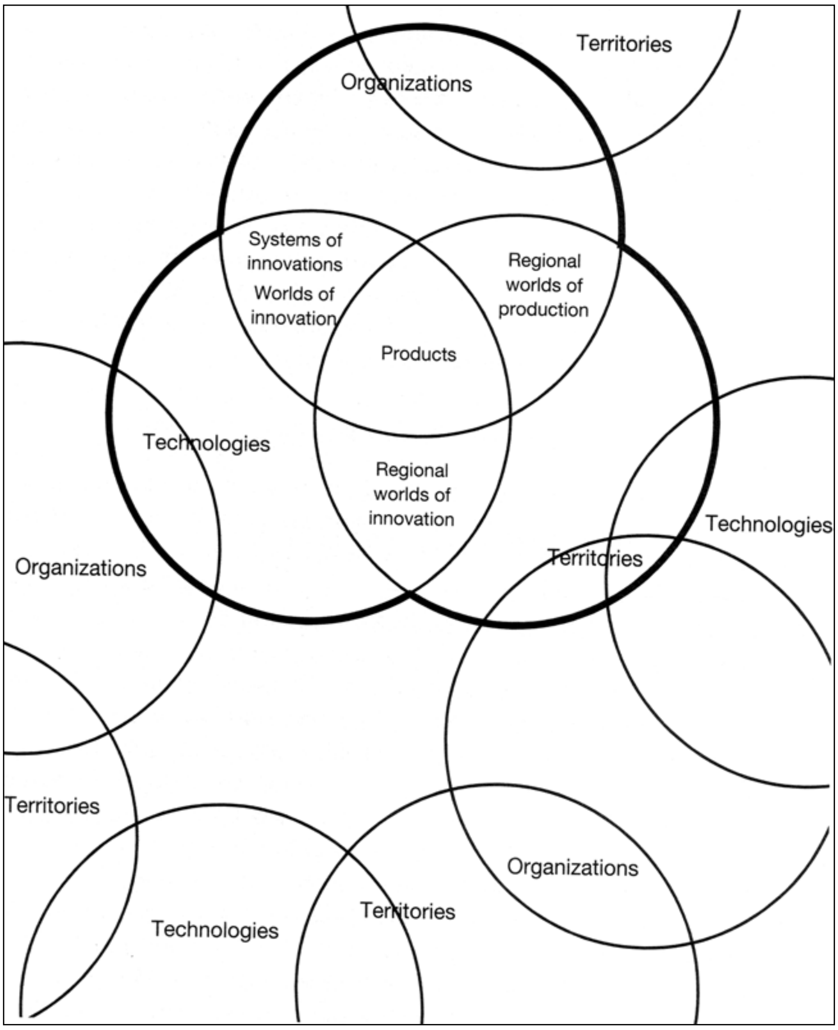

Figure 1. Storper’s ‘holy trinity of technologies, organizations, and territories’ provides an overlap in the resulting ‘products’.

Using the triple helix model of university-industry-government relations, Leydesdorff (1997: 112) noted that the three circles boldfaced in Figure 1 do not have to overlap in a common zone like the area indicated with ‘Products.’ He proposed the following configuration as an alternative:

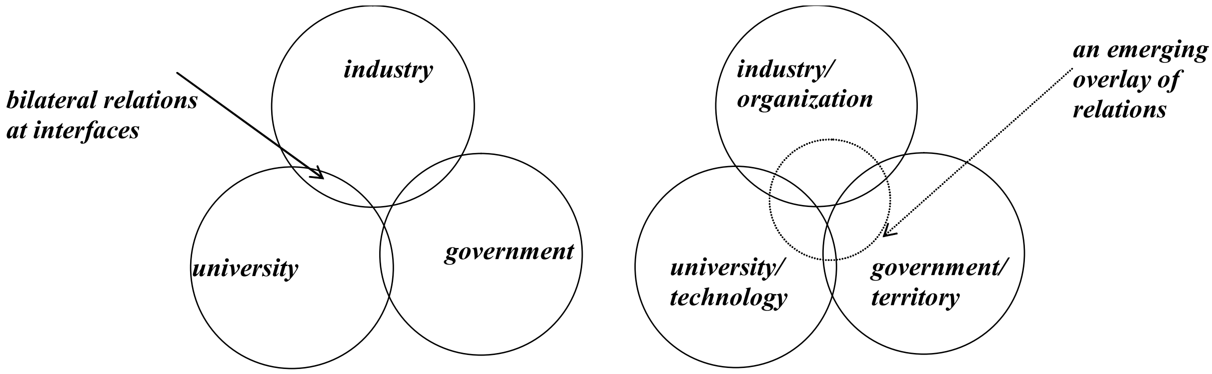

Figure 2a and b. A decentralized variant of The Triple Helix model (a) and its extension to an overlay (b) of interacting relations.

In a networked arrangement an 'overlay' can under certain conditions replace the function of central integration. In this case, a virtual hyper-cycle instead of observable products can close the complex system into a knowledge-based regime.

In a recent elaboration of this model, Leydesdorff (2003) operationalized university-industry-government relations in terms of the mutual information in three dimensions. It could be shown that a so-called 'interaction information' (McGill, 1954) varies considerably in triple-helix configurations among nations and world regions (Leydesdorff, 2003: 460). In this study, we extend the scientometric approach in measuring the knowledge base to economic regions at the national and subnational levels by applying this operationalization to data about the distribution of Dutch firms in three dimensions. This data has been used extensively in previous studies (Van der Panne & Dolfsma, 2001, 2003).

Unlike the mutual information in two dimensions (Shannon, 1948; Theil, 1972), the mutual information in three dimensions can become negative (McGill, 1954; Abramson, 1963). The gap in the overlap between the three circles in Figure 2 can thus be understood as a negative entropy. This configuration among attributes can be considered as the amount of information that is common to all attributes, but not present in any of the subsets. It has also been considered as 'configurational information' (Jakulin & Bratko, 2004).[1] The reduction of the uncertainty is in this case a consequence of the configuration at the network level; in other words, the configuration can be considered as an additional source of information. This reduction of the uncertainty at the systems level counteracts the tendency of any system towards equilibrium (Khalil, 2004).[2]

A similar idea about a common knowledge base emerging on the basis of previous interactions was recently articulated by Watts & Porter (2003). Focusing on the overlap, these authors hypothesized that 'as a technology matures, one would expect that base knowledge would be more commonly shared among factors (research clusters), thus increasing the measured entropy' (ibid.: 742f). However, they acknowledge that a reverse tendency remains empirically possible at the systems level. One would expect high-tech sectors to 'deepen and tighten' the knowledge base of the systems in which they operate (Mokyr, 2002). Firms in these sectors can be expected to act as 'specialized decision-making units whose function it is to improve coordination by structuring information flows' (Casson 1997: 80).

Although firms play an important role in constructing the knowledge-based economy, one should realize that they also compete and may therefore be reluctant to share their respective knowledge bases. The negative entropy at the network level emerges from the coordination and integration of information at the structural level of an economy. A knowledge-based

[1] This so-called interaction or configurational information is defined by these authors as the mutual information in three dimensions, but with the opposite sign (McGill, 1954; Han, 1980).

[2] Theil & Fiebig (1984: 12; cf. Frenken, 2000: 263; Sahal, 1979: 129) defined the mutual information in more dimensions as a straightforward extension of the mutual information in two dimensions. However, the decomposition of the mutual information in two and three dimension enables us to account for the configuration of bilateral and trilateral relations in Triple Helix configurations (Leydesdorff, 2003).

economy is not a result of the aggregate of individual actions at the firm level, but also of their interactions.

For example, we shall find below—in contrast to what we might expect—that medium-tech sectors contribute to this negative entropy more than high-tech ones. This result accords with Alexander's (1996) alternative explanation in a study of the relation between industry concentration and product diversity for the music industry: when an industry is moderately concentrated, diversity is highest. The Netherlands is well-known for having an open economy, and firms in the high and medium-tech sectors often operate in several markets concurrently. Thus, technology diffusion may be more important than technology creation in shaping the knowledge base of an economic system (Mokyr, 2002).

2. Methods and data

Data

The data consist of 1,131,668 records containing information based on the registration of enterprises by the Chambers of Commerce of The Netherlands. This data was collected by Marktselect plc. Our data specifically corresponds to the CD-Rom for the second quarter of 2001. Because registration with the Chamber of Commerce is obligatory for corporations, the dataset covers the entire population. We brought this data under the control of a relational database manager in order to enable us to focus on the relations more than on the attributes. Dedicated programs were developed for the further processing and computation where necessary; these are available from the authors upon request.

In addition to information at the company level, the data contain three variables which can be used as proxies for the dimensions of technology, organization, and geography at the systems level. Technology will be indicated by the sector classification (Pavitt, 1984; Vonortas, 2000), organization by the company size in terms of numbers of employees (Pugh *et al*., 1969a, 1969b; Blau & Schoenherr, 1971), and the geographical position by the postal codes in the addresses. Sector classifications are based on the European NACE system. This classification was further elaborated by the Dutch Chambers of Commerce into a five-digit system (BIK-codes).[3] In addition to major activities, most companies also provide information about second and third classification terms. However, we shall focus below on the main code using the two-digit level unless otherwise indicated.

The distribution by company size is provided in Table 1.

Size	Number of employees	Number of companies
1	None	223,231
2	1	453,842
3	2 to 4	279,835
4	5 to 9	88,862
5	10 to 19	42,047
6	20-49	27,246
7	50-99	8,913
8	100-199	4,303
9	200-499	2,313
10	500-749	503
11	750-999	225
12	> 1000	348
		N = 1,131,668

Table 1: Distribution of company data by size.

[3] NACE stands for Nomenclature générale des Activités économiques dans les Communautés Européennes. The NACE code can be translated into the International Standard Industrial Classificiation (ISIC) and in the Dutch national SBI (Standaard Bedrijfsindeling) developed by Statistics Netherlands. The Chambers of Commerce have elaborated this classification into the so-called BIK code (Bedrijfsindeling Kamers van Koophandel). However, these various codes can be translated unambiguously into one another.

Postal codes are a fine-grained indicator of geographical location. We used the two-digit level which provides us with 90 districts. Using this information the data can be aggregated into provinces (NUTS-2) and so-called COROP regions. The COROP regions correspond with the NUTS-3 level used for the statistics of the OECD and Eurostat.[4] The Netherlands are thus organized in twelve provinces and forty regions, respectively.

Knowledge-intensity and high-tech

The OECD (1986) first defined knowledge-intensity in manufacturing sectors on the basis of R&D intensity. R&D intensity was defined for a given sector as the ratio of R&D expenditure to GDP at the national level, or value added at the level of sectors. Later this method was expanded to take account of the technology embodied in purchases of intermediate and capital goods (Hatzichronoglou, 1997). This new measure could also be applied to service sectors which tend to be technology users rather than technology producers. The discussion continues about how best to delineate knowledge-intensive services (Laafia, 1999, 2002a, 2002b; OECD, 2001, 2003: 140). The classification introduced in the *2001 STI Scoreboard* will be used here (OECD, 2001: 137 ff.). The relevant NACE categories for high- and medium-tech are as follows:

High tech Manufacturing	*Knowledge-intensive sectors (KIS)*
30 Manufacturing of office machinery and computers **32** Manufacturing of radio, television and communication equipment and apparatus **33** Manufacturing of medical precision and optical instruments, watches and clocks	**61** Water transport **62** Air transport **64** Post and telecommunications **65** Financial intermediation, except insurance and pension funding **66** Insurance and pension funding, except compulsory social security

[4] NUTS stands for Nomenclature des Unités Territoriales Statistiques (Nomenclature of Territorial Units for Statistics). COROP is the abbreviation of the Dutch 'Coordinatiecommissie Regionaal Onderzoeksprogramma.'

Medium-high tech manufacturing **24** Manufacture of chemicals and chemical products **29** Manufacture of machinery and equipment n.e.c. **31** Manufacture of electrical machinery and apparatus n.e.c. **34** Manufacture of motor vehicles, trailers and semi-trailers **35** Manufacturing of other transport equipment	**67** Activities auxiliary to financial intermediation **70** Real estate activities **71** Renting of machinery and equipment without operator and of personal and household goods **72** Computer and related activities **73** Research and development **74** Other business activities **80** Education **85** Health and social work **92** Recreational, cultural and sporting activities Of these sectors, **64, 72** and **73** are considered *high tech services*.

Table 2: Classification of high-tech and knowledge-intensive sectors according to Eurostat. Source: Laafia, 2002a: 7.

These classifications are based on normalizations across the member states of the European Union and the OECD, respectively. However, the percentages of R&D and therefore the knowledge-intensity at the sectoral level may differ in The Netherlands from the average for the OECD or the EU. In a recent report, for example, Statistics Netherlands (CBS, 2003) provided the following figures for R&D intensity (as percentages of value added) in 2001:

	% R&D / value added	NACE Classifications
High-tech and medium-tech industry		
Electrotechnical industry	27.66	30, 31, 32, 33
Chemical end products	16.10	24
Machine industry	11.11	29
Chemical basic products	6.38	24
Transport equipment	5.26	34, 35
Basic metal industry	4.42	27
Industry average	*5.51*	
Knowledge-intensive services		
Research & Development	116.93	73
Computer service bureaus	3.52	72
Renting and business services	2.10	70, 71
Architecture and engineering	1.57	74
All services	*1.02*	
Other sectors	*0.40*	
Mining	0.74	10, 11, 14
Agriculture, forestry & fishery	0.60	1, 2, 5
Subsidized education	14.07	80

Table 3: R&D Intensity 2001 for high-tech and medium-tech sectors of the Dutch economy. Source: CBS, 2003: 111. (NACE Classifications added.)

Unfortunately, this data for the Netherlands is aggregated at a level higher than the categories provided by Eurostat and the OECD. For example, the sector 'post and telecommunications' (64) is subsumed by Statistics Netherlands under the category of 'transport and communication.' This category also includes the NACE sectors 60, 61, 62, and 63. The R&D intensity of this aggregated sector is only 0.37% and therefore the sector is not rated as high-tech. However, one may expect the subcategory corresponding to the NACE classification 64 ('post and telecommunication') to be highly knowledge-intensive. For this reason, and, furthermore because the Dutch economy is heavily internationalized so that knowledge can easily spill over from neighboring countries, we decided to use the Eurostat categories provided in Table 2 to distinguish levels of knowledge-intensity among sectors.

Regional differences

The reader may need some descriptive statistics to understand the context, since the geographical make-up of the Netherlands is different from its image. The share of employment in high-tech and medium-tech manufacturing in The Netherlands rates only above Luxembourg, Greece, and Portugal (OECD, 2003: 140f.). The economically leading provinces of the country, like North- and South-Holland and Utrecht, rank among the lowest on this indicator in the European Union.[5] The south-east part of the country is integrated in terms of high and medium-tech manufacturing with neighbouring parts of Belgium and Germany. More than 50% of private R&D in The Netherlands is located in the regions of

[5] Laafia (1999) provides maps of Europe with indication of employment rates in high-tech manufacturing sectors and high-tech service sectors respectively. Laafia (2002a) adds relevant figures.

Southeast North-Brabant and North-Limburg (regions 36 and 37 in Table 6; Wintjes & Cobbenhagen, 2000).

The core of the Dutch economy has traditionally been concentrated on services. These sectors are not necessarily knowledge-intensive, but the situation is somewhat brighter with respect to knowledge-intensive services than in terms of knowledge-based manufacturing. Utrecht and the relatively recently reclaimed province of Flevoland[6] score high on this employment indicator, while both North- and South-Holland are in the middle range. South-Holland is classified as a leading EU region in knowledge-intensive services (in absolute numbers), but the high-tech end of these services has remained underdeveloped. In summary, the country is not homogenous on any of these indicators. Both relatively advanced and less advanced regions are indicated. On the basis of these employment statistics, the geographical distribution seems almost opposite for high-tech manufacturing and knowledge-intensive services, with provinces specialized in one of the two.

Employment data have been central in defining the 'knowledge economy' since the term was first introduced (Machlup, 1962; Cooke, 2002; Schwartz, 2005). The concept of a knowledge-based economy, however, refers to the structure of an economy (Foray & Lundvall, 1996; Cooke & Leydesdorff, 2005). The study of national innovation systems (Lundvall, 1988, 1992; Nelson, 1992) introduced a focus on sectoral differences (e.g., Pavitt, 1984), intellectual property rights (e.g., Granstrand, 1999; Jaffe & Trajtenberg, 2002), and the relations between technologies and institutions (e.g., Nelson, 1994). The operationalization of the knowledge-based economy in terms of the interaction among these structural parameters,

[6] This newly reclaimed (polder) province is the only Dutch province amenable for EU support through the structural funds.

however, has hitherto not been elaborated (Godin, 2005; Leydesdorff, 2005). Mutual information in more than two dimensions can be considered as an operationalization of the knowledge base of an economy, that is, as an indicator of this next-order structure. The measure adds a network perspective to the aggregated data provided by employment statistics.

Methodology

Unlike a covariation between two variables, a dynamic interaction among three dimensions can generate a complex pattern (Schumpeter, 1939: 174f; Li &Yorke, 1975). The two configurations possible among three subdynamics were depicted above as integrating or differentiating (in Figures 1 and 2, respectively). In the case of overlapping Venn diagrams, the dynamics can be considered as relatively integrated, e.g., in the resulting products (Storper, 1997: 49; see Figure 1), while in the absence of overlap the system remains more differentiated. In this latter case, it operates in terms of different systems interfacing each other at the network level. In other words, Figure 2 depicts a 'failing' center. The overlap among the three domains has become negative, and by using the mutual information this can be indicated as negative entropy.[7]

The mutual information in three dimensions can be used to measure the extent of integration and differentiation in the interaction among three subsystems. In general, two interacting systems determine each other in their mutual information and condition each other in the remaining uncertainty. They reduce the uncertainty on either side with the mutual information (or, equivalently, co-variation). Using Shannon's formulas, the mutual

[7] The relation between the geometrical metaphor of overlap or overlay and the algorithmic measure of mutual information is not strictly one-to-one, but the metaphor is helpful for the understanding.

information is defined as the difference between the sum of the uncertainty in two systems without the interaction ($H_x + H_y$) minus the uncertainty contained in the two systems when they are combined (H_{xy}). This can be formalized as follows:

$$T_{xy} = H_x + H_y - H_{xy} \quad (1)$$

H_x is the uncertainty in the distribution of the variable *x* (that is, $H_x = - \sum_x p_x \, {}^2\log p_x$), and analogously, H_{xy} is the uncertainty in the two-dimensional probability distribution (matrix) of *x* and *y* (that is, $H_{xy} = - \sum_x \sum_y p_{xy} \, {}^2\log p_{xy}$). The mutual information T_{xy} is sometimes called the transmission and therefore indicated with a T. If the basis two is used for the logarithm all values are expressed in bits of information.

Abramson (1963: 129) derived from the Shannon formulas that the mutual information in three dimensions is:

$$T_{xyz} = H_x + H_y + H_z - H_{xy} - H_{xz} - H_{yz} + H_{xyz} \quad (2)$$

While the bilateral relations between the variables reduce the uncertainty, the trilateral integration (in the overlap among the Venn diagrams) reduces the reduction by the bilateral relations, and therefore adds to the uncertainty. The layers thus alternate in terms of the sign. When the bilateral relations prevail, a negative entropy is generated. One may also wish to say that the network generates a selective structure with accordingly a minus sign, while a next-order selection can be considered as a positive stabilization or a second-order variation.

In Figure 1, for example, Storper indicated the positive overlap with 'Products.' In the network mode of Figure 2, however, the mutual information in three dimensions can be negative. A system without integration in the center reduces uncertainty by providing a differentiated configuration. This differentiation can be reproduced if the dimensions of the complex communication are codified along different axes. The puzzles of integration at the interfaces are then solved in a non-hierarchical, that is, reflexive or knowledge-based mode.

3. Results

Let us apply this measure to the data. We will first provide the descriptive statistics (Table 4). As noted, the data allows us to disaggregate in terms of geographical regions (NUTS-2 and NUTS-3), and we are able to distinguish high-tech, medium-tech sectors, and knowledge-intensive services. The various dimensions can also be combined in order to compute the transmissions in a next step (Table 5).

	$H_{Geography}$	$H_{Technology}$	$H_{Organization}$	H_{GT}	H_{GO}	H_{TO}	H_{GTO}	N
NL	6.205	4.055	2.198	10.189	8.385	6.013	12.094	1131668
% H_{max}	*95.6*	*69.2*	*61.3*	*82.5*	*83.2*	*63.7*	*75.9*	
Drenthe	2.465	4.134	2.225	6.569	4.684	6.039	8.413	26210
Flevoland	1.781	4.107	2.077	5.820	3.852	6.020	7.697	20955
Friesland	3.144	4.202	2.295	7.292	5.431	6.223	9.249	36409
Gelderland	3.935	4.091	2.227	7.986	6.158	6.077	9.925	131050
Groningen	2.215	4.192	2.220	6.342	4.427	6.059	8.157	30324
Limburg	2.838	4.166	2.232	6.956	5.064	6.146	8.898	67636
N-Brabant	3.673	4.048	2.193	7.682	5.851	6.018	9.600	175916
N-Holland	3.154	3.899	2.116	6.988	5.240	5.730	8.772	223690
Overijssel	2.747	4.086	2.259	6.793	5.002	6.081	8.749	64482
Utrecht	2.685	3.956	2.193	6.611	4.873	5.928	8.554	89009
S-Holland	3.651	3.994	2.203	7.582	5.847	5.974	9.528	241648
Zeeland	1.802	4.178	2.106	5.941	3.868	6.049	7.735	24339

Table 4: Expected information contents (in bits) of the distributions in the three dimensions and their combinations.

Table 4 shows the probabilistic entropy values in the three dimensions (*G* = geography, *T* = technology/sector, and *O* = organization) for The Netherlands as a whole and the decomposition at the NUTS-2 level of the provinces. The provinces are very different in terms of the numbers of firms and their geographical distribution over the postal codes. While Flevoland contains only 20,955 units, South-Holland provides the location for 241,648 firms.[8] This size effect is also reflected in the distribution of postal codes: the uncertainty in the geographical distribution—measured as $H_{Geography}$—correlates significantly with the number of firms N ($r = 0.76$; $p = 0.005$). The variance in the probabilistic entropies among the provinces is high (> 0.5) in this geographical dimension, but the variance in the probabilistic entropy among sectors and the size categories is relatively small (< 0.1). Thus, the provinces are relatively similar in terms of the uncertainty in their sector and size distributions.[9]

The second row of Table 4 informs us that the probabilistic entropy in the postal codes of firms is larger then 95% of the maximum entropy of this distribution at the level of the nation. Although the postal codes are more fine-grained in metropolitan than in rural areas, this indicates that the firm-density is not a major source of variance in relation to the population density. However, the number of postal-code categories at the level of the provinces makes these values incomparable among each other and with those of the country. Postal codes are nominal variables which cannot be compared across provinces or regions.

The corresponding percentages for the technology (sector) and the organization (or size) distributions are 69.2 and 61.3%, respectively. The combined uncertainty of technology and

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[8] The standard deviation of this distribution is 80,027.04 with a means of 94,305.7.

[9] The value of H for the country corresponds to the mean of the values for the provinces in these dimensions: $\overline{H}_T = 4.088 \pm 0.097$ and $\overline{H}_O = 2.196 \pm 0.065$.

organization (H_{TO}) does not add substantially to the redundancy. In other words, organization and technology have an influence on the three-dimensional distribution different from that of postal codes. In the provincial decomposition, the highly developed and densily populated provinces (North and South-Holland, and Utrecht) show a more specialized pattern of sectoral composition (H_T) than Friesland, Groningen, and Limburg. These latter provinces are further distanced from the center of the country. Flevoland shows the highest redundancy in the size distribution, perhaps because certain traditional formats of middle-sized companies may still be underrepresented in this new province.

The combination of technological and organizational specialization exhibits a specific position of North-Holland (H_{TO} = 5.730 or 60.7% of the maximum entropy) versus Friesland (H_{TO} = 6.223 or 65.9% of the maximum entropy) at the other end of the distribution. Since the mean of the distribution is in this case 63.8% with a standard deviation of 1.3, North-Holland is really an exception in terms of an interaction effect between the technological specialization and its relatively low variation in the size distribution.

Table 5 provides the values for the transmissions (T) among the various dimensions. These values can be calculated straightforwardly from the values of the probabilistic entropies provided in Table 4 using Equations 1 and 2 provided above. The first line for The Netherlands as a whole shows that there is more mutual information between the geographical distribution of firms and their technological specialization (T_{GT} = 0.072 bits) than between the geographical distribution and their size (T_{GO} = 0.019). However, the mutual information between technology and organization (T_{TO} = 0.240) is larger than T_{GO} by an order of magnitude. The provinces exhibit a comparable pattern.

	T_{GT}	T_{GO}	T_{TO}	T_{GTO}
NL	0.072	0.019	0.240	-0.034
Drenthe	0.030	0.005	0.320	-0.056
Flevoland	0.068	0.006	0.164	-0.030
Friesland	0.054	0.008	0.274	-0.056
Gelderland	0.040	0.004	0.242	-0.043
Groningen	0.065	0.007	0.353	-0.045
Limburg	0.047	0.006	0.251	-0.033
N-Brabant	0.039	0.016	0.223	-0.036
N-Holland	0.065	0.030	0.285	-0.017
Overijssel	0.040	0.004	0.263	-0.035
Utrecht	0.031	0.005	0.221	-0.024
S-Holland	0.062	0.006	0.223	-0.027
Zeeland	0.038	0.039	0.234	-0.039

Table 5: The mutual information in two and three dimensions disaggregated at the NUTS 2-level (provinces).

While the values for T_{GT} and T_{GO} can be considered as indicators of the geographical clustering of economic activities (in terms of technologies and organizational formats, respectively), the T_{TO} provides an indicator for the correlation between the maturity of the industry (Anderson & Tushman, 1991) and the specific size of the firms involved (Suárez & Utterback 1995, Utterback & Suárez 1993; cf. Nelson, 1994). The relatively low value of this indicator for Flevoland indicates that the techno-economic structure of this province is less mature than in other provinces. The high values of this indicator for Groningen and Drenthe indicates that the techno-economic structure in these provinces is perhaps relatively over-mature. This indicator can thus be considered as representing a strategic vector (Abernathy & Clark, 1985; Watts & Porter, 2003).

All values for the mutual informations in three dimensions (T_{TGO}) are negative. When decomposed at the NUTS-3 level of regions, these values are also negative, with the exception of two regions that contain only a single postal code at the two digits level. (In these two cases the uncertainty is by definition zero.)[10] At first glance, the figures suggest an inverse relationship between the mutual information in three dimensions and the intuitively expected knowledge intensity of regions and provinces, with North-Holland, Utrecht, and South-Holland at the one end and Drenthe and Friesland at the other. However, these values cannot be compared among geographical units without a further normalization because the unique postal codes are one of the composing dimensions, and therefore the hypothesis cannot be tested. For example, the zeros for the COROP regions 2 and 31 are an artifact of the concentration of all firms in one postal zone. Thus, the geographic dimension has a character different from the other two dimensions. In a next section, we will focus on the relative effects of decompositions in terms of high- and medium-tech sectors on the geographical units of analysis, but let us first turn to the normalization in the geographical dimension in order to validate the indicator.

4. The regional contributions to the knowledge base of the Dutch economy

One of the advantages of statistical decomposition analysis is the possibility to specify the within-group variances and the between-group variances in great detail (Theil, 1972; Leydesdorff, 1995). However, a full decomposition at the lower level is possible only if the categories for the measurement are similar among the groups. Had we used a different indicator for the regional dimension—for example, percentage 'rural' versus percentage 'metropolitan'—we would have been able to compare and therefore to decompose along this axis, but the unique postal codes cannot be compared among regions in a way similar to the size or the sectoral distribution of the firms.

[10] These are the regions Delfzijl and Zeeuwsch-Vlaanderen (COROP / NUTS-3 regions 2 and 31).

The decomposition algorithm (Theil, 1972) enables us to study the next-order level of the Netherlands as a composed system (NUTS-1) in terms of its lower-level units like the NUTS-2 provinces and the NUTS-3 regions. Note that in this case, the regions and provinces are not compared in terms of their knowledge intensity among themselves, but in terms of their weighted contributions to the knowledge base of the Dutch economy as a whole. The distributions are weighted in the various dimensions for the number of firms in the groups *i* by summing first the uncertainties within the different groups ($\sum_i (n_i/N) * H_i$; $N = \sum_i n_i$). The in-between group uncertainty H_0 is then defined as the difference between this sum and the uncertainty prevailing at the level of the composed system:

$$H = H_0 + \sum_i (n_i/N) H_i \qquad (3)$$

Or equivalently for the transmissions:[11]

$$T = T_0 + \sum_i (n_i/N) T_i \qquad (3)$$

For example, if we use the right-most column of Table 4 indicating the number of firms in each of the provinces for the normalization given the total number of firms registered (N = 1,131,668), we obtain the following table for the decomposition of the mutual information in three dimensions at the level of the provinces:

[11] The formula is equally valid for the transmissions because these are based on the probability distributions in the mutual information between two or more probability distributions. The probability distribution in the transmission T_{ab} can be written as the intersect between the distributions for *a* and *b,* or in formula format as $\sum p_T = \sum (p_a \text{ AND } p_b)$.

	ΔT_{GTO} (= n_i * T_i /N) in millibits of information	n_i
Drenthe	-1.29	26210
Flevoland	-0.55	20955
Friesland	-1.79	36409
Gelderland	**-4.96**	131050
Groningen	-1.20	30324
Limburg	-1.96	67636
N-Brabant	**-5.56**	175916
N-Holland	**-3.28**	223690
Overijssel	-1.98	64482
Utrecht	-1.86	89009
S-Holland	**-5.84**	241648
Zeeland	-0.83	24339
Sum ($\sum_i P_i T_i$)	-31.10	1131668
T_0	**-2.46**	
NL	-33.55	N = 1131668

Table 6: The mutual information in three dimensions statistically decomposed at the NUTS 2-level (provinces) in millibits of information.

The table shows that the knowledge base of the country is concentrated in South-Holland ($\Delta T = -5.84$ mbits), North-Brabant (− 5.56), and Gelderland (− 4.96). North-Holland follows with a contribution of − 3.28 mbits of information. The other provinces contribute to the knowledge base less than the in-between provinces interaction effect at the national level ($T_0 = -2.46$ mbit). Figures 3 and 4 visualize how the knowledge base of the country is geographically organized at the NUTS-2 and the NUTS-3 level, respectively.

Figure 3: Contribution to the knowledge base of the Dutch economy at the provincial (NUTS-2) level.

Figure 4: Contribution to the knowledge base of the Dutch economy at the regional (NUTS-3) level.

The further disaggregation in Table 7 informs us about the contribution of regions at the NUTS-3 level (Figure 4). The contribution of South-Holland is concentrated in the Rotterdam area, the one in North-Brabant in the Eindhoven region, and North-Holland exclusively in the agglomeration of Amsterdam. Utrecht, the Veluwe (Gelderland) and the northern part of Overijssel have also above average contributions on this indicator. However, an important part of the reduction of the uncertainty is provided at a level higher than the NUTS-3 regions ($T_0 = -9.09$ mbit).[12] We shall therefore focus in the next section on the NUTS-2 level. These

[12] More detailed analysis teaches that the provincial structure reduces the uncertainty in the mutual information between the sectoral and the size distribution as two dimensions with − 7.79 mbits, while this uncertainty is reduced with − 20.06 mbits by the finer-grained structure of COROP regions. Unlike the effect on the mutual

tables and pictures, however, validate our indicator since the results correspond with common knowledge about the industrial structure of The Netherlands (e.g., Van der Panne & Dolfsma, 2001 and 2003).

	NUTS-3 Regions (Corop)	ΔT_{GTO} (= n_i * T_i /N) in millibits of information	n_i
1	Oost-Groningen	-0.20	7571
2	Delfzijl en omgeving	0.00	2506
3	Overig Groningen	-0.81	20273
4	Noord-Friesland	-0.99	17498
5	Zuidwest-Friesland	-0.37	7141
6	Zuidoost-Friesland	-0.41	11744
7	Noord-Drenthe	-0.44	9702
8	Zuidoost-Drenthe	-0.39	9121
9	Zuidwest-Drenthe	-0.13	7327
10	**Noord-Overijssel**	**-1.04**	20236
11	Zuidwest-Overijssel	-0.16	7333
12	Twente	-0.57	36971
13	**Veluwe**	**-1.38**	43489
14	Achterhoek	-0.76	24995
15	Arnhem/Nijmegen	-0.85	43388
16	Zuidwest-Gelderland	-0.69	19192
17	**Utrecht**	**-1.86**	88997
18	Kop van Noord-Holland	-0.30	25978
19	Alkmaar en omgeving	-0.39	17145
20	IJmond	-0.07	11017
21	Agglomeratie Haarlem	-0.16	17376
22	Zaanstreek	-0.07	9865
23	**Groot-Amsterdam**	**-1.15**	117518
24	Het Gooi en Vechtstreek	-0.42	24818
25	Agglomeratie Leiden en Bollenstreek	-0.42	26738
26	*Agglomeratie 's-Gravenhage*	*-1.00*	50603
27	Delft en Westland	-0.28	19489
28	Oost-Zuid-Holland	-0.67	25262
29	**Groot-Rijnmond**	**-1.61**	92255
30	Zuidoost-Zuid-Holland	-0.91	27301
31	Zeeuwsch-Vlaanderen	0.00	6840
32	Overig Zeeland	-0.39	17499
33	West-Noord-Brabant	-0.78	43954
34	Midden-Noord-Brabant	-0.61	32332
35	*Noordoost-Noord-Brabant*	*-1.00*	47214
36	**Zuidoost-Noord-Brabant**	**-1.13**	52416
37	Noord-Limburg	-0.53	16753
38	Midden-Limburg	-0.17	15272
39	Zuid-Limburg	-0.79	35611
40	Flevoland	-0.55	20928
	Sum ($\sum_i P_i T_i$)	-24.46	1131668

information in three dimensions, these reductions of the uncertainty at the NUTS-2 and the NUTS-3 levels are independent of the distribution of postal codes (since specified at these higher levels of aggregation).

	T_0	**-9.09**	
	NL	-33.55	N = 1131668

Table 7: The mutual information in three dimensions statistically decomposed at the NUTS-3 level (COROP regions) in millibits of information. Regions with a ΔT > 1.00 mbit are boldfaced; ΔT = 1.00 mbits in italics.

As noted, the normalization involves the number of firms in the geographical unit of analysis as a factor in the weighting. Therefore, these results inform us both about the industrial structure of the country and about the knowledge base of the economy.[13] Among the regions, for example, Utrecht (region 17) contributes most to the uncertainty at the national level, while as a province the same value for Utrecht (ΔT = − 1.86 mbits) remains below the average contribution. In general, the mutual information in three dimensions provides a composite measure of the three factors involved in Storper's holy trinity (geography, technology, and organization). These three factors can be decomposed along each axis.[14] We turn in the next section to the sectoral axis, and particularly to the effects of indicating knowledge intensity along this axis.

5. The sectorial decomposition

While the geographical comparison is compounded with traditional industrial structure like firm density, we will focus in the remainder of this study on decomposing the set in terms of the sectorial classification of high- and medium-tech sectors and knowledge-intensive services as provided by the OECD and Eurostat (see Table 2 above). All effects will be expressed as a relative effect on the mutual information in three dimensions, that is, as a

[13] The correlation between the contributions ΔT and the number of firms is high and significant both in the case of analysis at the NUTS-2 level ($r = 0.872$; $p < 0.01$) and the NUTS-3 level ($r = 0.801$; $p < 0.01$).

[14] The contribution of northern Overijssel to the knowledge base of the Dutch economy is a bit of a surprise because this region is not generally recognized as an economically active region. Perhaps, it profits from a spill-over effect of neighbouring regions, but this requires further investigation.

percentage increase of its negative value when a specific selection is compared with the full set. Thus, we focus in this section exclusively on the knowledge-based dimension of the economy.

T_{xyz}	All sectors	High Tech	% increase	N
NL	-0.034	-0.060	80.2	45128
Drenthe	-0.056	-0.093	67.6	786
Flevoland	-0.030	-0.036	20.6	1307
Friesland	-0.056	-0.136	144.9	983
Gelderland	-0.043	-0.094	120.1	4885
Groningen	-0.045	-0.066	48.1	1204
Limburg	-0.033	-0.068	105.9	2191
N-Brabant	-0.036	-0.058	61.2	6375
N-Holland	-0.017	-0.034	103.4	9346
Overijssel	-0.035	-0.079	127.6	2262
Utrecht	-0.024	-0.039	65.9	4843
S-Holland	-0.027	-0.044	61.7	10392
Zeeland	-0.039	-0.067	73.3	554

Table 8: The mutual information in three dimensions when comparing high-tech sectors in industrial production and services.

Table 8 provides the results of comparing the subset of enterprises indicated as high-tech manufacturing (sectors 30, 32, and 33) and high-tech services (64, 72, and 73) with the full set. The column headed with 'All sectors' corresponds to the right-most column in Table 4. The third column provides the mutual information in three dimensions for the high-tech sectors in both manufacturing and services. In the fourth column the percentage increase is indicated in relative terms. This indicates the influence of these high-tech sectors and services on the knowledge base of the economy. The results confirm our hypothesis that the mutual information in three dimensions is more negative (and thus indicative of a knowledge base in the system as a configuration) for high-tech sectors and high-tech services than for the economy as a whole. The dynamics created by these sectors deepen and tighten the knowledge base more than is the case for firms on average.

	All sectors	High & medium tech Manufacturing	% increase	N	Knowledge-Intensive Services	% increase	N
NL	-0.034	-0.219	544	13422	-0.024	-27.3	581196
Drenthe	-0.056	-0.363	549	366	-0.034	-39.1	11312
Flevoland	-0.03	-0.212	606	318	-0.018	-37.9	10730
Friesland	-0.056	-0.278	396	496	-0.037	-32.6	14947
Gelderland	-0.043	-0.262	508	1913	-0.025	-40.8	65112
Groningen	-0.045	-0.256	470	436	-0.029	-34.0	14127
Limburg	-0.033	-0.232	602	967	-0.018	-45.1	30040
N-Brabant	-0.036	-0.168	368	2593	-0.030	-16.6	86262
N-Holland	-0.017	-0.177	939	1831	-0.017	1.0	126516
Overijssel	-0.035	-0.196	460	1055	-0.020	-42.8	30104
Utrecht	-0.024	-0.215	795	914	-0.013	-45.0	52818
S-Holland	-0.027	-0.198	634	2284	-0.015	-45.5	128725
Zeeland	-0.039	-0.213	447	249	-0.028	-27.8	10503

Table 9: High-tech & medium-tech manufacturing versus knowledge-intensive services and the effects on the mutual information in three dimensions.

Table 9 provides the same figures and normalizations, but now on the basis of selections according to the classifications provided in Table 2 for high- and medium-tech manufacturing combined (middle section of Table 2) and knowledge-intensive services (right-side columns of Table 2), respectively. These results clearly indicate a major effect on the indicator for the sectors of high and medium-tech manufacturing. The effect is by far the largest in North-Holland with 939% increase relative to the benchmark of all sectors combined. Utrecht and South-Holland follow with 795 and 634%, respectively, but other regions like Flevoland and Limburg show an almost comparable effect (606 and 602%, respectively).

The number of companies in knowledge-intensive services is more than half (51.3%) of the total number of companies in the country. These companies are concentrated in North- and South-Holland, with North-Brabant in the third position. With the exception of North-Holland, the effect of knowledge-intensive services on this indicator of the knowledge base is always negative, that is, it leads to a decrease in the negative entropy. In the case of North-

Holland, the difference is marginally positive (+1.0 %), but this is not due to the Amsterdam region.[15] North-Brabant is second on this rank order with a decrease of −16.6%.

These findings accord with a theoretical expectation about the different contributions to the economy of services in general and KIS in particular (Bilderbeek *et al*., 1998; Miles *et al*., 1995; OECD, 2000; Windrum & Tomlinson 1999). Windrum & Tomlinson (1999) argued that to assess the role of KIS, it is crucial to look more at their degree of integration than at their percentage of representation in the economy. The measure adopted here focuses particularly on the degree of integration of KIS into the system. We find that KIS increases entropy in the techno-economic system of The Netherlands and its provinces. This indicates a relatively uncoupling effect from the geographically defined knowledge bases of the economy. This uncoupling can be considered as negative for the development of a knowledge base within a geographical unit.

This result contrasts with the expectations expressed in much of the relevant literature on the role of knowledge-intensive services in stimulating the knowledge base of an economy. For example, the European Summit on 23-24 March 2000 in Lisbon was specifically held 'to agree a new strategic goal for the Union in order to strengthen employment, economic reform and social cohesion as part of a knowledge-based economy.' The conclusion of this meeting was, among other things, that 'the shift to a digital, knowledge-based economy, prompted by new goods and services, will be a powerful engine for growth, competitiveness and jobs. In addition, it will be capable of improving citizens' quality of life and the environment.'[16] Our

[15] Only in COROP / NUTS-3 region 18 (North-Holland North) the value of the mutual information in three dimensions is more negative when zooming in on the knowledge-intensive services. However, this region is predominantly rural.
[16] at http://www.europarl.eu.int/summits/lis1_en.htm#b .

results suggest that the two concepts of a knowledge-based economy and the shift to a digital economy are not the same.

T_{xyz}	Knowl-intensive services	High-Tech services	% increase	N
NL	-0.024	-0.034	37.3	41002
Drenthe	-0.034	-0.049	45.2	678
Flevoland	-0.018	-0.018	-4.6	1216
Friesland	-0.037	-0.087	131.5	850
Gelderland	-0.025	-0.046	82.3	4380
Groningen	-0.029	-0.044	49.5	1070
Limburg	-0.018	-0.039	118.7	1895
N-Brabant	-0.030	-0.035	16.1	5641
N-Holland	-0.017	-0.020	17.0	8676
Overijssel	-0.020	-0.046	133.1	1999
Utrecht	-0.013	-0.020	49.8	4464
S-Holland	-0.015	-0.025	69.8	9650
Zeeland	-0.028	-0.045	59.7	483

Table 10: The subset of high-tech services improves the knowledge base in the service sector.

Table 10 shows the relative deepening of the mutual information in three dimensions when the subset of sectors indicated as 'high-tech services' is compared with KIS in general. 'High-tech services' are only 'post and telecommunications' (NACE code 64), 'computer and related activities' (72), and 'research and development' (73). More than knowledge-intensive services in general, high-tech services can be expected to produce and transfer technology-related knowledge (Bilderbeek *et al*., 1998). These effects of strengthening the knowledge base seem highest in regions which do not have a strong knowledge base in medium and high-tech manufacturing, such as Friesland and Overijssel. The effects of this selection for N-Brabant and N-Holland, for example, are among the lowest. This negative relation, however, is not significant ($r = -0.352$; $p = 0.262$). At the NUTS-3 level, the corresponding relation is also not significant. Thus, the effects of high- and medium-tech manufacturing and high-tech services on the knowledge base of the economy are not related to each other.

6. Conclusions and discussion

Before we proceed to draw conclusions and consider policy implications, we should emphasize that this effort was primarily methodological. We had developed independently, on the one hand, an indicator of interaction effects at the network level which provided us with a quantitative measure for the reduction of the uncertainty that cannot be attributed to the individual players in a network. The reduction of this uncertainty is configurational when a next-order system operates as an overlay. On the other hand, the data allowed us to use proxies for the three main dimensions of Storper's 'holy trinity' of technology, organization, and territory, although the operationalization of organization in terms of numbers of employees obviously remains debatable.

Our collaboration provided us with an opportunity to validate the scientometric indicator of triple-helix relations in an economic context. It could be shown that this indicator can be used to measure the knowledge base of an economy and its decomposition in terms of geographical subunits and in considerable detail. However, the nominal character of the postal codes made it impossible to compare directly among regions and provinces (but only in terms of their contribution to the national economy). The effects of these problems on the data in relation to the indicator and its interpretation made us hesitant to decompose below the NUTS-2 level of the provinces because this may suggest an exactness which cannot be achieved using this data. Nevertheless, our results are very clear. They allow us to draw the following conclusions:

1. The knowledge base of the (regional) economy is carried by high and more specifically by medium-tech manufacturing; high-tech services contribute to the knowledge base independently, but to a smaller extent.
2. Medium-tech manufacturing provides the backbone of the techno-economic structure of the country; this explains why high-tech manufacturing contributes less to the knowledge infrastructure than might expected, for example, on the basis of patent portfolios (Leydesdorff, 2004).
3. The knowledge-intensive services which are not high-tech have a negative effect on the territorial knowledge base. One could say that these services tend to uncouple the knowledge base from its territorial dimension.
4. The Netherlands is highly developed as a knowledge-intensive service economy, but the high-tech end of these services has remained more than an order of magnitude smaller in terms of the numbers of firms.

As a policy implication, it follows that regions which are less developed may wish to strengthen their knowledge infrastructure by trying to attract medium-tech manufacturing and high-tech services. The efforts of firms in medium-tech sectors can be considered as focused on maintaining absorptive capacity (Cohen & Levinthal, 1989) so that knowledge and technologies developed elsewhere can more easily be understood and adapted to particular circumstances. High-tech manufacturing firms may be more focused on the (internal) production and global markets than on the local diffusion parameters. High-tech services, however, mediate technological knowledge more than knowledge-intensive services which are medium-tech. The latter services have a negative effect on territorially defined knowledge-based economies.

Perhaps the most important contribution of this paper is the procedure presented for measuring the knowledge base of an economy. The indicator captures the knowledge base of an economy at the structural level using relatively straightforward parameters. The various dimensions correspond to the classifications that are already available from the OECD and Eurostat databases, and the geographical address information of the units is also used. Unlike the focus on comparative statics in employment statistics and the *STI Scoreboards* of the OECD (OECD, 2001, 2003; Godin, 2005), this algorithmic indicator was developed for measuring the knowledge base of an economy as an emergent property (Jakulin & Bratko, 2004; cf. Ulanowicz, 1986: 142 ff.). Furthermore, the indicator could be specified as an operationalization with reference to two bodies of theorizing in evolutionary economics, namely regional studies (e.g., Storper, 1997; Van der Panne & Dolfsma, 2003) and the study of knowledge-based systems of innovation (e.g., David & Foray, 2002; Leydesdorff & Etzkowitz, 1998).

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