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THE RELATION BETWEEN SYNERGY AND CYCLE VALUES IN THE REGIONAL INNOVATION SYSTEMS IN NORWAY

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The innovation capacity of Norwegian innovation system, according Triple Helix model of innovations approach, is analyzed in terms of mutual information among geographical, sectorial, and size distributions of firms as dimensions of probabilistic entropy. Negative entropies can be considered as a consequence of synergy among these dimensions. Three different techniques for evaluation of temporal synergy evolution are used: *R/S* analysis, *DFT*, and geographical synergy decomposition. The calculations are based on data for all Norwegian firms registered between 2002 and 2014. The results suggest that the synergy at the level of both the country and its seven regions show non-chaotic oscillatory behavior and resonate in a set of natural frequencies.

Keywords: knowledge base, innovations, triple helix, cyclic processes

JEL: O10, O30, R11

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1. Introduction

Multi-dimensional systems of various types, such as social or biological, can be considered eco-systems, that can flourish if uncertainty in the relations among constituent parts is reduced (Ulanowicz, 1986). The Triple Helix (TH) model of university-industry-government relations can serve as a specific example of such systems. Innovation capacity of the system is provided by the synergy of interaction among the constituent actors. Mutual information in three or more dimensions may lead to reduction of uncertainty at the system level. This negative entropy can be considered a measure of synergy, which can be expressed in negative bits of information using the Shannon-formula (Abramson, 1963; Theil, 1972; Leydesdorff, 1995).[1]

The synergy of a TH system can, for example, be measured as reduction of uncertainty using mutual information among the three dimensions of firm sizes, the technological knowledge bases of firms, and geographical locations. A number of studies have been devoted to measuring synergy in this way across different countries and regions, such as the Netherlands (Leydesdorff, Dolfsma, & Van der Panne, 2006), Germany (Leydesdorff & Fritsch, 2006), Hungary (Lengyel & Leydesdorff, 2011), Norway (Strand & Leydesdorff, 2013), Sweden (Leydesdorff & Strand, 2012), West Africa (Mêgnigbêto, 2013), China (Leydesdorff & Zhou, 2014), and Russia (Leydesdorff, Perevodchikov, & Uvarov, 2015). One obtains maps of synergy distribution across the territory. However, having only static measurement results, one is unable to answer a series of questions, such as what is the temporal character of synergy evolution; does the synergy value affect its temporal evolution? Note that a TH system cannot be static (Etzkowitz & Leydesdorff, 2000). Rather it is an ever-evolving system, and therefore one can expect that the synergy in this system also evolves with the passage of time.

Various economic variables show signs of cyclic behavior. This has been a research topic since Schumpeter, Kuznets, and Kondratieff. Recently, Luckraz (2013) has analyzed innovation cycles in a finite discrete R&D game, concluding that strategic interaction between the firms are

[1] A problem in applying Shannon's formula to trilateral and higher-order dimensional interactions is that mutual information is then a signed information measure (Yeung 2008, Leydesdorff 2010). A negative information measure cannot comply with Shannon's definition of information (Krippendorff 2009a, b). This contradiction can be solved by considering mutual information as different from mutual redundancy (Leydesdorff & Ivanova, 2014). In the three-dimensional case, however, mutual information is equal to mutual redundancy and, thus, mutual information in three dimensions can be considered a Triple-Helix indicator of synergy in university-industry-government relations (Leydesdorff *et al*, 2014).

sufficient to generate cycles. De Groot and Franses have investigated cycles in basic innovations (de Grooth & Franses, 2009) and more general socio-economic cycles (de Grooth & Franses, 2012). These authors conclude that there seems to be a common set of cycles across various socio-economic variables. Regional dimensions of business cycles have been investigated by Dixon and Shepherd (2001, 2013), who filter the data into trends, cycles, and noise, and thus are able to show that similarities in cycles can be explained by regional industry structure and the size of regions. Various techniques, like autoregressive growth-rated models (Hodrick-Prescott, 1997) and frequency filter models, have been used to analyze cyclic data; see Dixon and Shepherd (2013) for a review. From another perspective, Frøyland et al. (1988) used fractal statistics and rescaled range (R/S) analysis (as found in Feder, 1988) to analyze cycles in various processes in nature.

The core research questions of the present paper regarding temporal synergy evolution in a TH system are as follows: how do the synergies evolve (e.g., is there trend-like, chaotic, oscillatory, or some other functional dependency)? Do synergy values affect the temporal evolution (i.e. is there a difference in synergy evolution between configurations with high and low synergy)? Can numerical indicators of synergy evolution be provided?

The temporal dynamics of synergy in the Norwegian innovation system is analyzed as an example. The choice of the Norwegian system is guided by the ready availability of data. However, the method is generic and can be applied to any data for a time series that meets the criterion of possessing three (or more) independent dimensions.

2. Methods and data

2.1 Methods

The mutual information of interaction between two actors can be numerically evaluated using the formalisms of Shannon's information theory by measuring mutual information as the reduction of uncertainty. In the case of three interacting dimensions, the mutual information in a configuration T_Σ can be defined by analogy with mutual information in two dimensions, as follows (Abramson, 1963; McGill, 1954):

$$T_\Sigma = H_1 + H_2 + H_3 - H_{12} - H_{13} - H_{23} + H_{123} \quad (1)$$

Here, H_i, H_{ij}, H_{ijk} denote probabilistic entropy measures in one, two, and three dimensions:

$$H_i = -\sum_i p_i log_2 p_i$$

$$H_{ij} = -\sum_{ij} p_{ij} log_2 p_{ij} \quad (2)$$

$$H_{ijk} = -\sum_{ijk} p_{ijk} log_2 p_{ijk}$$

The values of p represent the probabilities, which can be defined as the ratio of the corresponding frequency distributions:

$$p_i = {}^{n_i}/_N; \;\; p_{ij} = {}^{n_{ij}}/_N; \;\; p_{ijk} = {}^{n_{ijk}}/_N \quad (3)$$

N is the total number of events, and n_i, n_{ij}, n_{ijk} denote the numbers of events relevant in subdivisions. For example, if *N* is the total number of firms, n_{ijk} is the number of firms in the *i* -th county, the *j*-th organizational level (defined by the number of staff employed), and the *k*-th technology group. Then n_i and n_{ij}can be calculated as follows:

$$n_i = \sum_{jk} n_{ijk}; \qquad\qquad n_{ij} = \sum_k n_{ijk}$$

A set of *L* mutual information values for a certain time period, considered as a finite time signal, can be spectrally analyzed with the help of the discrete Fourier transform (Kester, 2000):

$$T_{\Sigma} = \sum_{l=0}^{L/2} F_l(w) \quad (4)$$

Here:

$$F_0 = A;\ F_l(w) = B_l \cos(2\pi lw/L) + D_l \sin(2\pi lw/L) \quad (5)$$

The Fourier decomposition by itself cannot provide us with information regarding synergy evolution except the values of the spectral coefficients: A, B_i, and D_i. Because the aggregate (country-related) synergy T_{Σ} is determined by additive entropy measures (Eq. (1), it can also be decomposed as a sum of partial (county-related) synergies $T_1, \ldots T_{\mathrm{n}}$:[*]

$$T_{\Sigma} = T_1 + T_2 + \cdots T_{\mathrm{n}} \quad (6)$$

So that each partial synergy can be written in the same form as Eq. (4):

$$T_1 = \sum_{l=0}^{L/2} f_{1l}(w)$$

$$T_2 = \sum_{l=0}^{L/2} f_{2l}(w)$$

$$(7)$$

$$\ldots$$

[*] This decomposition is different from that used in our previous studies (e.g., Leydesdorff & Strand, 2013; Strand & Leydesdorff, 2013).

$$T_{\mathrm{L}} = \sum_{l=0}^{L/2} f_{1L}(w)$$

Here:

$$f_{0l} = a_{0l};\ f_{nl}(w) = b_{nl}\cos(2\pi lw/L) + d_{nl}\sin(2\pi lw/L)$$

After substituting Eqs. (4) and (7) into (6) and re-grouping the terms, one obtains:

$$F_l(w) = f_{1l}(w) + f_{2l}(w) + .. + f_{nl}(w) \qquad (8)$$

Leydesdorff and Ivanova (2014a) showed that mutual information in three dimensions is equal to mutual redundancy ($T_{123} = R_{123}$). Aggregated redundancy can equally be decomposed as a sum of partial redundancies, corresponding to the geographical, structural, or technological dimensions of the innovation system under study. Mutual redundancy changes over time, so that one can write:

$$R_{123}(t) = R_1(t) + R_2(t) + \cdots + R_n(t) \qquad (9)$$

In another context, Ivanova & Leydesdorff (2014b) expressed the redundancy that can be obtained as follows (i= 1, 2 … n):

$$R_i = a_i' + b_i'\cos(r_i t) + d_i'\cos(r_i t) \qquad (10)$$

The oscillating function in Eq. (10) can be considered a natural frequency of the TH system. This natural frequency is far from fitting observed redundancy values for R_{123}. However, real data for the definite time interval can be fit with the help of the discrete Fourier transform, comprising a finite set of frequencies. Each frequency in the set composing Eq. (9) can be considered a natural frequency of the TH system:

$$R_{123} = A + \sum_{k=1}^{n}(B_k \cos(kt) + D_k \sin(kt)) \tag{11}$$

Comparing Eq. (11) with Eq. (10) one can approximate the empirical data for three-dimensional redundancy R_{123} as a sum of partial redundancies R_i corresponding to frequencies that are multiples of the basic frequency: *w, 2w, 3w* … etc.

$$R_{123} = R_1 + R_2 + \cdots + R_n \tag{12}$$

In other words, a TH system can be represented as a string resonating in a set of natural frequencies with different amplitudes. Frequency-related amplitudes, which can be defined as modules of the corresponding Fourier coefficients, can be considered the spectral structure of the TH system. Absolute values of the Fourier-series coefficients C_k can be defined as follows

$$C_l = \sqrt{(B_l^2 + D_l^2)} \tag{13}$$

These coefficients determine the relative contributions of the harmonic functions with corresponding frequencies to the aggregate redundancy (R_{123} in Eq. (11)).

2.2 Transmission power and efficiency

Following (Mêgnigbêto, 2014, p. 287), the transmission power of the synergy can be calculated according to the following formula:

$$\tau = \begin{cases} \tau_1 = \frac{T_{GOT}}{H_{GOT} - H_G - H_O - H_T} & if\ T_{GOT} < 0 \\ \tau_2 = \frac{T_{GOT}}{H_{GOT}} & if\ T_{GOT} > 0 \\ 0 & if\ T_{GOT} = 0 \end{cases} \qquad (14)$$

The transmission power is designed to measure the efficiency of the mutual information. While the transmission defines the total amount of configurational information, the transmission power represents the share of the synergy in the system relative to its size. For positive transmission values, it is simply the ratio of overlapping surface area in a corresponding Venn diagram. Mêgnigbêto (2014, p.290) argued that "… with such indicators, a same system may be compared over time; different systems may also be compared".

2.3 Characteristics of Norwegian regions

The regions in Norway are indicated in Figure 1. Norway is divided into 19 counties at NUTS 3 level and seven regions at NUTS 2. These regions are the geographical units of analysis in this study.

Fig. 1: Norwegian regions (NUTS 2 level)

Characteristics for the seven regions are given in Table 1. Data on population and number of firms are provided from Statistics Norway (SN, 2015). The most populated area is the capital region Oslo og Akershus (OA), the sparsely populated and areas dominated by primary industries are found inland (Hedmark og Oppland (HO)) and in the north (Nord-Norge (NN)). The center of the oil- and gas industry is in Agder and Rogaland (AR) in south west, with Stavanger as the most important city. The region of Trøndelag (TR) includes the city of Trondheim where the main technical university and several research institutes are located, as well as agricultural areas in the northern part of the region. The region Sør-Østlandet (SE) is composed of several counties with a diverse industry structure. Vestlandet (WE) is the center for marine and maritime related industries in Norway.

According to the Regional Innovation Scoreboard 2015, OA, WE, TR, and NN are classified as innovation followers, whereas HO, SE, and AR are classified as moderate innovators. Results from an analysis of TH synergy, based on register data from 2008 are also given in Table 1. From this it can be observed that the synergy is highest in the regions Vestlandet (WE) and Sør-Østlandet (SE). Low levels of synergy are found in Oslo and Akershus (OA), Hedemark og Oppland (HO) and Trøndelag (TR). Moderate levels are found in Agder and Rogaland (AR) and Nord-Norge (NN).

	Regional Innovation Scoreboard, 2015	Number of firms (SN, 2015)	Population (SN, 2015)	TH synergy (Strand & Leydesdorff, 2013)
Oslo og Akershus (OA)	Follower	132,262	1,232,575	-7.88
Hedmark og Oppland (HO)	Moderate	44,847	383,960	-9.58
Sør-Østlandet (SE)	Moderate	99,157	976,550	-18.06
Agder og Rogaland (AR)	Moderate	72,437	761,946	-14.05
Vestlandet (WE)	Follower	85,754	884,246	-22.10
Trøndelag (TR)	Follower	45,131	445,785	-9.84
Nord-Norge (NN)	Follower	47,114	480,740	-15.94

Table 1: Characteristics of Norwegian regions

In order to compare the industry structure in various regions, this paper will apply a firm based version of the Krugman index of dissimilarity (Dixon and Shepherd (2013).

For each industry sector *i*, data on the number of firms in region *A*; X_{Ai} and X_{Bi} are provided. The total number of firms in each region is: X_A and X_B. The dissimilarity between the industry sectors in the two regions can then be calculated as:

$$KID_{AB} = \sum_i \left| \left(\frac{X_{iA}}{X_A} \right) - \left(\frac{X_{iB}}{X_B} \right) \right| \tag{14}$$

A value of zero indicates that the industry structures in the two regions are equal. The opposite, when the two structures have nothing in common would give an index value of 2.

2.4 Data

Norwegian establishment data were retrieved from the database of Statistics Norway at https://www.ssb.no/statistikkbanken/selecttable/hovedtabellHjem.asp?KortNavnWeb=bedrifter&CMSSubjectArea=virksomheter-foretak-og-regnskap&PLanguage=1&checked=true. The data include time series of Norwegian companies during the period 2002-2014, and encompass approximately 400,000 firms per year. The data include the number of establishments in the three relevant dimensions: geographical (*G*), organizational (*O*), and technological (*T*).

Seven regions are distinguished in the geographical dimension. In the organizational dimension, establishments are subdivided with reference to different numbers of employees by eight groups: no-one employed; 1-4 employees; 5-9 employees; 10-19 employees; 20-49 employees; 50-99 employees; 100-249 employees; and 250 or more employees. The number of employees can be expected to correlate with the establishment's organizational structure.

The technological dimension indicates domains of economic activity. The data during the period 2002-2008 were organized according to the NACE Rev. 1.1 classification, and the data during the period 2009-2014 were organized according to the NACE Rev. 2 classification. Some of the criteria for the construction of the new classification, were reviewed: but there is no one-to-one correspondence between NACE Rev. 1.1 (with 17 sections and 62 divisions) and NACE Rev. 2 (with 21 sections and 88 divisions) (EUROSTAT 2014 a). To correctly merge the NACE Rev. 1.1 and NACE Rev. 2 data one has to turn to a higher level of aggregation (Appendix B) containing 10 classes (EUROSTAT 2014 b).

3. Results

3.1 Descriptive statistics

Regional synergy is calculated as a sum of the synergies at the county level in accordance with Eq. (6). The results of the calculations during the period 2002-2014 years (in bits of information) are shown in Figure 2 for the national level and Figure 3 for the regional level.

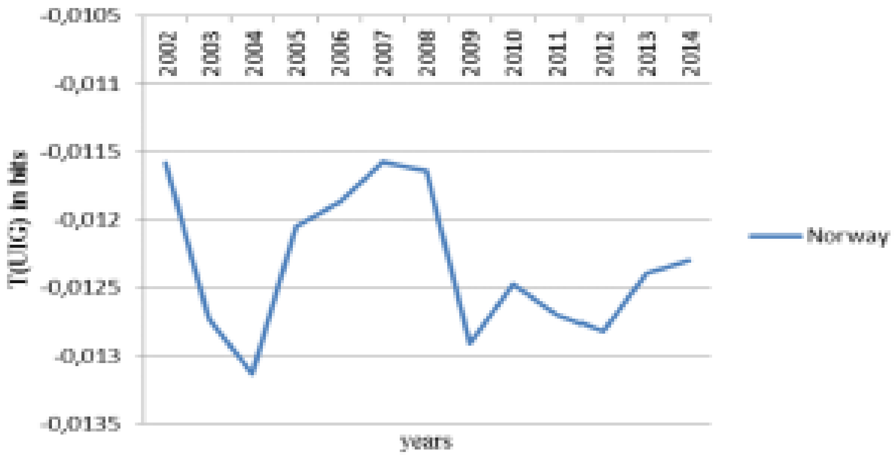

Fig. 2: Summary of the development of TH synergy at the national level during the period 2002-2014 (in bits of information)

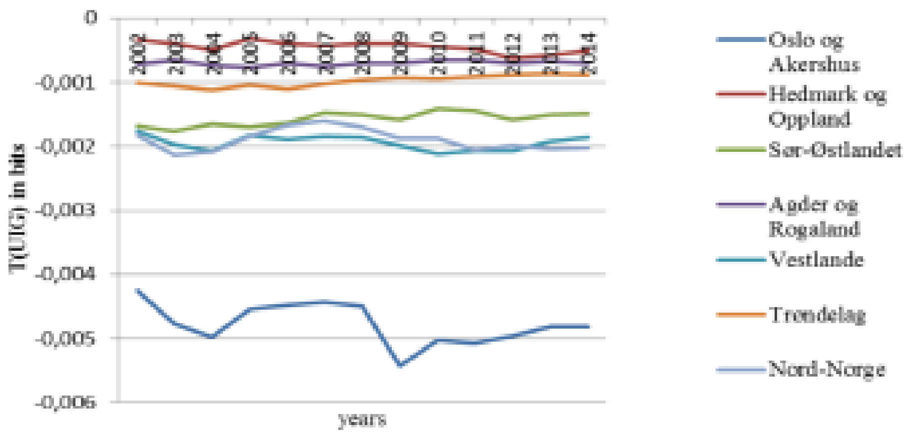

Fig. 3: Partial ternary synergy for the seven regions of Norway, during the period 2002-2014 (in bits of information)

The synergy at the national level follows in general a lateral trend with alternating upwards and downwards sectors. More negative *T(uig)* is observed until 2004, then a decrease in synergy takes place until the economic crisis in 2008, and after that a recovery is present where synergy shows a positive trend. As can be seen from Figure 3, the country synergy is in large part shaped by the synergy in the capital region OA[2]. The other six Norwegian districts demonstrate a relatively stable development. These regions are subdivided into two visually separated strands with respect to synergy values: HO, AR, TR, and WE, SE, NN.

Fluctuations in synergy data can be interpreted as synergy cycles. Like economic cycles, synergy cycles indicate endogenous characteristics of an innovation system such as cyclic oscillations of the market system (Morgan, 1991). An alternative to considering the fluctuations as cycles would be to consider them a result of noise in the data; this will be clarified this in the next section.

[2] In Strand & Leydesdorff (2013), the synergy calculations were based on municipal data, resulting in a singularity in the capital of the country (Oslo). In this paper, the calculations are based on the contributions of the counties to the national level, allowing the contribution of the capital to be specified.

3.2 Transmission power and efficiency

The transmission power at national and regional level are given in Figure 4 and 5.

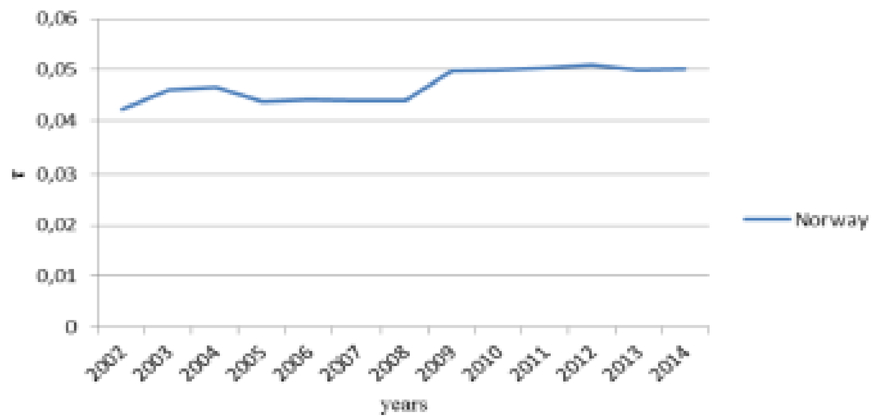

Fig. 4: Summary Norway transmission power τ (in relative units) during the period 2002-2014.

As can be seen from Figure 4, transition power shows stability at two steps with a shift in 2008. A linear trend line would have indicates a weak growing efficiency of the Norwegian innovation system at the national level. Figure 5 shows that the rate of efficiency growth is most accentuated in NN and HO regions. OA capital region with highest synergy values possesses medium transmission power. By comparing results for synergy and transmission power at regional level, it is indicated that high synergy in U-I-G interaction does not necessarily imply the most efficient innovation system construct.

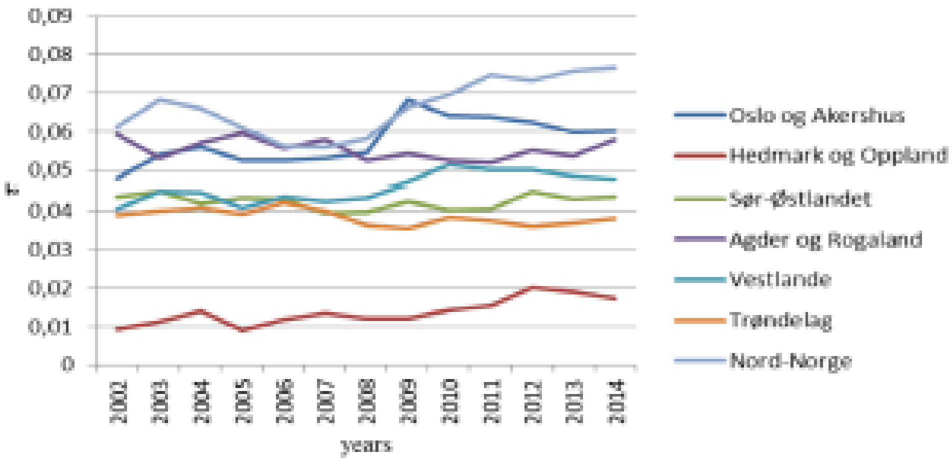

Fig.5: Transmission power τ for Norwegian regions, (in relative units) during the period 2002-2014.

Comparing the national level transmission power in Fig. 4 with the synergy in Fig. 2 shows slowly increased transmission power and accordingly increasing synergy over time. The dip in 2008 is more pronounced for static synergy data, than for the dynamic measure of transmission power. At the regional level, the same patterns are most pronounced in NN, HO, WE, and to some extent in SE. A decreasing value in transmission can be found in TR, whereas OA and NN show a more fluctuating development.

The percentage of the average efficiency deviation: $K = \frac{\tau_{iav} - \bar{\tau}_{iav}}{\bar{\tau}_{iav}} * 100\%$, where τ_{iav} is the efficiency for the *i*-th region averaged over the period 2002-2014; $\bar{\tau}_{iav}$ is the summary average efficiency averaged over all of the regions (Fig. 6), and the percentage of average synergy deviation $P = \frac{T_{iav} - \bar{T}_{iav}}{\bar{T}_{iav}} * 100\%$, where T_{iav} is the synergy for *i*-th county averaged over the period 2002-2014; and $\bar{T}_{iav}$ is the summary average synergy averaged over all of the regions (Fig.8).

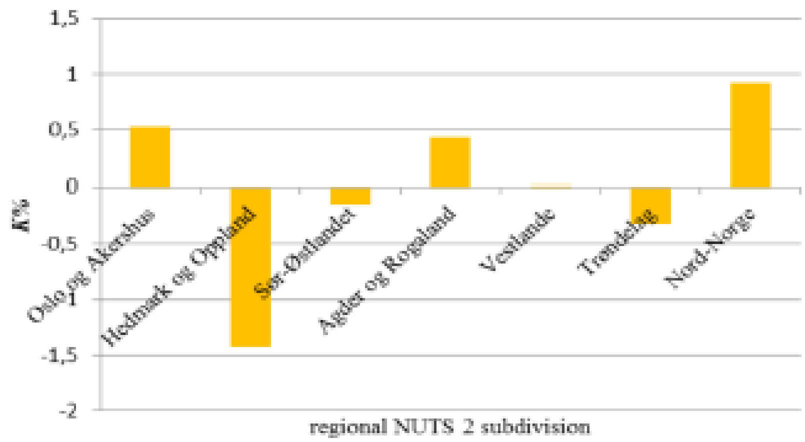

Fig. 6: Percentage of average efficiency deviation for the seven Norwegian regions during the period 2002-2014 (in percent)

Efficiency is above the country average in OA, NN and AR. Synergy is above average in OA, NN, WE. Comparing figures …., one can observe that the efficiency and synergy peaks do not coincide: regions with the highest synergy values are not always the most efficient. While for OA the above-average synergy value may indicate that the increase in synergy is caused by increased transmission power, in NN, on the contrary, relatively low synergy is accompanied by the highest value of efficiency. Spearman rank correlation between the percentages of synergy and the efficiency values is 0.64 (*n.s.*).

This value of Spearman rank correlation indicates that there is a monotonic dependence between the two variables. This sheds light on a need for more deep research of the parameters influencing innovation systems with respect to synergy-efficiency ratios.

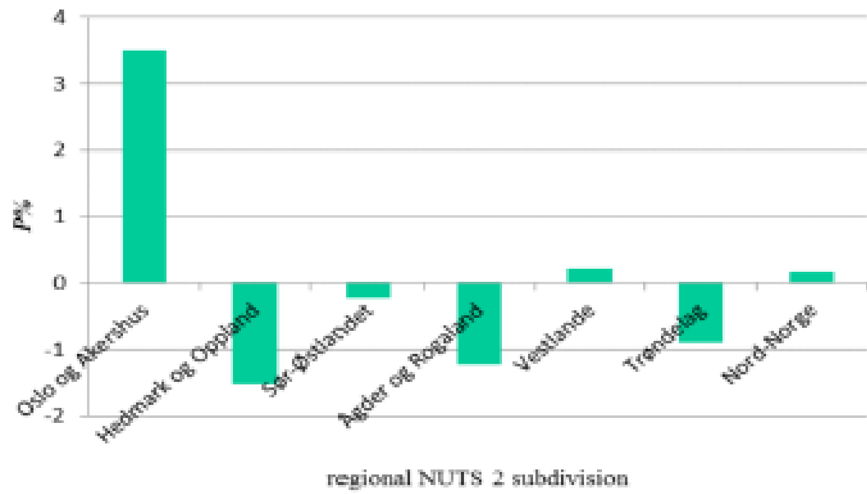

Fig. 7: Percentage of average synergy deviation for Norwegian regions during the period 2002-2014 (in percent)

As a next step, a deeper look into the structure of fluctuating behavior of the aggregate redundancy time series are taken. First the discrete Fourier transform is implement in accordance with Eq. (4). The inputs of different frequency modes to Norway's synergy (w, 2w, 3w, 4w, 5w, 6w, 7w), calculated according to Eq. (14), are shown in Fig. 9.

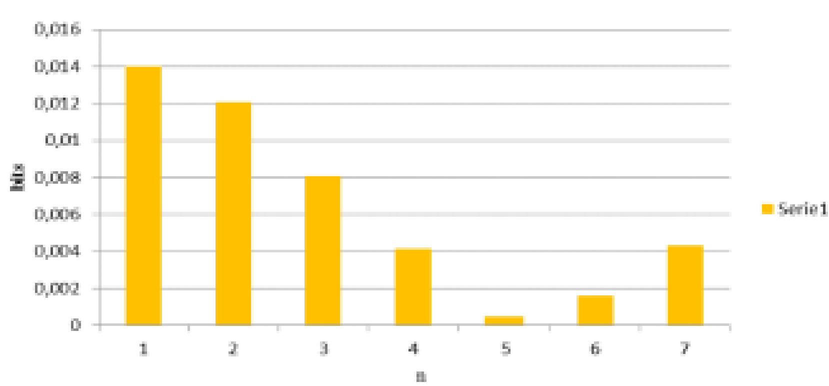

Fig. 8: Modules of Fourier series coefficients C versus frequency for summary ternary synergy at the national level (in bits of information)

Each of the regional synergies can be mapped as fluctuations around an average value. Thus, the average values can be taken as the first terms in the corresponding Fourier decomposition describing non-fluctuating terms (f_{0i} in Eq. (7)). These average values form the synergy line specter. Having calculated the modules of the Fourier series coefficients, which are the measures of different frequency modes, as well as the line specter synergy values, modules versus synergy values can be mapped. Because real-number data (during the period 2002-2014) are addressed, then, due to the symmetry of DFT coefficients, only half the number of input data with different frequency components (the first six) can be specified. C1 corresponds to a 12-year cycle; C2 to a 6-year cycle, and similarly the seventh component (C7) corresponds to the 1-year cycle, which is the highest frequency that can be calculated with this method.

In Fig. 9 synergies (in bits of information) are plotted versus frequency amplitudes for the seven regions. It can be seen from the figure that the various Fourier components have very high values in Oslo and Akershus (OA), indicating that synergy does not possess strong cyclic components at the frequencies observed. Vestlandet (WE) is the region with second largest amplitudes for Fourier components. A similar pattern with high values for the component is also found for Sør-Østlandet (SE), Vestlander (WE), and Nord Norge (NN). Hedemark og Oppland (HO), Agder og Rogaland (AR), and Trøndelag (TR) have the least accentuated oscillation behavior. Nord-Norge (NN) in contrast with other six regions is the region with the most dominant second component. Nord-Norge, where fishing and related industries play a dominant role is exposed to fluctuations in the high frequency component.

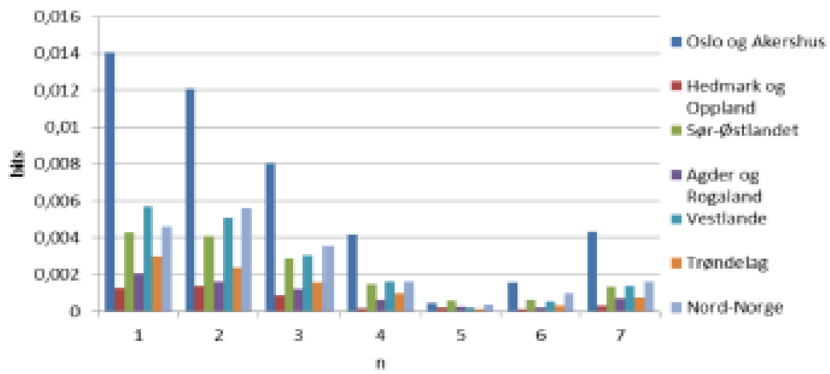

Fig. 9: Modules of Fourier series coefficients C versus frequency for seven Norwegian regions (in bits of information)

There is a monotone dependence between modules of Fourier coefficients and the percentage of average synergy deviations for Norwegian regions. The results of Spearman correlation between these two values are provided in Table 2. In other words, the more synergetic is the system, the more strongly are the fluctuations of synergy expressed.

Spearman Rank Correlation							
	C1	C2	C3	C4	C5	C6	C7
rho	1	0.964	0.964	0.964	0.321	0.893	0.964
2-sided p-value	0.0004	0.003	0.003	0.003	0.498	0.012	0.003
S	1.243	2.0	2.0	2.0	38	6.0	2.0

Table 2: Spearman correlation between percentage of average synergy deviation and modules of Fourier coefficients

Previous studies of business cycles have shown that the Krugman dissimilarity index may be used to explain cyclic variations in regions (Dixon and Shepherd 2013). Regions with high degree of similarity in the industry structure, which is indicated by a low Krugman index show similar cyclic patterns. The Krugman index as defined in Equation (14) is calculated, based on two-digit NACE codes and firm level data for 2015. The results are given in Table 3. As can be seen from this table, the capital region, Oslo and Akershus (OA), is most dissimilar to the other regions. The highest similarity (lowest index) is found between Vestlandet (WE) and Agder og Rogaland (AR), and between Sør-Østlandet (SE) and Agder og Rogaland (AR).

		OA	HO	SØ	AR	WE	TR	NN
		1	2	3	4	5	6	7
OA	1	0	0,634	0,410	0,427	0,443	0,469	0,520
HO	2	0,634	0	0,333	0,333	0,370	0,231	0,397
SØ	3	0,410	0,333	0	0,147	0,200	0,247	0,313
AR	4	0,427	0,370	0,147	0	0,124	0,216	0,284
WE	5	0,443	0,346	0,200	0,124	0	0,189	0,222
TR	6	0,469	0,231	0,247	0,216	0,189	0	0,275
NN	7	0,520	0,397	0,313	0,284	0,222	0,275	0

Table 3: Krugman index of dissimilarity in industry structure for Norwegian regions

The degree of synergy fluctuation randomness can also be evaluated using R/S analysis (Hurst, 1951; Feder, 1988). The standard algorithm and the calculation results are presented in the Appendix A. The Hurst rescaled range statistical measure H values in the range $0.5 < H < 1$ indicate a persistent or trend-like behavior described by monotone function. $H = 0.5$ corresponds to a completely chaotic time series behavior, like that of Brownian noise. Values in the range $0 < H < 0.5$ indicate anti-persistent or oscillating behavior. The obtained Hurst exponent value, in our case $H = 0.31$, is well below 0.5 indicating a strongly expressed oscillating time series behavior. That is, the system-generated synergy evolves over time as non-chaotic cycles (similar to long-term and business cycles).

Summary and Conclusions

Having studied TH synergy evolution the following conclusions can be derived: first, TH synergy shows non-chaotic oscillatory behavior. That is, one can study 'synergy cycles' in analogy to economic and technological cycles. Second, TH systems can be considered to be composed of a set of oscillatory modes, in terms of high and low frequency oscillations; from a theoretical perspective, TH systems are expected to have only a single oscillatory mode. The finding of a set of modes implies a complex TH structure, composed of many 'elementary' helices, which can be theorized in terms of a fractal TH structure (Carayannis and Champbell ,2009; Ivanova and Leydesdorff, 2014a). Third, oscillation amplitudes were found to be proportional to average synergy values. Thus, the synergy oscillations can be scaled with respect to the average synergies of TH constituent components. In summary, the TH structure (at the level of regions and nations) may be more complex than expected.

Three different techniques for the numerical evaluation of temporal synergy evolution in a three-dimensional system are used: *R/S* analysis, *DFT*, and geographical synergy decomposition. Briefly summarizing the results obtained from the study of the Norwegian innovation system, we can conclude that the synergy time series exhibits cyclic structures of a non-random nature. This is important from the perspective that synergy oscillations can be caused, in part, by system-inherent factors, and, in part, by external systemic factors. This feature should be taken into consideration by policy makers when developing related policies for innovation in areas under their sphere of competence, given that innovation efficiency is both locally and globally determined. It is demonstrate how the various methods can be used for mapping evolution of synergy. However, longer time series and shorter sampling intervals would be preferable, even though it involves big amounts of register data. It would then be possible to link the indicated synergy cycles to other and more well-established business cycles through co-integration of the time series. This could shed new light the synergy control mechanisms in a TH innovation system.

From a conceptual perspective, the synergy in the TH innovation systems can be analyzed as a set of harmonic partials at the system's level, while an analytically "pure" TH system can be expected to contain only a single harmonic (Ivanova and Leydesdorff, 2014b). The appearance of many oscillatory modes indicates a more complex and self-organized TH structure than was traditionally thought. For example, Norway's national innovation system can be presented as a geographically distributed network with nodes relating to corresponding regions, and one should account for innovation systems at scales other than the national.

The synergy value is a monotonic function of frequency. Because the frequency values are also a proxy of the speed of change of the corresponding frequency-related transmission parts (and otherwise, a proxy of volatility), one can expect frequency-related synergy volatility growth proportional to the value of synergy. This is the case for both transmission increases and decreases. In other words, the synergy in more coherently interacting systems grows faster than that in less-coherent ones. In the case of decline, however, initially more coherent systems degrade faster. In other words, synergy formation is self-reinforcing, but so is its decay.

Policy implications

The relative contribution of long-term frequencies increases with the increase of synergy values leading to a frequency shift. In other words, one can expect the synergy volatility to increase with synergy growth. This means that regions with high synergy values are expected to exhibit more fluctuations in synergy than low-synergy regions, demonstrating strong range fluctuations in periods of boost or decline. Based on the various techniques used in this study, it would be possible to develop indicators to monitor the innovation systems' response to external shocks like the dramatic crack in the oil prices in 2015 and the structural effect of various political measures, like the Norwegian governments crisis interventions in the petroleum dependent region of Agder og Rogaland in 2016. Such indicators could guide government towards carefully considering both the timing, the regional setting, and the time-scale of political measures. Government interventions at national level could amplify or dampen out the synergy fluctuations dependent on the actual region. Governments' intervention in regions dominated by one industry sector can have unwanted effect if applied nationally or to regions with high industry activity. Regarding time scales, political measures should be design to create long term (low frequency) positive economically effects, rather than short time (high frequency) political effects.

Further research

Another result refers to the distinction between the synergy of interactions within a TH system and the system's efficiency. It may conclude that these two measures are statistically correlated though they capture different kinds of information. The study of factors influencing these two important features of innovation systems is a topic of future research.

This raises further research questions which are relevant to innovation studies. One can downscale the analysis from the region to firm-size level. on the assumption that the results remain the same, this may raise further research questions with respect to firm dynamics. According Gibrat's Law for all firms in a given sector, the growth of a firm (i.e. the proportional change in the firm size) is independent of its size (Gibrat, 1931). The studies of the number of firms relating to early 50^{th} confirmed Gibrat's law (Samuels, 1965). However one can expect a dependence between the firm's growth and its innovation capacity, which is proportional to synergy in interactions among the constituent actors. The actual functional relation between the firm's size and its innovation and growth capacities needs further investigation to complement what is already found in the literature with respect to the economics of innovation.

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Appendix A

The Hurst method is used to evaluate autocorrelations of the time series. It was first introduced by Hurst (1951) and was later widely used in fractal geometry (Feder, 1988). The essence of the method is as follows (Quan, Rasheed, 2004, p.2004):

For a given time series $(T_1, T_2, \ldots T_N\ )$, in our case, yearly ternary transmissions for a given time period, one can consistently perform the following steps:

a) calculate the mean m

$$m = \frac{1}{N}\sum_{i=1}^{N} T_i \tag{A1}$$

b) calculate mean adjusted time series:

$$Y_t = T_t - m \tag{A2}$$

c) form cumulative deviate time series:

$$Z_t = \sum_{i=1}^{t} Y_i \tag{A3}$$

d) calculate range time series:

$$R_t = \max(Z_1, Z_2, \ldots\ Z_t) - min(Z_1, Z_2, \ldots\ Z_t) \tag{A4}$$

e) calculate standard deviation time series:

$$S_t = \sqrt{\frac{1}{t}\sum_{i=1}^{t}(T_i - \overline{T}_t)^2} \tag{A5}$$

where

$$\overline{T}_t = \frac{1}{t}\sum_{i=1}^{t} T_i \tag{A6}$$

f) calculate rescaled range time series

$$\left({}^{R}\!/_{S}\right)_t = \frac{R_t}{S_t} \tag{A7}$$

in expressions (A2) - (A7) t=1,2…N. Under the supposition that

$$\left({}^{R}/_{S}\right)_t = Ct^H \tag{A8}$$

The Hurst exponent H can be calculated by rescaled range (R/S) analysis and defined as linear regression slope of ${}^{R}/_{S}$ vs. t in log-log scale. In our case H=0.0655 (Fig. A1).

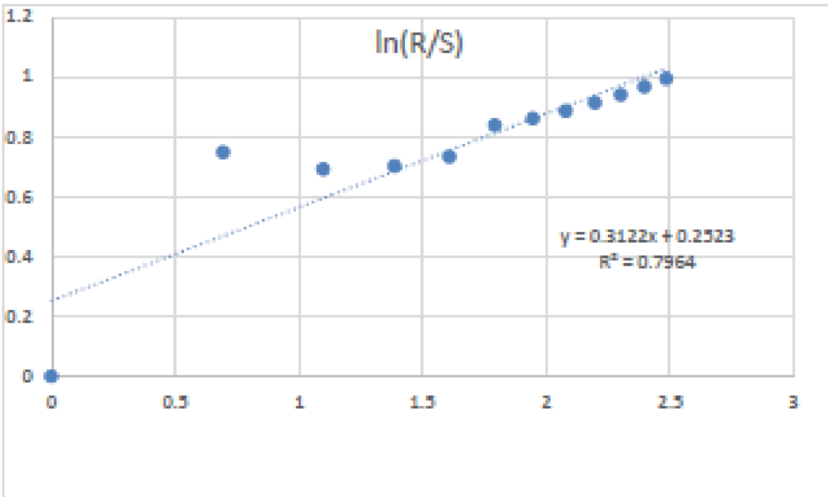

Fig. A1 R/S analysis for Norwegian synergy from 2002 to 2014

Values of H = 0.5 indicate a random time series, such as Brownian noise. Values in the interval 0 < H < 0.5 indicate anti-persistent time series in which high values are likely to be followed by low values. This tendency is more pronounced the closer the value of H comes to zero. That is, one can expect oscillating behavior. Values in the interval 0.5 < H < 1 indicate persistent time series. That is, the time series is likely to be monotonically increasing or decreasing. The case H=0.0655 corresponds to oscillatory behavior.

Appendix B

Table 1 Correspondence of high level aggregation to NACE Rev 1.1 and NACE Rev. 2 classifications (http://www.ine.es/daco/daco42/clasificaciones/cnae09/estructura_en.pdf)

<table>
<tr><th>High level aggregation</th><th>NACE Rev.2</th><th>NACE Rev.1.1</th></tr>
<tr><td>1

1-5;

74.14; 92.72</td><td>A 1, 2, 5; Agriculture, forestry and fishing
1; 2; 5;
74.14; 92.72;</td><td rowspan="3">A 01 Agriculture, hunting and related service activities
A 02 Forestry, logging and related service activities
A 05 Fishing, fish farming and related service activities</td></tr>
<tr><td rowspan="4">2

10-41;

01.13; 01.41; 02.01; 51.31; 51.34; 52.74; 72.50; 90.01; 90.02; 90.03</td><td>B 10-14 Mining and quarrying
10 -14</td></tr>
<tr><td>C 15-37 Manufacture
15 - 36;
01.13; 01.41; 02.01; 10.10; 10.20; 10.30; 51.31; 51.34; 52.74; 72.50;</td></tr>
<tr><td>D 40 Electricity, gas and steam
40;</td><td rowspan="5">B 10 Mining of coal and lignite, extraction of peat
B 11 Extraction of crude petroleum and natural gas, service activities incidental to oil and gas etc.
B 12 Mining of uranium and thorium ores
B 13 Mining of metal ores
B 14 Other mining and quarrying</td></tr>
<tr><td>E (+4) 41 Water supply, sewerage, waste
41; 37; 90
14.40; 23.30; 24.15; 37.10; 37.20; 40.11; 90.01; 90.02; 90.03</td></tr>
<tr><td>3 45;
20.30; 25.23; 28.11; 28.12; 29.22; 70.11;</td><td>F 45 Construction
45;
20.30; 25.23; 28.11; 28.12; 29.22; 70.11;</td></tr>
<tr><td rowspan="3">4 50-63;

11.10; 64.11; 64.12;</td><td>G 50-52 Wholesale and retail trade: repair of motor vehicles and motorcycles
50- 52;</td></tr>
<tr><td>H 60-63 Transportation and storage
60- 63;
11.10; 50.20; 64.11; 64.12;</td></tr>
<tr><td>I 55 Accommodation and food service activities
55;</td><td rowspan="3">C 15 Manufacture of food products and beverages
C 16 Manufacture of tobacco
C 17 Manufacture of textiles
C 18 Manufacture of wearing apparel, dressing and dyeing of fur
C 19 Tanning and dressing of leather, manufacture of luggage, handbags, saddlery, harness and footwear</td></tr>
<tr><td>5 64, 72;
22.11; 22.12; 22.13; 22.15; 22.22; 30.02; 92.11; 92.12; 92.13; 92.20;</td><td>J 64,72 Information and communication
64; 72;
22.11; 22.12; 22.13; 22.15; 22.22; 30.02; 92.11; 92.12; 92.13; 92.20;</td></tr>
<tr><td>6 65-67;</td><td>K 65-67 Financial and insurance activities</td></tr>
</table>

74.15;	65- 67; 74.15;	C 20 Manufacture of wood and of products of wood and cork, except furniture C 21 Manufacture of pulp, paper and paper products C 22 Publishing, printing and reproduction of recorded media C 23 Manufacture of coke, refined petroleum products and nuclear fuel C 24 Manufacture of chemicals and chemical products C 25 Manufacture of rubber and plastic products C 26 Manufacture of other non-metallic mineral products C 27 Manufacture of basic metals C 28 Manufacture of fabricated metal products, except machinery and equipment C 29 Manufacture of machinery and equipment n.e.c. C 30 Manufacture of office machinery and computers C 31 Manufacture of electrical machinery and apparatus n.e.c. C 32 Manufacture of radio, television and communication equipment and apparatus C 33 Manufacture of medical, precision and optical instruments, watches and clocks C 34 Manufacture of motor vehicles, trailers and semi-trailers C 35 Manufacture of other transport equipment C 36 Manufacture of furniture, manufacturing n.e.c.
7 70;	L 70 Real estate activities 70;	
8 71-74; 01.41; 05.01; 45.31; 63.30; 63.40; 64.11; 70.32; 75.12; 75.13; 85.20; 90.03; 92.32; 92.34; 92.40; 92.62; 92.72;	M (+10) 71,73 Professional, scientific and technical activities 73; 74; 05.01; 63.40; 85.20; 92.40;	
	N (-2) 74 Administrative and support service activities 71; 01.41; 45.31; 63.30; 64.11; 70.32; 74.50;74.87; 75.12; 75.13; 90.03; 92.32; 92.34; 92.62; 92.72;	
9 75-85; 63.22; 63.23; 74.14; 92.34; 92.62; 93.65;	O 75 Public administration and defense: compulsory social security 75;	
	P 80 Education 80; 63.22; 63.23; 74.14; 92.34; 92.62; 93.65;	
	Q 85, 90,91 Human health and social work activities 85; 75.21;	
10 92-99; 01.50;29.32; 32.20; 36.11; 36.12; 36.14; 52.71; 52.72; 52.73; 52.74; 72.50; 75.14; 91;	R 92 Arts, entertainment and recreation 92; 75.14;	
	S (+2) 93 Other service activities 93; 91; 01.50;29.32; 32.20; 36.11; 36.12; 36.14; 52.71; 52.72; 52.73; 52.74; 72.50;	
	T 95 Households as employers activities 95;	
	U 99 Extraterritorial organizations and bodies	
	Unspecified	C 37 Recycling

		D 40 Electricity, gas, steam and hot water supply
		E 41 Collection, purification and distribution of water
		F 45 Construction
		G 50 Sale, maintenance and repair of motor vehicles and motorcycles, retail sale of automotive fuel G 51 Wholesale trade and commission trade, except motor vehicles and motorcycles G 52 Retail trade, except motor vehicles and motorcycles, Repair of personal and household goods
		I 55 Hotels and restaurants
		H 60 Land transport, transport via pipelines H 61 Water transport H 62 Air transport H 63 Supporting and auxiliary transport activities, activities of travel agencies
		J 64 Post and telecommunications
		K 65 Financial intermediation, except insurance and pension funding
		K 66 Insurance and pension funding, except compulsory social security
		K 67 Activities auxiliary to financial intermediation
		L 70 Real estate activities
		M 71 Renting of machinery and equipment without operator and of personal and household goods
		J 72 Computers and related activities
		M 73 Research and development
		N 74 Other business activities
		O 75 Public administration

		and defense, compulsory social security
		P 80 Education
		Q 85 Health and social work
		Q 90 Sewage and refuse disposal, sanitation and similar activities
		Q 91 Activities of membership organizations n.e.c.
		R 92 Recreational, cultural and sporting activities
		S 93 Other service activities
		T 95 Activities of households with employed persons
		U 99 Extra-territorial organizations and bodies

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