Master Thesis – Master Innovation Sciences

The dynamics of the intellectual and social organization of the sciences

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Abstract

Knowledge production remains poorly understood. Especially research on organizational structures of knowledge fields and their dynamics lacks reliable knowledge gained through quantitative studies and compels actors to generalize policies. This exploratory and longitudinal study aimed to explore the structure dynamics of four emerging and four mature fields. It aimed to give answer to the question of how organizational structures of different knowledge fields change over time. All papers in every four years (1990, 1994, 1998, 2002, 2006, and 2010), during a 20 year time period, were collected (436.074 publications). Over 50 conventional and experimental indicators were placed in the framework of Whitley's organizational theory which focuses on the mutual dependency and task uncertainty of researchers. These two dimensions are further decomposed in their analytical counter parts: the functional dependence, strategic dependence, technical task uncertainty, and the strategic task uncertainty of researchers.

It is found that the structures of fields are different and that even the analytical parts within dimensions can greatly differ. Overall, it is concluded that mature fields are more stable in their topics and intellectual leaders, while showing higher rates of knowledge accumulation. Mature fields tend to operate under a higher functional and possibly strategic dependence while showing lower levels of technical and strategic task uncertainty. The absolute levels however, highly depend on the nature of the field. The 'big sciences' for example are mature fields characterized by a high mutual dependence and low task uncertainty. In contrast, a field like Applied Mathematics is mature, but is due to its nature low in its (strategic) mutual dependence. Arguably because it lacks the necessity to mobilize research resources as opposed to the 'big sciences'.

Lastly, additional non-maturity dynamics, are found for all fields which could imply dynamics bound to the time period of 1990-2010. The most striking trend concerns the intensification of research collaborations, the increasing institution citation inequality and institution ranking stability.

Ultimately the truth is likely to lay somewhere in the middle when returning to the research question. Yes, fields seem to be prone to a certain maturity dynamic in its organizational structure as discussed earlier, but its time period in which it finds itself and its nature highly influences the extend of this dynamic.

In conclusion, this paper has explored the dynamics of organizational structures of different fields and hoped, by doing so, to spark future scientific debates on how to further research this topic.

Keywords: organizational structure; knowledge fields; scientometrics; knowledge dynamics.

Content

Abstract 2
Introduction 5
Theory 7
- Introduction to Whitley's organizational structure 7
- Mutual dependency 7
- Task uncertainty 8
- Whitley's concept combination 9
- Organizational structure dynamics 10
- Dynamics implications 11

Method 13
- Research design 13
- Data collection and sampling strategy 13
- The empirical cases and context 14
- Operationalization 16
- Data analysis 22
- Research quality 22

Results 24
- Green & Sustainable Science & Technology 24
- Artificial Intelligence 33
- Nanotechnology 42
- Biotechnology 52
- Particle & Field Physics 62
- Applied Mathematics 71
- Astrophysics 79
- Organic Chemistry 88
- Field comparison 96

Conclusion 107
Discussion 108
- Limitations 108
- Theoretical contribution 108
- Practical contribution 110
- Future research 111

References 113
Appendices 117

LIST OF TABLES

TABLE 1: EXPECTED RELATIVE ORGANIZATIONAL STRUCTURE LEVELS 15
TABLE 2: OPERATIONALIZATION TABLE. FROM CONCEPTS TO QUANTITATIVE MEASUREMENT 17
TABLE 3: DESCRIPTIVE INDICATORS FOR GREEN & SUSTAINABLE SCIENCE & TECHNOLOGY 24
TABLE 4: RESULTS FUNCTIONAL DEPENDENCE GREEN & SUSTAINABLE SCIENCE & TECHNOLOGY 25
TABLE 5: RESULTS STRATEGIC DEPENDENCE GREEN & SUSTAINABLE SCIENCE & TECHNOLOGY 26
TABLE 6: RESULTS TECHNICAL TASK UNCERTAINTY GREEN & SUSTAINABLE SCIENCE & TECHNOLOGY 29
TABLE 7: RESULTS STRATEGIC TASK UNCERTAINTY GREEN & SUSTAINABLE SCIENCE & TECHNOLOGY 31
TABLE 8: DESCRIPTIVE RESULTS ARTIFICIAL INTELLIGENCE 33
TABLE 9: RESULTS FUNCTIONAL DEPENDENCE ARTIFICIAL INTELLIGENCE 34
TABLE 10: RESULTS STRATEGIC DEPENDENCE ARTIFICIAL INTELLIGENCE 35
TABLE 11: RESULTS STRATEGIC TASK UNCERTAINTY ARTIFICIAL INTELLIGENCE 39
TABLE 12: DESCRIPTIVE RESULTS NANOTECHNOLOGY 42
TABLE 13: RESULTS FUNCTIONAL DEPENDENCE NANOTECHNOLOGY 43
TABLE 14: RESULTS STRATEGIC DEPENDENCE NANOTECHNOLOGY 44
TABLE 15: RESULTS TECHNICAL TASK UNCERTAINTY NANOTECHNOLOGY 47
TABLE 16: RESULTS STRATEGIC TASK UNCERTAINTY NANOTECHNOLOGY 50
TABLE 17: DESCRIPTIVE RESULTS BIOTECHNOLOGY 52
TABLE 18: RESULTS FUNCTIONAL DEPENDENCE BIOTECHNOLOGY 53
TABLE 19: RESULTS STRATEGIC DEPENDENCE BIOTECHNOLOGY 54
TABLE 20: RESULTS TECHNICAL TASK UNCERTAINTY BIOTECHNOLOGY 56
TABLE 21: RESULTS STRATEGIC TASK UNCERTAINTY BIOTECHNOLOGY 59
TABLE 22: DESCRIPTIVE RESULTS PARTICLE & FIELD PHYSICS 62
TABLE 23: RESULTS FUNCTIONAL DEPENDENCE PARTICLE & FIELD PHYSICS 63
TABLE 24: RESULTS STRATEGIC DEPENDENCE PARTICLE & FIELD PHYSICS 64
TABLE 25: RESULTS TECHNICAL TASK UNCERTAINTY PARTICLE & FIELD PHYSICS 66
TABLE 26: RESULTS STRATEGIC TASK UNCERTAINTY PARTICLE & FIELD PHYSICS 69
TABLE 27: DESCRIPTIVE RESULTS APPLIED MATHEMATICS 71
TABLE 28: RESULTS FUNCTIONAL DEPENDENCE APPLIED MATHEMATICS 72
TABLE 29: RESULTS STRATEGIC DEPENDENCE APPLIED MATHEMATICS 73
TABLE 30: RESULTS TECHNICAL TASK UNCERTAINTY APPLIED MATHEMATICS 75
TABLE 31: RESULTS STRATEGIC TASK UNCERTAINTY APPLIED MATHEMATICS 77
TABLE 32: DESCRIPTIVE RESULTS ASTROPHYSICS 79
TABLE 33: RESULTS FUNCTIONAL DEPENDENCE ASTROPHYSICS 80
TABLE 34: RESULTS STRATEGIC DEPENDENCE ASTROPHYSICS 81
TABLE 35: RESULTS TECHNICAL TASK UNCERTAINTY ASTROPHYSICS 83
TABLE 36: RESULTS STRATEGIC TASK UNCERTAINTY ASTROPHYSICS 86
TABLE 37: DESCRIPTIVE RESULTS ORGANIC CHEMISTRY 88
TABLE 38: RESULTS FUNCTIONAL DEPENDENCE ORGANIC CHEMISTRY 89
TABLE 39: RESULTS STRATEGIC DEPENDENCE ORGANIC CHEMISTRY 90
TABLE 40: RESULTS TECHNICAL TASK UNCERTAINTY ORGANIC CHEMISTRY 92
TABLE 41: RESULTS STRATEGIC TASK UNCERTAINTY ORGANIC CHEMISTRY 94
TABLE 42: DIMENSION LEVELS PER FIELD AT BEGINNING OF PERIOD 104
TABLE 43: DIMENSION LEVELS PER FIELD AT END OF PERIOD 104

Introduction

Knowledge is increasingly recognized as one of the essential drivers for economic growth and solutions to societal challenges. Consequently, policymakers have shifted their focus on knowledge and the production hereof. The broader recognition of this phenomena has led to the term 'knowledge-based economy' (OECD, 1996). Nevertheless, knowledge production is complex and remains poorly understood (Bonaccorsi, 2008; Frickel & Gross, 2005; Heimeriks & Leydesdorff, 2012). Studies on knowledge production have shown that scientific fields often differ significantly in their dynamics and interaction with the socio-economic environment (Heimeriks & Leydesdorff, 2012). Differences present themselves among others in dissimilar knowledge production growth rates; degrees of divergence and level of complementarity (Heimeriks & Leydesdorff, 2012). This complexity compels policymakers to replicate best practices in research and innovation policy but this is expected to fail due to the limited generalization of scientific fields (Asheim et al., 2006).

Knowledge is constantly accumulating, diverging and evolving; occasionally resulting in new fields while others 'disappear'. Therefore focusing on static characteristic seems unwise while researching its dynamics offers promising prospects. Numerous existing studies have focused on different dynamics of knowledge production (Gibbons, 1994; Heimeriks & Boschma, 2013; Whitley, 1984) such as the modes of knowledge production; path- and place dependency and organizational structures. While researchers have focused mainly on the first two, the latter still lacks understanding. Whitley (1984; 2000) has provided a useful framework for grasping different characteristics of the organizational structure of knowledge production by using two dimensions: the *task uncertainty* and *mutual dependency* of researchers (Fry, 2006; Fry & Talja, 2007).

Task uncertainty refers to the uncertainty that research activities are not repetitive and predictable (Whitley, 1984, 2000). Fields differ in the role this uncertainty plays. For example highly cumulative fields with a shared agenda of important research topics are associated with a low task uncertainty. Subsequently, mutual dependency refers to the extent of interdependency of actors in order for them to significantly contribute to the scientific collective (Whitley, 1984, 2000). The dimensions and interaction of these in Whitley's framework have important implications. One of them is for example the legitimization coordination of expensive infrastructures. This is easier done for stable research fields that are of low task uncertainty and high mutual dependence such as the field of Astrophysics (Heimeriks & Balland, 2015).

Hence, Whitley's work is considered as a significant contribution but is insufficiently supported by reliable empirical data or other sources (Fry & Talja, 2007). As Randal Collings (1988) formulates it*: 'He (Whitley) cites the empirical studies of the various sciences only cursorily and in an impressionistic way, so it remains to be seen by more systematic comparisons to what extent the model holds up'* (pp. 295-296). Only few studies have explored whether Whitley's stationary theory holds up (Engwall, 1994; Fry & Talja, 2007; Giesbers, 2014; Heimeriks & Balland, 2015; Hoedemaekers, 2013; Lu, 1992). Furthermore, Whitley seems to fail to adequately deal with change in the organizational structure while some of his statements insinuate the awareness of the phenomena that he to a great extend neglects. Subsequently, it seems unlikely that fields are static in their mutual dependency and task uncertainty since contextual factors (e.g. technological change, the educational systems, etc.) most likely have influenced the degree hereof. The introduction of information and communication technologies (ICT), for example, influenced the global communication and coordination and therefore most likely the organizational structure of most intellectual organizations (Fry, 2004; Fry & Talja, 2007; Heimeriks & Vasileiadou, 2008).

Conclusively, there is little known about the organizational structure of knowledge fields, not to mention their dynamics over time. However, with the arrival of large databases of codified knowledge it is finally possible to quantitatively fill the knowledge gap as described above and more accurately research the dynamics of the organizational structure of knowledge production with less reliance on qualitative case studies. In contrast to most exploratory studies regarding this topic, this study has focused on the changes over time of a field's organizational structure instead of a less insightful static 'snapshot'. The aim of this study is thus to find out whether and how scientific fields differ and change in their organizational structure (mutual dependency & task uncertainty) over time. This leads up to the following research question:

How do organizational structures of different knowledge fields change over time?

In addition, a better understanding of Whitley's dimensions would not only add fundamental theoretical knowledge for the emerging knowledge field of the science of the sciences, which it is currently lacking. It would also practically aid agents in adequately coping with the dimensions to make knowledge production more fruitful. Stimulating collective research agendas, allocating resources, optimizing cognitive proximities, changing the reputational autonomy and changing the control of intellectual production are some of the tools that allow steering of knowledge production towards socially desirable goals (Whitley, 1984) which, for example, is crucial for the recently introduced, but popular, mission-oriented innovation policy framework (Goetheer, 2018; Mazzucato, 2017). The quantification and comparison of these dimensions is also shown to be important for strategic decision making regarding sustainable smart specialization of regions (Heimeriks & Balland, 2015) and maximizing the returns of public investments in science by (strategic) funding agencies (Braun, 1998) since it provides essential insights for these respectively. Just some of these insights concern for example the 'stability' of knowledge fields; the presence and influence of intellectual leaders; the need for intellectual conformity; the overall dependency of researchers and their uncertainty (Whitley, 1984, 2000) which can have tremendous implications for how fields react to science policies. This will be further elaborated in the theory section of this paper. The implications of this theory for the management of the sciences thus seem indisputably important, but the theory needs to be comprehensively validated and knowledge fields need to be better understood before one intervenes. Hence, this study aims to shed light upon the organizational structures of knowledge fields and how these change over time. This is expected to be fundamental for the understanding of the evolutionary process of the sciences.

This study has researched the dynamics of eight fields of which four are emerging domains (Nanotechnology, Biotechnology, Artificial Intelligence and Green & Sustainable Science & Technology) that show a high economic potential (OECD, 2005, 2017, 2018b, 2018a), and four mature and more traditional fields (Astrophysics, Organic Chemistry, Applied Mathematics and Particle & Field Physics) for comparison. This paper first elaborates in more detail what Whitley's theory of the organizational structure of the sciences entails. Subsequently, the theory section reflects on how this aligns with relevant literature; what sub questions are derived from this; and what some of the implications are of dynamic organizational structures. The method section then explains what research method fits this study and what the research encompassed. Lastly, the results and conclusions are described which are further reflected on in the discussion.

Theory

This theoretical section further elaborates on Whitley's theory of the organizational structure in the sciences. This study heavily relies on this, not only because of the mentioned knowledge gaps that strongly relate to his theory, but mostly due to the lack of any other suitable and overarching theory on the topic of organizational structures in the sciences.

First, Whitley's definition of the organizational structure will be explained. Subsequently, the dimension definitions of this structure will be given followed by defining its analytical aspects. Then this section will explain why its assumed that these concepts differ across fields and why these concepts are expected to change over time. Subsequently, a brief section is dedicated to emphasize the importance of validating and expending Whitley's theory by mentioning some few implications of this.

Introduction to Whitley's organizational structure

An organizational structure is a system that controls how activities are steered in order for it to achieve its collective goals. In the context of the sciences, it entails how scientific work is organized and controlled. Whitley argues that the sciences form a system of social actors that distinguishes itself from other professional organizations in mainly two aspects in its organizational structure. This concerns its 'reputational system' and the 'degree of personal autonomy' which both organize and control activities (Whitley, 1984).

The reputational system

Collectively researchers have formed an organizational structure which Whitley calls the 'reputational system'. It is a system that steers the researching actors, to a certain degree, into a 'desired' direction. Researchers seek higher reputations and for this have to convince prestigious colleagues of their competences in following standardized research methods and, in addition, convince them of their own research significance and relevance (Whitley, 1984, 2000).

The degree of personal autonomy

On the other hand Whitley points out that the organizational structure allows for a certain degree of personal autonomy of researchers. This autonomy is influenced by a combination of bureaucratic control and professional socialization which refers to the explicit and implicit hierarchy of the sciences. This is highly influenced by high-ranked researchers and their ability to mobilize material reward (e.g. financial resources and access to research instruments) and with this control over what work is done and how it is done (Whitley, 1984, 2000).

This abstraction of the organizational structure is simplified by further breaking this structure down into two dimensions; the mutual dependency of researchers (linked to the degree of personal autonomy) and the task uncertainty of researchers (linked to the reputational system).

Mutual dependency

As Whitley (1984) puts it: *'This dimension refers to scientists' dependence upon particular groups of colleagues to make competent contributions to collective intellectual goals and acquire prestigious reputations which lead to material rewards. Increasing the degree of mutual dependence implies that scientists become more reliant upon a particular group of colleagues for reputations and access to resources.' (pp. 87-88).*

The concept mutual dependency can be divided into two analytical aspects that are likely similar in their level. This is *the degree of functional dependence* which refers to the extent to which researchers have to adopt specific research results, processes and ideas of colleague specialists for them to form knowledge claims that are regarded as valuable and competent contributions. It refers to the presence of an elite intellectual group and their influence on the intellectual organization. The second analytical aspects concerns *the degree of strategic dependence* which describes the extent to which researchers have to persuade fellow researchers of the relevance and significance of their issue and approach in order for them to gain prestige. A higher degree of strategic dependence is here associated with a higher necessity to collaborate in order to mobilize a sufficient amount of resources (Whitley, 1984).

It is expected that the mutual dependency between researchers across fields differs. A 'big science' such as astrophysics for example relies heavily on unique and massive infrastructures like telescopes

(Price, 1963). A single actor is in most cases not able to fund these large research facilities (Nooijen, Rijnders-Nagle, & Zuijdam, 2013). Legitimizing these substantial expenditures (as an intellectual collective) to finance these instruments is therefore inevitable which implies a high degree of strategic dependence of researchers. Furthermore, the homogeneity of disciplines in astrophysics research groups is high, indicating that researchers have to 'fit in' intellectually. Hence, the degree of functional dependence is likely to be high too (Heidler, Jansen, & Görtz, 2010).

On the other hand, Applied Mathematics, is concerned with research which generally speaking is not bound to the necessity to collaborate or mobilize resources (Behrens & Luksch, 2011; Newman, 2004). This would imply a low strategic dependence. Subsequently, the field is characterized by an interdisciplinary nature, operating in a wide variety of other knowledge fields (Xie, Duan, Ouyang, & Zhang, 2015). This would imply that there is likely no single, stable and homogeneous group of intellectual elites. Which could imply a low functional dependence.

The comparison between Astrophysics and Applied Mathematics shows that a difference in the degree of mutual dependency between knowledge fields is likely. The assumption that fields can differ in their dependence is supported by exploratory studies regarding this phenomena (Giesbers, 2014; Heidler et al., 2010; Heimeriks & Balland, 2015) but still demands for further validation. Following Whitley's theory and above reasoning, it is expected that fields characterized by its expensive and scarce resources, centralized control and intellectual leader are associated with a high degree of mutual dependency. This difference in mutual dependency has never been comprehensively and quantitatively captured. Whitley's contribution (1984, 2000) would suggest that the functional dependencies should be measured by measuring hierarchies and the stabilities hereof. Collaborations for the sake of resource mobilization are likely to form a representative locus for the concept of strategic dependence. This leads up to the first sub question of this study:

SQ1: How can differences in mutual dependency characteristic levels between fields be quantitatively measured?

The method section of this paper will elaborate on the proposed quantitative indicators that are expected to capture the differences in mutual dependency characteristics.

If differences in the degree of mutual dependency between researchers across fields can be measured and shown to be present, then this has tremendous practical implications for the management of the sciences. The stimulation of collaborations through the deployment of broker agents; the organization of conferences; the establishment of research groups, research facilities and large research projects would be more necessary in some field than others. Overall, the role of centralized control within these fields through organizations and influential researchers is expected to be far more important than that of other fields (Frickel & Gross, 2005). A field accompanied with a high mutual dependency would very likely be forced to converge and agree on collective goals in order to function effectively. Fields with a low degree of mutual dependency are able to conduct research more independently and therefore more freely. This allows for the knowledge production to diverge and branch off (Hoedemaekers, 2013; Whitley, 1984, 2000).

Task uncertainty

In addition, Whitley (1984) describes task uncertainty as in that it is *'uncertain that the outcomes are not repetitious and highly predictable. Research however is highly methodical and systematic so that results are stable and replicable. Tacit knowledge however is hard to learn and can cause ambiguity.' (pp. 119-120).* A low task uncertainty is assumed to be associated with a formalization of control procedures, coordination of outcomes through pre-planned tasks and thus centralization of authority.

Just like mutual dependency, task uncertainty too can be divided into two analytical aspects. This is *the degree of technical task uncertainty* which refers to the extent that research techniques are uniformly understood and produce liable results in the field. A high degree of technical task uncertainty is associated with ambiguous interpretations and very tacit and personally bound knowledge. The other aspect of the task uncertainty dimension is *the degree of strategic task uncertainty*. This covers the uncertainty of research priorities, its significance and the favored way of addressing these priorities.

Furthermore, it encompasses the expected reputational reward of the research strategy and its impact on the collective (scientific) goals.

The degree of technical task uncertainty most likely differs in fields. A mature field like organic chemistry, for example, is standardized to a degree that research methods and procedures are found in textbooks and are strictly taught in the educational system to minimize ambiguity (Heimeriks & Balland, 2015; Whitley, 2000). Consequently, relatively young fields like artificial intelligence (<50 years) or ICT for Development research (<20 years), are much broader in their task technicality. These fields are still in disagreement on appropriate research methods (Islam & Grönlund, 2011; Pfeifer & Iida, 2003) and the educational programs are much more heterogeneous than that of organic chemistry.

Fields like astrophysics and nanotechnology are both associated with a high degree of strategic (mutual) dependency due to, among others, the importance of legitimization of substantial research expenditures (Heimeriks & Balland, 2015). However, the latter is rather heterogeneous in its topics (Bonaccorsi & Thoma, 2007; Giesbers, 2014) and is thus associated with a higher strategic task uncertainty. This could potentially be explained by the fact that nanotechnology has a higher variety of topics that can make a significant impact on collective goals like the economy and technological capabilities (OECD, 2009) or by the higher variety of knowledge users i.e. heterogeneous industrial entities. This implies that diversification is therefore more 'allowed' by the organizational structure than is the case in astrophysics. This example shows that fields most likely differ in their degree of strategic task uncertainty.

Consequently, the cases above indicate that a difference in the degree of the task uncertainty between fields is possibly present. This assumption is supported by the exploratory study of Heimeriks & Balland (2015) and Hoedemaekers (2013) but still demands for further validation. Following Whitley's theory and above reasoning, it is expected that fields characterized by a high technical task uncertainty will show heterogeneous knowledge bases and research techniques. A heterogeneous and unstable pool of research topics is expected to be found in strategic task uncertain fields. It leads up to the second sub question of this study:

SQ2: How can differences in task uncertainty characteristic levels between fields be quantitatively measured?

The method section of this paper will elaborate on the proposed quantitative indicators that are expected to capture the differences in task uncertainty characteristics.

If the presence of task uncertainty differences between fields can be measured then this has great implications. Task uncertain fields are more fluid in their research priorities and ways of conducting studies. This means that research topics possibly change faster, making it more risky for actors to specialize and invest in these fields (Heimeriks & Balland, 2015; Waardenaar, Tjerk, de Jong, & Hessels, 2014). Financing expensive research instruments might not provide the desired returns of investments due to a change of research priorities. The scientific (and societal) value of these instruments could diminish as soon as the intellectual organization has shifted its focus. In addition, task uncertain fields are associated with ambiguity, highly different educational programs and a more dominant role of tacit and local knowledge. Lacking a consensus regarding the research techniques causes a disagreement on the value of research and publications, making the expected reputational payoff for researcher uncertain as well (Joergers & Nowotny, 2003; Whitley, 1984, 2000). Connecting researchers and coming to a consensus could potentially stabilize the field, making strategic management decisions for the field less risky (Waardenaar et al., 2014; Whitley, 1984, 2000).

Whitley's concept combination

Whitley (1984, 2000) reasons that it is unlikely that both analytical aspects of both the dimensions, mutual dependency and task uncertainty, differ. This means that a high strategic dependence is likely to be accompanied with a high functional dependence while a high technical task uncertainty is likely to be accompanied with a high strategic task uncertainty within a knowledge field. This is due to their interrelated nature (Fry & Talja, 2007; Lu, 1992). However, some results have found that this is not always the case (Hoedemaekers, 2013) and therefore demands for more research. This leads up to our third sub question:

SQ3: To what extent can differences in analytical aspect levels of dimensions in knowledge fields be quantitatively identified?

Organizational structure dynamics

As discussed above, the degree of mutual dependency and task uncertainty is most likely bound to the characteristics of the organizational structure of the specific scientific fields. Therefore, it is likely that the dependencies and uncertainties change when this structure changes (Whitley, 1984, 2000). Thus, changes in the educational system; the emergence of new journals and the reallocation of resources are a few contextual changes that most likely have great implications on the intellectual organization.

Researchers like Whitley (1984), Pfeffer (1993), Hambrick & Chen (2008) recognized that the organizational structure influences the knowledge fields and vice versa. When fields mature and more resources need to be mobilized to conduct research effectively, then the degree of mutual dependency is likely to increase. The necessity for the presence of intellectual leaders and along with this, the necessity for centralized control grows to cope with this dependency. Their presence gives the field the opportunity to converge, create collective agendas and allocate resources more effectively. These leaders and centralized organization, in addition, possess the legitimate position to influence the educational system, academic positions, research standards and associated intellectual perspectives (Collins, 1998; Hoedemaekers, 2013) which means that this would decrease the task uncertainty on its turn. Pfeffer (1993) found that a decrease in technical uncertainty is beneficial for the growth of the intellectual organization, and that this growth, in return, furthermore decreases the technical uncertainty. A low degree of strategic task uncertainty is beneficial for the return of investments in science and therefor progresses the knowledge field and increases the chances on a successful research expenditure legitimization (Whitley, 1984, 2000).

From this reasoning described by Whitley (1984, 2000), it is assumed that novel fields tend to start off in a position with a low degree of mutual dependency, because researchers can easily operate independently to harvest the ‘low hanging fruits’, and high task uncertainty due to the, not yet, uniformly agreed upon research standards, methods, techniques and topic priorities. Mature fields (especially big sciences) are expected to find themselves in a high degree of mutual dependency and a low task uncertainty to maximize the organizational efficiency and chances on funding, and thus to mitigate research risks (Whitley, 1984, 2000). This risk averse transition is likely easier than a backward transition, since the organizational structure has become increasingly more stable and fixed over time.

However, reliable quantitative empirical data over a longer period of time to back this claim up is missing. Nevertheless, qualitative case studies have shown that fields can change in their organizational structural dimensions and their two respective analytical aspects (Frickel & Gross, 2005). Economics, for example, underwent a great shift in its technical task uncertainty when the field moved from a qualitative research approach to a quantitative one with the emergence of econometrics in the early 1970s (Diebold, 2001; Kishtainy, 2017). Political science radically changed in the 1960s when scholars increasingly more used uniformly agreed upon theories borrowed from the field of economics, consequently reducing the technical uncertainty as well (Pfeffer, 1993). Subsequently, astrophysics has shown that increasing research instruments expenditures have increased the degree of strategic mutual dependency (Nooijen et al., 2013).

In addition to these qualitative cases, it is probable that knowledge fields have changed in the last decades due to contextual factors e.g. globalization and the rise of new technologies. Especially ICT has most likely influenced the coordination of intellectual organizations and the (internal) communication hereof to a great extent. Not to mention, the effects of computing capabilities on (international) collaborations and research techniques and methods (Heimeriks & Vasileiadou, 2008). New technologies often offer new research opportunities. ICT has brought researchers many new fields like computer science, bibliometrics, and bioinformatics and new data collection, analysis and visualization methods (Flick, 2002; Heimeriks & Vasileiadou, 2008; Lenoir, 1999; Robertsen, 2003). Therefore, this increased the heterogeneity of research topics, strategies and methods resulting in a temporary increase in the task uncertainty (Heimeriks & Vasileiadou, 2008). Whitley’s theory assumes however, that fields need to lower their task uncertainty to function properly (Whitley, 1984, 2000). This reasoning implies that new fields are accompanied with a temporary increased task uncertainty, to only decrease this on its turn when the field becomes more standardized and controlled. Moreover, ICT has changed the reputational system through for example the emergence of large databases (e.g. WoS, Scopus and Google Scholar) which have increased the traceability and visibility of researchers, allowing for more feedback. This implies that ICT has had an influence on the (functional) mutual dependency of fields as well. This is thus just one example of a contextual factor that likely has changed the organizational structure characteristics of a range of knowledge fields.

This reasoning above, with the use of a variety of studies, implies the presence of some sort of maturity process in which mature fields operate under a higher mutual dependency and lower task uncertainty. In addition, contextual factors arguably also influence the organizational structure. Both assumptions lack reliable studies to back this up and therefor demand for a study on these dynamics. Currently however, the majority of scholars researching organizational structures of knowledge fields heavily, and often solely, rely on Whitley's theory although this is unjustified. Whitley's theory is based on mid-20th century qualitative cases while it neglected quantitative approaches. In addition, science generally speaking has obviously changed in many aspects. It is thus to be seen if his theory still holds up. If a maturity process is present, then it is expected that organizational structure characteristics of fields can change relative to each other; ergo these are symptoms of their maturity stage. Although broader contextual factors can also create relative differences – fields can react differently to policies for example – it is assumed that universal absolute differences in organizational structure characteristic metrics would be a more explicit symptom of this phenomenon. It is expected that clear absolute changes in characteristics can be identified for all fields due to the introduction of ICT, globalization or other overarching changes in the landscape. Research collaboration is one case that is anticipated to be affected by this contextual factor. It is thus reasonable to assume that one can measure these changes of the structure over time. This leads up to the fourth and fifth sub question of this study[1]:

SQ4: How have organizational structure characteristics of knowledge fields changed relative to each other over time?

SQ5: What universal absolute changes in the organizational structure characteristics can be identified throughout the time period?

Dynamics implications

Conclusively, structure dynamics have not been studied comprehensively enough but seem of great importance to actors in the intellectual organization. There are countless of theoretical and practical implications of these dynamics on all levels of the organization. This last section very briefly and superficially aims to touch upon a few of them, from an individual level to global level, to emphasize its importance.

From an individual perspective, this organizational dynamic implies that actors continuously frame their research topics, standards and methods to emphasize their importance and significance (Whitley, 1984, 2000). This mutual interaction between scholars, assuming the presence of structure dynamics, would result in an organizational isomorphism which leads up to the diminishment of task uncertainties. This phenomenon could explain Bonaccorsi's (2008) findings, that suggest that emerging fields diverge to a greater extent than mature ones; it would be the organizational structure that allows/obstructs this diverging capability of a field. This puts the researching actor in an organizational paradox in which one strives for radical novel research with prestige as one of the goals, but in which the organizational structure steers the actor to low risk, reliable and incremental research. Thence, researching 'low hanging fruits' becomes the tendency of actors over time which on its turn could increase competition and thus greatly effects the individual actor.

In addition to this, the presence of dynamics in the organizational structure would make it possible to connect the currently stationary theory of Whitley with that of adjacent theories on transition or evolution. Especially the connection to the widely accepted evolutionary theory of Nelson & Winter (1982) would aid in better understanding the rationale behind the behavior of individual scholars. Especially a dynamic in the task uncertainty (research routines) would show that not only researchers would be inclined to adopt specific topics and research methods (inheritance), but that this isomorphism is accompanied with

[1] The difference between relative and absolute differences can be confusing. A visual and more elaborate explanation is given in appendix 9.

a degree of novelty in their routines (variation) to gain and increase their prestige and move higher up the intellectual hierarchy (selection).

Another evident example for which the understanding of the organizational structure is essential, is the educational system of knowledge institutions. Setting up new programs and designing their curriculum is highly influenced by the research standards and techniques (technical task uncertainty), the courses given (strategic task uncertainty), the extent to which students will have to learn to cooperate (strategic dependency) and the familiarization with work of leading scholars in the field (functional dependency). In addition, structure dynamics will create a new rationale for ever changing educational curricula.

Moreover, it is likely that not only scholars and knowledge institutions are effected by their organizational structure. Knowledge regions (e.g. science parks) are constantly faced with the knowledge specialization/generalization dilemma. But the success hereof is, as Heimeriks & Balland (2015) showed co-dependents on the organizational structure of the fields of interest. Knowledge fields that are stable in their author/institution/topic ranking are harder to enter for newcomers. Turbulent fields however, offer opportunities for institutions and authors just like emerging markets do for businesses in economics. Better understanding this phenomenon would thus practically aid actors involved in the management of the sciences or innovation/science policy to make better grounded decisions.

Furthermore, a use case for which the understanding of dynamics is important is that for the return of investment in the sciences from a governmental perspective. Nations are ever faced with the investment dilemma especially between costly and (assumingly) very mutually dependent fields e.g. Nanotechnology and Biotechnology. Although many aspect co-determine the investment, it should be considered that highly mutually dependent fields with a low task uncertainty are characterized by a more uniformly agreed upon research agenda with more stable research topics and priorities. These fields are thus associated with a lower risk than mutually dependent fields with high task uncertainties (Whitley, 1984, 2000). Thus, understanding the structure of fields helps in identifying and estimating the risk of highly (economically) relevant investment opportunities, and on its turn, aids in maximizing the returns of investment.

Lastly, on a global scale, many scholars, policy makers and industrial actors have aimed to understand technological development. One of the most useful theories for this is the Technological Innovation System (TIS) (Hekkert, Suurs, Negro, Kuhlmann, & Smits, 2007). Knowledge development (F2) is herein acknowledge as an essential part of this development that one needs to comprehend in order to estimate the developmental state of a technology. However, knowledge production is largely seen as a black box and the framework only touches upon few superficial questions regarding this (Hekkert, Negro, Heimeriks, & Harmsen, 2011). However, it is implied that the knowledge development system, as part of the TIS, consist of actors, institutions and infrastructure that are likely to form a sub system of the larger TIS. The dynamics of this knowledge development system however are not yet explored and understood. It is likely that the organizational structure not only influences the institutions but also the abilities, interactions and roles of actors. A lower task uncertainty, for example, increases the intellectual conformity and thus is expected to make it harder for scholars to diverge in terms of topics, methods, techniques and standards. Therefore, this implies a changing window of opportunity for scholars to diverge and thus gives a new meaning to (institutional) entrepreneurship when placed in the context of the sciences. Subsequently, leading scholars are expected to defend their hierarchical position and are thus likely to take on the role of the incumbent. This implies that the understanding of the dynamics of organizational structures in the sciences would thus aid in further understanding this knowledge production system, especially regarding its actors and institutions and therefore add to the understanding of knowledge development in the context of technological development.

It subsequently seems apparent that all levels within the scientific system would benefit from a better understanding of the organizational structures and its dynamics. The method section explains how this phenomenon is captured and explored.

Method

Research design

This study aimed to capture empirical quantitative differences between knowledge fields in their organizational structure characteristics (i.e. mutual dependency and task uncertainty) and their changes over time. In contrast to most exploratory studies regarding this topic, this study focusses on the dynamics over time instead of a ‘snapshot’ of a fields organizational structure. Subsequently, this concerns a longitudinal quantitative publication analysis of specific codified knowledge fields. By doing so, this research gives a better and more reliable understanding of Whitley’s concepts, their analytical parts, their dynamics and how fields differ relative to each other. Its structure is exploratory and descriptive because it aims to find and describe a dynamical phenomenon that has not been fully captured before. To provide additional insight, this study will capture data of multiple knowledge fields to find whether rough differences and similarities in Whitley’s dimensions and dynamics can be found between knowledge fields. The unit of analysis is a scientific field e.g. Nanotechnology, Astrophysics, etc. wherein the research publication will be the unit of observation.

Data collection and sampling strategy

Data is collected from the Web of Science (WoS) which is a rich database containing codified knowledge. As mentioned earlier, this research will study the knowledge dynamics of eight research fields i.e. Astrophysics, Organic Chemistry, Applied Mathematics, Particle & Field Physics, Nanotechnology, Biotechnology, Artificial Intelligence and Green & Sustainable Science & Technology. The first four are classified as mature fields, while the latter are younger ones. Publication practices within and between fields are heterogeneous, therefore a clear delineation of knowledge fields, and thus the unit of analysis, is difficult. Subsequently, there is not a black and white border in which a field finds itself in (Hambrick & Chen, 2008).

Hence, a comprehensive publication sample size, representing a specific knowledge field as a whole, is created by means of purposive sampling. The WoS links publications to specific subject categories which can be used to demarcate knowledge fields. By doing so, irrelevant articles that are found in research field specific journals can be neglected while at the same time the categories are associated with less ambiguous interpretations than for example publication title words or keywords which can have a significant different meaning in different contexts. In addition, this method will provide more data than the journal central tendency method which focuses purely on the core journals (Leydesdorff & Cozzens, 1993). Therefore, less knowledge field central publications in less central journals are still incorporated in the data, thus giving a more comprehensive view on the branching of the field which is essential for capturing the (strategic) task uncertainty dynamics (Whitley, 1984, 2000).

Publications over a period of 20 years for all 8 fields can be collected to give insight in the dynamics. However collecting all publications in the last 20 years (2.313.542 publications) is not feasible due to the enormous quantity in combination with the 500 publication download limit of WoS. Therefore, the timeframe is moved to 1990-2010 to reduce the total quantity (1.500.826 publications) while still maintaining the 20 year time period. In addition, this time period is associated with influential contextual factors e.g. the emergence of the digital age and the increasing globalization, which should provide interesting dynamics for this study. To increase the feasibility of this study, publications are downloaded for every 4 years i.e. 1990, 1994, 1998, 2002, 2006, and 2010 (436.074 publications), consequently maintaining insights in the dynamics.

The empirical cases and context

As mentioned earlier, this study is interested in the maturity process of fields. Therefore a distinction is made between mature and emerging fields for the chosen knowledge fields of interest. Furthermore, the eight empirical cases for our operationalization have been selected based on the expectation that all emerging, and all mature fields, will as much as possible fall in different categories of Whitley's organizational structure's taxonomy (levels of mutual dependency versus task uncertainty). To increase the practical value of the results of this research, emerging fields with a high societal relevance are chosen (OECD, 2005, 2017, 2018b). This section will introduce the chosen empirical cases; elaborate its expected position in Whitley's structure taxonomy; and argue why it is believed they fall in the mature or emerging field category.

Green & Sustainable Science & Technology

Green & Sustainable Science & Technology, predominantly known as 'Cleantech', is an emerging field, originating approximately from the 90s (Caprotti, 2012). It is highly influenced by the private sector, subsequently operating in the context of application and making it a market-driven field (Caprotti, 2012). However, due to its societal necessity, it is in addition supported by governments (Caprotti, 2012; OECD, 2012; Weber, 2008). Hence, this provides a diverse range of funding resources (Hansen, 2015), making it presumably a low mutually dependent field since the financial necessity for collaboration is low. Private research and industry-university partnerships, in addition, reduce the influence of intellectual elites due to the differences in the reputational reward system; the emphasis of performance measurement lays less on publishing, and more on valorization and the effects on private R&D. Furthermore, the task uncertainty is expected to be high, since it is a diverse field with many technologies still competing for its dominance (Hansen & Coenen, 2015; Owusu & Asumadu-sarkodie, 2016).

Artificial Intelligence

The term Artificial Intelligence was first coined in 1959 and started to take form in the decades after (Kaplan & Haenlein, 2019). It is a field characterized by highly different perspectives, expectations and topics, making it a diverse field (Kaplan & Haenlein, 2019; Pfeifer & Iida, 2003; Tegmark, 2017). Subsequently, there is a broad audience ranging from economical, philosophical, political, military, and medical fields to many more, thus creating a diverse demand of knowledge (Höne, Perucica, Saveska, Hibbard, & Maciel, 2019; Kaplan & Haenlein, 2019). Research coordination through conferences and global agendas has been close to non-existing before 2017 (Höne et al., 2019; Tegmark, 2017). Hence it is assumed to be a field of a high task uncertainty. The necessity to collaborate is likely to be low since the field requires no great resources or facilities for its research. The lack of coordination; the broad audience and the low necessity to collaborate is most likely an indication of a low mutual dependency in the field.

Nanotechnology

Technology has continuously explored the limits of miniaturization, but the term Nanotechnology has presumably been coined first in 1974 in Taniguchi's work on ultra-precise machining (Selin, 2007) making it an emerging field. Nanotechnology is a high growth, diverse and interdisciplinary field with a relatively high amount of scholars (Heidler et al., 2010; Heimeriks & Balland, 2015) . It has a broad audience due to its diverse range of applications and topics (Selin, 2007). This indicates that the field is most likely high in its task uncertainty. Research on Nanotechnology often requires cleanrooms and special facilities (Giesbers, 2014; Heimeriks & Balland, 2015). In addition, its interdisciplinary nature most likely forces scholars to collaborate and mobilize knowledge. Hence, the mutual dependency of this field is expected to be high.

Biotechnology

The very roots of biotechnology were set in the 19th century with applications in the food sector, but the word biotechnology was only first used in 1917 (Thackray, 1998). However, contemporary biotechnology as we know it today, only came about with the establishment of the double helix model of DNA (1953); the discovery of mutations as the result of gene expressions (1961) and the development of the polymerase chain reaction (1985) (Hess & Rothaermel, 2016). Biotechnology is an interdisciplinary and diverse field that operates in the context of application (Bonaccorsi, 2008; Heimeriks & Balland, 2015). It contains many branches due to its broad potential usage and audience (Heimeriks & Leydesdorff, 2012). Furthermore, this diversification in topics; and the broad range of knowledge users indicate that the task uncertainty is probably high (Heimeriks & Balland, 2015). The research facilities are less scarce than that of the ‘big sciences’ but remain an essential requirement for research. Also, collaboration is, to a certain degree, necessary due to its interdisciplinary nature, which together indicates a medium mutual dependency (Lee, 2012). Therefore, the mutual dependency is likely medium in comparison to other fields.

Particle & Field Physics

Particle & Field Physics emerged in the early 20th century (Landua, 2010; Walter & Wolfendale, 2012). It is a field that requires advanced and expensive research instruments and facilities and is characterized by large collaborations (Luukkonen, Persson, & Sivertsen, 2019). It is therefore assumed that researchers are highly mutually dependent in this field. Particle & Field Physics is led by a clear collective research agenda, and is highly funded by governments (Irvine & Martin, 1985). Research priorities and the desired way of tackling scientific challenges is likely to be rather homogeneous. The reason for this is that research instruments are unique and require the collective mobilization of resources and expenditure legitimization. Following this reasoning, it is assumed that without a low task uncertainty, the field would probably not be productive since an insufficient level of consensus would be achieved to properly operate.

Applied Mathematics

Applied Mathematics is a mature and rather individualistic field where relatively few and small collaborations takes place (Behrens & Luksch, 2011; Newman, 2004). However, it is also characterized by its diversity and interdisciplinarity, showing strong overlaps with fields like chemistry and computer sciences (Xie et al., 2015) probably giving researchers an incentive, to a certain degree, to collaborate. Nevertheless, the low necessity to collaborate indicates that researchers can independently conduct research. Hence, the mutual dependency is expected to be low in this field. The diversity and interdisciplinarity of applied mathematics shows that there is a broad range of audiences and that branching is allowed in this field.

Astrophysics

Astrophysics is a highly monodisciplinary field with mere overlapping with particle physics (Heidler et al., 2010). In addition, it forms a highly ‘collective science’. Intense collaborations and a clear collective research agenda are apparent (Giesbers, 2014; Heidler et al., 2010). Research instruments and facilities are expensive and demand collaboration and collective legitimization of expenditures (Heimeriks & Balland, 2015). Governmental funding in this field is inevitable and therefore makes it a rather risk averse field (Price, 1963). This clear research agenda; risk-aversity, and monodisciplinary nature aid in creating a low task uncertainty. The inevitable collaborations, and the necessity of collective legitimization of actions and expenditures makes researchers highly mutually dependent.

Organic Chemistry

Organic Chemistry is a mature field dating back from the 19th/20th century (Sharif, 2016). It is characterized by its highly cumulative knowledge production and its relatively stable research topic patterns (Heimeriks & Balland, 2015). It is found to be a field in which researchers are relatively low mutually dependent and face low levels of task uncertainty (Heimeriks & Balland, 2015).

To conclude, the eight fields have been given an expected low/high score for their mutual dependency and task uncertainty as can be seen in Table 1.

Table 1: Expected relative organizational structure levels

Field	**Mutual Dependency**	**Task Uncertainty**
Green & Sustainable Science & Technology	Low	High
Artificial Intelligence	Low	High
Nanotechnology	High	High
Biotechnology	Medium	High
Particle & Field Physics	High	Low

Applied Mathematics	Low	Low
Astrophysics	High	Low
Organic Chemistry	Low	Low

Operationalization

This section elaborates on how variables are used to analyze the analytical aspects and their changes over time. This is done by briefly defining the analytical aspects again to, subsequently, then connect these with operationalized indicators. Due to the exploratory nature of this study and the fact that there is often no single scientometric indicator that forms a perfect representation of the concept, multiple indicators have been linked to some concepts of this study. Apart from the concepts of interest, this study will in addition examine more descriptive statistics (i.e. the organizational size, growth and publication output of the knowledge field) to gain a more holistic understanding of its dynamics over time. All indicators are summed up in Table 2.

Functional dependence

Researchers have to adopt specific research results, processes and ideas for them to form knowledge claims that are regarded as valuable and competent. It is high prestige colleagues that often greatly influence these organizational norms and determine where resources go. This is why the presence and influence of intellectual elites is emphasized by Whitley as an indicator for this analytical concept. However, there is still an ongoing debate on what defines prestige and high performance in the sciences. Citation count; the h-index; impact through valorization and alt-metrics are just some of the plausible answers (Aksnes, Langfeldt, & Wouters, 2019; Hirsch, 2005; Pan & Fortunato, 2014). Citations and the h-index are still the most popular metrics (Aksnes et al., 2019), however the latter is not possible to measure due to our limitations in the sampling strategy. Therefore, this study uses citation counts as the main measure for the identification of elite intellectual groups and thus the functional dependence.

Strategic dependence

Researchers have to persuade fellow researchers of the relevance and significance of their issue and approach in order to mobilize resources and ultimately gain prestige. Fields with a high strategic dependence are characterized by frequent and intensive collaborations due to the need for this mobilization of resources (funding, knowledge, instruments, etc.) (Whitley, 1984, 2000). Therefore, collaborations will be at the locus of this concept.

Technical task uncertainty

This is the extent that research techniques are uniformly understood and produce liable results in the field (Whitley, 1984, 2000). It is rather difficult to quantitatively measure whether this is the case. However, uniformly understood techniques most likely imply a similar knowledge base and thus a high cognitive proximity between researchers. Previous studies have quantitatively measured cognitive proximities and identified knowledge bases with the use of references and collaborations (Mustafee, Bessis, Taylor, & Sotiriadis, 2013; Saviotti, Felice, & Pavia, 2013). Although it is true that collaborations demand for a proximity of a degree that can be bridged, it does not insinuate a high proximity per definition. In practice, collaborations occur even when the cognitive distance is too great. They are just assumed to be less fruitful (Nooteboom & Stam, 2008). This is why references as a focus for this concept is preferred over collaborations.

Strategic task uncertainty

Strategic task uncertainty is the uncertainty of research priorities, its significance and the favored way of addressing these priorities. When there are few research topics that the field focusses on, then this implies a uniform course of research and consequently a low strategic task uncertainty (Whitley, 1984, 2000). This is why research topics, its homogeneity and stabilities are central to this analytical aspect.

Operationalization table

Table 2 elaborates on how the concepts and their description, as mentioned in the theory section, are translated to measures and indicators used for this study.

Table 2: Operationalization table. From concepts to quantitative measurement

Concept	Description	Measure	Score
Functional dependence	The extent to which researchers have to adopt specific research results, processes and ideas of colleague specialists for them to form knowledge claims that are regarded as valuable and competent contributions. This refers to the presence and influence of an elite intellectual group (Whitley, 1984).	The distribution of the citation count of authors, represents the (dis)balance of the influence authors have on the intellectual organization. The more skewed the author citation count, the greater the influence of an intellectual elite group on the intellectual organization as a whole (Cole, 1983). Interesting scores would be the variance; its inequality; its distribution and stability.	(ind. 1) The annual Std. deviation of the author citation count.
			(ind. 2) The Gini-index of the author citation count. The Gini-index is an wealth equality measure used in economics. In this study, it will be used for the distribution equality of citations.
			(ind. 3) The Gini-index of the fractionalized author citation count.
			(ind. 4) The fractionalized citation proportion of the 1% most cited authors of all citations.
			(ind. 5) The fractionalized citation proportion of the 10% most cited authors of all citations.
			(ind. 6) The fractionalized citation proportion of top 10 most cited authors of all citations.
		The distribution of the citation count of research institutes operating in a knowledge field form an indication of the degree of influence an entity has (UNESCO, 2010).	(ind. 7) The annual Std. deviation of the organizational citation count.
			(ind. 8) The Gini-index of the institution citation count.
			(ind. 9) The Gini-index of the fractionalized institution citation count.
			(ind. 10) The fractionalized citation proportion of top 10 most cited institutions of all citations.
		A stable ranking of the top 10 most cited institutions gives insight in the stability of the functional dependence (Heimeriks & Balland, 2015).	(ind. 11) The amount of institutions in the top 10 that has been in the top 10, 4 years ago.
		The proportion of papers in which a researcher takes on the lead role, indicates their collaborative dominance in the intellectual organization (Kumar & Kumar, 2008). Interesting scores would be the variance and its inequality.	(ind. 12) The annual Std. deviation of the dominance factor. The dominance factor is the proportion of amount of multi-authored papers of an author as first author to total amount of multi-authored papers of the author.
			(ind. 13) The Gini-Index of the authors dominance factor.
		An author collaboration network: a network where nodes are authors and	(ind. 14) the Gini-index of the author degree centrality. The author degree centrality gives

		links are co-authorships as the latter is one of the most well-documented forms of scientific collaboration (Glänzel & Schubert, 2004). It gives insight in the overall collaborations in the intellectual organization. Interesting scores are the degree centrality, betweenness centrality and authority score of authors.	insight in the amount of links authors have. It's exactly the inequality of this that helps understand the inequality in influence and therefore the functional dependence.
			(ind. 15) The annual Std. deviation of the authors degree centrality.
			(ind. 16)) the Gini-index of the author betweenness centrality. The betweenness centrality gives insight in the brokers position of authors. A brokers position is accompanied with a certain type of influence of authors. Therefor the inequality of this can give insight in the inequality of influence and therefore the functional dependence.
			(ind. 17) The annual Std. deviation of the authors betweenness centrality.
			(ind. 18) The Gini-index of the author authority score. The authority score of an author is high when it has many linkages (collaborations) to other authors with many linkages. A low score is associated with authors having little links with authors that have little links. It's the inequality that helps us understand the presences of an elite intellectual group.
			(ind. 19) The annual Std. deviation of the authors authority score.
		A stable citation ranking gives insight in the stability of the functional dependence (Heimeriks & Balland, 2015).	(ind. 20) The stability of the top 100 most cited authors. It is the amount of authors in the top 100, that were already in the top 100, 4 years ago.
			(ind. 21) The stability of the top 50 most cited institutions. It is the amount of institutions in the top 50, that were already in the top 50, 4 years ago.
Strategic dependence	The extent to which researchers have to persuade fellow researchers of the relevance and significance of their issue and approach in order for them to gain prestige. A high strategic	Co-author count: The reward system of the sciences is focused on the individual reputation. Collaboration is risky if not fruitful enough. Therefore, a higher author count implies a higher need to collaborate, and thus a higher strategic dependence (Al-aufi &	(ind. 22) The annual mean co-author count.

	dependence implies that researchers have to work together and mobilize resources (Whitley, 1984, 2000).	Lor, 2012; Birnholtz, 2006; Das, 2015)	
		The collaboration frequency: The reward system of the sciences is focused on the individual reputation. Collaboration is risky if not fruitful enough. Therefore, a higher frequency of collaborations in a field is associated with a higher strategic dependence.	(ind. 23) The annual collaboration coefficient. It represents the proportion of papers written in collaboration.
		Co-author count	(ind. 24) The Std. deviation of co-author count
			(ind. 25) The Gini-index of the co-author count.
		The connectivity of the field:	(ind. 26) The network degree centrality
			(ind. 27) The network density
Technical task uncertainty	The extent that research techniques are uniformly understood and produce liable results in the field (Whitley, 1984, 2000). This is strongly connected to the cognitive distance of researchers in the same field. When knowledge bases are similar, then the cognitive proximity must be high and consequently, the technical task uncertainty is low.	When papers are more knowledge/reference dense then authors rely more on each other's knowledge (Rodriguez-ulibarri, Lo, Sesma-sanchez, & Urrea-mico, 2014; Xhignesse & Osgood, 1967), which implies a more uniformly agreed upon set of standards, norms and claims.	(ind. 28) The mean amount of references per paper
		The lower the task uncertainty, the less text is likely to be needed to communicate theory, concepts and findings due to an established jargon.	(ind. 29) The mean amount of pages per paper.
		When papers are more knowledge/reference dense then authors rely more on each other's knowledge (Rodriguez-ulibarri et al., 2014; Xhignesse & Osgood, 1967), which implies a more uniformly agreed upon set of standards, norms and claims.	(ind. 30) The mean amount of references per page.
		Co-occurrence of references (knowledge bases): references used by authors form a good representative for their knowledge base (Aria & Cuccurullo, 2017). When the reference use in a field is similar, then the technical task uncertainty	(ind. 31) The proportion of the top 10 most used references of the total references count in the year. It is the proportion in which a highly influential reference returns in papers in the whole field. The proportions of the top 10 most used references are summed up to indicate the dominance of these references.

		is likely to be low (Engwall, 1994).	
		The higher the stability of the knowledge base, the lower the technical task uncertainty	(ind. 32) The stability of the top 10 most used references. It is the amount of references in top 10, that remains in the top 10 after 4 years.
		Co-occurrence of references: see measure of ind. 31	(ind. 33) The reference sum of the top 10 most used manuscripts divided by the total publication output of the field.
		Bibliographic coupling network analysis (Kessler, 1963): references used by authors form a good representative for their knowledge base (Aria & Cuccurullo, 2017). When the reference use in a field is similar, then the technical task uncertainty must be low (Engwall, 1994). Interesting indicators are the inequality and overall density of references-to-reference connectivity.	(ind. 34) The Gini-index of the reference degree centrality. A higher inequality shows a more dominant knowledge base in the field, therefore it should imply a lower technical task uncertainty.
			(ind. 35) The Std. deviation of the reference degree centrality
			(ind. 36) The overall network's degree centrality: A higher network's degree centrality implies a greater difference in influence between knowledge bases.
			(ind. 37) The overall network density. A higher density points out a higher overall reference-to-reference connectivity, which could imply a more mature field.
		Citing behavior: When citing behavior is stable, then the technical task uncertainty should be low (Giesbers, 2014). When citing behavior is cumulative, the field is associated with a low technical task uncertainty (Heimeriks & Balland, 2015; Towne, Wise, & Winters, 2005). This is the case because fields with standardized methods can faster build forth on each other (Towne et al., 2005).	(ind. 38) the top 100 reference stability: the amount of references remaining in the top 100 after 4 years' time.
			(ind. 39) Citing half-life: The median year of cited references in a field. It represents the 'scientific front' of a field. The lower the citing half-life, the more novel the used knowledge is.
			(ind. 48) The citing mean-life. It is similar the citing half-life, but uses the mean value instead of the median.
			(ind. 51) the knowledge accumulation rate (KAR): see appendix 18. A lower score means a higher knowledge accumulation rate.
Strategic task uncertainty	The uncertainty of research priorities, its significance and the favored way of addressing these priorities. When there are a	Keyword words usage: This represents the topic priority of the research field. A proportionally high keyword count indicates a dominant research topic in the field (Heimeriks & Balland, 2015).	(ind. 40) The sum of the top 10 author keyword occurrence proportions. It indicates the extent to which the top 10 author keywords are dominant in the field.

<table>
<tr><td rowspan="9"></td><td rowspan="7">few research topics that the field focusses on, then this implies a uniform course of research and consequently a low strategic task uncertainty. Many different topics imply a disagreement on the relevant research priorities and thus imply a high strategic task uncertainty. Keywords form a good representation of the research topic (Al-aufi & Lor, 2012; Heimeriks & Leydesdorff, 2012)</td><td rowspan="3"></td><td>(ind. 41) The stability of the top 10 most used author keywords. It is the amount of keywords remaining in the top 10 after 4 years.</td></tr>
<tr><td>(ind. 42) The sum of the top 10 keyword plus occurrence proportions. It indicates the extent to which the top 10 keyword plus are dominant in the field.</td></tr>
<tr><td>(ind. 43) The stability of the top 10 most used keyword plus. It is the amount of keywords remaining in the top 10 after 4 years.</td></tr>
<tr><td rowspan="4">Keyword co-occurrence network: A network gives insight in the connectivity of certain keywords (topics) and how they relate to each other. A more skewed network, indicates a more directed field. Interesting indicators are the node degree centrality; the graph degree centrality and density</td><td>(ind. 44) The Gini-index of the author keyword node degree centrality.</td></tr>
<tr><td>(ind. 45) The Std. deviation of the node degree centrality.</td></tr>
<tr><td>(ind. 46) The network degree centrality</td></tr>
<tr><td>(ind. 47) The network density</td></tr>
<tr><td rowspan="2">The uncertainty of research priorities, its significance and the favored way of addressing these priorities.</td><td rowspan="2">Keyword words usage: This represents the topic priority of the research field. When highly stable, the uncertainty must be low.</td><td>(ind. 49) The stability of the top 100 keyword plus tags. It is the amount of tags that remain in the top 100 after 4 years.</td></tr>
<tr><td>(ind. 50) The stability of the top 100 author keywords. It is the amount of keywords that remain in the top 100 after 4 years.</td></tr>
<tr><td>Size of the intellectual organization (descriptive)</td><td>The size of a knowledge field in terms of human capital.</td><td>Amount of authors</td><td>Annual author count</td></tr>
<tr><td>Organizational growth rate (descriptive)</td><td>The growth of the intellectual organization in terms of human capital</td><td>Growth rate in amount of authors</td><td>Proportional author count growth in percentages</td></tr>
<tr><td>Scientific output (descriptive)</td><td>The scientific output of a knowledge field.</td><td>The amount of publications</td><td>Annual publication count</td></tr>
<tr><td>Output growth rate (descriptive)</td><td>The growth of the scientific output of a knowledge field</td><td>Growth rate in amount of publication</td><td>Proportional publication count growth in percentages</td></tr>
</table>

Data analysis

The collected data is analyzed in the software program 'R' with the help of its 'bibliometrix' package. This software and package aids in converting and analyzing publications with standard data science functions. Publications are analyzed per year. Due to the size of the sample, it is not feasible to fully harmonize the data. However, integrated features of the bilbiometrix package will help with cleaning importing the data. Descriptive statistics will be computed per field and per year to provide additional insight. These include the number of publications, the number of authors and the growth rate of the these. Subsequently, the data per field and per year is analyzed on the measures as mentioned in the operationalization table above. These represent Whitley's analytical dimensions of interest and, when aggregated, form patterns over time. Data points include among others the author names, keywords and references. These measures are then visualized in graphs so that patterns and differences over time are clearly visible. Due to the exploratory nature of this research, it is unclear what indicator is more valuable than others. Hence, it is unclear what the right method is to aggregate indicators to a score for an analytical aspect. However, due to the fact that indicators fall under the same analytical aspects, it can be expected that there will be some degree of coherency in the scores. In addition, universal absolute trends and relative trends should be visible. This is why levels of the analytical aspects are estimated based on these relative trends.

Research quality

The following section elaborates on the reliability, internal validity, external validity and construct validity as quality indicators and how potential risks are mitigated.

Reliability

Reliability refers to the repeatability of the research (Bryman, 2008). This is partly insured by the fact that the data collection and analysis method of this research is transparent and quantitative. The R analysis code is available to the public via the website https://mjwiarda.wixsite.com/thesis. Hence, this allows researchers to copy the exact same method and gain a similar result. Converting results to conclusions is, however, more complex. The aggregation and interpretation of the indicators in the light of Whitley's theory has not been done before. Therefore, the conclusion from the results are prone to interpretations and hence a starter for scientific debates. This is why this study cannot emphasize enough, that the nature of this study is explorative and that it aims to open the scientific dialogue on this topic. Consequently, this study consciously, and rightfully so, does not claim complete reliability in the indicator aggregation process.

Internal validity

Internal validity is concerned with the causality between the dependent and independent variables (Bryman, 2008). This study does not aim to find a causal relationships. Therefore, internal validity is not relevant for this study.

External validity

External validity refers to whether the results of this study can be generalized to other research contexts (Bryman, 2008). Generalization of exact knowledge dynamics patterns to other fields seems unlikely since every knowledge field is unique. However, the potential capturing of the knowledge dynamics differences between fields could emphasize the necessity of this research. Ultimately, it is the lack of external validity that demands for better understanding of field specific dynamics.

Construct validity

Construct validity is concerned with the right operationalization of the to be measured concepts. Very little research has been done on the quantitative operationalization of Whitley's analytical aspects. However, existing literature has studied similar, if not identical, elements in other contexts. No indicator is assumed to be a perfect representation of the analytical concepts. However, construct validity is guaranteed as much as possible through the use of common scientometric indicators derived from peer reviewed papers. Some additional experimental indicators are added, but its epistemological nature is taken into account for its interpretation and reflected on in the discussion. Moreover, a more fruitful and in-depth insight can be derived from the data by using multiple indicators per concept. Furthermore, publication databases like the WoS do not form a perfect representation of the output of intellectual organizations as a whole since publications are not always uploaded. However, the WoS has a bigger dataset and more in-depth information than other databases e.g. Scopus (Kokol, 2018; Mongeon & Paul-hus, 2015). In addition, natural sciences, engineering and biomedical sciences are better represented than the social sciences, arts and humanities (Mongeon & Paul-hus, 2015). This is why this research focusses on the knowledge fields that fall in the first three categories. Lastly, English articles are better represented in the WoS than other languages (Li, Qiao, Li, & Jin, 2014). This study focuses on English articles so that keywords can be feasibly analyzed.

Results

In this section the results per empirical case are described and positioned in the conceptual framework of Whitley's organizational structure. Along this path, it is explored how every field performs in regards to their mutual dependency and task uncertainty levels. The aim hereof is to deep dive into specific knowledge fields and aggregate indicators to relative analytical aspect levels. Subsequently, this section will consequently compare fields to derive insights in the purpose of theory building (see p.96).

Green & Sustainable Science & Technology

This field has become an official WoS category as of 1994. Publication output has grown from 308 publications in 1994 to 2025 publications in 2010. The organizational size consisted of 525 active researchers in 1994 and has grown to a size of 6489 researchers. The annual organizational size and output size have seen annual growths and declines, but the field has seen a netto growth of 657% in its output size and a 1240% growth in its organizational size in the 16 years as can be seen in Table 3.

Table 3: Descriptive indicators for Green & Sustainable Science & Technology

Year	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Organizational Size	NA	NA	NA	NA	525	261	643	362	471	730
Size Growth (%)	NA	NA	NA	NA	NA	-50	146	-44	30	55
Output Size	NA	NA	NA	NA	308	131	335	175	246	348
Output Growth (%)	NA	NA	NA	NA	NA	-57	156	-48	41	41

Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Organizational Size	570	771	971	1280	1161	1701	1877	2884	4347	5448	6514
Size Growth (%)	-22	35	26	32	-9	47	10	54	51	25	20
Output Size	255	324	371	467	436	596	667	963	1402	1782	2025
Output Growth (%)	-27	27	15	26	-7	37	12	44	46	27	14

Functional Dependence

Table 4 show the quantitative results for the concept functional dependence in the field of Green & Sustainable Science & Technology. The field has witnessed an inverse U-shape in its author citation variance (ind. 1) over the time period. The variance increased until 2002 and then slowly decreased again. Regardless of this pattern, the field has become more egalitarian in terms of its author citation count, based on the author citation count Gini-index (ind. 2) which has decreased by approximately 0.15 in the 16 year time span. A similar trend is to be seen for the fractionalized citation count (ind. 3). In addition It can be seen that the proportion of citations in possession of the top 1% most cited authors (ind. 4) has dropped over time. The same can be noticed for the top 10% (ind. 5) and the top 10 most cited authors (ind. 6). Subsequently, the stability of the top 100 most cited authors (ind. 20) has been, and remained highly unstable, fluctuating between 0 and 5 authors remaining in the top 100 after 4 years. Regardless of these trends, the author citation count distribution was and remains highly skewed but no stable elite author group has been identified.

Green & Sustainable Science & Technology has seen mostly an increase in its institution citation standard deviation (ind. 7), showing a similar trend to the standard deviation of the author citation count. Although the institution's citation count variance has increased, the Gini-index (ind. 8) has decreased. It decreased less than that of the index for the authors. The same can be identified for the fractionalized Gini-index (ind. 9), both remaining higher than the indexes for authors in the end of the time period. The Gini-index of the institution fractionalized citation count has decreased, among other reasons, due to the decreasing proportion of citations in possession of the top 10 institutions (ind. 10). Their proportion has dropped from 20% (1994) of all citations, to 7.36% (2010). Nevertheless, the stabilities of the top 10 (ind. 11) and top 50 (ind. 21) most cited institutions have increased overtime with zero institutions remaining in the top 10 (1998, 2002) to 4 and 3 remaining in 2006 and 2010 respectively. Overall, the institution citation count distribution has become more egalitarian, but was and remains highly skewed.

The standard deviation of the authors dominance factor (ind. 12) has in general remained the same, while slight increases and decreases over time are apparent. Rises and declines in the author equality in terms of their dominance factor can be observed based on the author dominance factor Gini-index (ind. 13), but no clear pattern seems to present itself.

In addition, the results of the author collaboration network analysis show that the standard deviation of the authors degree centrality (ind. 15) has decreased, accompanied with the decrease of the Gini-index of the author degree centrality (ind. 14) implying that the amount of collaborations with unique fellow colleagues has become more egalitarian. The same cannot be concluded for the betweenness centrality of authors. The Gini-index (ind. 16) hereof is extremely high and stable, pointing out that the broker positions are highly unequal whilst the variance seems to have increased as well (ind. 17). The authority score of authors (ind. 18) was, similar to that of the betweenness centrality, immensely high and increased from 0.975 to 0.991 implying almost total inequality. This means that authors with a large collaboration network are connected with other authors that have a great network.

The relative high equality in author and institution (fractionalized) citation count; the instability of the most cited actors; and the equalitarian dominance factor show that the field is lacking stable intellectual elites. Therefore, the functional dependence is estimated to be low.

Table 4: Results functional dependence Green & Sustainable Science & Technology

Indicator	1	2	3	4	5	6	7	8	9	10
1990	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1994	14.8011	0.708163	0.724559	0.157029	0.562473	0.259416	19.8428	0.691923	0.700998	0.200531
1998	31.33223	0.63557	0.624204	0.123358	0.491749	0.231657	35.96055	0.643617	0.671737	0.378404
2002	104.5349	0.627768	0.631171	0.123011	0.496713	0.130224	136.9501	0.658472	0.667683	0.283267
2006	72.36312	0.571944	0.609555	0.118673	0.466177	0.078882	104.3021	0.618202	0.658877	0.170448
2010	62.81012	0.555946	0.576089	0.091194	0.424	0.020497	116.9927	0.617041	0.65244	0.072648

Indicator	11	12	13	14	15	16	17	18	19
1990	NA	NA	NA	NA	NA	NA	NA	NA	NA
1994	NA	0.152647	0.047088	0.485364	0.00306	0.98531	1E-05	0.975191	0.161261
1998	0	0.135626	0.039455	0.487828	0.004494	0.981882	2.05E-05	0.974656	0.127212
2002	0	0.151725	0.042787	0.400961	0.002961	0.987329	2.51E-05	0.980311	0.126733
2006	4	0.143347	0.040871	0.390588	0.001405	0.99284	5.72E-05	0.990565	0.081873
2010	3	0.199106	0.073697	0.436777	0.000946	0.983497	0.000187	0.991215	0.093226

Indicator	20	21
1990	NA	NA
1994	NA	NA
1998	4	4
2002	0	5
2006	3	8
2010	5	11

Strategic Dependence

Table 5 shows the quantitative indicators used for the concept strategic dependence in the field of Green & Sustainable Science & Technology. The field has seen a fundamental shift in the collaboration coefficient (ind. 23). Approximately 50% of all papers were written in collaboration in 1994 while this has risen to 91% in 2010. The mean co-author count (ind. 22) has increased in this period from 1.92 authors per paper to 3.66. The standard deviation (ind. 24) of this co-author count has grown from 1.21 in 1994 to 2.23 in 2010 while the inequality of the co-author count in the form of the Gini-index has decreased (ind. 25). The overall network degree centrality (ind. 26) and network density (ind. 27) in the field has witnessed an inverted U-shape.

When one observes the author collaboration network analysis (Figure 1) of the top 500 most cited authors, one can conclude that collaborations have intensified. Clusters became greater in size, decreasing the amount of different clusters in the network which implies increasingly more coherent collaborations over time.

Based on these results, it can be concluded that Green & Sustainable Science & Technology has seen an increase in its strategic dependence, forcing researchers to collaborate on a greater scale but that its dependence is still low to medium in comparison to other fields (see results of other fields).

Table 5: Results strategic dependence Green & Sustainable Science & Technology

Indicator	**22**	**23**	**24**	**25**	**26**	**27**
1990	NA	NA	NA	NA	NA	NA
1994	1.915584	0.496753	1.210439	0.31235	0.00797528	0.0034751
1998	2.097561	0.593496	1.333491	0.307689	0.02966978	0.00437277
2002	2.962264	0.797844	1.773279	0.300224	0.02653763	0.00335927
2006	3.116942	0.823089	1.840844	0.305496	0.00992659	0.00183183
2010	3.658765	0.91358	2.234212	0.284264	0.00953655	0.00074128

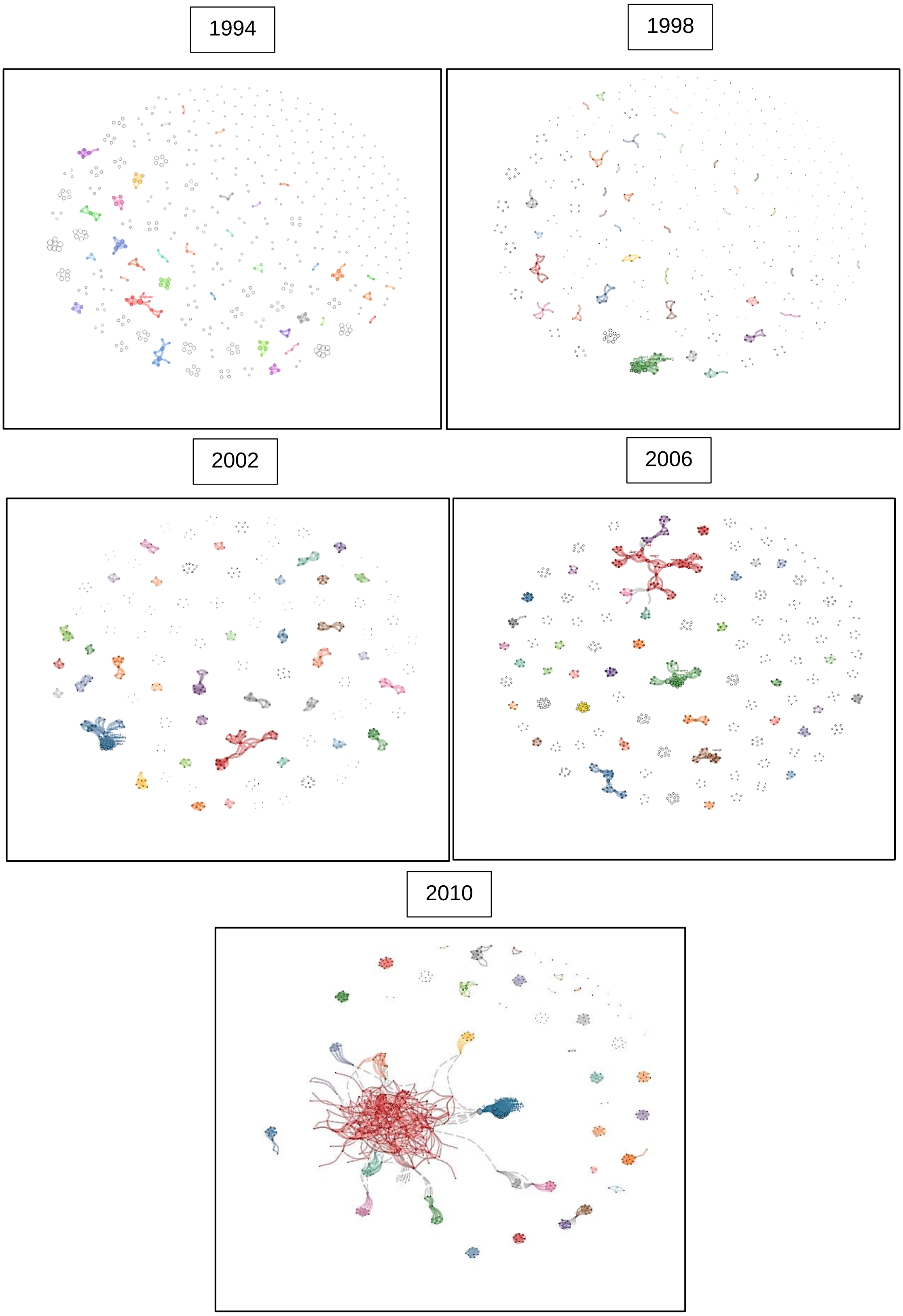

Figure 1: Author Collaboration Network (1994, 1998, 2002, 2006 & 2010) of Green & Sustainable Science & Technology. N= max. 500

Technical Task Uncertainty

By observing the indicators used for the concept technical task uncertainty, one can notice that the mean cited reference count (ind. 28) has risen greatly from 10.2 references per paper in 1994 to 33.6 in 2010. Papers have not only seen an increase in reference count, but also in mean page count (ind. 29), shifting from 5.96 pages to an average of 7.81 pages per paper. From these indicators one can conclude that papers became more reference dense based on the increase in mean reference per page (ind. 30) from 1.71 to 4.31.

The dominance of the top 10 references has fluctuated greatly based on the proportion of the top 10 most used references of the total references count per year (ind. 31). A similar trend is found when controlling for the publication output size of the field by dividing the sum of the top 10 most used references by the total publication output size (ind. 33). This instability is plausibly an explanation for the instability of the top 10 most used references (ind. 32), with 0 references of 1994 remaining in the top 10 in 1998 compared to the 6 of 2002 remaining in the top 10 in 2006. The references that did remain in the top 10 often remained there not only for 4 years but in most cases even 8. With influential references and therefor reoccurring manuscripts from Welton T. (1999), Anastas T. (1998), Duffie J.A. (1991) & Wasserscheid (2000). Although these have formed top level manuscripts, the authors (apart from Welton) have not reached the top 10 most cited author list of the field in one of the empirical years. The top 100 most used references stability (ind. 38) appears to be extremely high in some years, but its stability dropped greatly in 2010.

Based on a bibliographic coupling network of the field, it can be found that the inequality of the reference degree centrality (ind. 34) has gradually dropped, indicating that the equality of reference-to-reference connectivity has increased, while its standard deviation (ind. 35) fluctuated. The overall bibliographic coupling network's degree centrality (ind. 36) has undergone an inverted U-shape which has a similar dynamic as the network's density (ind. 37).

It has a stable citing half-life (ind. 39) of approximately 6 years, which would be relatively 'normal' in 1994 but relatively low in 2010 (see results of other fields and conclusion). Its citing mean life (ind. 48) appeared to be instable but maintained normal levels in comparison to other fields. The field shows an instable and low knowledge accumulation rate (ind. 51).

The bibliographic coupling networks of the top 500 most used references (Figure 2) show that the network and its clusters have gotten bigger in size. This in combination with the reference publication year spectroscopy (RPYS, see Appendix 1) shows an increase in reference usage, which implies that the knowledge base of the field has grown.

Ultimately, it is difficult to derive clear conclusions from empirical data regarding the technical task uncertainty of a field. However, the data shows that papers have become more reference dense although its density remains low; its bibliographic coupling network has grown in size and shows that clusters tend to become bigger in reference count although the reference base remains scattered; and the knowledge accumulation indicator shows that it is not a cumulative field. Therefore, the field is estimated to be high in its technical task uncertainty.

Table 6: Results technical task uncertainty Green & Sustainable Science & Technology

Indicator	**28**	**29**	**30**	**31**	**32**
1990	NA	NA	NA	NA	NA
1994	10.20238	5.961039	1.711511	0.198413	NA
1998	11.83256	6.410569	1.845789	0.125581	0
2002	21.95095	8.450135	2.597705	0.359673	1
2006	26.11429	9.583208	2.725004	0.18797	6
2010	33.63241	7.81023	4.3062	0.112154	3

Indicator	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**48**	**51**
1990	NA	NA	NA	NA	NA	NA	NA	NA	NA
1994	0.162338	0.8998527	0.00965257	0.05531114	0.00332078	NA	6	8.935455	NA
1998	0.087662	0.8992618	0.00459186	0.03517505	0.00155965	95	6	9.72758	0.5473033
2002	0.355795	0.8035481	0.02591214	0.09804764	0.01276317	49	7	10.256152	2.3124647
2006	0.187406	0.8241968	0.01171626	0.068432	0.00514157	90	6	9.396987	1.3646617
2010	0.112099	0.7137689	0.00664538	0.04608378	0.0038174	14	6	9.217161	2.9701451

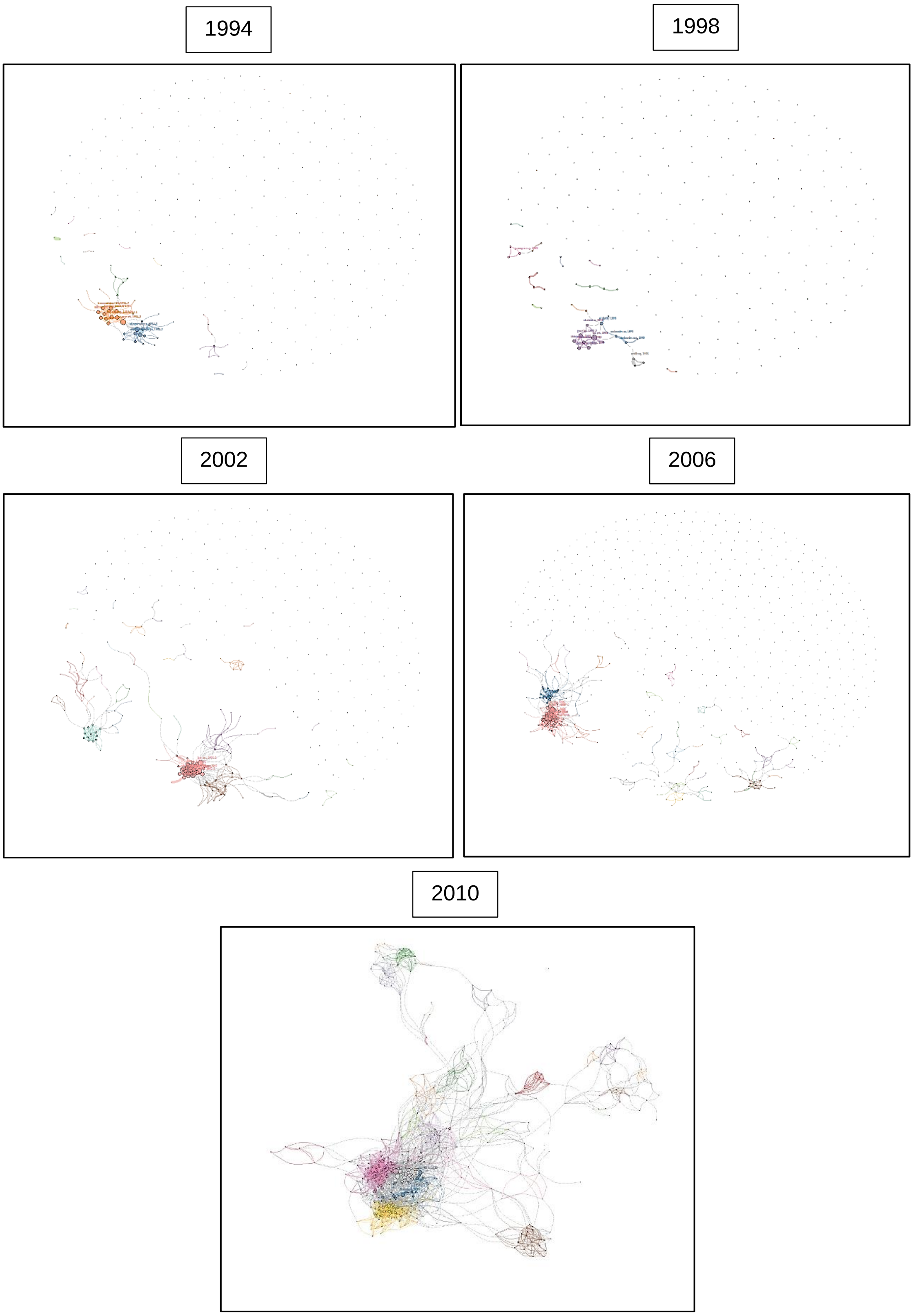

Figure 2: Bibliographic Coupling Network (1994, 1998, 2002, 2006 & 2010) of Green & Sustainable Science & Technology, N=500

Strategic Task Uncertainty

By exploring the indicators used for the concept strategic task uncertainty, one can gain a more comprehensive understanding of its nature in the field Green & Sustainable Science & Technology.

The field shows a diverging dynamic based on the sum of the proportional occurrence of the top 10 author keywords (ind. 40). The sum of their occurrence proportion reached 0.45 in 1994 but dropped to 0.27 in 2010. A similar dynamic is found for its keyword plus counter partner (ind. 42), which dropped from 0.55 to 0.38. The stability of the top 10 author keywords seemed to have slightly increased from 3 in 1994/1998 to 4 in 2006/2010 (ind. 41). Based on a closer look at the top 10 ranked author keywords, it can be concluded that the field shifted from a focus on renewable energy production (i.e. solar, wind, biomass) to a, what could be argued to be, a broader theme (i.e. sustainable development, industrial ecology, life cycle assessment, sustainability, climate change). The stability of the keyword plus top 10 ranking (ind. 43) is less stable, fluctuating between 1 and 6 stable keywords in the time period. Also here, one can notice a subtle change in content. 1994 focused on solar radiation, insolation, performance, alloy solar cells and systems, while 2010 shifted to water, management, design, removal and biomass. Similar patterns are found for title words (see Appendix 4). The top 100 author keyword (ind. 49) and keyword plus stability (ind. 50) has been tremendously low and remained low regardless of the increase in stability over time.

Based on the author keyword co-occurrences network, it is seen that the Gini-index author keyword node degree centrality (ind. 44) has decreased from 0.49 to 0.44. Meaning that the co-occurrences of author keywords has become more equal. The extent to which certain keywords dominate in their connectivity has thus decreased, making the field more dispersed. Its standard deviation (ind. 45) has shown an inverse U-shape, indicating that the variance initially increased but decreased again as of 2002. The overall degree centrality (ind. 46) and density (ind. 47) of the field has seen a similar trend, ultimately decreasing again but remaining higher in 2010 than in 1994.

Figure xx shows the annual author keyword co-occurrence network of the top 500 most used author keywords, which shows that the field became more mature. Clusters increase in size and become more connected with other clusters which indicates that isolated topics bond and form one field.

The results of the indicators clearly show that the field has dispersed in its topics with new topic clusters connecting to the core. In addition, the top 10/100 topic ranking is unstable and remains unstable. The degree centrality of keywords has become more equal, showing that the ‘direction’ of the field tends to become less clear. Therefore, it is concluded that the strategic task uncertainty is high and remains high in this field.

Table 7: Results strategic task uncertainty Green & Sustainable Science & Technology

Indicator	**39**	**40**	**41**	**42**	**43**	**44**
1994	6	0.446429	NA	0.547619	NA	0.4853636
1998	6	0.512195	3	0.58	3	0.4878275
2002	7	0.363057	3	0.349558	1	0.4009612
2006	6	0.323887	5	0.336658	2	0.3905877
2010	6	0.271636	4	0.378886	6	0.4367766

Indicator	**45**	**46**	**47**	**49**	**50**
1994	0.00305995	0.00797528	0.0034751	NA	NA
1998	0.00449373	0.02966978	0.00437277	27	14
2002	0.00296141	0.02653763	0.00335927	16	12
2006	0.00140461	0.00992659	0.00183183	24	44
2010	0.00094634	0.00953655	0.00074128	34	54

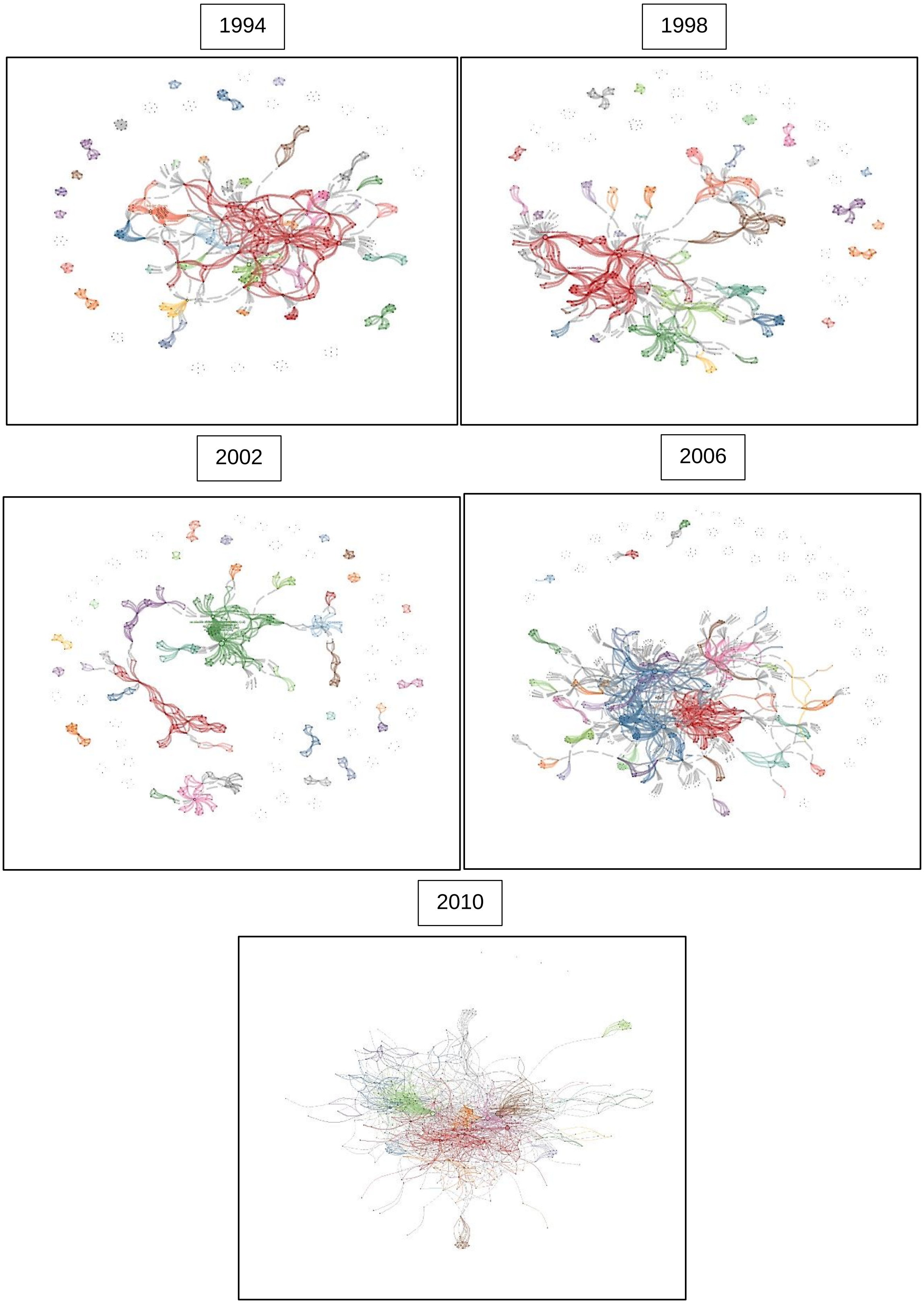

Figure 3: Author Keyword Co-occurrences Network (1994, 1998, 2002, 2006 & 2010) of Green & Sustainable Science & Technology. N= max.500

Artificial Intelligence

Artificial Intelligence has grown from 813 publications in 1990 to 8831 publications in 2010. The organizational size consisted of 1474 active researchers in 1990 and has grown to a size of 19095 researchers. The annual organizational size and output size have seen annual growths and declines, but the field has seen a netto growth of 1086% in output size and a 1295% growth in organizational size in the 20 year period as can be seen in Table 8.

Table 8: Descriptive results Artificial Intelligence

Year	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Organizational Size	1474	2526	3689	3681	4200	6495	6897	8444	8390	9876
Size Growth (%)		71	46	0	14	55	6	22	-1	18
Output Size	813	1421	1952	1957	2208	3442	3687	4531	4425	5019
Output Growth (%)		75	37	0	13	56	7	23	-2	13

Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Organizational Size	10696	10329	15623	19425	23143	27618	28595	14490	15618	17665	19095
Size Growth (%)	8	-3	51	24	19	19	4	-49	8	13	8
Output Size	5378	5298	7975	10384	12250	15910	16537	6582	7449	8623	8831
Output Growth (%)	7	-1	51	30	18	30	4	-60	13	16	2

Functional Dependence

Table 9 show the quantitative results for the concept functional dependence in the field of Artificial Intelligence. The field has roughly witnessed an inverse U-shape in its author citation variance (ind. 1) over the time period. The variance decreased between 1990 and 1994, but increased from 1994 until 2002 and then slowly decreased again. Regardless of this pattern, the field has become more egalitarian in terms of its author citation count, based on the author citation count Gini-index (ind. 2) which has decreased by approximately 0.082 in the 20 year time span. A similar trend is to be seen for the fractionalized citation count (ind. 3). In addition It can be seen that the proportion of citations in possession of the top 1% most cited authors (ind. 4) show a similar pattern as that of ind. 1. The proportion has briefly dropped between 1990 and 1994 but then increases until 2002 and decreases again. The same can be seen for the top 10% (ind. 5) and the top 10 most cited authors (ind. 6). Subsequently, the stability of the top 100 most cited authors (ind. 20) has been highly unstable but became progressively more stable, moving from 4 to 18 authors remaining in the top 100. Regardless of these trends, the author citation count distribution was and remains highly skewed.

Artificial Intelligence has seen the same pattern for its institution citation standard deviation (ind. 7); its institution's citation count Gini-index (ind. 8) and its fractionalized Gini-index (ind. 9). The Gini-index of the institution fractionalized citation count has shown this pattern, among other reasons, due to the proportion dynamics of citations in possession of the top 10 institutions (ind. 10). Their proportion has dropped from 32.6% (1990) to 18.7% (1994) and then shows the inverse U-shaped pattern ultimately dropping its proportion to a 8.7% of all citations (2010). Nonetheless, the stabilities of the top 10 (ind. 11) and top 50 (ind. 21) most cited institutions have been unstable overtime but did increase in their stabilities. Overall, the institution citation count distribution has become more egalitarian in 2010 in comparison to 1990, but was and remains highly skewed.

The standard deviation of the authors dominance factor (ind. 12) has shown a gradual increase. A continuous decline in the author equality in terms of their dominance factor can be observed based on the author dominance factor Gini-index (ind. 13). Authors have become, based on the index, almost 4 times as unequal in the collaboration dominance.

In addition, the results of the author collaboration network analysis show that the standard deviation of the authors degree centrality (ind. 15) has decreased but eventually stagnated. This is accompanied with a slight increase in the Gini-index of the author degree centrality (ind. 14) implying that the amount of collaborations with unique fellow colleagues has become slightly less equal. The Gini-index of the author betweenness centrality (ind. 16) is very high, pointing out that the broker position is highly unequal whilst the variance predominantly seems to have increased as well (ind. 17). The authority score of authors (ind. 18) was, similar to that of the betweenness centrality, immensely high due to its constant score of around 0.997 implying almost total inequality. This means that authors with a large collaboration network connect with other authors that have a great network.

Based on these results, it can be concluded that the field is highly unequal in its author and institution (fractionalized) citation count. The most cited institution and author rankings are turbulent implying no stable elite actor group, and its network indicator levels are 'normal' in comparison to other fields. This is why the functional dependence is estimated to be medium.

Table 9: Results functional dependence Artificial Intelligence

Indicator	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1990	271.6718	0.800203	0.822013	0.341785	0.725404	0.306497	434.4724	0.804647	0.822703	0.326284
1994	128.5727	0.789207	0.806911	0.296643	0.705739	0.1294	198.1788	0.789946	0.807118	0.187222
1998	206.8194	0.790044	0.809125	0.357341	0.715551	0.137187	421.6996	0.816063	0.827874	0.207619
2002	307.3597	0.827296	0.835369	0.39525	0.744256	0.118545	565.511	0.841511	0.85351	0.217659
2006	126.9853	0.790757	0.809305	0.326974	0.702243	0.083697	348.366	0.834421	0.850745	0.157942
2010	137.0321	0.718106	0.731221	0.26069	0.619482	0.050082	343.9195	0.78894	0.798196	0.087161

Indicator	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
1990	NA	0.127939	0.032366	0.403305	0.000909	0.976954	1.99E-06	0.994569	0.077927
1994	0	0.149054	0.043676	0.392947	0.000341	0.975447	3.82E-07	0.998329	0.043659
1998	1	0.195114	0.076492	0.420066	0.00026	0.972121	5.6E-07	0.998039	0.042793
2002	1	0.210972	0.09024	0.446011	0.000281	0.991619	7.9E-05	0.995997	0.06331
2006	0	0.267687	0.14853	0.473302	0.000239	0.963177	0.000288	0.985577	0.036046
2010	3	0.23975	0.113903	0.446916	0.000283	0.972168	0.000237	0.997047	0.036513

Indicator	**20**	**21**
1990	NA	NA
1994	4	13
1998	9	14
2002	6	18
2006	8	24
2010	18	20

Strategic Dependence

Table 10 shows the quantitative indicators used for the concept strategic dependence in the field of Artificial Intelligence. The field has seen a great shift in the collaboration coefficient (ind. 23). Approximately 70% of all papers were written in collaboration in 1990 while this has risen to 89% in 2010. The mean co-author count (ind. 22) has increased in this period from 2.07 authors per paper to 2.98. The standard deviation (ind. 24) of this co-author count has grown from 0.98 in 1990 to 1.49 in 2010 while the inequality of the co-author count in the form of the Gini-index has roughly remained the same (ind. 25). The overall network degree centrality (ind. 26) has increased while the network density (ind. 27) in the field has witnessed a decrease.

When one observes the author collaboration network analysis (Figure 4) of the top 500 most cited authors, one can roughly conclude that collaborations have intensified. Clusters, predominantly, became greater in size, decreasing the amount of different clusters in the network's core which implies increasingly more coherent collaborations over time.

Based on these results, it can be concluded that Artificial Intelligence has seen an increase in its strategic dependence, forcing researchers to collaborate on a greater scale but was and remains on a low level.

Table 10: Results strategic dependence Artificial Intelligence

Indicator	**22**	**23**	**24**	**25**	**26**	**27**
1990	2.066421	0.696187	0.982866	0.2437	0.00565125	0.00113762
1994	2.182971	0.721467	1.081223	0.255262	0.00193358	0.00045363
1998	2.385537	0.776045	1.274868	0.2606	0.00254882	0.00028706
2002	2.576677	0.809906	1.489317	0.26474	0.00416668	0.00019062
2006	2.864607	0.879603	1.370473	0.242503	0.00774033	0.0001433
2010	2.980523	0.890726	1.491791	0.248355	0.00751095	0.00020846

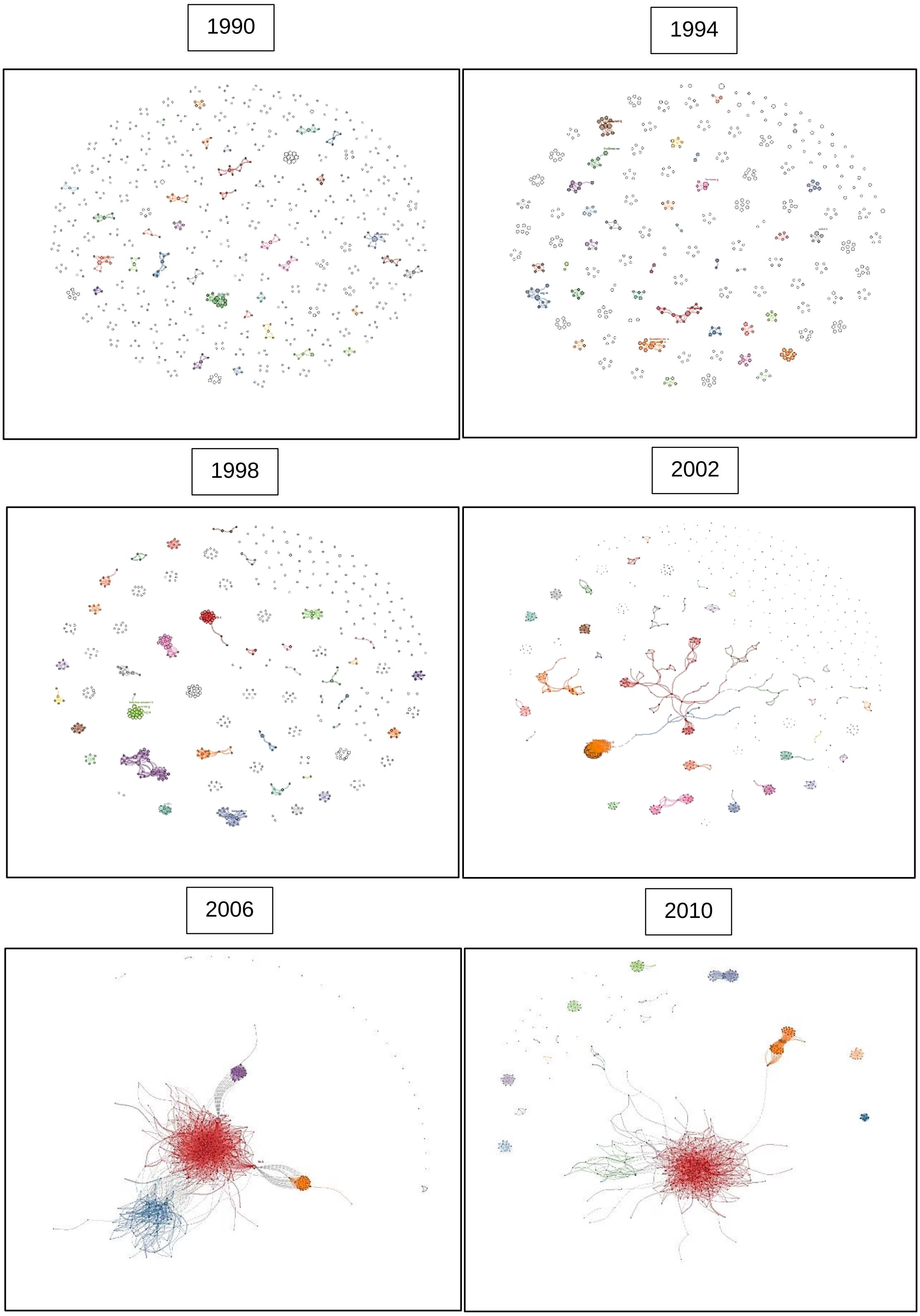

Figure 4: Author Collaboration Network (1990, 1994, 1998, 2002, 2006 & 2010) of Artificial Intelligence. N= max. 500

Technical Task Uncertainty

By observing the indicators used for the concept technical task uncertainty, one can notice that the mean cited reference count (ind. 28) has risen greatly from 20.2 references per paper in 1990 to 32.8 in 2010. Papers have, however, seen a slight decrease in mean page count (ind. 29), shifting from 13.5 pages to an average of 12.9 pages per paper. From these indicators one can conclude that papers became more reference dense based on the increase in mean reference per page (ind. 30) from 1.50 to 2.54.

The dominance of the top 10 references has decreased greatly based on the proportion of the top 10 most used references of the total references count in the year (ind. 31). A similar trend is found when controlling for the publication output size of the field by dividing the sum of the top 10 most used references by the total number of publications (ind. 33). When we dive deeper in the references, it can be found that the top 10 most used references (ind. 32) has remained rather stable. The references that did remain in the top 10 often remained there not only for 4 years but in most cases even 8. With influential references and therefor reoccurring manuscripts from Rumelhart D.E. (1986), Duda R.O. (1973), Goldberg D.E. (1989) and Pearl J. (1988). Although these have formed top level manuscripts, the authors have not reached the top 10 most cited author list of the field in one of the empirical years. The top 100 most used references stability (ind. 38) appears to be rather low in some years, but its increased in 2010 with 60 references from 2006 remaining in the top 100.

Based on a bibliographic coupling network of the field, it can be found that the inequality of the reference degree centrality (ind. 34) has gradually increased, indicating that the equality of reference-to-reference connectivity has decreased, while its standard deviation (ind. 35) fluctuated. The overall bibliographic coupling network's degree centrality (ind. 36) has been instable and does not show a clear pattern. The network's density (ind. 37) however, has decreased over time.

The field has seen an increasing citing half-life (ind. 39) moving from 5 (1990) to 7 (2010) years which both can be considered low in comparison to other fields. Its citing mean life (ind. 48) appeared to incrementally increase over and appears to be relatively average. In addition, the field shows a low and instable rate of knowledge accumulation (ind. 51).

The bibliographic coupling networks of the top 500 most used references (Figure 5) show that the network has become more dense over time. This in combination with the RPYS (appendix 1) which shows an increase in reference usage implies that the knowledge base of the field has grown.

Ultimately, it is difficult to derive clear conclusions from empirical data regarding the technical task uncertainty of a field. However, the data shows that papers have become more reference dense although its density remains relatively low; its bibliographic coupling network has grown in density; and the knowledge accumulation indicator shows that it is not a cumulative field. Therefore, the field is estimated to be high in its technical task uncertainty.

Indicator	**28**	**29**	**30**	**31**	**32**
1990	20.1642	13.47767	1.496119	0.376851	NA
1994	23.16914	13.80935	1.677786	0.221965	2
1998	23.28417	13.41502	1.73568	0.163303	6
2002	21.42354	12.24557	1.749493	0.137882	4
2006	19.0122	10.4488	1.819559	0.118257	8
2010	32.78965	12.92338	2.537234	0.175403	5

Indicator	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**48**	**51**
1990	0.344403	0.5785718	0.02876033	0.15416053	0.02564242	NA	5	8.095476	NA
1994	0.216938	0.5714909	0.01656812	0.09566136	0.01459272	23	5	8.288425	2.4254969
1998	0.160904	0.5948048	0.01286953	0.10804999	0.01060943	24	5	8.600259	1.3806691
2002	0.134545	0.6630679	0.00906506	0.08525229	0.0061734	47	6	9.065285	1.1933822
2006	0.117192	0.6671141	0.00739342	0.07067542	0.00499143	21	6	9.188584	1.3702014
2010	0.175065	0.6025351	0.01347049	0.08472323	0.01097326	60	7	10.43925	0.7232512

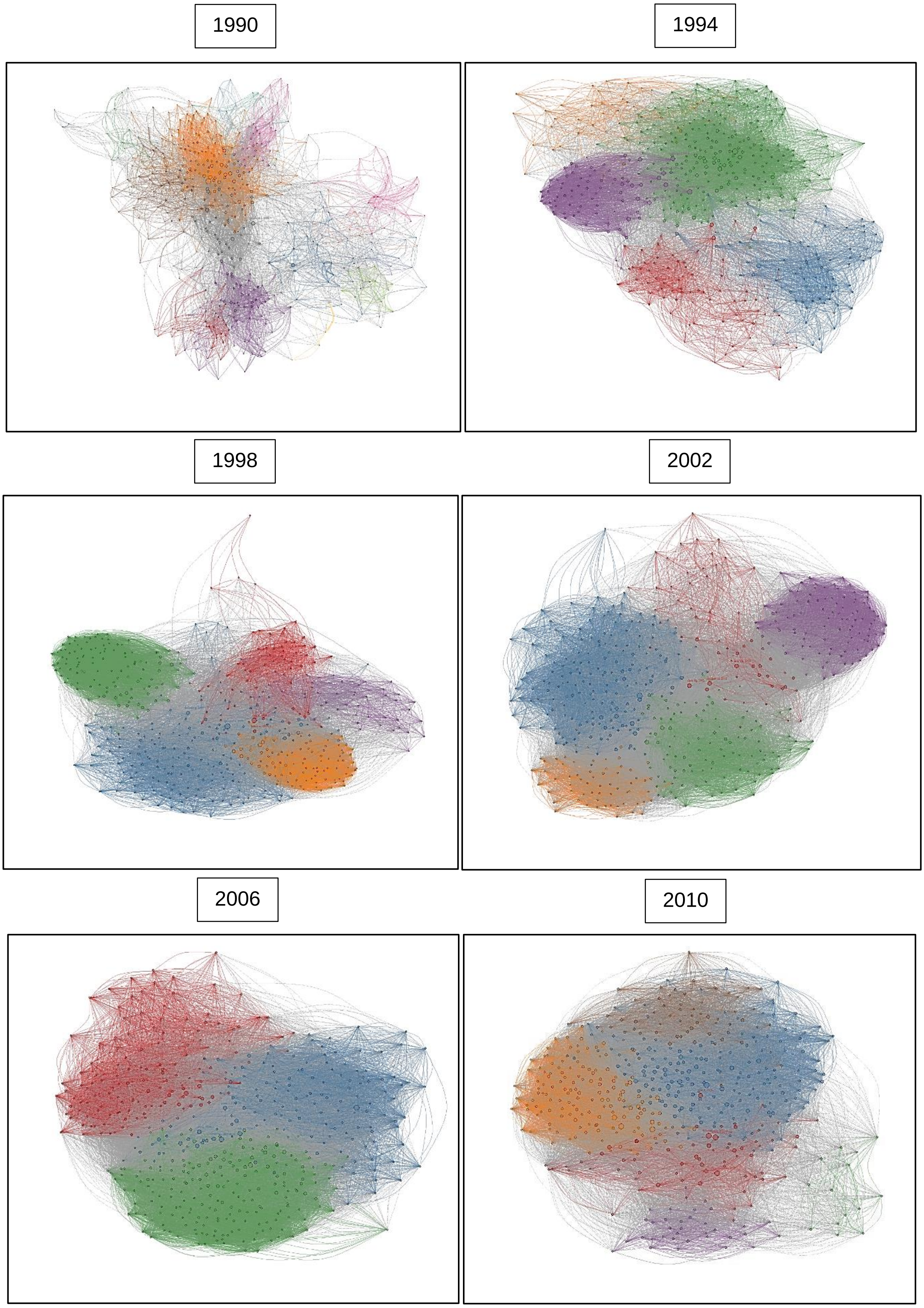

Figure 5: Bibliographic Coupling Network (1990, 1994, 1998, 2002, 2006 & 2010) of Artificial Intelligence, N= max. 500

Strategic Task Uncertainty

By exploring the indicators used for the concept strategic task uncertainty, one can gain a more comprehensive understanding of its nature in the field Artificial Intelligence.

The field shows a diverging dynamic based on the sum of the proportional occurrence of the top 10 author keywords (ind. 40). The sum of their occurrence proportion reached 0.42 in 1990 but dropped to 0.15 in 2010. A similar dynamic is found for its keyword plus counter partner (ind. 42), which dropped from 0.75 to 0.55. The stability of the top 10 author keywords (ind. 41) seemed to have increased from 1 remaining in the top 10 over 1990/1994 to 8 in 2006/2010. Based on a qualitative analysis of the dynamics of the top 10 author keywords, it can be concluded that the field remarkably shifted from an incoherent, and an arguably vague, set of topics (i.e. expert systems, intelligent control, knowledge representation, active vision, CAD CAM, edge detection, etc.) to a coherent and therefore seemingly directed set of topics (i.e. data mining, classification, neural networks, clustering, machine learning, etc.). It is true that this line of thought might be biased due to the low frequency of author keywords used in papers in 1990. Here the top 10 keywords reoccur in total 27 times that year in comparison to the total 309 top 10 author keywords occurrences in papers in 1994. It is exactly 1994 in which an coherency can be first found in its keywords i.e. neural networks, pattern recognition, image processing and computer vision. Nevertheless, the field seemed to have shifted from image processing, computer vision and pattern recognition (1994) to a field of data mining and a broader application of machine learning (2010). The stability of the keyword plus top 10 ranking is eventually more stable, rising from 4 keyword plus tags remaining in the top 10 (1990/1994) to almost complete stability in the 1998-2010 time period. Also here, one can notice a change in content as noticed in the author keywords; from vision and image recognition to a broader application of artificial intelligence. Similar patterns are found for title words and abstract words (see appendix 4 & 5). Lastly, the stability of the top 100 author keywords (49) and top 100 keyword plus tags (50) has risen tremendously but remains relatively low in its stability once compared to other fields.

Based on the author keyword co-occurrences network, it is seen that the Gini-index author keyword node degree centrality (ind. 44) has slightly increased from 0.40 to 0.45. Meaning that the co-occurrences of author keywords has become more inequal. The extent to which certain keywords dominate in their connectivity has thus increased, making the field more directed. Its standard deviation (ind. 45) has shown a decrease, indicating that the variance has decreased. The overall degree centrality (ind. 46) and density (ind. 47) of the field have seen a an increase.

Figure 6 shows the annual author keyword co-occurrence network of the top 500 most used author keywords which visualizes that the field became more mature. Clusters increase in size and become more connected with other clusters which indicates that isolated topics bond and form one field.

The results of the indicators clearly show that the field has gained more focus in terms of topics. The topic node degree centrality has become less equal; the top 10/top 100 most used keywords have become more stable and coherent and the density of the field has increased. Therefore, it is concluded that the strategic task uncertainty was rather high in this field but managed to reduce this uncertainty over the time period to a medium/high.

Table 11: Results strategic task uncertainty Artificial Intelligence

Indicator	40	41	42	43	44
1990	0.419355	NA	0.75	NA	0.4033054
1994	0.236378	1	0.359471	6	0.3929471
1998	0.219188	6	0.423172	7	0.4200664
2002	0.170924	6	0.386551	9	0.446011
2006	0.171838	8	0.366655	10	0.4733016
2010	0.151288	8	0.547662	8	0.4469159

Indicator	**45**	**46**	**47**	**49**	**50**
1990	0.00090903	0.00565125	0.00113762	NA	NA
1994	0.00034141	0.00193358	0.00045363	21	31
1998	0.00026019	0.00254882	0.00028706	55	66
2002	0.00028119	0.00416668	0.00019062	58	71
2006	0.00023875	0.00774033	0.0001433	66	80
2010	0.00028256	0.00751095	0.00020846	69	79

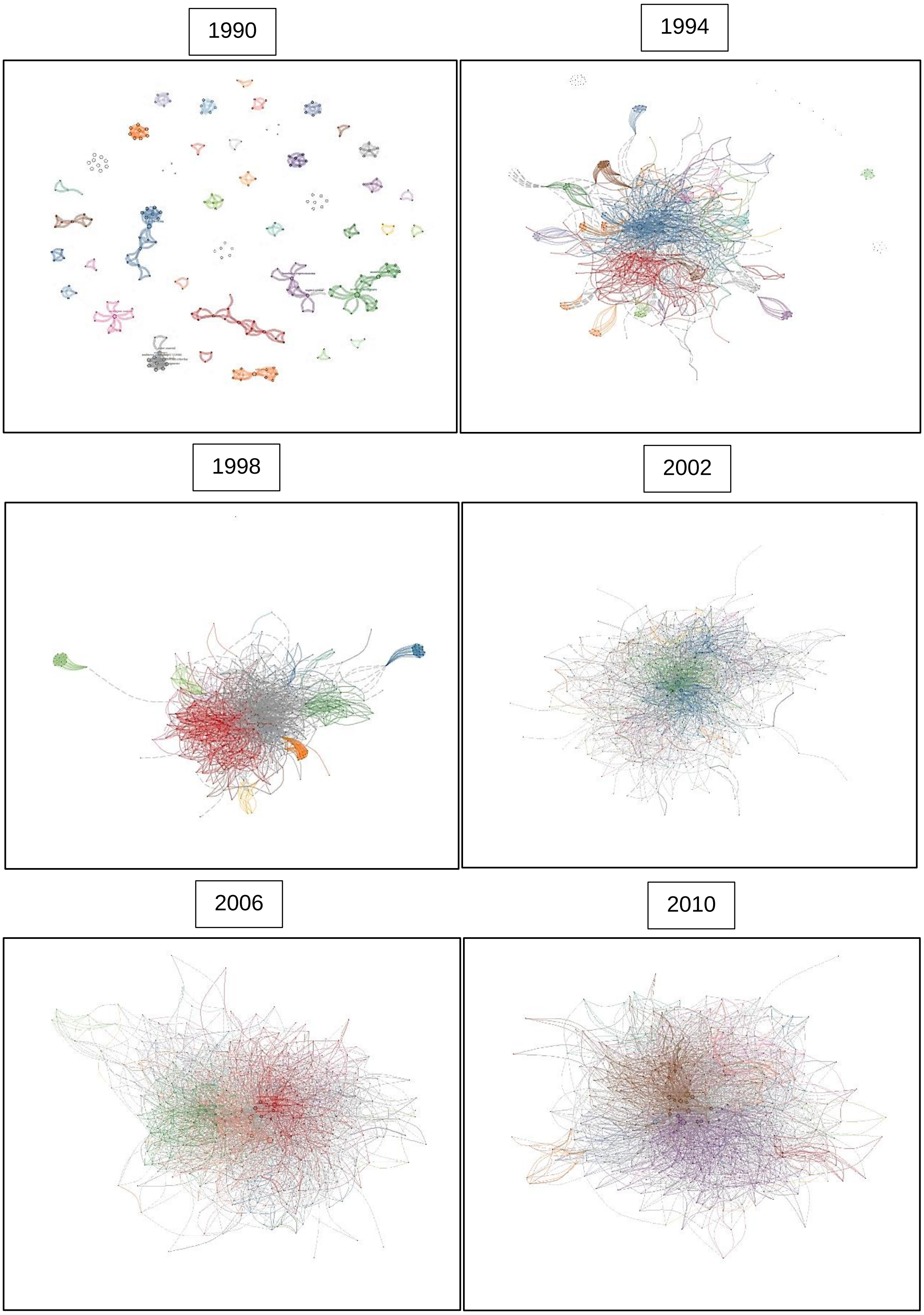

Figure 6: Author Keyword Co-occurrences Network (1990, 1994, 1998, 2002, 2006 & 2010) of Artificial Intelligence. N= max. 500

Nanotechnology

Nanotechnology has grown from 799 publications in 1990 to 20182 publications in 2010. The organizational size consisted of 2189 active researchers in 1990 and has grown to a size of 54967 researchers in 2010. The annual organizational size and output size have seen annual growths and declines, but the field has seen a netto growth of 2526% in output size and a 2511% growth in organizational size in the 20 year period as can be seen in Table 12.

Table 12: Descriptive results Nanotechnology

Year	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Organizational Size	2189	5801	4600	4573	5885	6100	8124	9374	10969	10482
Size Growth (%)		165	-21	-1	29	4	33	15	17	-4
Output Size	799	2185	1653	1664	2219	2064	2969	3459	3742	3493
Output Growth (%)		173	-24	1	33	-7	44	17	8	-7

Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Organizational Size	12865	14376	14854	18704	22294	25218	31178	39730	45414	48485	54967
Size Growth (%)	23	12	3	26	19	13	24	27	14	7	13
Output Size	4222	4899	4928	6111	7503	8516	10873	14067	16925	17557	20182
Output Growth (%)	21	16	1	24	23	14	28	29	20	4	15

Functional Dependence

Table 13 show the quantitative results for the concept functional dependence in the field of Nanotechnology. The field has roughly witnessed an increase in its author citation variance (ind. 1) over the time period. This increase in variance is accompanied with an increase of the author citation count Gini-index (ind. 2) which has increased by approximately 0.13 in the 20 year time span. A similar trend is to be seen for the fractionalized citation count (ind. 3). Although the proportion of the top 10 most cited authors (ind. 6) has decreased, this is not in line with the proportion of the top 10% (ind. 5) and top 1% (ind. 4) most cited authors which both have seen an increase in the time. Subsequently, the stability of the top 100 most cited authors (ind. 20) has been highly unstable but became increasingly more stable at the of the time period. Based on these patterns, we can conclude that the field has become less equal in their author citation count.

Nanotechnology has seen a similar trend for its institution citation standard deviation (ind. 7); its institution’s citation count Gini-index (ind. 8) and its fractionalized Gini-index (ind. 9) as that for the authors. It shows that the citation counts of institutions has become more unequal over time. The top 10 most cited institutions have seen an inverse U-shape in its pattern of proportional citation possession (ind. 10), overall remaining the same in 2010 (11%) as in 1990 (11%). In addition, the stability of the top 10 (ind. 11) and top 50 (ind. 21) most cited institutions has been unstable overtime but did increase in its stability. With only 1 and 3 institutions remaining in the top 10 after a time period of 4 years in 1990/1994 and 1994/1998 respectively as opposed to 3 and 6 in 200/2006 and 2006/2010. Overall, the institution citation count distribution has become les equal and remains highly skewed.

The standard deviation of the authors dominance factor (ind. 12) has shown a gradual increase. A decrease in the author equality in terms of their dominance factor can be observed based on the author dominance factor Gini-index (ind. 13). Authors have become, based on the index, almost twice as unequal in the collaboration dominance.

Subsequently, the results of the author collaboration network analysis show that the standard deviation of the authors degree centrality (ind. 15) has decreased from 0.0015 (1990) to 0.00036 (2010). This is accompanied with a parabola shaped trend in the Gini-index of the author degree centrality (ind. 14) which ultimately resulted in an increase in its inequality, implying that the amount of collaborations with unique fellow colleagues has become slightly less equal. The Gini-index of the author betweenness centrality (ind. 16) is very high, pointing out that the broker position is highly unequal whilst the variance predominantly seems to have increased as well (ind. 17). Unfortunately, indicator 16 and 17 could not be computed for 2010 due to an integer overflow. The authority score of authors (ind. 18) was, similar to that of the betweenness centrality, immensely high but decreased from 0.99 (1990) to 0.91 (2010).

Overall the field has witnessed a great increase in its author and institution citation inequality accompanied with the an increase of the collaboration dominance inequality, implying that researchers got significantly more functionally dependent on one another over the time period of 20 years. In the beginning of the time period nanotechnology operated with a low functional dependence but moved to relatively high one.

Table 13: Results functional dependence Nanotechnology

Indicator	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1990	31.94986	0.622899	0.676058	0.17314	0.52559	0.121257	40.83876	0.626497	0.662468	0.110652
1994	42.92467	0.641847	0.689457	0.175576	0.544755	0.071623	68.52087	0.656103	0.686325	0.11151
1998	79.3584	0.67999	0.71056	0.187138	0.568311	0.058231	202.1731	0.737953	0.761257	0.128085
2002	161.5953	0.704663	0.721556	0.204412	0.586707	0.04294	416.1237	0.762003	0.799178	0.151392
2006	167.623	0.693967	0.701383	0.189326	0.564772	0.021555	579.1803	0.798694	0.825958	0.112382
2010	383.5007	0.754159	0.748584	0.287747	0.645126	0.025347	1004.566	0.841353	0.864776	0.111241

Indicator	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
1990	NA	0.17191	0.059073	0.417125	0.001512	0.969999	5.15E-06	0.991316	0.09517
1994	1	0.245115	0.120819	0.426442	0.000738	0.984722	0.000195	0.994801	0.061946
1998	3	0.234075	0.11142	0.382096	0.000363	0.977943	0.000624	0.997073	0.041981
2002	4	0.2486	0.126112	0.380603	0.000303	0.964988	0.000619	0.997907	0.041909
2006	3	0.282845	0.166842	0.417136	0.000264	0.951724	0.000543	0.909167	0.027278
2010	6	0.306251	0.194654	0.489653	0.000361	NA	NA	0.915658	0.027359

Indicator	**20**	**21**
1990	NA	NA
1994	2	12
1998	6	18
2002	6	22
2006	4	27
2010	31	29

Strategic Dependence

Table 14 shows the quantitative indicators used for the concept strategic dependence in the field of Nanotechnology. The field has seen a shift in the collaboration coefficient (ind. 23). Approximately 84% of all papers were written in collaboration in 1990 while this has risen to 98% in 2010. The mean co-author count (ind. 22) has increased in this period from 3.20 authors per paper to 4.93. The standard deviation (ind. 24) of this co-author count has grown from 2.03 in 1990 to 2.45 in 2010 while the inequality of the co-author count in the form of the Gini-index has slightly decreased (ind. 25). The overall network degree centrality (ind. 26) has fluctuated, while the network density (ind. 27) in the field clearly shows a decrease over time.

When one observes the author collaboration network analysis (Figure 7) of the top 500 most cited authors, one can roughly conclude that collaborations have intensified. Clusters, predominantly, became greater in size, decreasing the amount of different clusters in the network which implies increasingly more coherent collaborations over time.

Based on these results, it can be concluded that Nanotechnology has seen an increase in its strategic dependence, forcing researchers to collaborate on a greater scale. Its dependence was already medium/high in the beginning of the period, but increased to relatively higher levels.

Table 14: Results strategic dependence Nanotechnology

Indicator	**22**	**23**	**24**	**25**	**26**	**27**
1990	3.197747	0.836045	2.03132	0.316776	0.00737525	0.00176552
1994	3.492114	0.863903	2.164203	0.316367	0.01540095	0.00076926
1998	3.830839	0.916088	2.124432	0.290258	0.00619206	0.00044817
2002	4.222808	0.950081	2.232541	0.278039	0.00493557	0.00036385
2006	4.458199	0.964867	2.247868	0.26756	0.00840794	0.00021842
2010	4.927411	0.977406	2.446339	0.266395	0.01663758	0.00017112

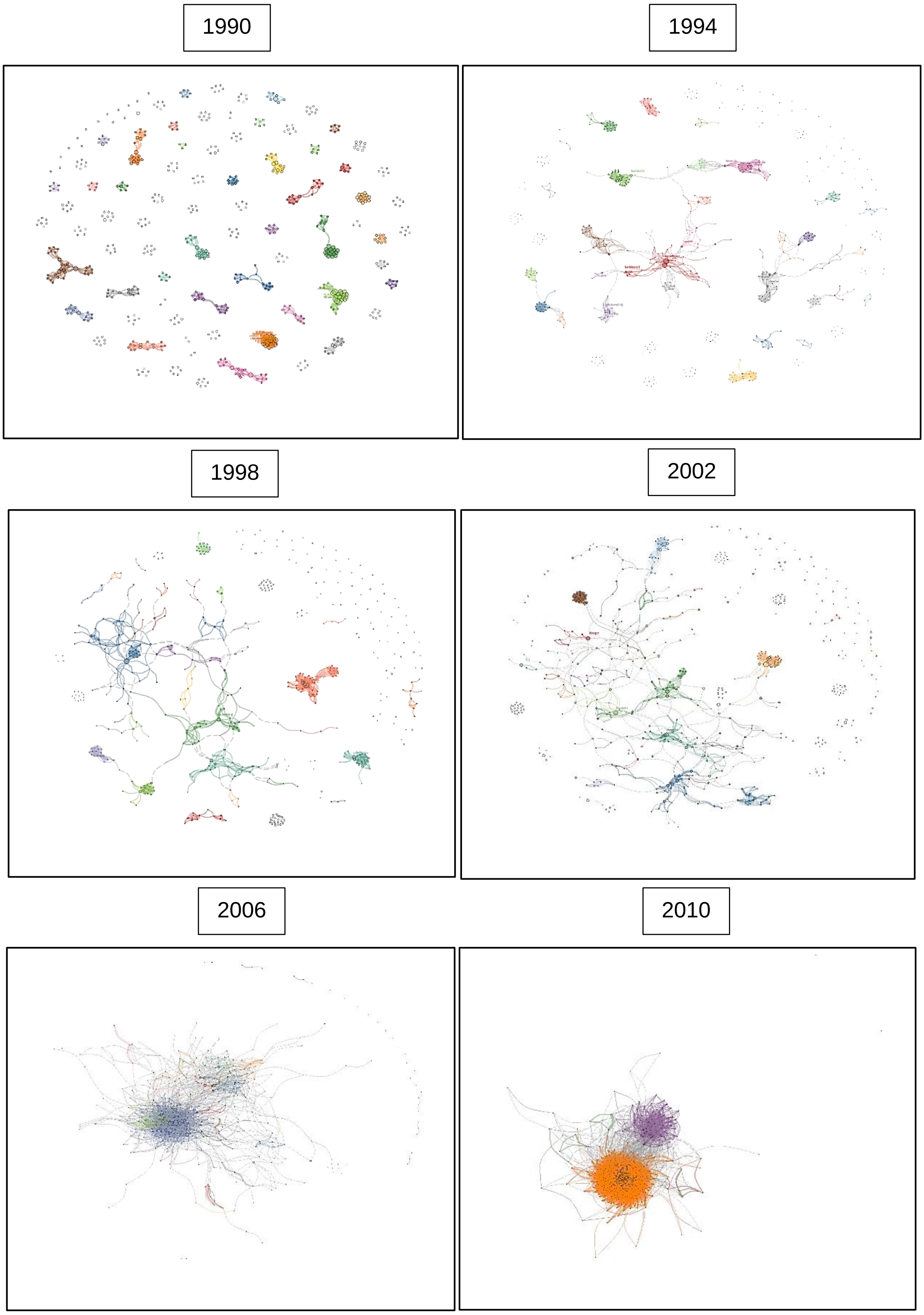

Figure 7: Author Collaboration Network (1990, 1994, 1998, 2002, 2006 & 2010) of Nanotechnology. N= max. 500

Technical Task Uncertainty

By observing the indicators used for the concept technical task uncertainty, one can notice that the mean cited reference count (ind. 28) has risen greatly from 16.6 references per paper in 1990 to 32.7 in 2010. Papers have, however, seen a stable mean page count (ind. 29) over the years. From these indicators one can conclude that papers became more reference dense based on the increase in mean reference per page (ind. 30) from 2.8 to 5.5.

The dominance of the top 10 references has increased slightly based on the proportion of the top 10 most used references of the total references count in the year (ind. 31). A similar trend is found when controlling for the publication output size of the field by dividing the sum of the top 10 most used references by the total publication output size (ind. 33). When we dive deeper in the references, it can be found that the top 10 most used references (ind. 32) has remained rather stable but low. Some remarkable references that remained in the top 10 for not only 4 but 8 years were manuscripts from Iljima S. (1991), Sze S.M. (1981), and Beck J.S. (1992). Although these have formed top level manuscripts, the authors have not reached the top 10 most cited author list of the field in one of the empirical years. Xia Y.N. however, managed to reach both top 10 lists (most cited author and most cited references) but only remained there for 4 years. The top 100 most used references stability (ind. 38) showed an inverse U-shape ultimately becoming highly unstable in 2010 with only 6 references maintaining a top 100 position.

Based on a bibliographic coupling network of the field, it can be found that the inequality of the reference degree centrality (ind. 34) has slightly fluctuated but remained roughly at the same level, indicating that the equality of reference-to-reference connectivity has barely changed, while its standard deviation (ind. 35) grew. The overall bibliographic coupling network's degree centrality (ind. 36) has risen and its density (ind. 37) ultimately too.

The field has seen a stable citing half-life (ind. 39) of 6 years which can be considered medium/low in comparison to other fields. Its citing mean life (ind. 48) appeared to be stable and medium/low too. The field shows a unstable and low rate of knowledge accumulation (ind. 51).

The bibliographic coupling networks of the top 500 most used references (Figure 8) show that the network has become more dense over time while cluster have grown in size. This in combination with the RPYS (Appendix 1) which shows an increase in reference usage implies that the knowledge base of the field has grown.

Ultimately, it is difficult to derive clear conclusions from empirical data regarding the technical task uncertainty of a field. However, the data shows that papers have become more reference dense although its density remains low; its bibliographic coupling network has grown in density; and the knowledge accumulation indicator shows that it is not a cumulative field. Therefore, the field is estimated to be high in its technical task uncertainty.

Table 15: Results technical task uncertainty Nanotechnology

Indicator	**28**	**29**	**30**	**31**	**32**
1990	16.56145	5.982478	2.768326	0.094972	NA
1994	16.69301	13.84438	1.20576	0.10537	0
1998	17.35255	5.781798	3.001237	0.058443	2
2002	19.2429	5.5015	3.497756	0.071502	3
2006	23.81146	5.54438	4.294702	0.105278	2
2010	32.65134	5.922913	5.512716	0.13223	2

Indicator	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**48**	**51**
1990	0.085106	0.6196163	0.00446087	0.02396793	0.00360099	NA	6	8.655379	NA
1994	0.093736	0.641153	0.00446659	0.02801396	0.00312322	12	5	8.521034	1.790219
1998	0.05799	0.602139	0.00248756	0.01651497	0.00194904	76	6	9.117434	1.255553
2002	0.071023	0.6652127	0.00480764	0.03702967	0.00305172	17	6	8.751883	0.972006
2006	0.105123	0.668688	0.00709257	0.06111381	0.00466356	6	6	8.540116	1.825841
2010	0.132197	0.6098764	0.00940706	0.07296267	0.00750906	6	6	8.535175	1.713047

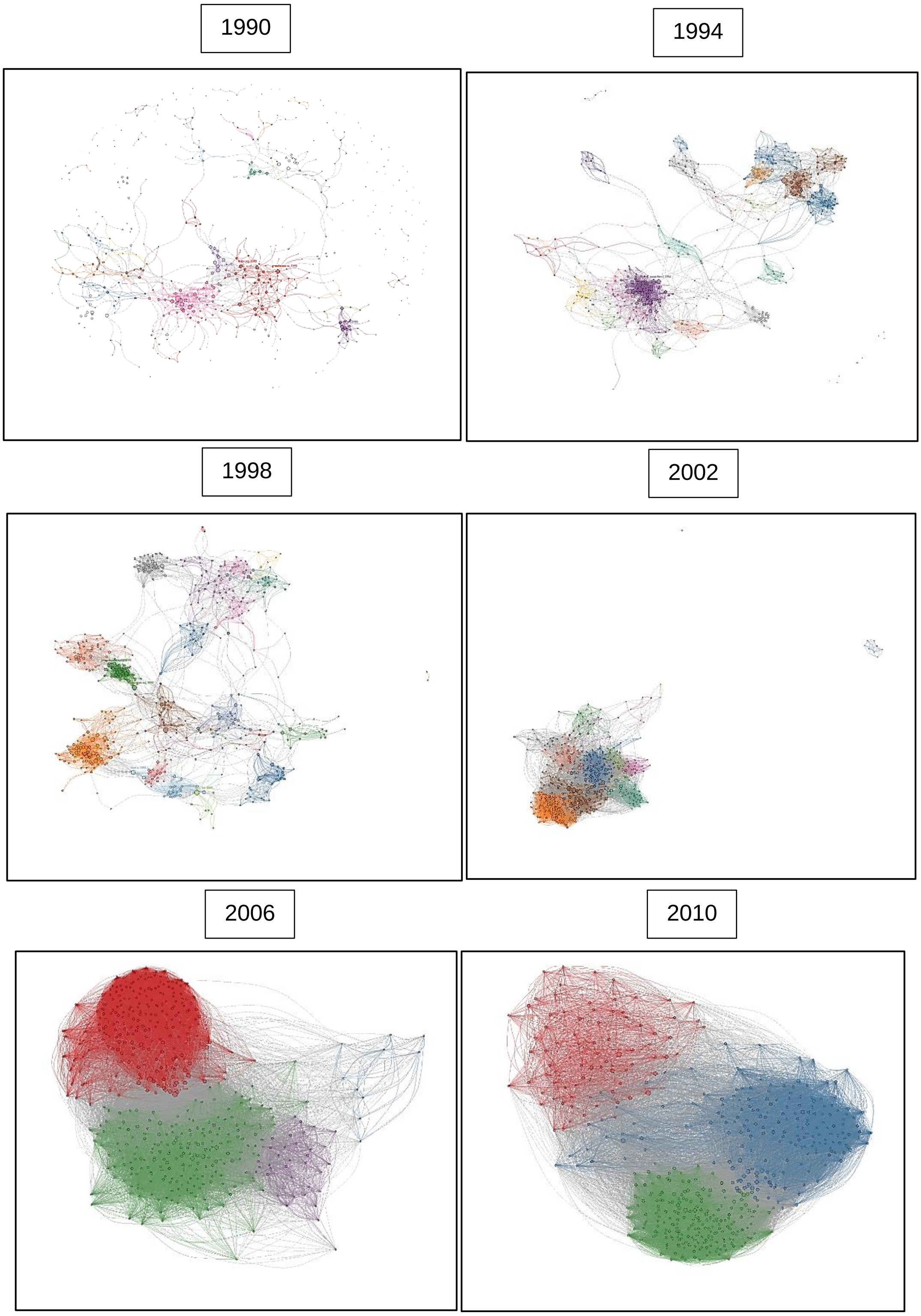

Figure 8: Bibliographic Coupling Network (1990, 1994, 1998, 2002, 2006 & 2010) of Nanotechnology, N= max. 500

Strategic Task Uncertainty

By exploring the indicators used for the concept strategic task uncertainty, one can gain a more comprehensive understanding of its nature in the field Nanotechnology.

The field shows an initially diverging but then stagnant dynamic based on the sum of the proportional occurrence of the top 10 author keywords (ind. 40). Author keywords are absent in the database for this field in the year 1990. But the sum of their occurrence proportion reached 0.40 in 1994 but dropped to 0.17 in 1998 and remained roughly on this level. A similar dynamic is found for its keyword plus counter partner (ind. 42), which dropped from 0.59 (1990) to 0.46 (2010). The stability of the top 10 author keywords (ind. 41) seemed to have increased from 1 remaining in the top 10 over 1994/1998 to 8 in 2006/2010. Based on a qualitative analysis of the dynamics of the top 10 author keywords, it can be concluded that the field greatly shifted from a seemingly coherent biomedical oriented domain (i.e. biosensor, glucose oxidase, enzyme electrode, flow injection analysis, glucose sensor, etc.) to one that is directed to perhaps a more structural and mechanical focused field (i.e. nanoparticles, graphene, carbon nanotubes, microstructure, self-assembly, mechanical properties, etc.). The stability of the keyword plus top 10 ranking (ind. 43) is arguably just as stable as the author keywords ranking, but content wise the shift in topics is less evident. This is probably the case due the highly generic words reoccurring in the keyword plus top 10 ranking (i.e. films, growth, fabrication, surface, particle, films, etc.). Lastly, the stabilities of the top 100 author keywords (ind. 49) and top 100 keyword plus tags (ind. 50) have risen tremendously but remain relatively low in its stability once compared to other fields.

Based on the author keyword co-occurrences network, it is seen that the Gini-index author keyword node degree centrality (ind. 44) showed an inverse U-shape but ultimately increased from 0.43 to 0.49. Meaning that the co-occurrences of author keywords has become more inequal. The extent to which certain keywords dominate in their connectivity has thus increased, making the field more directed. Its standard deviation (ind. 45) has shown decrease, indicating that the variance has decreased. The overall degree centrality (ind. 46) has dropped but recovered at the end of the period. The density (ind. 47) however, has decreased which could point out an increased segregation of topics.

Figure 9 shows the annual author keyword co-occurrence network of the top 500 most used author keywords which visualizes that the field became more mature; clusters increased in size and became more connected with other clusters which indicates that isolated topics bonded and form one more coherent field.

The results of the indicators clearly show that the field has gained more focus in terms of topics. The topic node degree centrality has become less equal; the top 10/top 100 most used keywords were unstable but became increasingly more stable over time while the density of the field has decreased. Therefore, it is concluded that the strategic task uncertainty was rather high in this field but managed to reduce this uncertainty over the time period to a medium/high.

Table 16: Results strategic task uncertainty Nanotechnology

Indicator	40	41	42	43	44
1990	NA	NA	0.59434	NA	NA
1994	0.404762	NA	0.364011	2	0.4264417
1998	0.168617	1	0.313053	9	0.382096
2002	0.182574	6	0.324907	5	0.3806032
2006	0.160481	5	0.423097	6	0.4171362
2010	0.199031	8	0.463391	7	0.4896532

Indicator	45	46	47	49	50
1990	NA	NA	NA	NA	NA
1994	0.00073833	0.01540095	0.00076926	NA	26
1998	0.00036274	0.00619206	0.00044817	11	64
2002	0.00030306	0.00493557	0.00036385	43	71
2006	0.00026388	0.00840794	0.00021842	58	78
2010	0.00036064	0.01663758	0.00017112	55	80

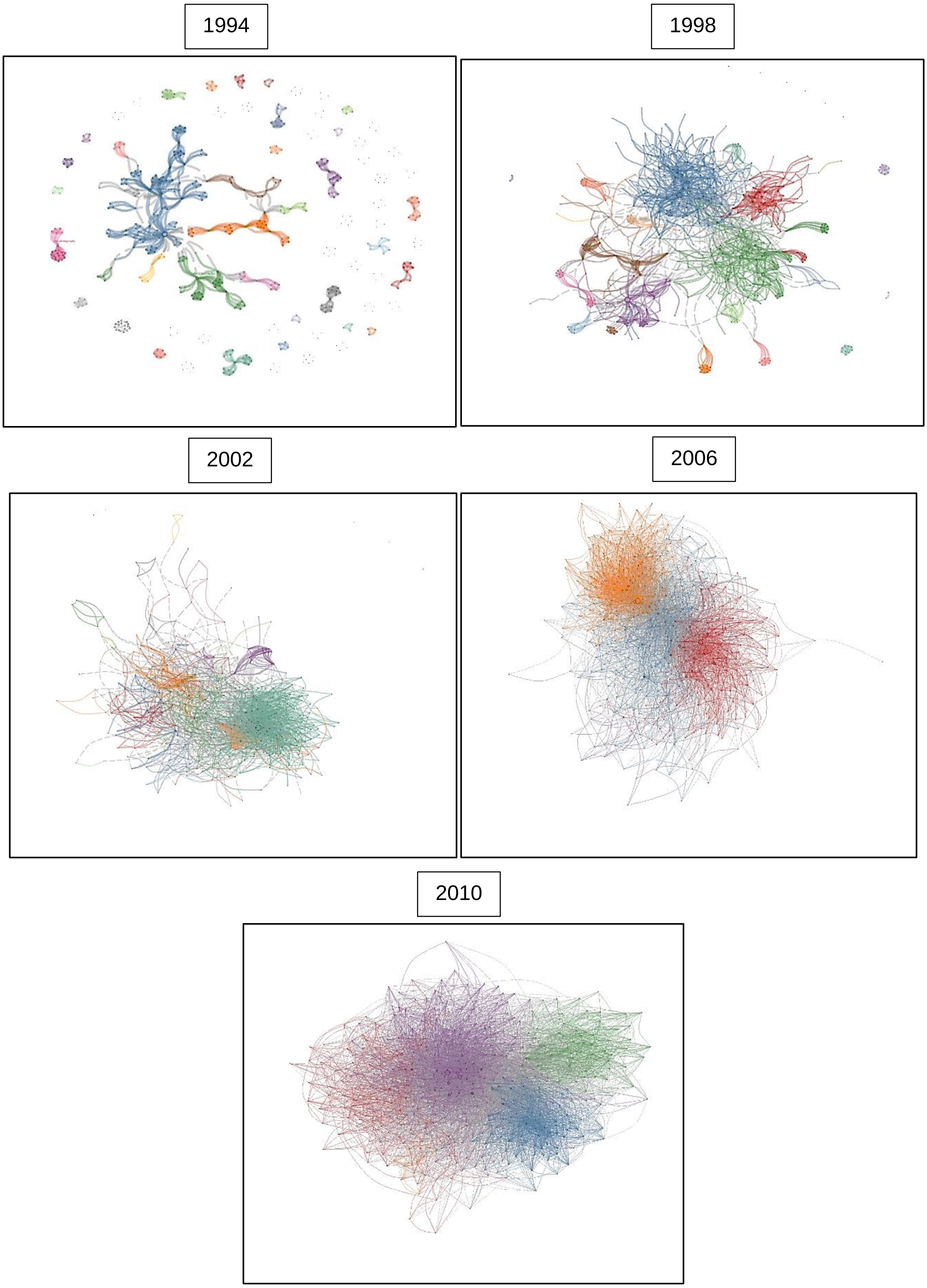

Figure 9: Author Keyword Co-occurrences Network (1994, 1998, 2002, 2006 & 2010) of Nanotechnology. N= max. 500

Biotechnology

Biotechnology has grown from 5230 publications in 1990 to 23202 publications in 2010. The organizational size consisted of 14685 active researchers in 1990 and has grown to a size of 80845 researchers. The annual organizational size and output size have seen annual growths and declines, but the field has seen a netto growth of 444% in output size and a 551% growth in organizational size in the 20 year period as can be seen in Table 17.

Table 17: Descriptive results Biotechnology

Year	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Organizational Size	14685	17381	20038	21027	24698	29701	35026	36705	38411	38766
Size Growth (%)		18	15	5	17	20	18	5	5	1
Output Size	5230	6446	7080	7381	8615	10345	12261	12318	12845	12824
Output Growth (%)		23	10	4	17	20	19	0	4	0

Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Organizational Size	39843	39765	41098	45937	49680	52354	59993	65510	70628	74977	80845
Size Growth (%)	3	0	3	12	8	5	15	9	8	6	8
Output Size	12704	12570	13087	14054	14644	15621	17336	18803	20410	21563	23202
Output Growth (%)	-1	-1	4	7	4	7	11	8	9	6	8

Functional Dependence

Table 18 show the quantitative results for the concept functional dependence in the field of Biotechnology. The field has roughly witnessed an increase in its author citation variance (ind. 1) over the time period. This increase in variance is accompanied with an increase of the author citation count Gini-index (ind. 2) which has increased by approximately 0.06 in the 20 year time span. A similar trend is to be seen for the fractionalized citation count (ind. 3). The proportions of citations in possession of the top 10 (ind. 6), the top 1% (ind. 4) and top 10% (ind. 5) most cited authors have increased over time. Subsequently, the stability of the top 100 most cited authors (ind. 20) has been highly unstable, but has witnessed a great shift in its stability in 2010. Based on these patterns, we can conclude that the field has become less equal in their author citation count.

Biotechnology has seen a similar trend for its institution citation standard deviation (ind. 7); its institution's citation count Gini-index (ind. 8) and its fractionalized Gini-index (ind. 9) as that for the authors. It shows that the citation counts of institutions has become more unequal over time. The top 10 most cited institutions (ind. 10) have seen a rough inverse U-shape in its pattern of proportional citation possession, overall remaining quite similar in 2010 (6.9%) to that of 1990 (7.1%). In addition, the stabilities of the top 10 (ind. 11) and top 50 (ind. 21) most cited institutions have been relatively stable, fluctuating around 2 institutions out of 10 remaining in the top 10 after 4 years. Overall, the institution citation count distribution has become les equal and remains highly skewed.

The standard deviation of the authors dominance factor (ind. 12) has shown a gradual increase. A decrease in the author equality in terms of their dominance factor can be observed based on the author dominance factor Gini-index (ind. 13). Authors have become, based on the index, almost twice as unequal in the collaboration dominance.

Subsequently, the results of the author collaboration network analysis show that the standard deviation of the authors degree centrality (ind. 15) displays a parabola shaped trend, resulting in a similar level in 2010 as in 1990. This is accompanied with an increase in the Gini-index of the author degree centrality (ind. 14) which ultimately resulted in an increase in its inequality, implying that the amount of collaborations with unique fellow colleagues has become slightly less equal. The Gini-index of the author betweenness centrality (ind. 16) is very high, pointing out that the broker position is highly unequal whilst the variance predominantly seems to have increased as well (ind. 17). Unfortunately, indicator 16 and

17 could not be computed for the years of 2006 and 2010 due to an integer overflow. The authority score of authors (ind. 18) was, similar to that of the betweenness centrality, immensely high.

Overall the field has witnessed a clear increase in its author and institution citation inequality accompanied with the an increase of the collaboration dominance inequality, implying that researchers got more functionally dependent on one another over the time period of 20 years. Although the field seemed to be low in its functional dependence in the beginning of the period, the field now has relative medium levels to coop with.

Table 18: Results functional dependence Biotechnology

Indicator	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1990	94.48943	0.618867	0.642859	0.153174	0.498329	0.034611	205.7083	0.687364	0.712596	0.068756
1994	73.57337	0.592769	0.62373	0.145686	0.480164	0.020307	225.0445	0.704881	0.732838	0.067901
1998	179.869	0.635574	0.669998	0.212277	0.537356	0.065605	462.4814	0.762151	0.792876	0.116921
2002	171.4738	0.627299	0.645614	0.183051	0.514511	0.033276	449.6991	0.757684	0.783701	0.084297
2006	182.8685	0.650095	0.646413	0.190418	0.519271	0.033178	565.7702	0.785416	0.797162	0.067843
2010	193.1397	0.681374	0.684472	0.256995	0.570161	0.046178	503.2184	0.804551	0.822773	0.071272

Indicator	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
1990	NA	0.197345	0.076501	0.390842	0.000245	0.990402	8.5E-05	0.998496	0.038462
1994	3	0.218491	0.095034	0.396788	0.000173	0.982701	0.000173	0.998852	0.033861
1998	2	0.236719	0.110976	0.395486	0.000128	0.974127	0.000259	0.998712	0.022535
2002	1	0.238851	0.112291	0.411022	0.000147	0.972029	0.000266	0.998292	0.033108
2006	2	0.258847	0.13109	0.456744	0.000194	NA	NA	0.993363	0.046801
2010	1	0.277044	0.147998	0.498008	0.000252	NA	NA	0.981117	0.044161

Indicator	**20**	**21**
1990	NA	NA
1994	4	21
1998	7	24
2002	5	28
2006	2	27
2010	19	28

Strategic Dependence

Table 19 shows the quantitative indicators used for the concept strategic dependence in the field of Biotechnology. The field has seen an increase in the collaboration coefficient (ind. 23). Approximately 92% of all papers were written in collaboration in 1990 while this has risen to 96% in 2010. The mean co-author count (ind. 22) has increased in this period from 3.49 authors per paper to 5.19. The standard deviation (ind. 24) of this co-author count has grown from 1.96 in 1990 to 3.36 in 2010 while the inequality of the co-author count in the form of the Gini-index has roughly remained 0.29 (ind. 25). The overall network degree centrality (ind. 26) has fluctuated but ultimately increased, while the network density (ind. 27) in the field gradually decreased over time.

When one observes the author collaboration network analysis (Figure 10) of the top 500 most cited authors, one can roughly conclude that collaborations have intensified. Clusters, predominantly, became greater in size, decreasing the amount of different clusters in the network which implies increasingly more coherent collaborations over time.

Based on these results, it can be concluded that Nanotechnology has seen an increase in its strategic dependence, forcing researchers to collaborate on a greater scale.

Table 19: Results strategic dependence Biotechnology

Indicator	**22**	**23**	**24**	**25**	**26**	**27**
1990	3.492925	0.917017	1.956656	0.282019	0.00353507	0.00029288
1994	3.777133	0.920488	2.164097	0.291269	0.00455282	0.00019663
1998	4.0232	0.898482	2.364699	0.305092	0.00247476	0.00014531
2002	4.275541	0.906778	2.640321	0.309694	0.00333301	0.00015004
2006	4.804107	0.94324	3.115031	0.30701	0.00737488	0.00013115
2010	5.193949	0.963365	3.364328	0.292466	0.01218631	0.00011712

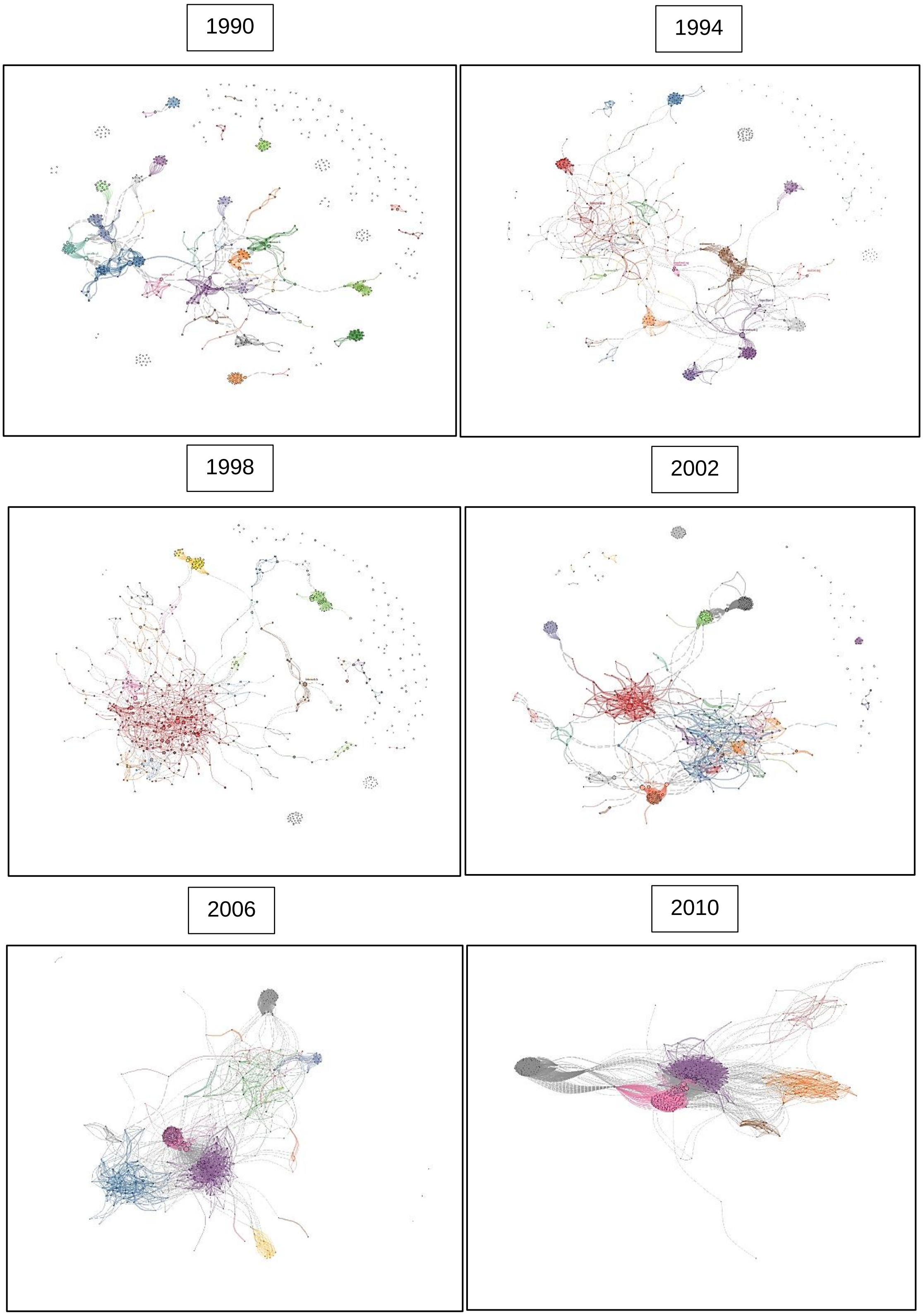

Figure 10: Author Collaboration Network (1990, 1994, 1998, 2002, 2006 & 2010) of Biotechnology. N= max. 500

Technical Task Uncertainty

By observing the indicators used for the concept technical task uncertainty, one can notice that the mean cited reference count (ind. 28) has risen greatly from 23.8 references per paper in 1990 to 34.8 in 2010. Papers have, however, seen a stable mean page count (ind. 29) over the years until 2010 in which it dropped almost 2.5 pages. From these indicators one can conclude that papers became more reference dense based on the increase in mean reference per page (ind. 30) from 3.6 to 7.7.

The dominance of the top 10 references has dropped to almost half its size based on the proportion of the top 10 most used references of the total references count in the year (ind. 31). A similar trend is found when controlling for the publication output size of the field by dividing the sum of the top 10 most used references count by the total publication output size (ind. 33). When we dive deeper in the references, it can be found that the stability of the top 10 most used references (ind. 32) has remained rather stable but high. Here we find that there are four manuscripts in particular that appear to have formed a fundament for the field i.e. Bradford M.M. (1976), Sambrook J. (1989), Lowry O.H. (1951), and Laemmli U.K. (1970). These papers have been in the top 10 for at least 12 years in a row which sets the ranking of Biotechnology apart from other that of other fields. Although these have formed top level manuscripts, the authors have not reached the top 10 most cited author list of the field in one of the empirical years like in the previous discussed fields. The top 100 most used references stability (ind. 38) is average, which contrasts the stability of the top 10 references.

Based on a bibliographic coupling network of the field, it can be found that the inequality of the reference degree centrality (ind. 34) is high and has roughly remained at the same level, indicating that the equality of reference-to-reference connectivity has barely changed, while its standard deviation (ind. 35) decrease by over 50%. The overall bibliographic coupling network's degree centrality (ind. 36) has decreased and its density (ind. 37) ultimately too.

The field has seen a slight increase in its citing half-life (ind. 39), moving from 6 to 7 years which are relatively average citing half-lives when considering the other fields. Its citing mean-life (ind. 48) appeared to slightly have increased too, and can be considered relatively average in its level as well. The field shows a medium rate of knowledge accumulation (ind. 51).

The bibliographic coupling networks of the top 500 most used references (Figure 11) show that the network was already relatively dense. Over the years, clusters seem to compete for this top 500 position while they are highly interconnected. The RPYS (Appendix x1 shows an increase in reference usage which implies that the knowledge base of the field has grown.

Ultimately, it is difficult to derive clear conclusions from empirical data regarding the technical task uncertainty of a field. However, the data shows that papers are relatively low in page count and high in reference density showing that the field contains a mature theoretical base; it shows that there is a dominant top 10 reference base; its reference degree centrality inequality is high, implying the presence of a group of influential references; its bibliographic coupling network is rather saturated; and the knowledge accumulation indicator shows that it is a cumulative field. Therefore, the field is therefore estimated to be low in its technical task uncertainty and remains low.

Table 20: Results technical task uncertainty Biotechnology

Indicator	**28**	**29**	**30**	**31**	**32**
1990	23.81868	6.589244	3.614782	0.399831	NA
1994	25.71278	6.479707	3.968201	0.369076	7
1998	26.34465	6.174998	4.266342	0.274342	7
2002	28.51516	6.72321	4.241302	0.271021	6
2006	31.84239	6.942043	4.586891	0.23132	8
2010	34.85126	4.538999	7.678183	0.193075	8

Indicator	33	34	35	36	37	38	39	48	51
1990	0.361759	0.7553725	0.0334707	0.1604987	0.01917983	NA	6	8.845222	NA
1994	0.35798	0.7438647	0.03416129	0.18307122	0.02018748	34	6	8.791376	1.3269998
1998	0.259712	0.7739235	0.02148238	0.12914372	0.01130037	56	6	8.936046	1.0018954
2002	0.258119	0.7759212	0.02069768	0.12937023	0.01072713	72	7	9.129182	0.7981339
2006	0.225542	0.7446531	0.0152777	0.11647926	0.00852796	34	7	9.222952	1.083759
2010	0.190113	0.726145	0.01178649	0.09085909	0.00681653	35	7	9.685663	1.0957914

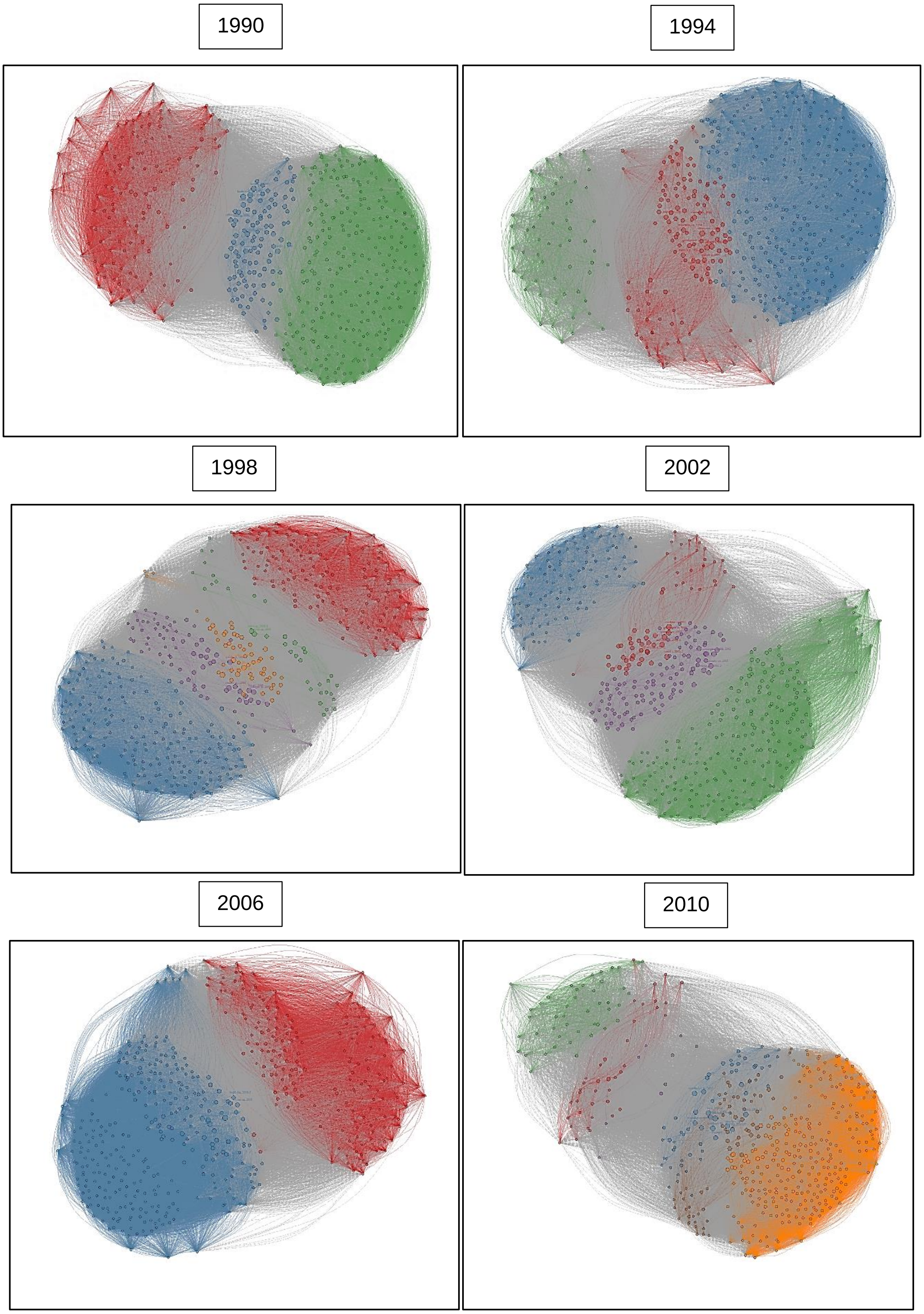

Figure 11: Bibliographic Coupling Network (1990, 1994, 1998, 2002, 2006 & 2010) of Biotechnology, N= max. 500

Strategic Task Uncertainty

By exploring the indicators used for the concept strategic task uncertainty, one can gain a more comprehensive understanding of its nature in the field Biotechnology.

The field shows a diverging dynamic based on the sum of the proportional occurrence of the top 10 author keywords (ind. 40). The sum of their occurrence proportion contained a quarter of all keyword tags in 1990 but dropped to 0.097 in 2010. A similar but less dramatic dynamic is found for its keyword plus counter partner (ind. 42), which dropped from 0.55 (1990) to 0.46 (2010). The stability of the top 10 author keywords (ind. 41) seemed to have increased from 1 remaining in the top 10 over 1990/1994 to 7 in 2006/2010. The stability of the keyword plus top 10 ranking (ind. 43) is showing higher levels of stability than the author keywords ranking. Lastly, the stabilities of the top 100 author keywords (ind. 49) and top 100 keyword plus tags (ind. 50) have risen and predominantly move along high and medium levels of stability respectively.

Based on the author keyword co-occurrences network, it is seen that the Gini-index author keyword node degree centrality (ind. 44) has increased from 0.39 to 0.50. Meaning that the co-occurrences of author keywords has become more inequal. The extent to which certain keywords dominate in their connectivity has thus increased, making the field more directed. Its standard deviation (ind. 45) has shown an increase, indicating that the variance has increased. The overall degree centrality (ind. 46) has increased. The density (ind. 47) however, has decreased which could point out an increased segregation of topics.

Figure 12 shows the annual author keyword co-occurrence network of the top 500 most used author keywords which visualizes that the field became more mature but was already fairly developed when comparing it to other fields; clusters increased in size and became more connected with other clusters which indicates that isolated topics bonded and form a more coherent field. It is notable that even though the top 500 most used author keywords seem rather connected, it still entails a rather heterogeneous network of clusters. Apparently Biotechnology is therefore rather dispersed in its topics.

The results of the indicators clearly show that the field has gained more focus in terms of topics. The topic node degree centrality has become less equal; the top 10/top 100 most used keywords were already stable but have seen an additional increase of this. Therefore it is concluded that the strategic task uncertainty, compared to the other fields, was medium but decreased its uncertainty to medium/low levels.

Table 21: Results strategic task uncertainty Biotechnology

Indicator	**40**	**41**	**42**	**43**	**44**
1990	0.248408	NA	0.549839	NA	0.3908422
1994	0.153242	1	0.553935	7	0.3967882
1998	0.11671	9	0.537109	10	0.3954859
2002	0.137351	7	0.502032	9	0.4110222
2006	0.111987	6	0.492049	10	0.4567436
2010	0.097064	7	0.455436	9	0.4980083

Indicator	**45**	**46**	**47**	**49**	**50**
1990	0.00024464	0.00353507	0.00029288	0	0
1994	0.00017292	0.00455282	0.00019663	17	60
1998	0.00012795	0.00247476	0.00014531	59	85
2002	0.00014736	0.00333301	0.00015004	63	86
2006	0.00019413	0.00737488	0.00013115	69	87
2010	0.00025223	0.01218631	0.00011712	70	84

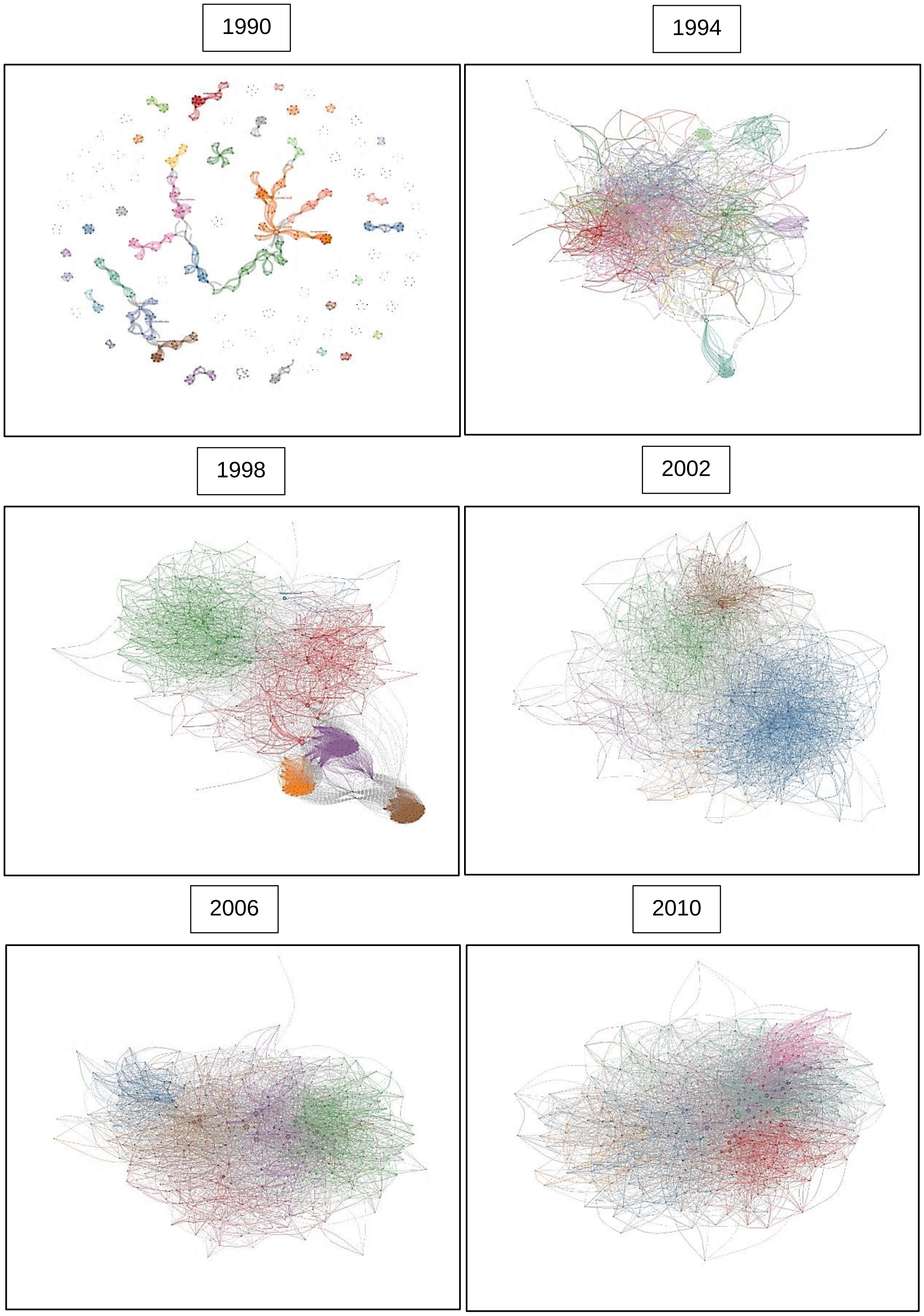

Figure 12: Author Keyword Co-occurrences Network (1990, 1994, 1998, 2002, 2006 & 2010) of Biotechnology. N= max. 500

Particle & Field Physics

Particle & Field Physics has grown from 6330 publications in 1990 to 10576 publications in 2010. The organizational size consisted of 16795 active researchers in 1990 and has grown to a size of 34989 researchers. The annual organizational size and output size have seen annual growths and declines, but the field has seen a netto growth of 167% in output size and a 208% growth in organizational size in the 20 year period as can be seen in Table 22: Descriptive results Particle & Field PhysicsTable 22.

Table 22: Descriptive results Particle & Field Physics

Year	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Organizational Size	16795	15773	19056	20276	21903	21917	22751	22456	23538	24640
Size Growth (%)		-6	21	6	8	0	4	-1	5	5
Output Size	6330	6264	6836	7040	7646	7528	8144	8487	8762	9210
Output Growth (%)		-1	9	3	9	-2	8	4	3	5

Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Organizational Size	23971	24821	25769	26840	28386	30232	29950	30887	26764	31390	34989
Size Growth (%)	-3	4	4	4	6	7	-1	3	-13	17	11
Output Size	9023	9588	9511	9810	10562	10769	10185	10133	9853	10565	10576
Output Growth (%)	-2	6	-1	3	8	2	-5	-1	-3	7	0

Functional Dependence

Table 23 show the quantitative results for the concept functional dependence in the field of Particle & Field Physics. The field has roughly witnessed an increase in its author citation variance (ind. 1) while it has seen some rises and declines over the time period. The increase in variance is accompanied with a fluctuating author citation count Gini-index (ind. 2) which has ultimately decreased by approximately 0.054 in the 20 year time span. The fractionalized citation count (ind. 3) also shows a slight decrease but shows a different pattern over time with it inverse U-shape. The proportion of citations in possession of the top 10 (ind. 6), the top 1% (ind. 4) and top 10% (ind. 5) most cited authors has decreased over time and has the similar inverse U-shaped pattern like indicator 3. Subsequently, the stability of the top 100 most cited authors (ind. 20) has been and relatively stable but became increasingly more unstable as of 2002. Based on these patterns, we can conclude that the field has become more egalitarian in their author citation count even though most indicators show an opposite trend until 1998.

Particle & Field Physics has seen a similar trend for its institution citation standard deviation (ind. 7); its institution’s citation count Gini-index (ind. 8) and its fractionalized Gini-index (ind. 9) as that for the authors by showing the same inverted U-shape. However, the inequality has ultimately increased in the 20 years. It shows that the citation counts of institutions has become more unequal over time, implying a higher inequality in the reputational system. The top 10 most cited institutions (ind. 10) have seen a rough inverse U-shape in its pattern of proportional citation possession, overall remaining quite similar in 2010 (9.9%) to that of 1990 (9.0%). In addition, the stability of the top 10 (ind. 11) and top 50 most cited institutions (ind. 21) has been relatively stable, fluctuating around 5 institutions out of 10 remaining in the top 10 after 4 years. Overall, the institution citation count distribution has become less equal and remains highly skewed.

The standard deviation of the authors dominance factor (ind. 12) has shown a gradual increase. A decrease in the author equality in terms of their dominance factor can be observed based on the author dominance factor Gini-index (ind. 13).

Subsequently, the results of the author collaboration network analysis show that the standard deviation of the authors degree centrality (ind. 15) displays an inverse U-shaped trend, resulting in an netto increase of 0.02. This is accompanied with a slight decrease in the Gini-index of the author degree centrality (ind. 14) which ultimately resulted in an increase in its equality, implying that the amount of collaborations with unique fellow colleagues has become slightly more equal. The Gini-index of the author betweenness centrality (ind. 16) is very high but lower than the other empirical cases from the emerging category. The broker positions are highly unequal whilst the variance predominantly seems to have decreased (ind. 17). The authority score of authors (ind. 18) was, similar to that of the betweenness centrality, immensely high.

Overall the field has witnessed an increase in its author citation equality while the institution citation equality has decreased. This is accompanied with the an increase of the collaboration dominance inequality while the collaboration network analysis shows mixed results. Ultimately the citation inequality is high and the ranking are rather stable. Therefore the functional dependence is estimated to have been high and remain high.

Table 23: Results functional dependence Particle & Field Physics

Indicator	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1990	258.3621	0.760822	0.820659	0.314114	0.747136	0.062452	516.2727	0.769857	0.786313	0.090133
1994	215.9693	0.734841	0.823695	0.311416	0.742536	0.069911	611.4499	0.808655	0.819603	0.105827
1998	360.2824	0.754248	0.831684	0.342769	0.755335	0.08553	1186.003	0.837152	0.846849	0.171808
2002	252.2919	0.723664	0.814495	0.294329	0.724743	0.045197	920.9349	0.821582	0.836849	0.128124
2006	435.1692	0.783964	0.800114	0.239504	0.698068	0.028412	1345.794	0.864369	0.83094	0.088761
2010	403.5711	0.706096	0.795563	0.226828	0.693847	0.022311	948.2358	0.8255	0.837407	0.099289

Indicator	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
1990	NA	0.276361	0.158067	0.792568	0.011454	0.945819	0.000558	0.95201	0.179413
1994	4	0.304559	0.191466	0.7561	0.008806	0.937813	0.000399	0.954373	0.160891
1998	5	0.320234	0.217369	0.724902	0.008571	0.922403	0.000379	0.953944	0.159177
2002	5	0.314409	0.21539	0.73247	0.007292	0.923889	0.000373	0.934628	0.141019
2006	6	0.324896	0.225871	0.733658	0.008494	0.921601	0.000292	0.934156	0.141672
2010	4	0.333778	0.23828	0.765088	0.03427	0.926599	0.000272	0.881368	0.276761

Indicator	**20**	**21**
1990	NA	NA
1994	15	22
1998	20	25
2002	18	26
2006	13	30
2010	9	32

Strategic Dependence

Table 24 shows the quantitative indicators used for the concept strategic dependence in the field of Particle & Field Physics. The field has seen an increase in the collaboration coefficient (ind. 23). Approximately 73% of all papers were written in collaboration in 1990 while this has risen to 83% in 2010. The mean co-author count (ind. 22) has increased in this period from 7.40 authors per paper to 13.58. The standard deviation (ind. 24) of this co-author count has grown from 35.47 in 1990 to 108.10 in 2010. This shows that Particle & Field Physics is fundamentally different in its strategic dependence than the prior fields discussed. The inequality of the co-author count in the form of the Gini-index (ind. 25) has roughly risen from 0.74 to 0.83. The overall network degree centrality (ind. 26) has increased from 0.07 (1990) to 0.20 (2010), while the network density (ind. 27) in the field remained stable until 2010 in which it shows a dramatic increase.

When one observes the author collaboration network analysis (Figure 13) of the top 500 most cited authors, one can roughly conclude that collaborations have intensified. But in contrast to the prior fields, Particle & Field Physics already showed a strong collaboration network in 1990 and therefor seems more mature.

Based on these results, it can be concluded that the field of Particle & Field Physics operates under a high strategic dependence which, in addition, has seen an increase in the 20 years' time period.

Table 24: Results strategic dependence Particle & Field Physics

Indicator	**22**	**23**	**24**	**25**	**26**	**27**
1990	7.398262	0.725277	35.47173	0.739738	0.07119201	0.00574014
1994	9.210044	0.735156	42.23815	0.774222	0.05682786	0.00505265
1998	11.98494	0.751883	54.13832	0.817438	0.0810432	0.00541491
2002	9.497319	0.755967	42.82902	0.777218	0.06032539	0.00443
2006	12.04408	0.779381	59.95943	0.812683	0.08150759	0.00518114
2010	13.58444	0.828763	108.0954	0.82911	0.19638599	0.01985318

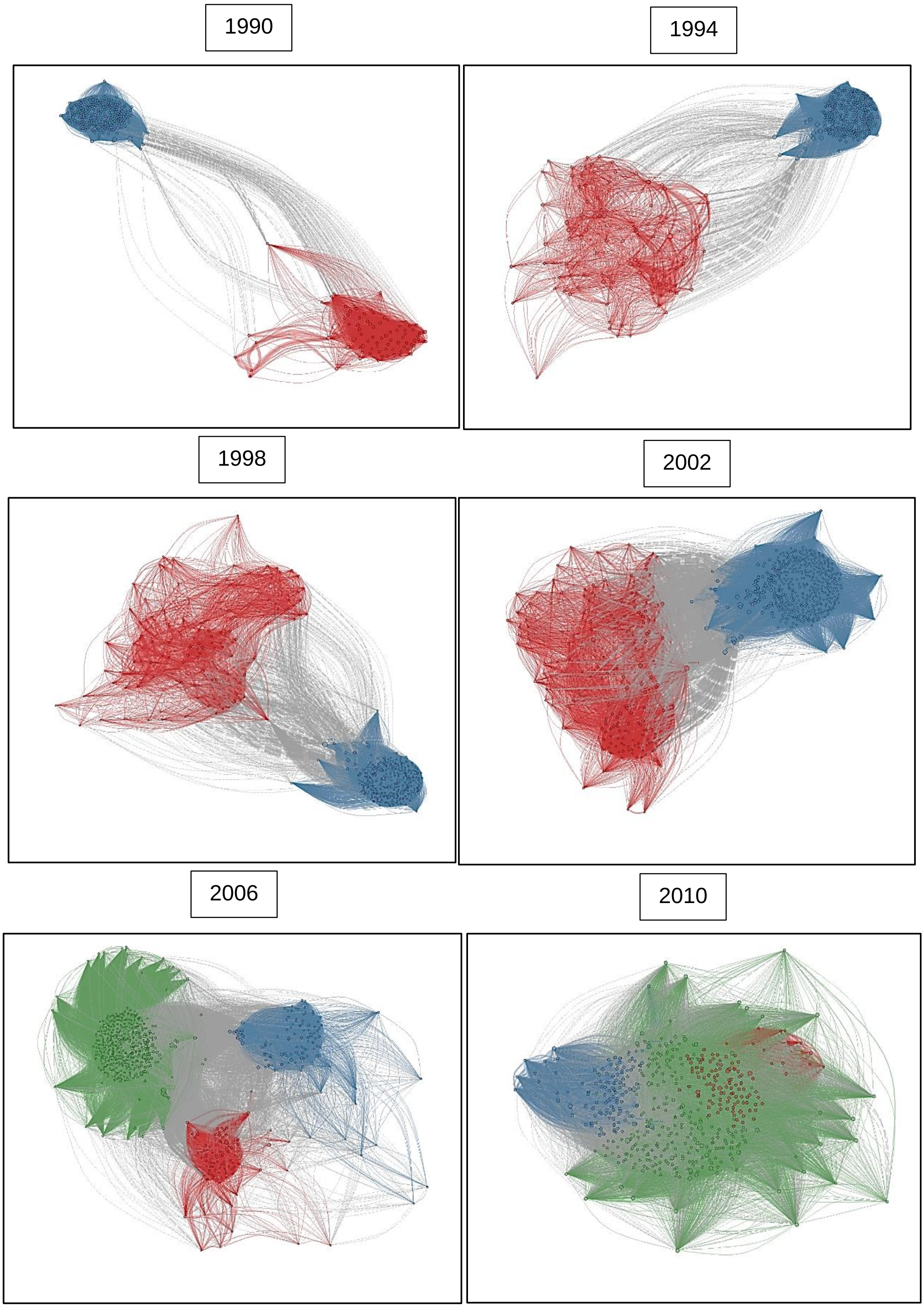

Figure 13: Author Collaboration Network (1990, 1994, 1998, 2002, 2006 & 2010) of Particle & Field Physics. N=500

Technical Task Uncertainty

By observing the indicators used for the concept technical task uncertainty, one can notice that the mean cited reference count (ind. 28) has risen greatly from 22.3 references per paper in 1990 to 38.8 in 2010. Papers have, however, seen a slight increase in its mean page count (ind. 29) over the years. From these indicators one can conclude that papers became more reference dense based on the increase in mean references per page (ind. 30) from 2.7 to 4.2.

The dominance of the top 10 references has increased dramatically based on the proportion of the top 10 most used references of the total references count in the year (ind. 31). A similar trend is found when controlling for the publication output size of the field by dividing the sum of the top 10 most used references by the total publication output size (ind. 33). When we dive deeper in the references, it can be found that the stability of the top 10 most used references (ind. 32) has been low and unstable. Here Witten E. (1998), Gubser S.S. (1998), Randall L. (1999), and Maldenca J.M. (1998) form manuscripts that managed to remain in the top 10 for at least 8 years. Witten E. is the only scholar that managed to not only write a reoccurring top cited manuscript, but was the only one that managed to be present and reoccur in the top 10 most cited author list. Surprisingly, the top 100 most used references stability (ind. 38) is medium/high, which contrasts the stability of the top 10 references.

Based on a bibliographic coupling network of the field, it can be found that the inequality of the reference degree centrality (ind. 34) is relatively average and has roughly remained at the same level, indicating that the equality of reference-to-reference connectivity has barely changed, while its standard deviation (ind. 35) almost doubled. The overall bibliographic coupling network's degree centrality (ind. 36) has increased and its density (ind. 37) ultimately too.

The field has seen an increase in its citing half-life (ind. 39), moving from 5 to 7 years which are relatively average citing half-lives compared to other fields. Its citing mean-life (ind. 48) appeared to have increased greatly, initially it was relatively low, but grew to medium/high levels. The rate of knowledge accumulation appears to be high and stable (ind. 51).

The bibliographic coupling networks of the top 500 most used references (Figure 14) show that the network was already relatively dense. Over the years, clusters seem to compete for this top 500 position while they are highly interconnected. Ultimately a converging trend in terms of clusters presented itself, making the top 500 more homogeneous.

Ultimately, it is difficult to derive clear conclusions from empirical data regarding the technical task uncertainty of a field. However, the data shows that papers are average in their reference density; it shows that there is an instable but very dominant top 10 reference base; a very stable top 100 reference base; its reference degree centrality inequality is average; its bibliographic coupling network is rather saturated and increasingly homogeneous; and the knowledge accumulation indicator shows that it is a highly cumulative field. Therefore, the field is therefore estimated to be medium/low in its technical task uncertainty.

Table 25: Results technical task uncertainty Particle & Field Physics

Indicator	**28**	**29**	**30**	**31**	**32**
1990	22.31688	8.352569	2.671859	0.202373	NA
1994	24.01228	9.031685	2.658671	0.159546	1
1998	25.49742	9.294966	2.743143	0.238799	1
2002	29.52222	9.578857	3.082019	0.303116	0
2006	31.81347	8.797765	3.616085	0.289891	5
2010	38.77187	9.286826	4.174932	0.364161	6

Indicator	33	34	35	36	37	38	39	48	51
1990	0.18594	0.6222581	0.01716619	0.10960072	0.01375844	NA	5	7.40027	NA
1994	0.156291	0.5815875	0.01459441	0.09651904	0.01283348	77	5	8.405943	0.8577339
1998	0.237845	0.6145379	0.02126824	0.10314208	0.0170634	54	6	3.829482	0.6887139
2002	0.302702	0.6263575	0.02565697	0.15421248	0.02002516	57	6	9.293156	0.7828867
2006	0.289151	0.639332	0.02651589	0.14143901	0.02002239	69	6	10.067279	0.764065
2010	0.363748	0.6166183	0.03683814	0.16673746	0.02949859	34	7	10.910861	0.853564

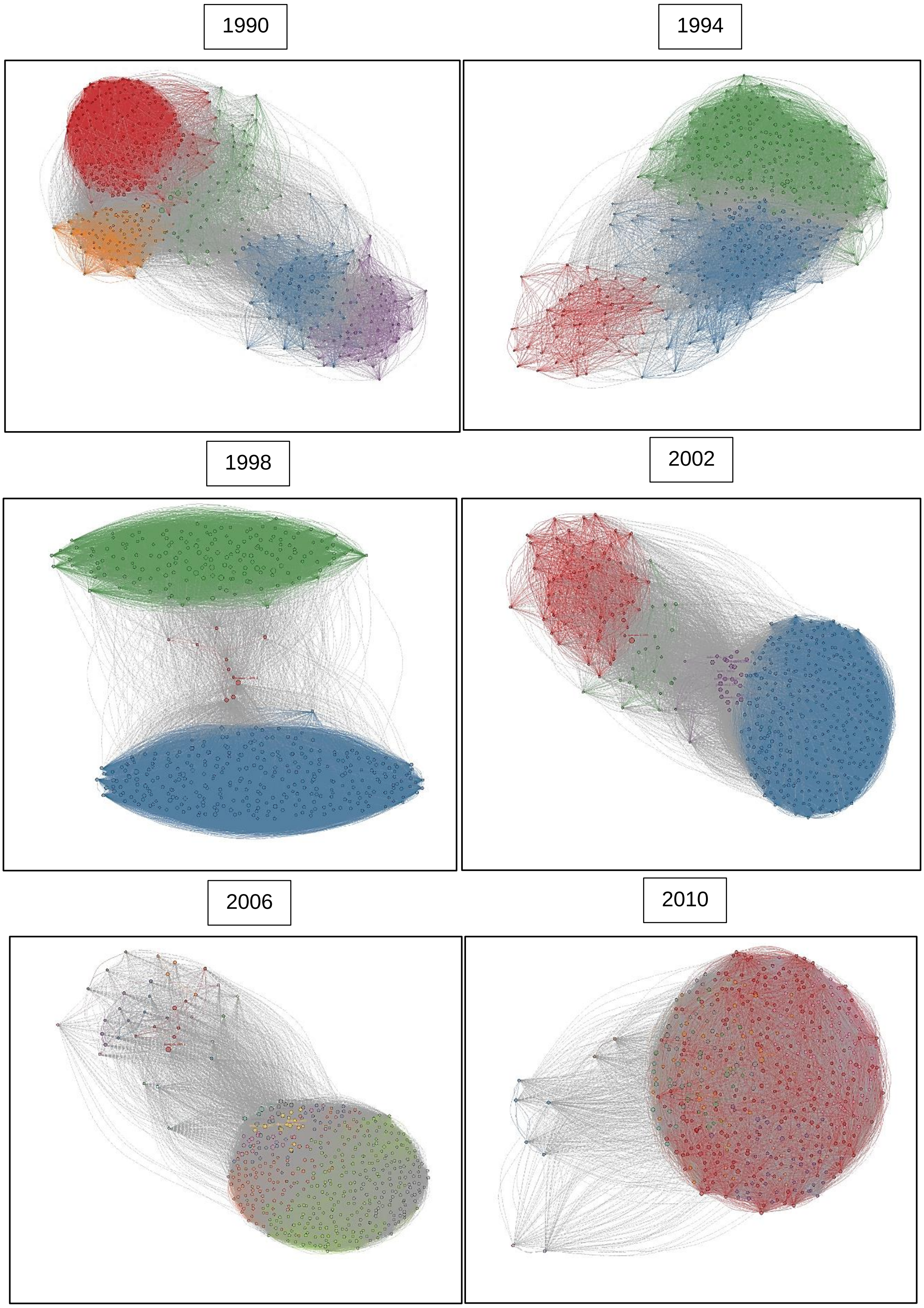

Figure 14: Bibliographic Coupling Network (1990, 1994, 1998, 2002, 2006 & 2010) of Particle & Field Physics, N= max. 500

Strategic Task Uncertainty

By exploring the indicators used for the concept strategic task uncertainty, one can gain a more comprehensive understanding of its nature in the field Particle & Field Physics.

Author keywords were unfortunately not yet integrated in the database in the year 1990. Subsequently, the field shows a diverging dynamic based on the sum of the proportional occurrence of the top 10 author keywords (ind. 40). The sum of their occurrence proportion contained 0.40 in 1994 but dropped to 0.28 in 2010. A contradicting trend is found for its keyword plus counter partner (ind. 42), which remained rather stable over the years. The stability of the top 10 author keywords (ind. 41) seemed to have increased from 0 remaining in the top 10 over 1990/1994 to 9 in 2006/2010. The stability of the keyword plus top 10 ranking (ind. 43) is showing higher levels of stability than the author keywords ranking. Lastly, the stability of the top 100 author keywords (ind. 49) and top 100 keyword plus tags (ind. 50) have risen and predominantly moved from low/medium levels of stability to relatively high ones.

Based on the author keyword co-occurrences network, it is seen that the Gini-index author keyword node degree centrality (ind. 44) has decreased but remains high. Meaning that the co-occurrences of author keywords was highly unequal and become slightly more egalitarian. Overall the implications of this is that the field seems highly directed in terms of topics. Its standard deviation (ind. 45) has predominantly grown. The overall degree centrality (ind. 46) and density (ind. 47) have increased.

Figure 15 shows the annual author keyword co-occurrence network of the top 500 most used author keywords which visualizes that the field became more mature; clusters increased in size and became more connected with other clusters which indicates that isolated topics bonded and form one more coherent field.

The results of the indicators clearly show that the field has gained more stability in terms of topics. The topic node degree centrality is and remains highly unequal; the top 10/top 100 most used keywords became increasingly more stable but have seen an additional increase of this. Therefore it is concluded that the strategic task uncertainty, compared to the other fields, was medium but decreased its uncertainty to low levels.

Table 26: Results strategic task uncertainty Particle & Field Physics

Indicator	**40**	**41**	**42**	**43**	**44**
1990	NA	NA	0.375854	NA	0.7925677
1994	0.404494	NA	0.367936	6	0.7561001
1998	0.245499	0	0.365579	5	0.7249021
2002	0.235466	3	0.334217	6	0.7324697
2006	0.233228	3	0.359731	8	0.7336577
2010	0.279596	9	0.380168	8	0.7650882

Indicator	**45**	**46**	**47**	**49**	**50**
1990	0.01145369	0.07119201	0.00574014	NA	NA
1994	0.00880644	0.05682786	0.00505265	NA	59
1998	0.00857066	0.0810432	0.00541491	6	75
2002	0.00729181	0.06032539	0.00443	46	79
2006	0.00849372	0.08150759	0.00518114	67	82
2010	0.03427009	0.19638599	0.01985318	73	85

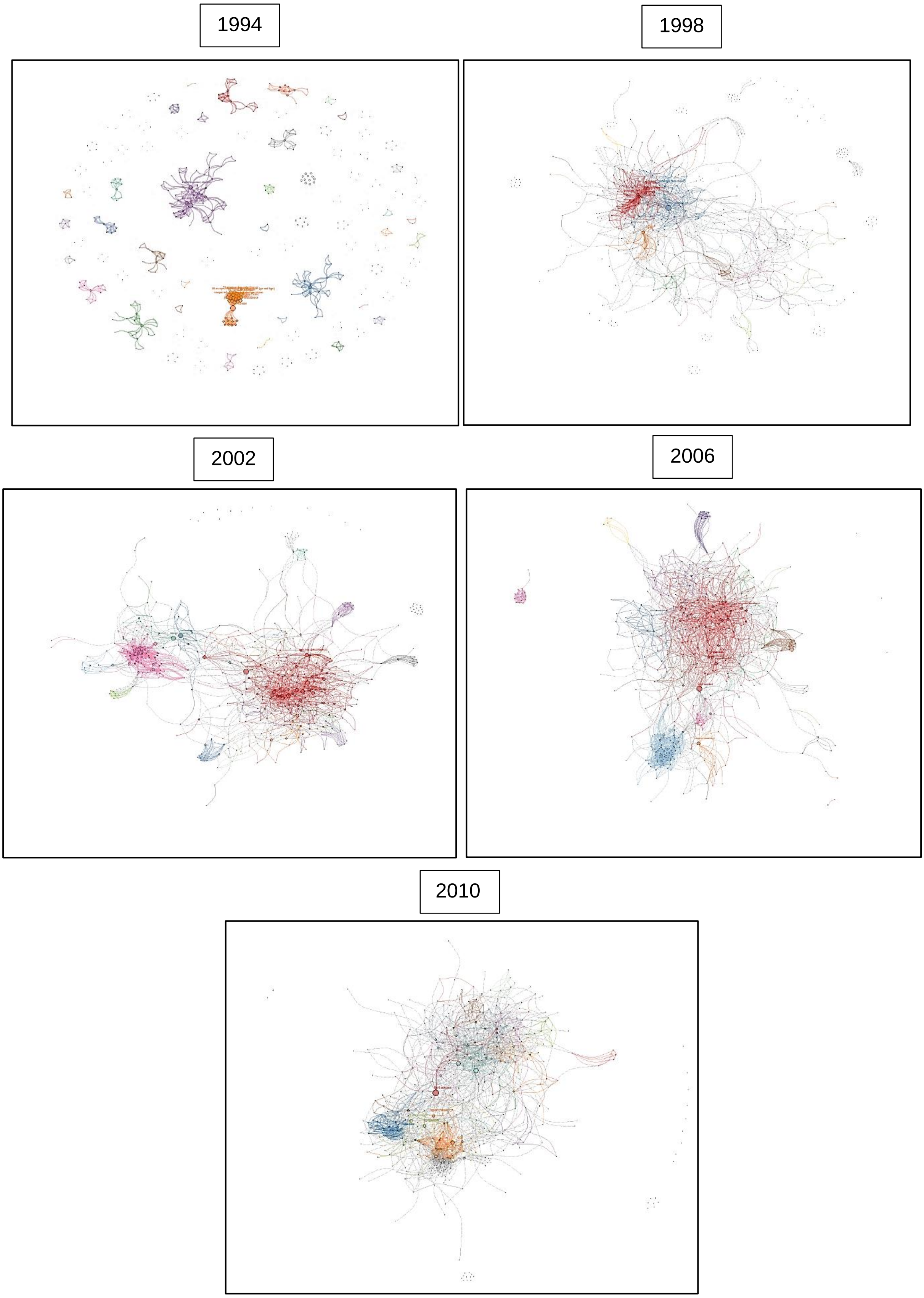

Figure 15: Author Keyword Co-occurrences Network (1994, 1998, 2002, 2006 & 2010) of Particle & Field Physics. N= max. 500

Applied Mathematics

Applied Mathematics has grown from 6328 publications in 1990 to 21944 publications in 2010. The organizational size consisted of 8522 active researchers in 1990 and has grown to a size of 29747 researchers. The annual organizational size and output size have seen mostly annual growths, and the field has seen a netto growth of 347% in output size and a 349% growth in organizational size in the 20 year period as can be seen in Table 27.

Table 27: Descriptive results Applied Mathematics

Year	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Organizational Size	8522	8475	9238	9645	10841	11778	12898	13699	14338	14350
Size Growth (%)		-1	9	4	12	9	10	6	5	0
Output Size	6328	6378	6802	7049	7688	8166	9090	9783	9973	9841
Output Growth (%)		1	7	4	9	6	11	8	2	-1

Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Organizational Size	15182	16992	16844	18358	19076	21619	24370	23979	27524	29408	29747
Size Growth (%)	6	12	-1	9	4	13	13	-2	15	7	1
Output Size	10601	11981	11705	13067	12999	15388	17360	17410	19986	21613	21944
Output Growth (%)	8	13	-2	12	-1	18	13	0	15	8	2

Functional Dependence

Table 28 show the quantitative results for the concept functional dependence in the field of Applied Mathematics. The field has witnessed a fluctuation in its author citation variance (ind. 1) remaining roughly the same after 20 years. The author citation count Gini-index (ind. 2) has seen a slight decrease after a parabola shaped pattern during the time period. This is also found for the fractionalized citation count (ind. 3). The proportion of citations in possession of the top 10 (ind. 6) and the top 10% (ind. 5) has dropped while the top 1% (ind. 4) has remained stagnant throughout the period. Subsequently, the stability of the top 100 most cited authors (ind. 20) has been unstable but increased in its stability in 2010. Based on these patterns, we can conclude that the equality is more stable than previous fields discussed although the citation distribution is still highly skewed.

Applied Mathematics has seen a fluctuating institution citation standard deviation (ind. 7); a fluctuating institution's citation count Gini-index (ind. 8) and a fluctuating fractionalized Gini-index (ind. 9) overall remaining on similar levels throughout the years. The top 10 most cited institutions (ind. 10) have seen an inverse U-shape in its pattern of proportional citation possession, ultimately moving from 2.9 % (1990) to 5.3% (2010). In addition, the stability of the top 10 (ind. 11) and top 50 most cited institutions (ind. 21) has been relatively stable, fluctuating between 2 and 5 institutions out of 10 remaining in the top 10 after 4 years. Overall, the institution citation count distribution is unequal but has remained rather stable throughout the years.

The standard deviation of the authors dominance factor (ind. 12) has shown a gradual increase. A decrease in the author equality in terms of their dominance factor can be observed based on the author dominance factor Gini-index (ind. 13).

Subsequently, the results of the author collaboration network analysis show that the standard deviation of the authors degree centrality (ind. 15) remained roughly the same. This is accompanied with a slight decrease in the Gini-index of the author degree centrality (ind. 14). The Gini-index of the author betweenness centrality (ind. 16) showed a slight inverse U-shape. The broker position is highly unequal and the variance predominantly seems to have increased (ind. 17). The authority score of authors (ind. 18) was, similar to that of the betweenness centrality, immensely high.

Overall the field shows a rather stable functional dependence in comparison to previously explored empirical cases. The dominance factor, however, has seemed to have increased. In comparison to other fields, its functional dependence was rather medium/high, but due to its stagnated levels, it became relatively medium in its levels due to an overall growth in functional dependence of other fields.

Table 28: Results functional dependence Applied Mathematics

Indicator	1	2	3	4	5	6	7	8	9	10
1990	70.7725	0.773853	0.777063	0.237469	0.646354	0.075194	150.4223	0.781982	0.77903	0.029272
1994	59.22957	0.738192	0.747411	0.205464	0.609799	0.048354	173.8758	0.770858	0.77332	0.092404
1998	107.1823	0.735234	0.736919	0.233622	0.60365	0.051509	320.8136	0.798417	0.799957	0.128885
2002	61.2199	0.696467	0.702739	0.179102	0.55694	0.033494	229.8942	0.777215	0.782997	0.081268
2006	66.08079	0.703605	0.715205	0.199748	0.575814	0.042494	241.2742	0.785664	0.794477	0.072736
2010	61.45425	0.712486	0.720487	0.223377	0.595231	0.027913	208.3161	0.786666	0.795451	0.053346

Indicator	11	12	13	14	15	16	17	18	19
1990	NA	0.172384	0.059427	0.495892	0.000166	0.980351	2.41E-07	0.998349	0.036191
1994	3	0.172655	0.060146	0.476566	0.000141	0.983396	5.35E-07	0.998771	0.030244
1998	3	0.198791	0.080003	0.454394	0.000119	0.992765	1.96E-05	0.999042	0.029666
2002	5	0.208012	0.086462	0.446088	0.000109	0.98682	0.000174	0.998608	0.02154
2006	2	0.235264	0.112501	0.46697	0.000136	0.971126	0.000133	0.996828	0.038649
2010	3	0.244203	0.121684	0.482479	0.000146	0.971451	0.000181	0.958766	0.02855

Indicator	20	21
1990	NA	NA
1994	3	18
1998	8	25
2002	10	26
2006	9	27
2010	22	20

Strategic Dependence

Table 29 shows the quantitative indicators used for the concept strategic dependence in the field of Applied Mathematics. The field has seen an increase in the collaboration coefficient (ind. 23). Approximately 50% of all papers were written in collaboration in 1990 while this has risen to 73% in 2010. The mean co-author count (ind. 22) has increased in this period from 1.69 authors per paper to 2.21. The standard deviation (ind. 24) of this co-author count has grown from 0.87 in 1990 to 1.07 in 2010. This shows that Applied Mathematics is an outlier in its strategic dependence than the prior fields discussed. Collaborations are less frequently present and lower in co-author count than other fields. The inequality of the co-author count in the form of the Gini-index (ind. 25) has remained low and very stable over time. The overall network degree centrality (ind. 26) has increased from 0.002 (1990) to 0.005 (2010), while the network density (ind. 27) in the field decreased.

Unfortunately the data of 1990 of this field was not suitable for a visualization, since continuous cluster algorithms failure occurred. When one observes the other author collaboration network analyses (Figure 16) of the top 500 most cited authors, one can roughly conclude that collaborations have intensified.

Based on these results, it can be concluded that applied mathematics operates under a low strategic dependence which has increased in the last 20 years but remained relatively low.

Table 29: Results strategic dependence Applied Mathematics

Indicator	**22**	**23**	**24**	**25**	**26**	**27**
1990	1.692794	0.504741	0.872167	0.246103	0.00207864	0.00015718
1994	1.802419	0.561134	0.928207	0.252134	0.0017871	0.00014057
1998	1.931816	0.623082	0.976439	0.253347	0.00134555	0.00012494
2002	2.027253	0.662965	1.023072	0.254288	0.00134505	0.0001148
2006	2.159389	0.71803	1.057208	0.248088	0.00358603	9.82E-05
2010	2.218693	0.733823	1.065411	0.248824	0.00473474	9.21E-05

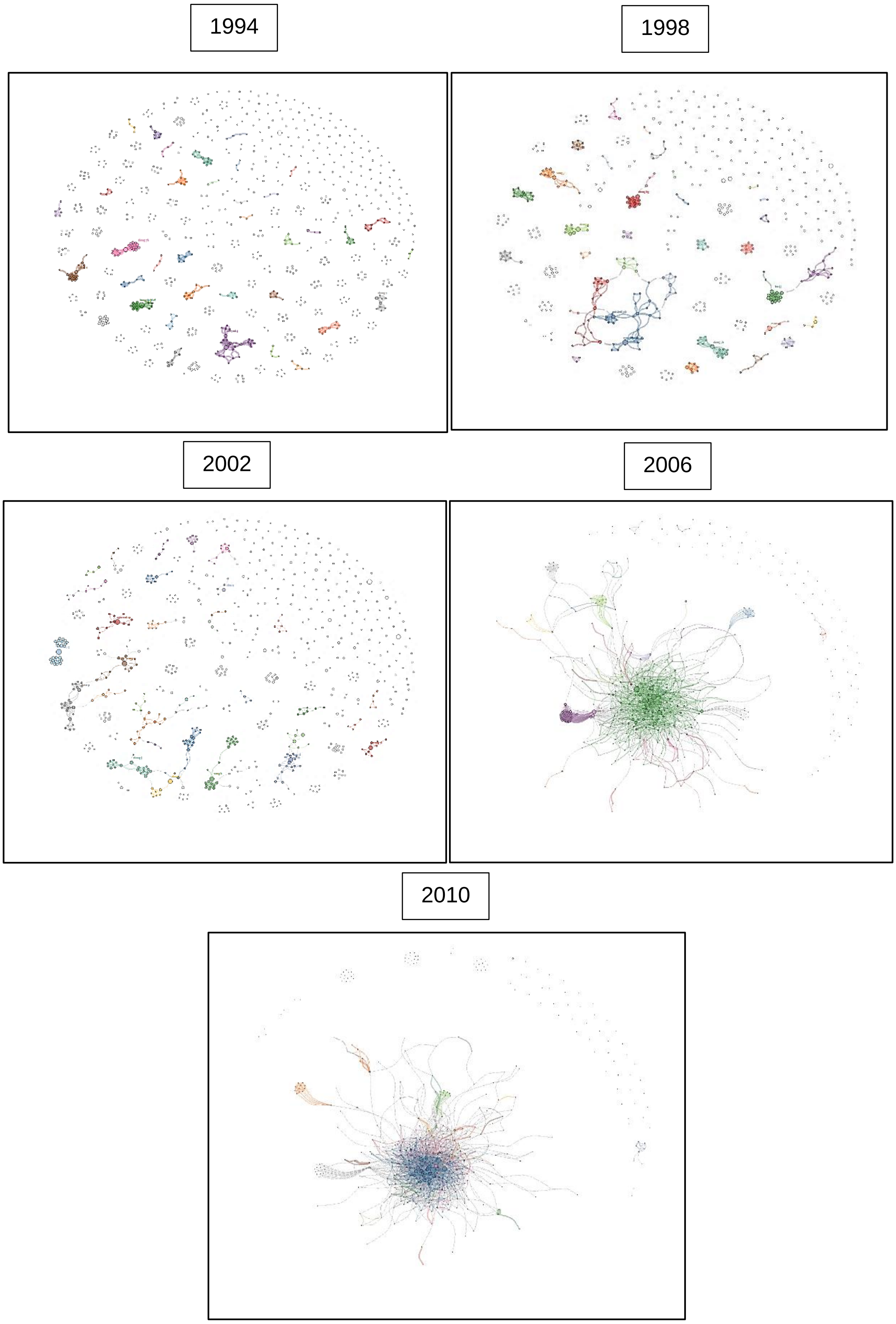

Figure 16: Author Collaboration Network (1994, 1998, 2002, 2006 & 2010) of Applied Mathematics. N=500

Technical Task Uncertainty

By observing the indicators used for the concept technical task uncertainty, one can notice that the mean cited reference count (ind. 28) has risen greatly from 14.4 references per paper in 1990 to 22.3 in 2010. Papers have seen a slight increase in its mean page count (ind. 29) over the years. From these indicators one can conclude that papers became slightly more reference dense, based on the increase in mean reference per page (ind. 30) from 1.12 to 1.56.

The dominance of the top 10 references is low and has decreased by approximately 1/3, based on the proportion of the top 10 most used references of the total references count in the year (ind. 31). A similar trend is found when controlling for the publication output size of the field by dividing the sum of the top 10 most used references by the total publication output size (ind. 33). When we dive deeper in the references, it can be found that the stability of the top 10 most used references (ind. 32) has been very high and stable. Here, a substantial amount of manuscripts manages to remain in the top 10 ranking longer than 4 years. Its top 100 most used references stability (ind. 38) is medium/high.

Based on a bibliographic coupling network of the field, it can be found that the inequality of the reference degree centrality (ind. 34) is relatively low and has decreased over time, indicating that the equality of reference-to-reference connectivity was low and became lower over time. This is accompanied with a decrease in its standard deviation (ind. 35). The overall bibliographic coupling network's degree centrality (ind. 36) has decreased and its density (ind. 37) ultimately too.

The field has seen an increase in its citing half-life (ind. 39), moving from 8 to 10 years which are high citing half-lives compared to other fields. Its citing mean-life (ind. 48) appeared to be incredibly high and has increased greatly over the time period. The rate of knowledge accumulation seems to be stable and medium (ind. 51).

The bibliographic coupling networks of the top 500 most used references (Figure 17) show that the network is relatively scattered. Over the years, this remains the same showing that Applied Mathematics is very heterogeneous in its reference core.

Ultimately, it is difficult to derive clear conclusions from empirical data regarding the technical task uncertainty of a field. However, the data shows that papers are low in their reference density; it shows that there is a stable but a non-dominant top 10 reference base; it shows average levels of stability in its top 100 reference base; its reference degree centrality inequality is low; its bibliographic coupling network is rather scattered and heterogeneous; and the knowledge accumulation indicator shows that it is a medium cumulative field. Therefore, the field is estimated to be high in its technical task uncertainty.

Table 30: Results technical task uncertainty Applied Mathematics

Indicator	**28**	**29**	**30**	**31**	**32**
1990	14.395	12.82626	1.122307	0.091623	NA
1994	16.52064	14.66819	1.126291	0.095556	7
1998	17.90512	15.11565	1.184541	0.091969	8
2002	18.45285	15.56799	1.185307	0.074191	7
2006	19.00894	14.40385	1.319713	0.05635	7
2010	22.30884	14.29532	1.56057	0.061366	8

Indicator	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**48**	**51**
1990	0.090392	0.6436992	0.00423931	0.02749539	0.0030088	NA	8	12.00843	NA
1994	0.094823	0.6272174	0.00447282	0.03117448	0.00331277	50	8	12.44042	1.1133787
1998	0.091748	0.6238719	0.00440612	0.02827309	0.00321508	60	8	13.1028	1.1395483
2002	0.074071	0.6072683	0.00336251	0.02976358	0.00253859	68	9	13.93003	0.9971647
2006	0.056279	0.5882532	0.0025523	0.02124891	0.002027	42	9	14.22195	1.2485337
2010	0.061201	0.5734264	0.00311795	0.02360158	0.00264825	19	10	15.15375	1.2076138

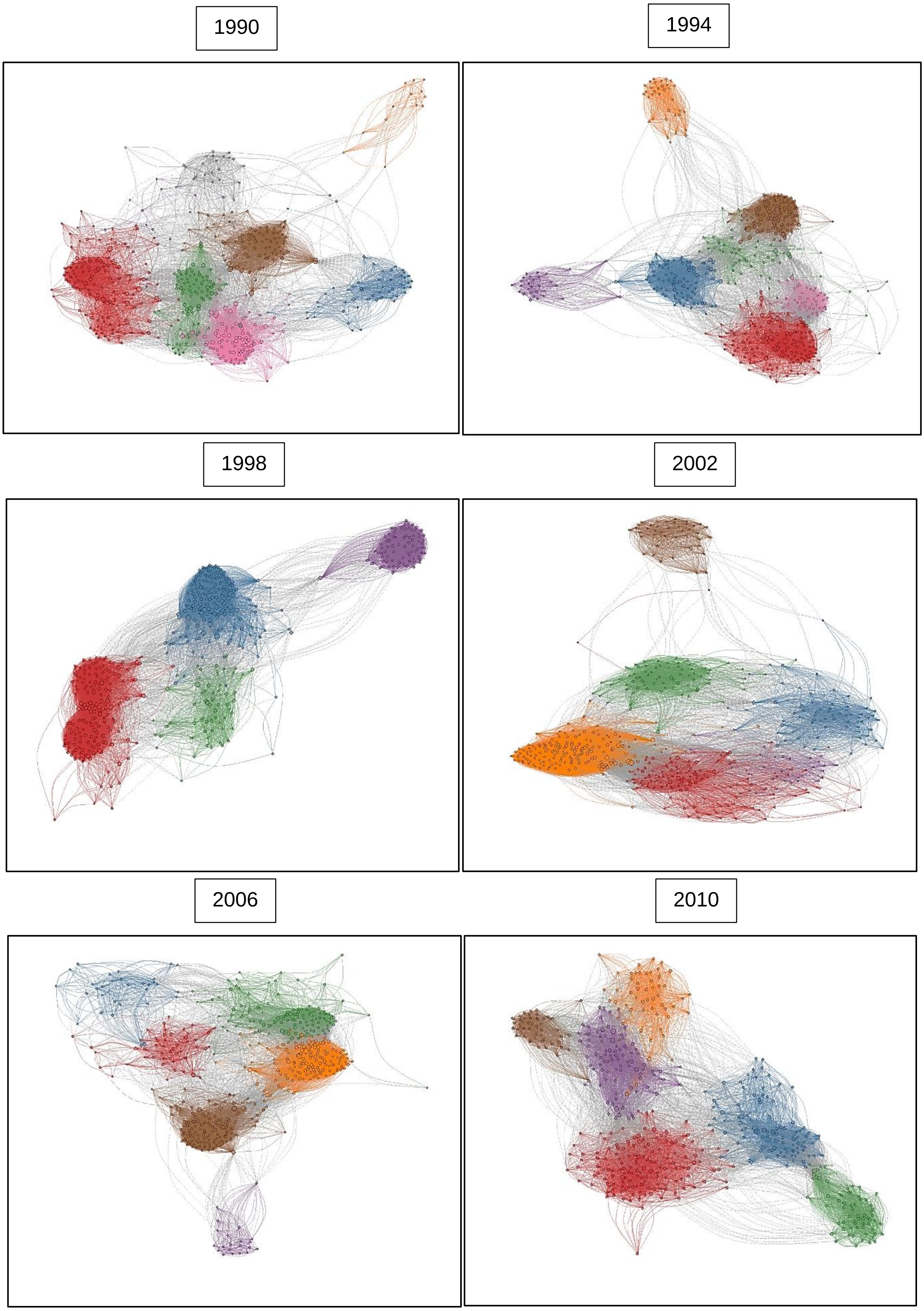

Figure 17: Bibliographic Coupling Network (1990, 1994, 1998, 2002, 2006 & 2010) of Applied Mathematics, N= max. 500

Strategic Task Uncertainty

By exploring the indicators used for the concept strategic task uncertainty, one can gain a more comprehensive understanding of its nature in the field Applied Mathematics.

The field shows a diverging dynamic based on the sum of the proportional occurrence of the top 10 author keywords (ind. 40). The sum of their occurrence proportion dropped from 0.15 in 1990 to 0.08 in 2010. A contradicting trend is found for its keyword plus counter partner (ind. 42), which actually increased over the years. The stability of the top 10 author keywords (ind. 41) seemed to have increased from 4 remaining in the top 10 over 1990/1994 to 7 in 2006/2010. When analyzing this ranking to a higher extend one can notice that although the field seems to shift to different coherent topics, it still encompasses overarching concepts throughout the whole period (i.e. optimization, finite element method, chaos, bifurcation, stability, etc.). The stability of the keyword plus top 10 ranking (ind. 43) is showing higher levels of stability than the author keywords ranking. Lastly, the stability of the top 100 author keywords (ind. 49) and top 100 keyword plus tags (ind. 50) have risen greatly, but its relative stability to other fields has remained on medium/high levels.

Based on the author keyword co-occurrences network, it is seen that the Gini-index author keyword node degree centrality (ind. 44) has decreased but managed to increase again as of 2006. Generally its inequality has thus fluctuated at medium/high levels. Meaning that the co-occurrences of author keywords was and remained unequal to a medium/high. Overall the implications of this is that the field seems fairly directed in terms of topics. Its standard deviation (ind. 45) has slightly dropped. The overall degree centrality (ind. 46) has increased while its density (ind. 47) has decreased.

Figure 18 shows the annual author keyword co-occurrence network of the top 500 most used author keywords which visualizes that the field became more mature; clusters became more connected with other clusters which indicates that isolated topics bonded and form one more coherent field.

The results show that the topic node degree centrality is and remains fairly unequal; the top 10/top 100 most used keywords became increasingly more stable. Therefore it is concluded that the strategic task uncertainty, compared to the other fields, was and remains medium/low.

Table 31: Results strategic task uncertainty Applied Mathematics

Indicator	**40**	**41**	**42**	**43**	**44**
1990	0.145833	NA	0.2625	NA	0.4958917
1994	0.087688	4	0.272243	7	0.4765659
1998	0.086473	4	0.304703	9	0.4543936
2002	0.079736	5	0.3076	10	0.4460884
2006	0.076865	7	0.344081	9	0.4669696
2010	0.078635	7	0.354143	9	0.4824785

Indicator	**45**	**46**	**47**	**49**	**50**
1990	0.00016622	0.00207864	0.00015718	0	0
1994	0.00014083	0.0017871	0.00014057	31	48
1998	0.00011905	0.00134555	0.00012494	65	78
2002	0.00010871	0.00134505	0.0001148	66	84
2006	0.00013591	0.00358603	9.82E-05	73	83
2010	0.00014609	0.00473474	9.21E-05	70	82

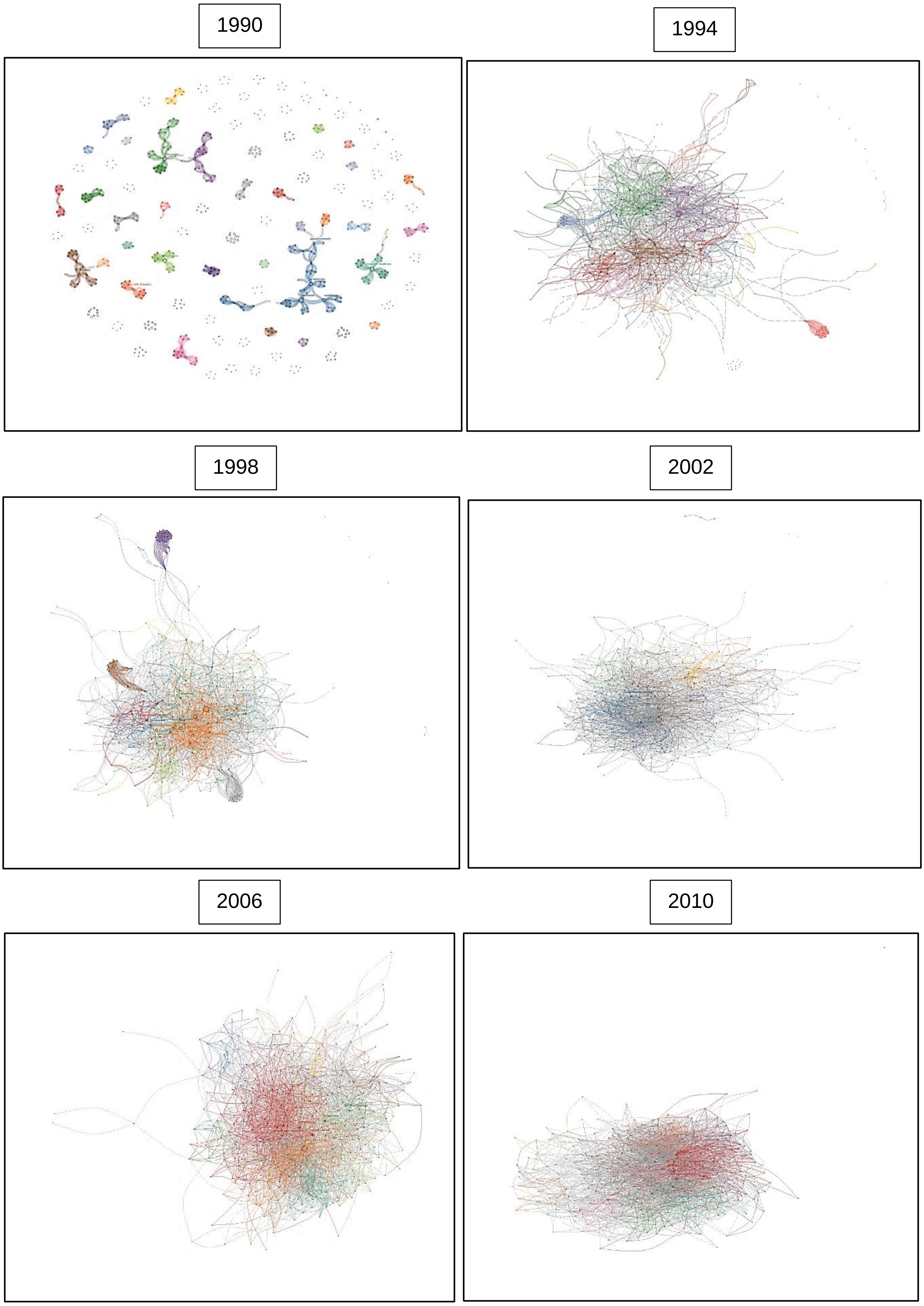

Figure 18: Author Keyword Co-occurrences Network (1990, 1994, 1998, 2002, 2006 & 2010) of Applied Mathematics. N= max. 500

Astrophysics

Astrophysics has grown from 9732 publications in 1990 to 17013 publications in 2010. The organizational size consisted of 18430 active researchers in 1990 and has grown to a size of 48183 researchers. The annual organizational size and output size have seen annual growths and declines, but the field has seen a netto growth of 1701% in output size and a 2614% growth in organizational size in the 20 year period as can be seen in Table 32.

Table 32: Descriptive results Astrophysics

Year	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Organizational Size	18430	18642	20142	22697	24580	25803	26031	27247	29254	28058
Size Growth (%)		1	8	13	8	5	1	5	7	-4
Output Size	9732	9706	9436	10825	11737	11769	12610	13016	13396	13369
Output Growth (%)		0	-3	15	8	0	7	3	3	0

Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Organizational Size	29309	30403	31258	33543	34801	36027	38141	37495	39104	41966	48183
Size Growth (%)	4	4	3	7	4	4	6	-2	4	7	15
Output Size	13221	14370	14294	14796	15743	15075	15547	15199	16135	16599	17013
Output Growth (%)	-1	9	-1	4	6	-4	3	-2	6	3	2

Functional Dependence

Table 33 show the quantitative results for the concept functional dependence in the field of Astrophysics. The field has shown an increase in its author citation variance (ind. 1) but the author citation count Gini-index (ind. 2) and its fractionalized counterpart (ind. 3) show a stable level of inequality. The proportion of citations in possession of the top 10 (ind. 6), the top 10% (ind. 5) and the top 1% (ind. 4) has slightly decreased throughout the period. Based on these patterns, we can conclude that the author citation equality is rather stable, but slowly became more equal. The stability of the top 100 most cited (ind. 20) authors has been medium but increased in its stability.

Astrophysics has seen a rise in its institution citation standard deviation (ind. 7); an increasing institution's citation count Gini-index (ind. 8) and a growing fractionalized Gini-index (ind. 9) overall implying a growing institution citation inequality. The top 10 most cited institutions (ind. 10) have seen an inverse U-shape in its pattern of proportional citation possession, ultimately moving from 9.7 % (1990) to 10.8% (2010). In addition, the stability of the top 10 most cited institutions (ind. 11) has been very stable, fluctuating between 5 to 8 institutions out of 10 remaining in the top 10 after 4 years. The top 50 most cited institutions has been extraordinary high. Most of the institutions continuously remain in the top. Overall, the institution citation count distribution is unequal and has shown an increase of this.

The standard deviation of the authors dominance factor (ind. 12) and the Gini-index hereof (ind. 13) show an increase, pointing to a change in the collaboration dominance of Astrophysics researchers.

Subsequently, the results of the author collaboration network analysis show that the standard deviation of the authors degree centrality (ind. 15) remained roughly the same until 2010 in which it dramatically increased to 0.019. This is accompanied with a stable Gini-index of the author degree centrality (ind. 14). The Gini-index of the author betweenness centrality (ind. 16) is high, but appears to be lower than previous cases and has decreased over time. The variance of this centrality predominantly seems to have decreased (ind. 17). Both indicator 16 and 17 could not be computed for the year 2010 due to an integer overflow. The authority score of authors (ind. 18) started off high in 1990 (0.96) but dropped to 0.92 in 2010.

Overall the field has contradicting results; showing a rather stable author citation distribution but an increase in the inequality on the institutional level. The dominance factor showed to have increased too, while the collaboration network analysis shows a relative egalitarian trend in centrality measures.

Regardless of their dynamics, the data shows overall that the field is characterized by a high functional dependence especially due to their extraordinary inequality in institution citation counts.

Table 33: Results functional dependence Astrophysics

Indicator	1	2	3	4	5	6	7	8	9	10
1990	189.1549	0.713584	0.767605	0.201583	0.631568	0.034946	650.2385	0.782124	0.808	0.097351
1994	189.5062	0.679429	0.768743	0.202563	0.632615	0.024735	883.3591	0.816409	0.835493	0.112559
1998	281.5221	0.681664	0.774173	0.235759	0.644916	0.050641	1703.349	0.836259	0.855634	0.157973
2002	333.3166	0.699032	0.756615	0.194936	0.620019	0.021047	1896.487	0.858008	0.860652	0.136452
2006	384.0442	0.726202	0.744376	0.177212	0.599165	0.013625	2107.202	0.863185	0.861336	0.131403
2010	464.3988	0.715619	0.745782	0.168521	0.594948	0.010334	2156.229	0.864138	0.862724	0.108177

Indicator	11	12	13	14	15	16	17	18	19
1990	NA	0.292334	0.190396	0.833905	0.008272	0.941796	0.000702	0.963176	0.176715
1994	8	0.310791	0.216653	0.802962	0.007244	0.930463	0.000437	0.964331	0.150415
1998	5	0.315084	0.228911	0.787156	0.00608	0.92429	0.000429	0.97046	0.14362
2002	7	0.323579	0.248035	0.787468	0.005339	0.91494	0.000363	0.955378	0.130852
2006	6	0.334555	0.263025	0.775544	0.005383	0.91442	0.0003	0.942778	0.097478
2010	8	0.349209	0.293401	0.81188	0.019362	NA	NA	0.92234	0.236145

Indicator	20	21
1990	NA	NA
1994	7	33
1998	9	37
2002	9	39
2006	11	35
2010	11	39

Strategic Dependence

Table 34 shows the quantitative indicators used for the concept strategic dependence in the field of Astrophysics. The field has seen an increase in the collaboration coefficient (ind. 23). Approximately 73% of all papers were written in collaboration in 1990 while this has risen to 88% in 2010. The mean co-author count (ind. 22) has increased in this period from 4.89 authors per paper to 9.55. The standard deviation (ind. 24) of this co-author count has grown from 26.60 in 1990 to 49.55 in 2010. The inequality of the co-author count in the form of the Gini-index (ind. 25) has remained low and very stable over time. The overall network degree centrality (ind. 26) has increased from 0.043 (1990) to 0.133 (2010), while the network density (ind. 27) shows a parabola shape, moving from 0.0035 (1990) to 0.0093 (2010).

When one observes the author collaboration network analyses (Figure 19) of the top 500 most cited authors, one can roughly conclude that collaborations have intensified but that Astrophysics was already a collaboration intense field in 1990. Based on these results, it can be concluded that Astrophysics operates under a high strategic dependence which has increased in the last 20 years.

Table 34: Results strategic dependence Astrophysics

Indicator	**22**	**23**	**24**	**25**	**26**	**27**
1990	4.891697	0.730991	26.59559	0.636367	0.04305678	0.00350225
1994	5.336427	0.759877	27.47561	0.639492	0.04982281	0.00358232
1998	7.042064	0.804943	36.36673	0.697655	0.05177354	0.00315536
2002	6.765756	0.820482	32.12219	0.668643	0.05022398	0.00269151
2006	8.923594	0.848531	46.35805	0.719446	0.05349366	0.0028267
2010	9.548838	0.883482	49.55374	0.707033	0.13271627	0.00933562

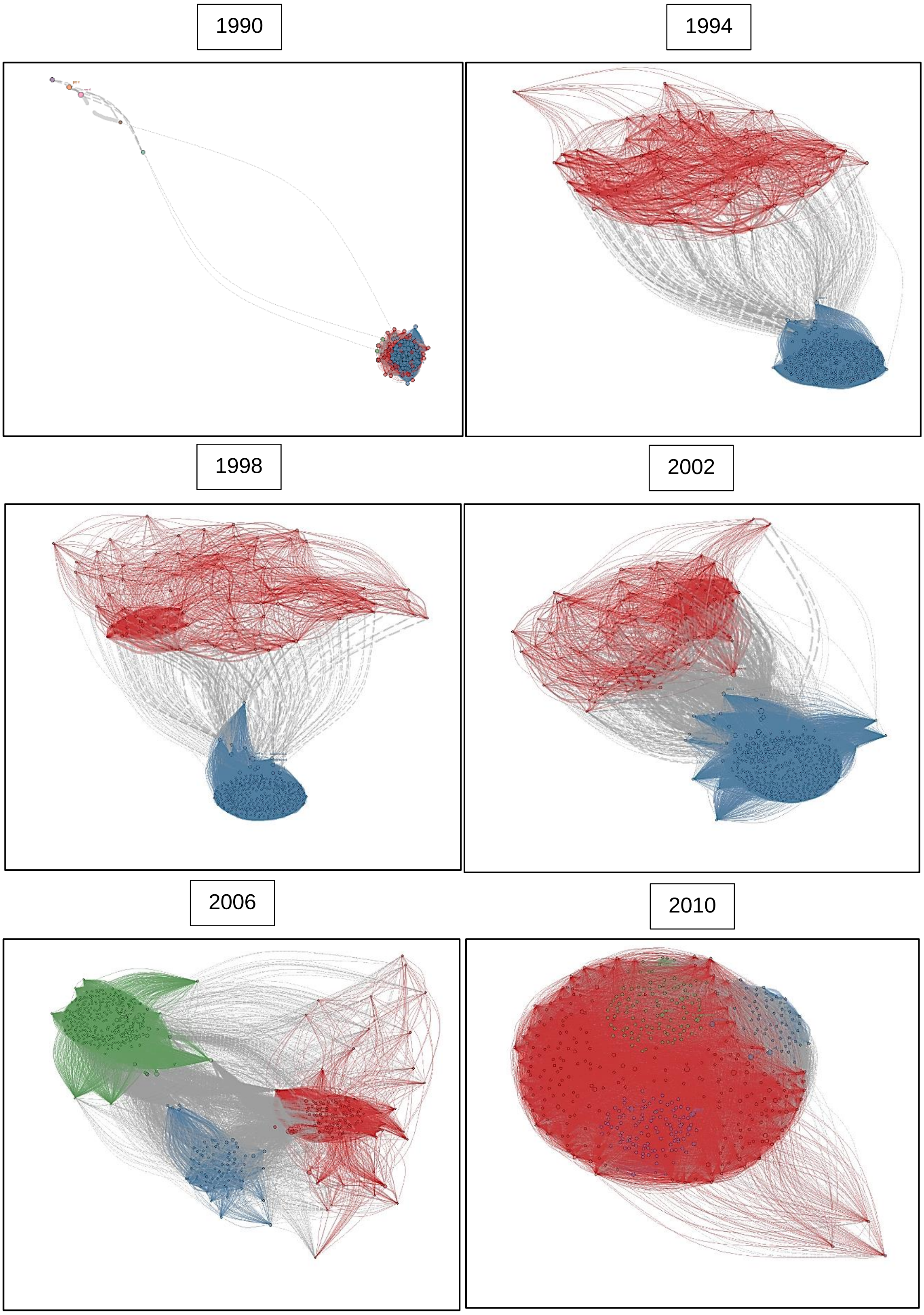

Figure 19: Author Collaboration Network (1990, 1994, 1998, 2002, 2006 & 2010) of Astrophysics. N= max. 500

Technical Task Uncertainty

By observing the indicators used for the concept technical task uncertainty, one can notice that the mean cited reference count (ind. 28) has risen greatly from 26.3 references per paper in 1990 to 45.7 in 2010. Papers have, however, seen just a slight increase in its mean page count (ind. 29) over the years. From these indicators one can conclude that papers became slightly more reference dense based on the increase in mean references per page (ind. 30) from 3.24 to 4.73.

The dominance of the top 10 references was medium/low but increased to a relative high level based on its proportion of the top 10 most used references of the total references count in the year (ind. 31). A similar trend is found when controlling for the publication output size of the field by dividing the sum of the top 10 most used references by the total publication output size (ind. 33). When we dive deeper in the references, it can be found that the stability of the top 10 most used references (ind. 32) was low/medium but increased to a high one with 6 references out of 10 remaining in the top 10 most used references remaining in this top after 4 years. Here, 7 manuscripts in the period managed to remain in the top 10 ranking for more than 8 years which implies a high stability of its references top 10. Its top 100 most used references stability (ind. 38) is and remains medium.

Based on a bibliographic coupling network of the field, it can be found that the inequality of the reference degree centrality (ind. 34) is and remained relatively low, indicating that the equality of reference-to-reference connectivity is low. This is accompanied with an increase in its standard deviation (ind. 35). The overall bibliographic coupling network's degree centrality (ind. 36) has increased and its density (ind. 37) ultimately too.

The field has seen an increase in its citing half-life (ind. 39), moving from 6 to 8 years which are medium/high citing half-lives compared to other fields. Its citing mean-life (ind. 48) appeared to move from a relative medium/low level to a medium/high level during the period. The rate of knowledge accumulation appears to be high and stable (ind. 51).

The bibliographic coupling networks of the top 500 most used references (Figure 20) show that the network initially contained 4 large clusters, but over the years this has become more homogeneous and more dense.

Ultimately, it is difficult to derive clear conclusions from empirical data regarding the technical task uncertainty of a field. However, the data shows that papers are medium/high in their reference density; it shows that there an unstable and non-dominant top 10 reference base, but this became an increasingly more stable and dominant one; it shows medium levels of stability in its top 100 reference base; its reference degree centrality inequality is low; its bibliographic coupling network is rather homogeneous and dense; and the knowledge accumulation indicator shows that it is a highly cumulative field. Therefore, the field is estimated to have been a medium/low to ultimately a low technical task uncertainty one.

Table 35: Results technical task uncertainty Astrophysics

Indicator	**28**	**29**	**30**	**31**	**32**
1990	26.29295	8.11659	3.239409	0.128917	NA
1994	28.62847	15.1339	1.891679	0.118261	3
1998	29.78488	8.531378	3.491216	0.125762	5
2002	33.41937	8.882445	3.762407	0.169178	4
2006	37.80035	8.811335	4.289968	0.235686	4
2010	45.70621	9.669043	4.727067	0.256584	6

Indicator	33	34	35	36	37	38	39	48	51
1990	0.122585	0.5477505	0.00951212	0.06632431	0.00873224	NA	6	8.309379	NA
1994	0.114936	0.5338903	0.009375	0.07885648	0.00896294	48	6	8.955956	0.8832255
1998	0.124813	0.5310395	0.01004028	0.06004465	0.00965006	68	6	6.598323	0.7592862
2002	0.168882	0.5452432	0.01343957	0.07937897	0.01258867	46	6	9.448138	0.7901199
2006	0.236444	0.5810429	0.02085358	0.12456433	0.01747894	33	7	10.035518	0.8310155
2010	0.256569	0.5484494	0.02337984	0.13307481	0.02166543	33	8	10.641817	0.9054495

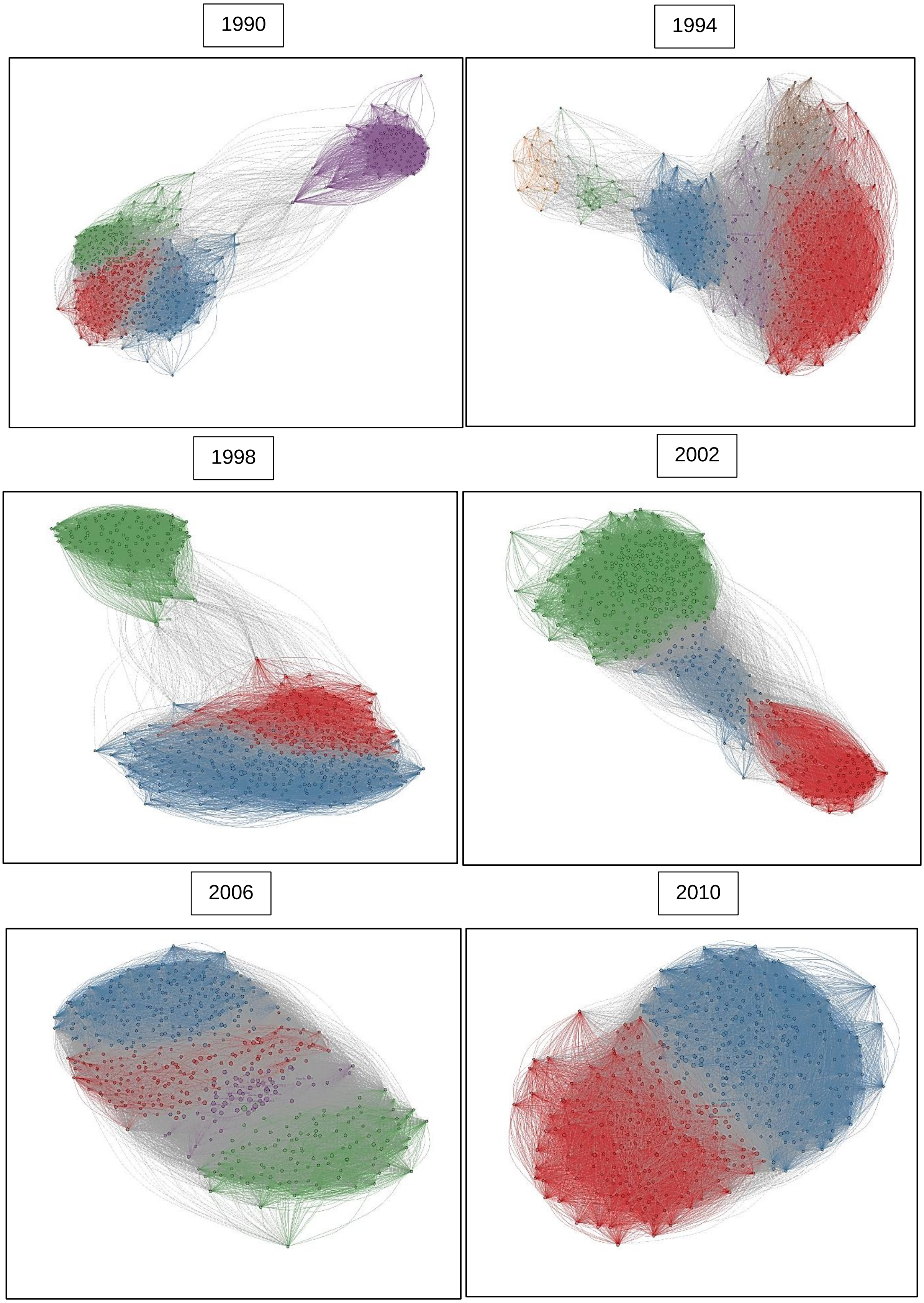

Figure 20: Bibliographic Coupling Network (1990, 1994, 1998, 2002, 2006 & 2010) of Astrophysics, N= max. 500

Strategic Task Uncertainty

By exploring the indicators used for the concept strategic task uncertainty, one can gain a more comprehensive understanding of its nature in the field Astrophysics.

The field shows a parabola dynamic based on the sum of the proportional occurrence of the top 10 author keywords (ind. 40). It even presents a sum proportional occurrence value of over 1, due to the high dominance of the top 10 in combination with the fact that papers contain multiple keywords. The sum of their occurrence proportion however, came back to its initial value of 0.35. A contradicting trend is found for its keyword plus counter partner (ind. 42), which increased over the years by a value of 0.1. The stability of the top 10 author keywords (ind. 41) seemed to have increased from 3 remaining in the top 10 over 1990/1994 to 6 in 2006/2010. When analyzing this ranking to a higher extend one can notice that the field has shifted from a focus on cosmological observation instruments and methods (i.e. photometry, spectroscopy, instruments, etc.) to a focus on galaxies and its development (i.e. galaxies evolution, stars formation, galaxies formation, planetary systems, etc.). The stability of the keyword plus top 10 ranking (ind. 43) is showing higher levels of stability than the author keywords ranking. Lastly, the stability of the top 100 author keywords (ind. 49) and top 100 keyword plus tags (ind. 50) have risen greatly. Initially its stability was already high in comparison to other fields, but even exceeded this relative stability by the end of the timer period of this study.

Based on the author keyword co-occurrences network, it is seen that the Gini-index author keyword node degree centrality (ind. 44) is tremendously high and managing to roughly stay at the same level. This means that the co-occurrences of author keywords was and remained highly unequal which in its turn implies a directed field. Its standard deviation (ind. 45) has slightly dropped. The overall degree centrality (ind. 46) has increased while its density (ind. 47) has decreased.

Figure 21 shows the annual author keyword co-occurrence network of the top 500 most used author keywords. It shows relatively dense and coherent networks, but at the same time, its dynamics seem diverging over time. It shows more clusters with increasingly scattered nodes.

The results show that the topic node degree centrality was and remained highly unequal; the top 10/top 100 most used keywords were and remained highly stable. Therefore it is concluded that the strategic task uncertainty, compared to the other fields, was and remains relatively low.

Table 36: Results strategic task uncertainty Astrophysics

Indicator	**40**	**41**	**42**	**43**	**44**
1990	0.349594	NA	0.315716	NA	0.8339054
1994	1.323554	3	0.3909	6	0.8029624
1998	0.580804	8	0.38999	9	0.7871557
2002	0.353859	4	0.411267	7	0.7874677
2006	0.328493	7	0.403908	7	0.7755436
2010	0.354372	6	0.401627	9	0.8118799

Indicator	**45**	**46**	**47**	**49**	**50**
1990	0.00827207	0.04305678	0.00350225	NA	NA
1994	0.00724415	0.04982281	0.00358232	26	57
1998	0.0060798	0.05177354	0.00315536	62	81
2002	0.00533875	0.05022398	0.00269151	61	79
2006	0.00538277	0.05349366	0.0028267	90	82
2010	0.0193621	0.13271627	0.00933562	83	89

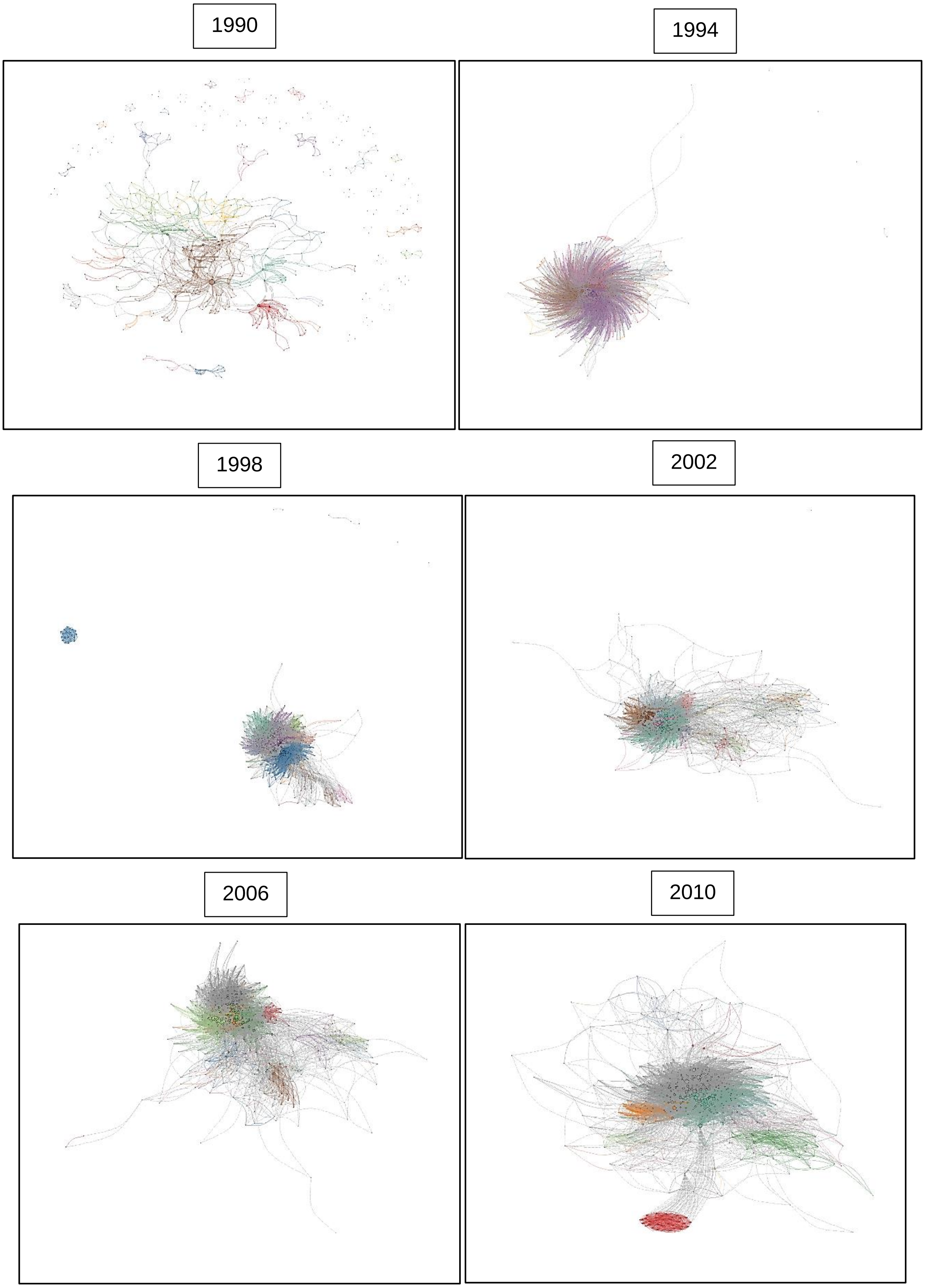

Figure 21: Author Keyword Co-occurrences Network (1990, 1994, 1998, 2002, 2006 & 2010) of Astrophysics. N= max. 500

Organic Chemistry

Organic Chemistry has grown from 8690 publications in 1990 to 18483 publications in 2010. The organizational size consisted of 18754 active researchers in 1990 and has grown to a size of 54129 researchers. The annual organizational size and output size have seen annual growths and declines, but the field has seen a netto growth of 213% in output size and a 289% growth in organizational size in the 20 year period as can be seen in Table 37.

Table 37: Descriptive results Organic Chemistry

Year	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Organizational Size	18754	20275	21614	23992	24353	25221	30661	31253	31751	33808
Size Growth (%)	NA	8	7	11	2	4	22	2	2	6
Output Size	8690	9041	9190	10138	10382	10473	13588	13590	13791	14612
Output Growth (%)	NA	4	2	10	2	1	30	0	1	6

Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Organizational Size	34791	37251	39186	41234	43714	45303	47743	49058	51617	52017	54129
Size Growth (%)	3	7	5	5	6	4	5	3	5	1	4
Output Size	14836	15417	15972	16232	16911	17457	18298	17989	18374	18581	18483
Output Growth (%)	2	4	4	2	4	3	5	-2	2	1	-1

Functional Dependence

Table 38 show the quantitative results for the concept functional dependence in the field of Organic Chemistry. The field has shown an increase in its author citation variance (ind. 1) but the author citation count Gini-index (ind. 2) and its fractionalized counterpart (ind. 3) show a rather stable level of inequality. Approximately 0.6 is in the economical context rather high, but in the citation context it is rather egalitarian in comparison to the other cases discussed previously. The proportion of citations in possession of the top 10% (ind. 5) and the top 1% (ind. 4) has slightly increased throughout the period but appears to be relatively stable while the proportion of the top 10 most cited authors (ind. 6) has decreased. The stability of the top 100 most cited authors has been very high and increasing. Based on these patterns, we can conclude that the author citation equality is stable, and relatively equal.

Organic Chemistry has seen a rise in its institution citation standard deviation (ind. 7); an increasing institution's citation count Gini-index (ind. 8) and a growing fractionalized Gini-index (ind. 9) overall implying a growing institution citation inequality. The top 10 most cited institutions (ind. 10) have seen an inverse U-shape in its pattern of proportional citation possession, ultimately moving from 4.9 % (1990) to 7.5% (2010). In addition, the stability of the top 10 most cited institutions (ind. 11) has been high, fluctuating between 5 and 6 institutions out of 10 remaining in the top 10 after 4 years. The stability of the top 50 institutions has been relatively high and increased over time. Overall, the institution citation count distribution is unequal and has shown an increase of this.

The standard deviation of the authors dominance factor (ind. 12) and the Gini-index hereof (ind. 13) show an increase, pointing to an change in the collaboration dominance of Astrophysics researchers.

Subsequently, the results of the author collaboration network analysis show that the standard deviation of the authors degree centrality (ind. 15) has followed an inverse U-shaped pattern, in the end, increasing. This is accompanied with an increasing Gini-index of the author degree centrality (ind. 14). The Gini-index of the author betweenness centrality (ind. 16) is high, but appears to have decreased over time. The variance of this centrality predominantly seems to have decreased too (ind. 17). Both indicator 16 and 17 could not be computed for the year 2006 and 2010 due to an integer overflow. The authority score of authors (ind. 18) started off high in 1990 (0.99) but dropped to 0.92 in 2010.

Overall the field has contradicting results; showing an equal and stable author citation distribution but an increase in the inequality on the institutional level. The dominance factor showed to have increased too, while the collaboration network analysis shows a relative egalitarian trend in centrality measures. Apart from the overall egalitarian trends, the field shows a high stability of rankings. This is why the field is estimated to operate under a low to medium levels of functional dependence.

Table 38: Results functional dependence Organic Chemistry

Indicator	1	2	3	4	5	6	7	8	9	10
1990	64.01287	0.599541	0.623739	0.134463	0.482759	0.017862	168.0928	0.686634	0.707752	0.049189
1994	56.32263	0.582969	0.612575	0.121474	0.468025	0.015188	191.5281	0.696394	0.720277	0.057593
1998	70.24213	0.585952	0.622332	0.136486	0.480936	0.011952	351.9734	0.739605	0.769092	0.089803
2002	89.52809	0.596039	0.645963	0.157788	0.508972	0.024233	380.9191	0.764604	0.798605	0.090846
2006	84.57699	0.589135	0.640745	0.150286	0.506401	0.009843	406.8912	0.759826	0.794442	0.07665
2010	88.05251	0.608816	0.6623	0.179188	0.53369	0.015287	301.5228	0.758641	0.795647	0.074521

Indicator	11	12	13	14	15	16	17	18	19
1990	NA	0.247476	0.128785	0.377831	0.000185	0.97377	0.000725	0.998648	0.028662
1994	5	0.259559	0.140877	0.393791	0.000179	0.96126	0.000679	0.99826	0.022648
1998	6	0.266501	0.150765	0.409282	0.000165	0.946855	0.000569	0.99796	0.026607
2002	6	0.271209	0.154553	0.41004	0.000146	0.946629	0.000551	0.998454	0.022492
2006	6	0.281867	0.167028	0.446545	0.000181	NA	NA	0.933985	0.020576
2010	5	0.289584	0.173708	0.471204	0.000254	NA	NA	0.923608	0.026967

Indicator	20	21
1990	NA	NA
1994	16	22
1998	19	27
2002	17	27
2006	17	31
2010	38	28

Strategic Dependence

Table 39 shows the quantitative indicators used for the concept strategic dependence in the field of Organic Chemistry. The field has seen an increase in the collaboration coefficient (ind. 23). Approximately 96% of all papers were written in collaboration in 1990 while this has risen to 99% in 2010. The mean co-author count (ind. 22) has increased in this period from 3.41 authors per paper to 4.94. The standard deviation (ind. 24) of this co-author count has grown from 1.55 in 1990 to 3.06 in 2010. The inequality of the co-author count in the form of the Gini-index (ind. 25) rose from 0.24 to 0.29. The overall network degree centrality (ind. 26) has increased from 0.0028 (1990) to 0.0097 (2010), while the network density (ind. 27) shows a parabola shape, moving from 0.00023 (1990) to 0.00017 (2010).

When one observes the author collaboration network analyses (Figure 22) of the top 500 most cited authors, one can roughly conclude that collaborations have intensified. Organic Chemistry sets itself apart from other fields because the frequency of collaboration is extremely high while the co-author count is rather medium/high. This is why the level of the strategic dependence of Organic Chemistry is hard grade but most likely finds itself on a high level with similar characteristics like biotechnology. This has risen in the time period, and thus remained on a rather high level.

Table 39: Results strategic dependence Organic Chemistry

Indicator	**22**	**23**	**24**	**25**	**26**	**27**
1990	3.409321	0.957307	1.551919	0.238997	0.00276668	0.00022541
1994	3.729339	0.964554	1.854537	0.255047	0.00245045	0.00020702
1998	3.889856	0.973098	2.018437	0.258764	0.0023415	0.00017946
2002	4.143251	0.97577	2.22404	0.265337	0.00292237	0.00015779
2006	4.501694	0.980599	2.67694	0.284193	0.00678639	0.0001585
2010	4.942271	0.985825	3.059322	0.291615	0.00974367	0.00017061

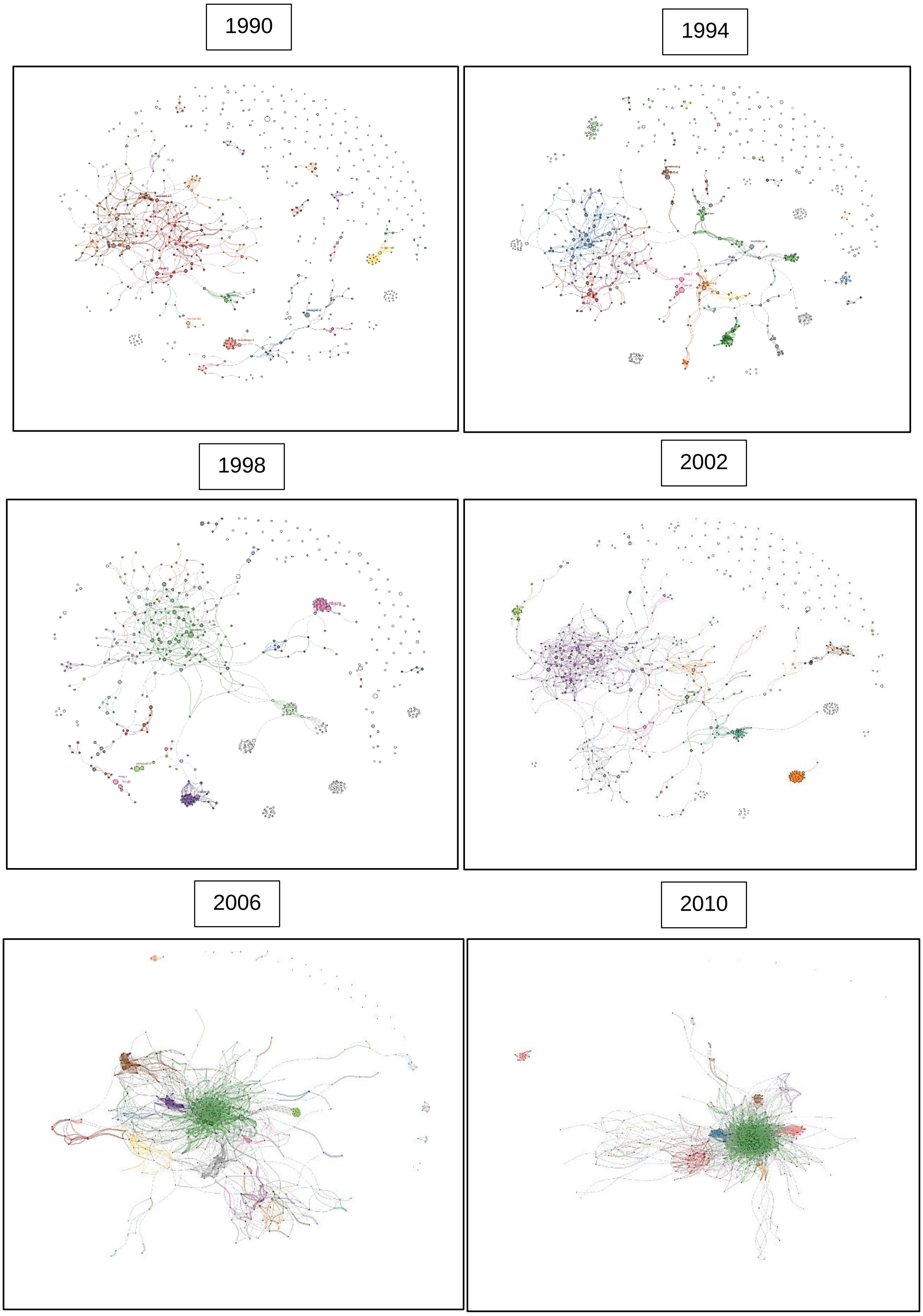

Figure 22: Author Collaboration Network (1990, 1994, 1998, 2002, 2006 & 2010) of Organic Chemistry. N= max. 500

Technical Task Uncertainty

By observing the indicators used for the concept technical task uncertainty, one can notice that the mean cited reference count (ind. 28) has risen greatly from 22.6 references per paper in 1990 to 38.7 in 2010. Papers have, however, seen a stable mean page count (ind. 29) over the years. From these indicators one can conclude that papers became slightly more reference dense based on the increase in mean references per page (ind. 30) from 3.94 to 6.76.

The dominance of the top 10 references was and remained low based on the field comparison of its proportion of the top 10 most used references of the total references count in the year (ind. 31). A similar trend is found when controlling for the publication output size of the field by dividing the sum of the top 10 most used references by the total publication output size (ind. 33). When we dive deeper in the references, it can be found that the stability of the top 10 most used references (ind. 32) was high but fluctuated in this over the years. Here, 8 manuscripts in the period managed to remain in the top 10 ranking for more than 8 years which implies a high stability of its references top 10. Its top 100 most used references stability (ind. 38) was relatively average but gained a high relative stability later in the period.

Based on a bibliographic coupling network of the field, it can be found that the inequality of the reference degree centrality (ind. 34) is and remained relatively medium/low, indicating that the equality of reference-to-reference connectivity is medium/low. This is accompanied with a slight increase in its standard deviation (ind. 35). The overall bibliographic coupling network's degree centrality (ind. 36) has fluctuated but its density (ind. 37) has progressively risen over time.

The field has seen a slight decrease in its citing half-life (ind. 39), moving from 9 to 8 years which are high to medium/high citing half-lives compared to other fields. Its citing mean-life (ind. 48) to very slightly decrease over time, but remains rather stable and high. The rate of knowledge accumulation appears to be high and stable (ind. 51).

The bibliographic coupling networks of the top 500 most used references (Figure 23) show that the network initially contained 4 large clusters, but over the years this has become more homogeneous and more dense.

Ultimately, it is difficult to derive clear conclusions from empirical data regarding the technical task uncertainty of a field. However, the data shows that papers are relatively high in their reference density; it shows a medium to high stability but non-dominant top 10 reference base; medium levels of stability in its top 100 reference base, but this rose to a high stability; its reference degree centrality inequality is on medium levels; its bibliographic coupling network is rather heterogeneous; and the knowledge accumulation indicator shows that it is a cumulative field. Therefore, the field is estimated to have a medium/low technical task uncertainty over the time period.

Table 40: Results technical task uncertainty Organic Chemistry

Indicator	28	29	30	31	32
1990	22.62285	5.735545	3.944325	0.113801	NA
1994	24.5412	5.929074	4.139129	0.112119	7
1998	25.59165	5.782515	4.425696	0.08984	4
2002	27.81906	5.095985	5.459016	0.106407	3
2006	32.02389	5.455457	5.870065	0.102104	6
2010	38.6845	5.723448	6.75895	0.147328	5

Indicator	33	34	35	36	37	38	39	48	51
1990	0.113579	0.6203213	0.00678802	0.04440539	0.00485229	NA	9	11.5463	NA
1994	0.111924	0.5941022	0.00649698	0.06061641	0.00508686	53	8	11.13356	0.9487651
1998	0.089769	0.568263	0.00543522	0.03988671	0.00471406	40	8	11.30859	0.9946395
2002	0.105748	0.6033019	0.0060521	0.05369484	0.0047272	59	8	11.32333	0.9209549
2006	0.102088	0.5861653	0.00658339	0.04987743	0.00532287	48	8	11.14195	0.96556
2010	0.147216	0.6189373	0.00973702	0.07567953	0.00726604	48	8	11.07848	0.8894804

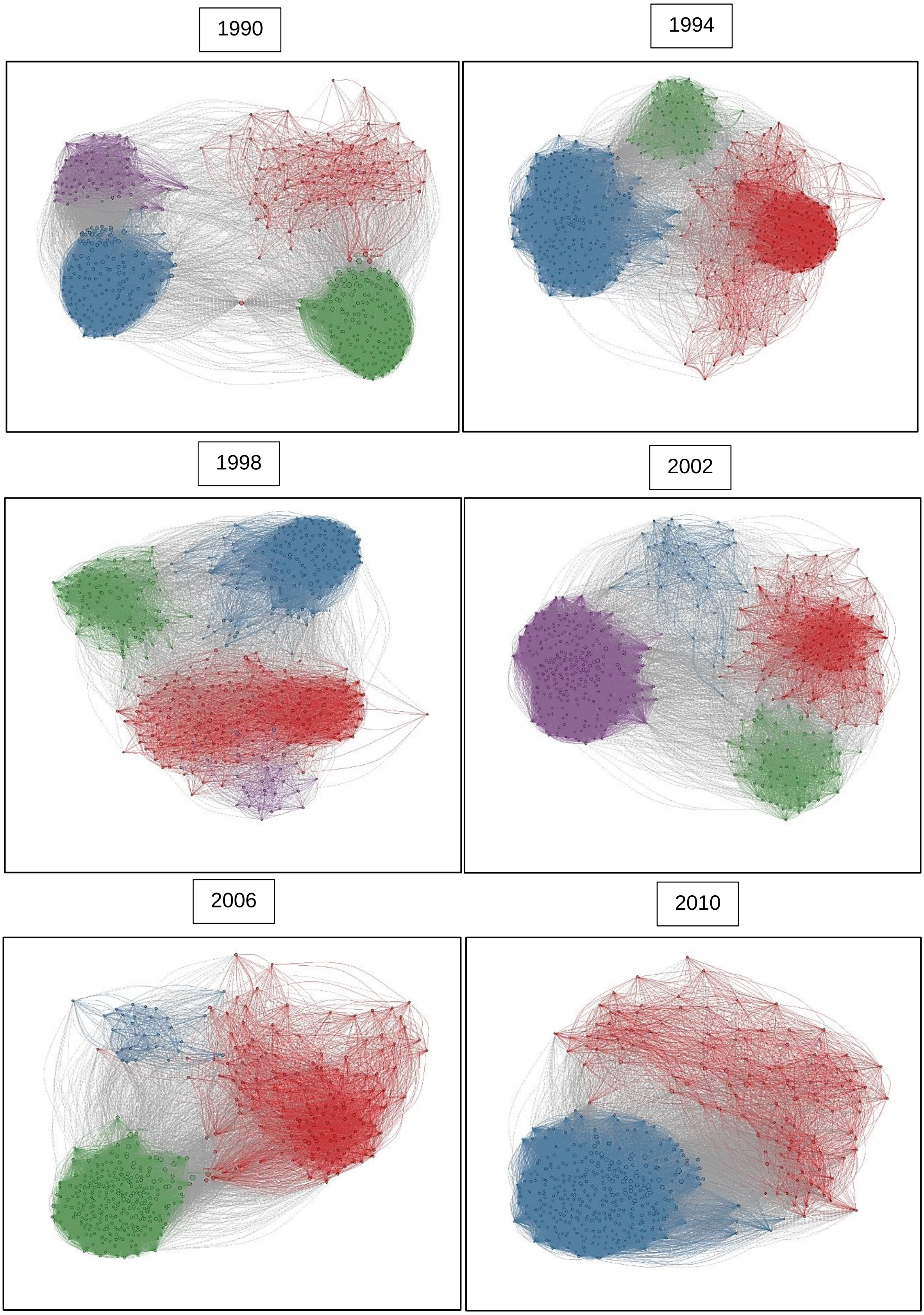

Figure 23: Bibliographic Coupling Network (1990, 1994, 1998, 2002, 2006 & 2010) of Organic Chemistry, N= max. 500

Strategic Task Uncertainty

By exploring the indicators used for the concept strategic task uncertainty, one can gain a more comprehensive understanding of its nature in the field Organic Chemistry.

The field shows a decreasing topic dominance based on the sum of the proportional occurrence of the top 10 author keywords (ind. 40). A contradicting trend is found for its keyword plus counter partner (ind. 42), which increased over the years. The stability of the top 10 author keywords (ind. 41) seemed to have increased from 1 remaining in the top 10 over 1990/1994 to 9 in 2006/2010. When analyzing this ranking to a higher extend, one can notice that the field has shifted from a focus on specific molecule structures (i.e. 1 Binaphthalene, Dithol, Diyldithioacetal, O Acetyl, etc.) to broader chemical processes (i.e. synthesis, cyclization, oxidation, catalysis, cross coupling, etc.). In all fairness, the keyword use is very low in 1990 with a sum of only 12 occurrences of the top 10 author keywords. This in combination with the high level of representativeness of all keywords used (see ind. 40, year 1990), makes that concluding that this dynamic is apparent could be rather idiosyncratic. However, the top 10 of 1994 (a sum of 673 top 10 author keyword occurrences) is showing a large proportion concerning specific molecules as well. Therefore, presumably, this trend still holds up. The stability of the keyword plus top 10 ranking (ind. 43) is showing higher levels of stability than the author keywords ranking. Lastly, the stability of the top 100 author keywords (ind. 49) and top 100 keyword plus tags (ind. 50) have risen greatly. Initially its stability was low in comparison to other fields, but eventually shifted to a high relative stability.

Based on the author keyword co-occurrences network, it is seen that the Gini-index author keyword node degree centrality (ind. 44) is very low but increased over time to a ‘normal’ level. This means that the co-occurrences of author keywords was highly equal but gained direction over time. The overall degree centrality (ind. 46) has increased while its density (ind. 47) has decreased.

Figure 24 shows the annual author keyword co-occurrence network of the top 500 most used author keywords. It shows an initially scattered network but shows a quick densification.

The results show that the topic node degree centrality was highly equal but increased to medium levels of inequality; the top 10/top 100 most used keywords were highly unstable but also this stabilized to a very high degree over the time period. Therefore it is concluded that the strategic task uncertainty, compared to the other fields, was medium/high but managed to lower this uncertainty to relative low levels.

Table 41: Results strategic task uncertainty Organic Chemistry

Indicator	**40**	**41**	**42**	**43**	**44**
1990	0.571429	NA	0.448649	NA	0.3778313
1994	0.414444	1	0.457451	6	0.3937907
1998	0.206095	4	0.47177	7	0.4092816
2002	0.214946	7	0.50538	9	0.4100395
2006	0.224974	5	0.581067	10	0.4465445
2010	0.222222	9	0.562686	8	0.4712038

Indicator	**45**	**46**	**47**	**49**	**50**
1990	0.00018487	0.00276668	0.00022541	NA	NA
1994	0.00017855	0.00245045	0.00020702	4	58
1998	0.00016493	0.0023415	0.00017946	43	86
2002	0.00014577	0.00292237	0.00015779	61	85
2006	0.00018137	0.00678639	0.0001585	65	82
2010	0.00025425	0.00974367	0.00017061	74	88

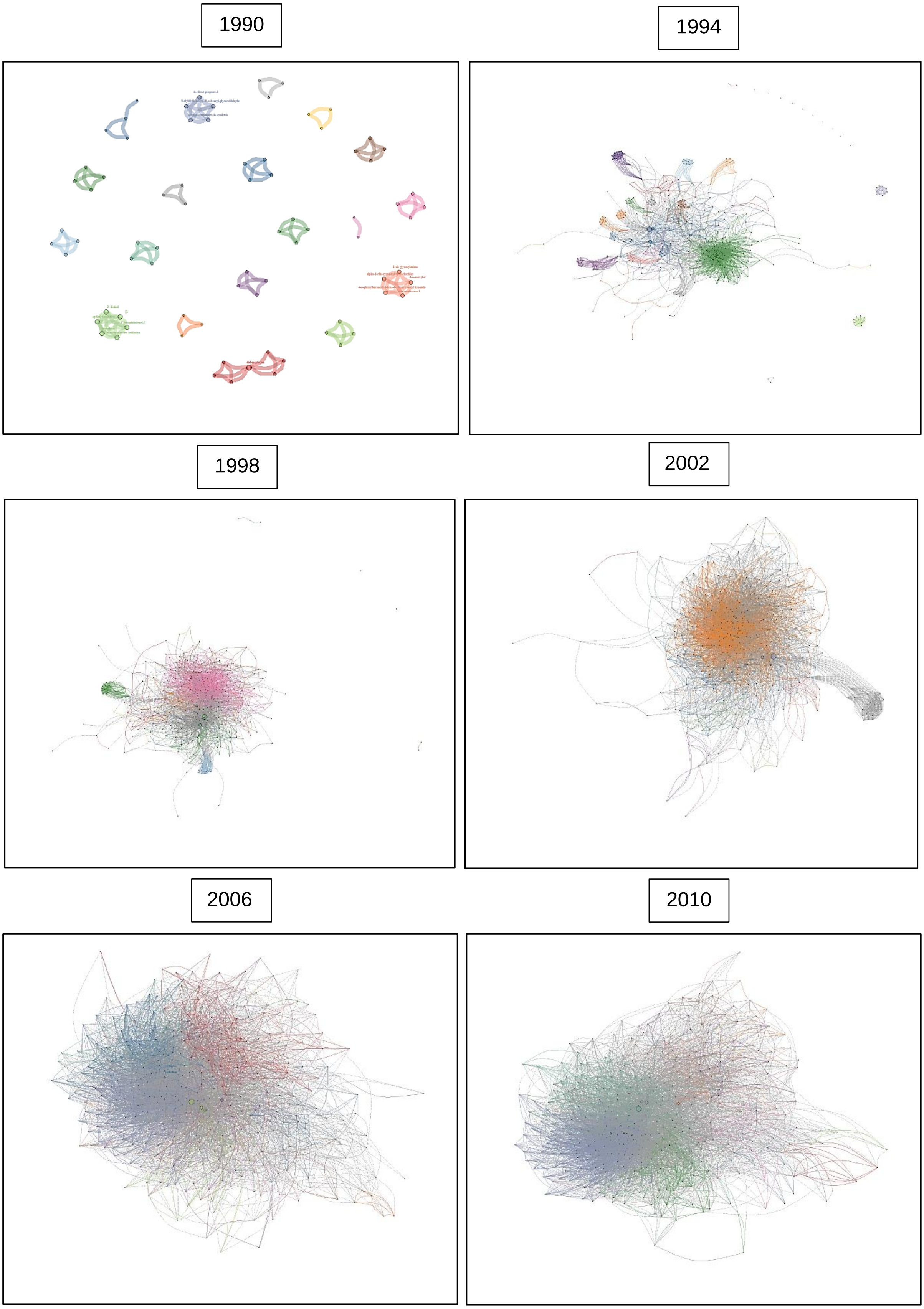

Figure 24: Author Keyword Co-occurrences Network (1990, 1994, 1998, 2002, 2006 & 2010) of Organic Chemistry. N=500

Field comparison

Now that the results per field are explored, one can aggregate these sections to a field comparison to derive answers for the sub questions. First, differences will be discussed for the dimension of mutual dependency followed by the task uncertainty. Lastly, differences in results between emerging and mature fields will be discussed, which could point out a maturity process. Lastly, absolute trends as symptoms for contextual factors are discussed.

Mutual dependency

A higher citation inequality implies a higher inequality in prestige and functional influence. The citation inequality on author level (Figure 25) and institution level (Figure 26) are arguably great between fields. The Gini-index for the fractionalized author count differs 0.22 between Particle & Field Physics and Green & Sustainable Science & Technology in 2010. This is, from an economical perspective, a massive inequality difference. The magnitude of this difference can be emphasized by comparing the index with that of Norway's economic wealth distribution inequality Gini-index which amounted for 0.26 in 2015 (The world bank, 2012). The difference between the wealth distribution in Norway and a total wealth equality is thus similar to the citation inequality differences between the two knowledge fields. In addition, there is not even one contemporary country's wealth distribution that could match the inequality of fractionalized author citations in any knowledge field used for this study (The world bank, 2012).

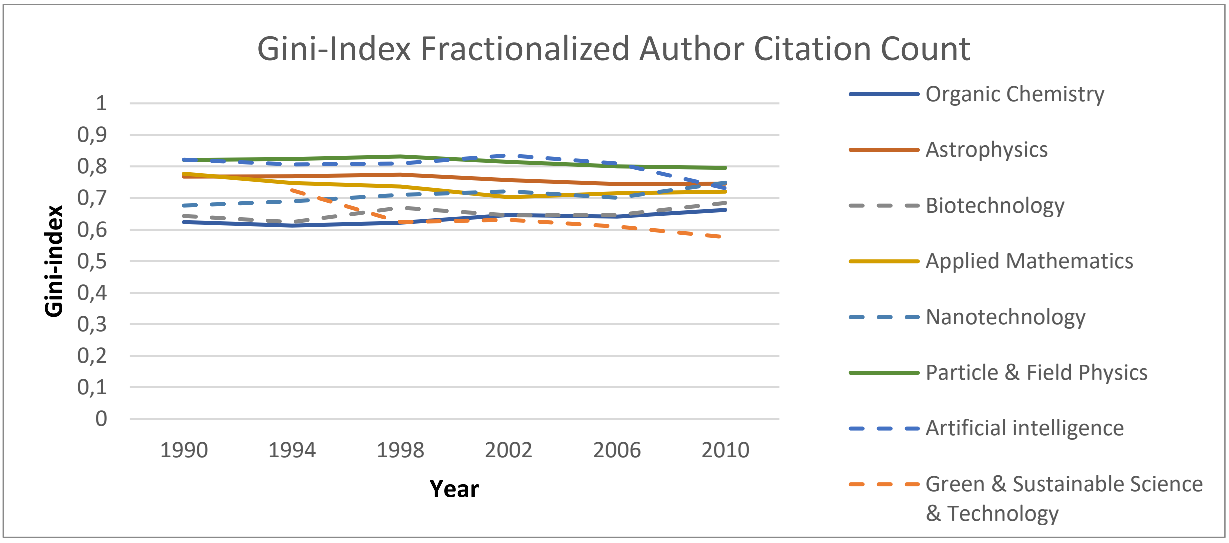

Figure 25: Gini-index fractionalized author citation count results

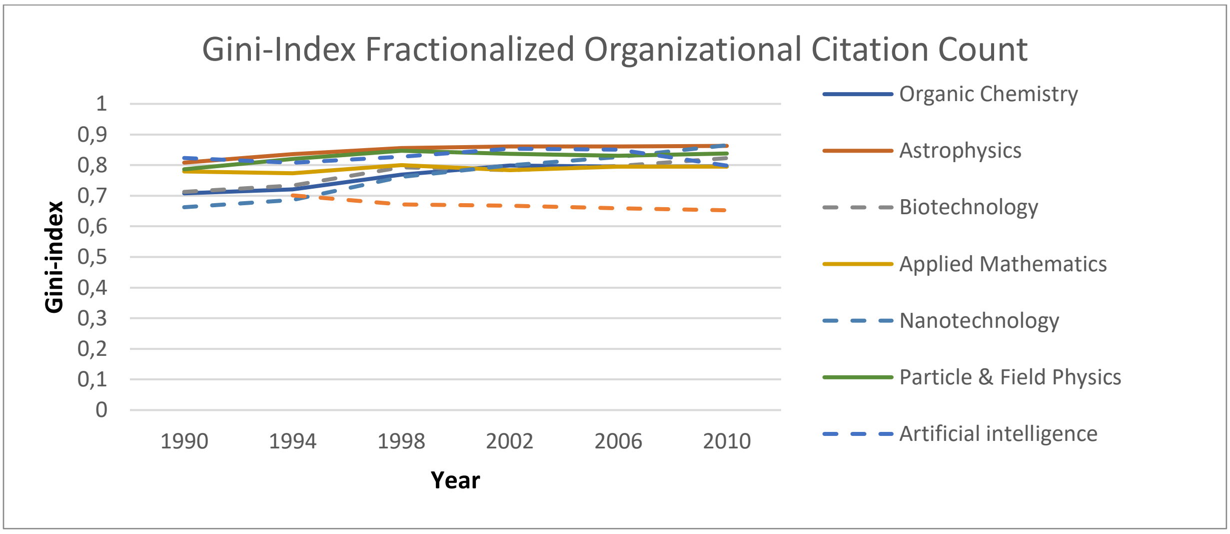

Figure 26: Gini-index fractionalized organizational citation count results

Subsequently, it is found that the 1% and 10% most cited authors possess a substantial proportion of citations in the fields (Figure 27 & Figure 28) but also here is an undisputable difference found between fields. In addition, notable differences are also apparent in the inequality of the authors dominance factor (Appendix 6), pointing out some hierarchical differences between fields. Inequalities are not only apparent in the citations and collaborative dominances, but also in the authors degree centrality regarding collaborations (Appendix 6. These results show that knowledge fields are highly hierarchical and vary in their extend hereof. Green & Sustainable Science & Technology, for example, is relatively low in its inequality compared to Particle & Field Physics.

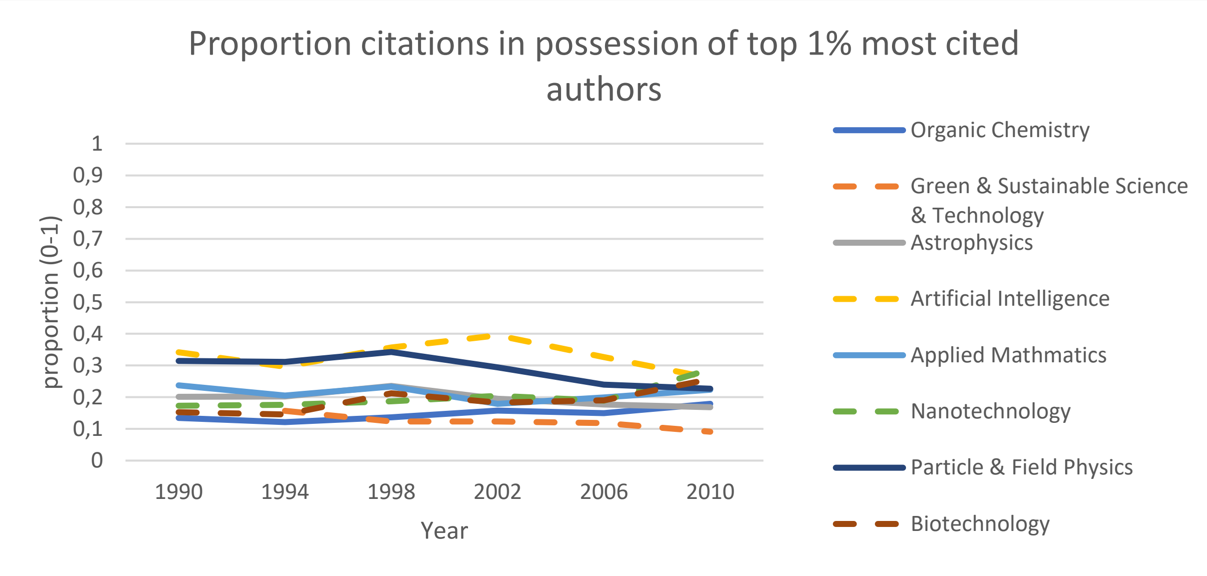

Figure 27: Proportion citation in possession of top 1% most cited authors

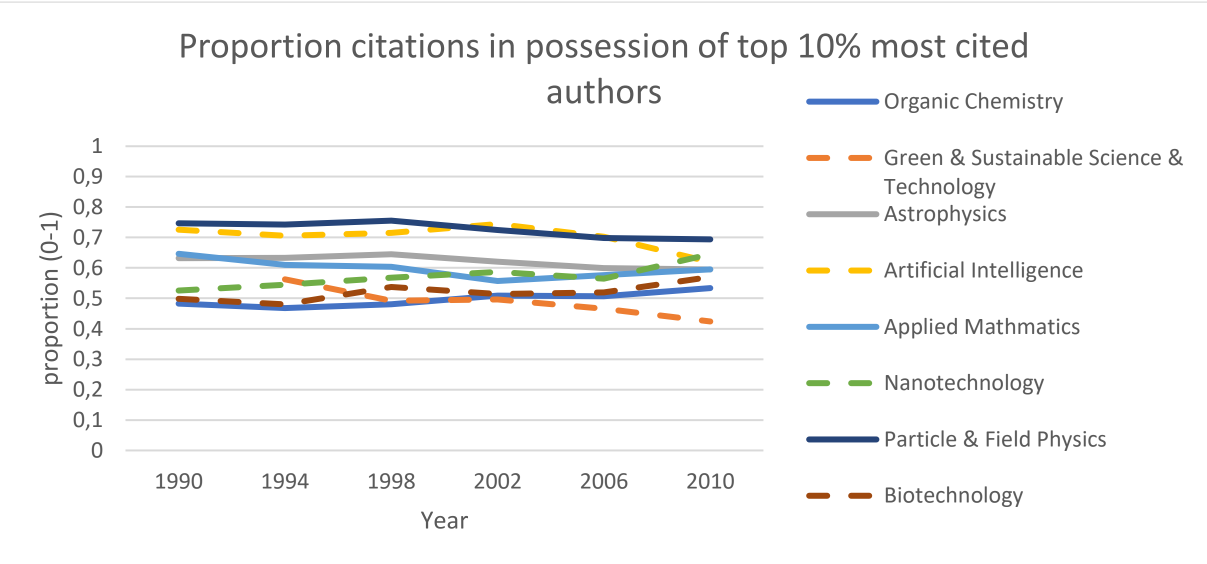

Figure 28: Proportion citations in possession of top 10% most cited authors

Furthermore, it is found that fields differ in the stability of these inequalities. Stabilities of the top 100 most cited authors (Figure 29); top 50 most cited institutions (Figure 30) and top 10 most cited institutions (Appendix 6) per field show that some fields have top level authors and institutions that manage to stay at the top for a considerable amount of time i.e. Organic Chemistry and Particle & Field Physics. A Field like Green & Sustainable Science & Technology, however, is much more turbulent in their ranking which implies a lower functional dependence. All these results show that the degrees of functional dependency vary greatly among fields.

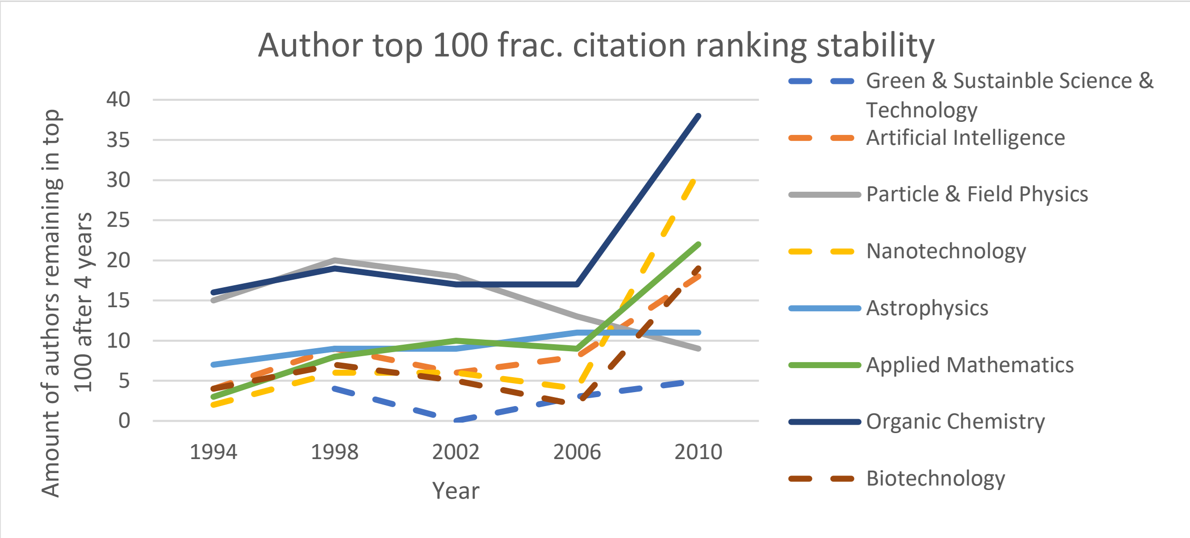

Figure 29: Author top 100 fractionalized citation ranking stability

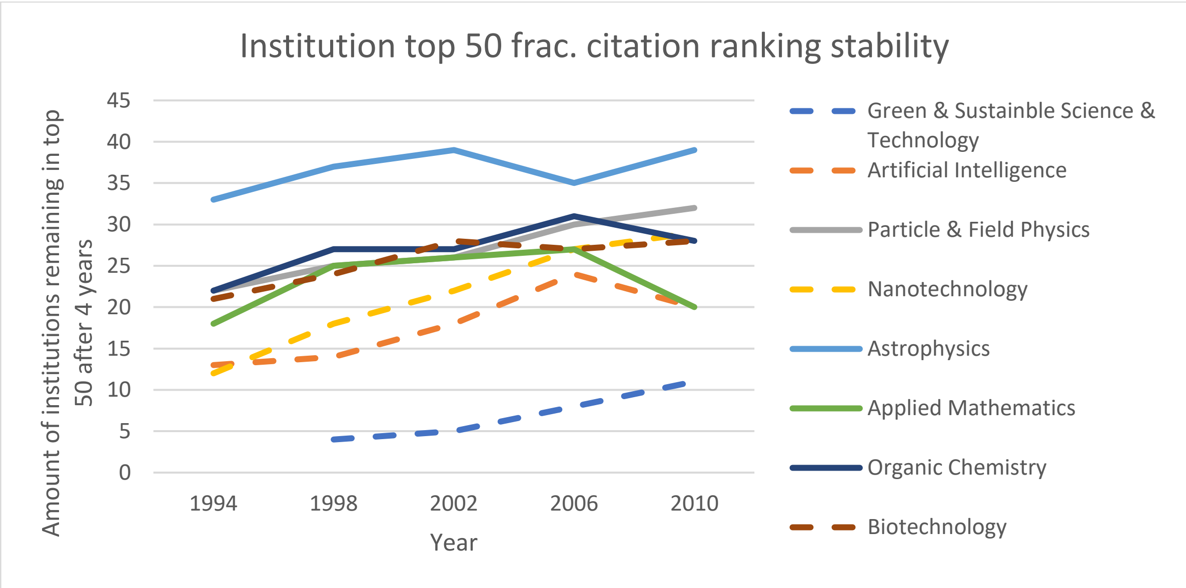

Figure 30: Institution top 50 fractionalized citation ranking stability

The other analytical aspect of mutual dependency that we have to consider is the strategic dependence. It is argued that fields with more frequent and more intense collaborations are characterized by a higher strategic dependence. The results show that fields greatly differ in this too. Figure 31 shows that ‘big sciences’ demand for great collaborations while Applied Mathematics is in contrast more an individual research field. Nonetheless, the size of the collaborations does not directly determine the frequency of collaborations. Organic Chemistry, for example, is a case in which collaborations are medium in size but are tremendously frequent.

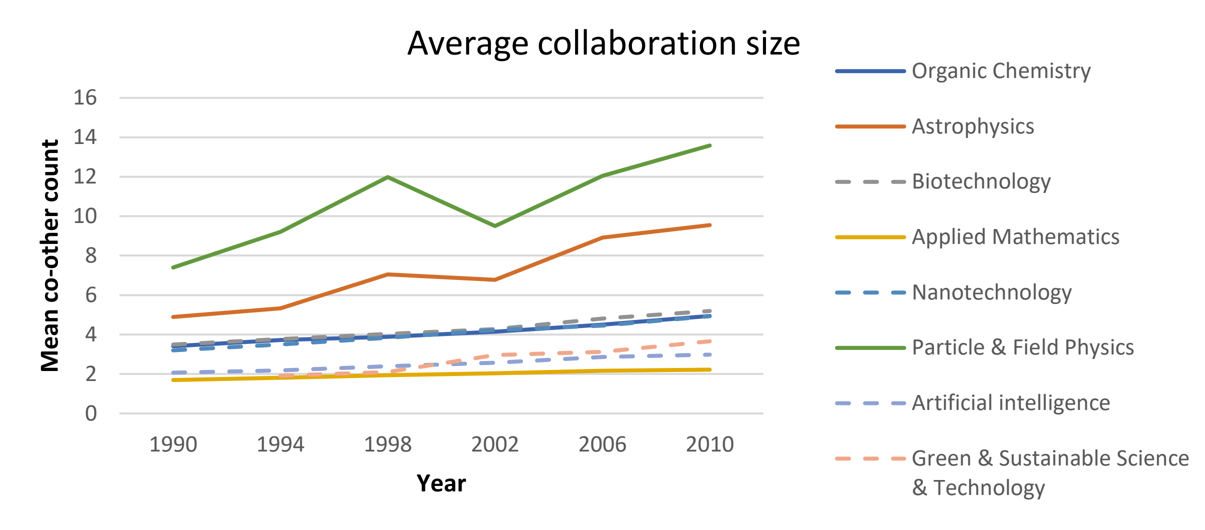

Figure 31: Average collaboration size per field

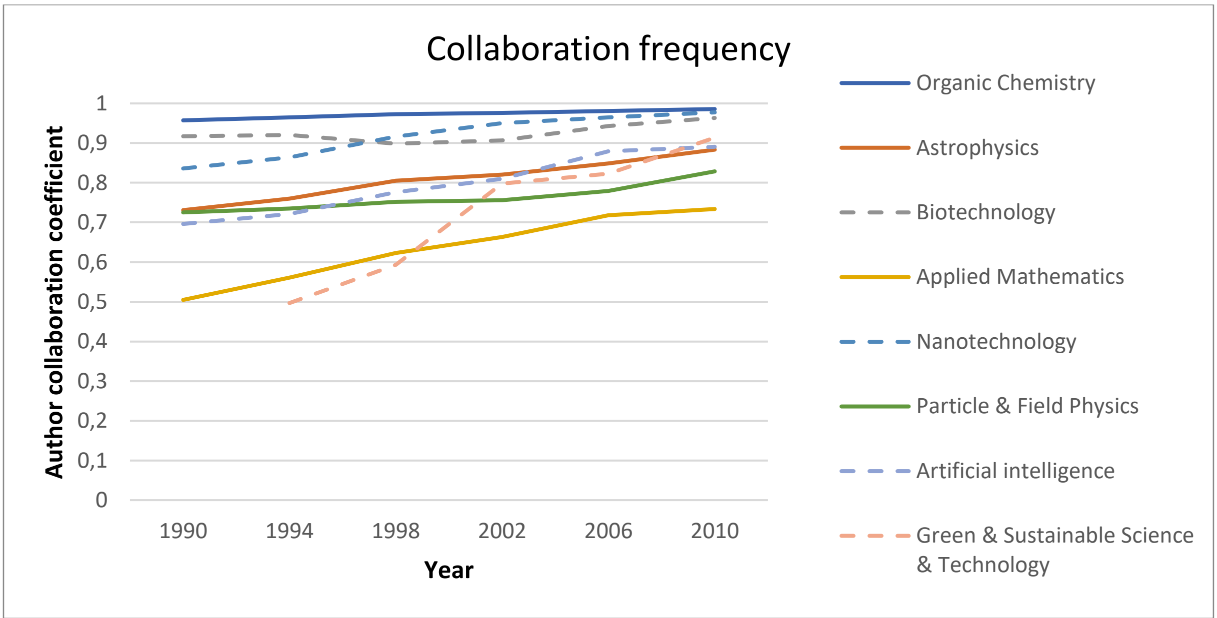

Figure 32: Collaboration frequency of knowledge fields

Based on these indicators it seems apparent that fields greatly vary in their degree of functional and strategic mutual dependence. A field like Green & Sustainable Science & Technology for example does not only have a relative limited and unstable hierarchy, it also has small and rather rare collaborations. Hence it is characterized by a low mutual dependency. Particle & Field Physics however, is characterized by great and stable hierarchies and large collaborations, which imply a high mutual dependency. Sub question 1: ‘How can differences in mutual dependency characteristic levels between fields be quantitatively measured?’ can thus be partly answered through measuring these hierarchies and collaborations. Nonetheless, these metrics can cause confusion. Fields like Organic Chemistry show paradoxical results for the strategic dependency in which collaborations are very frequent but small. Another paradox can be found for Artificial Intelligence for which hierarchies are great, but rather unstable. This occasionally makes it difficult to aggregate metrics to analytical aspect levels and therefor dimensions levels.

Task Uncertainty

When considering differences between fields in their task uncertainty, one has to examine the technical task uncertainty and strategic task uncertainty. This paper argues that the technical task uncertainty is hard to quantify but that it is likely linked to the knowledge base of researchers because this influences their perspective on research methods and standards. This study identifies knowledge bases through the use of references. First, the extent to which researchers rely on knowledge of others, is examined. This is done through the reference density of fields. Figure 33 shows that fields differ greatly in this. Organic Chemistry and Biotechnology, for example, are characterized by a high reliance on other manuscripts whereas this is not the case for Applied Mathematics and Artificial Intelligence.

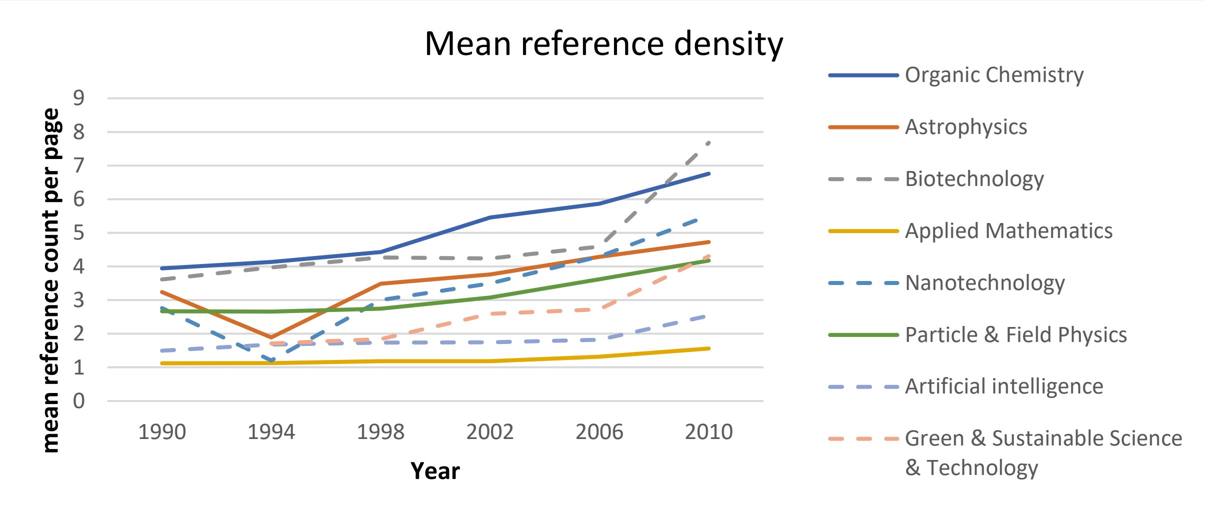

Figure 33: Mean reference density per field

In addition, we have seen in the results section that the size of knowledge bases in the bibliographic coupling networks vary greatly. Astrophysics, Particle & Field Physics and Biotechnology show large knowledge bases in the core of their network whereas Green & Sustainable Science & Technology, Applied Mathematics and Nanotechnology show much smaller ones (Figure 2, Figure 8, Figure 11, Figure 14, Figure 17 and Figure 20). In addition, the dominance of the top 10 most cited references differs greatly per field as is shown in Figure 34.

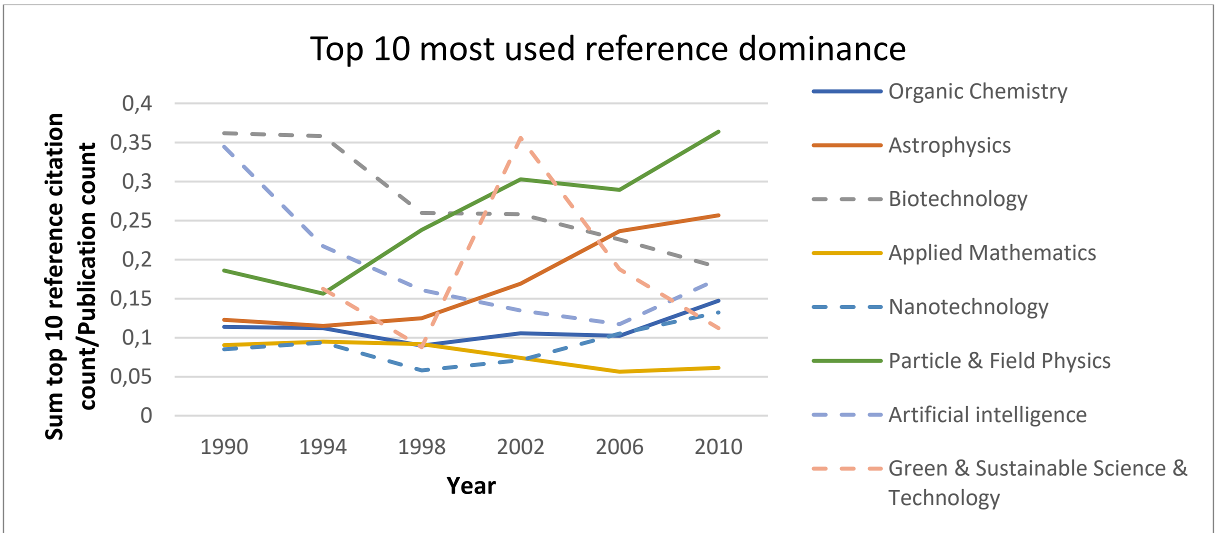

Figure 34: Top 10 most used reference dominance

Apart from differences in the reference usage dominance, this study has also found differences in the reference-to-reference connectivity. Emerging fields seem to have a higher bibliographic coupling reference degree centrality inequality than mature fields (Figure 35). This means that some references dominate in their connectivity and thus are more influential. This makes the field more homogeneous in their knowledge base core, but is also an indication for a high divergence from this core. This could have several meanings. One theory could be that these emerging fields show lower levels of uncertainties because their references (core) are more homogeneous. Another theory could be that the high uncertainty of scholars force them to use specific references in order for them to make claims that are regarded as valuable. The metrics are after all symptoms of the organizational structure instead of the other way around. Scholars in emerging fields have a smaller audience and fewer journals to publish in, thence they need to comply with the organizational norms to be able to publish their work and thus reap the reputational rewards in the first place.

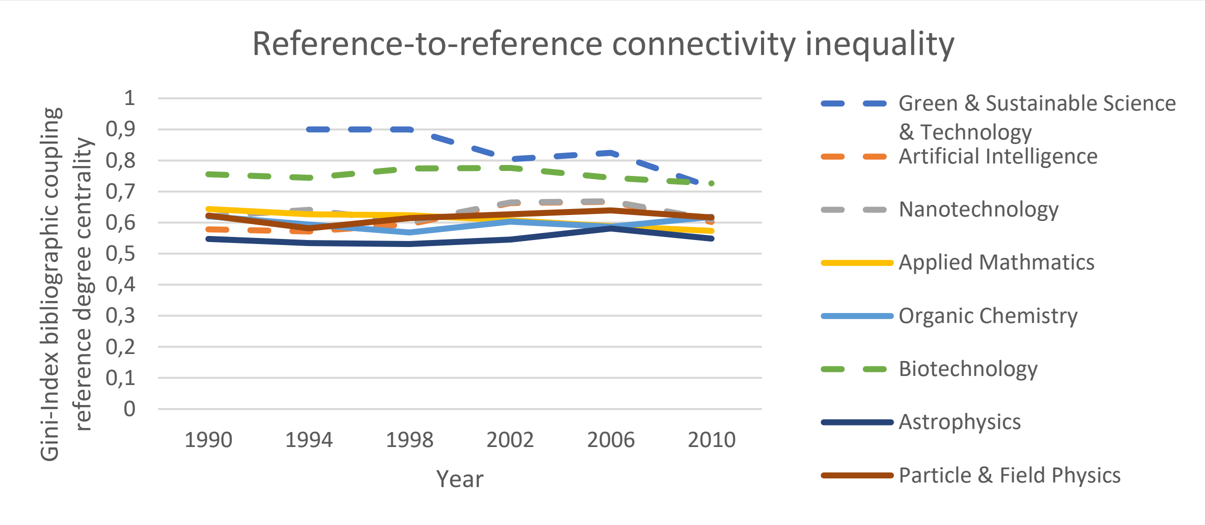

Figure 35: Reference-to-reference connectivity inequality

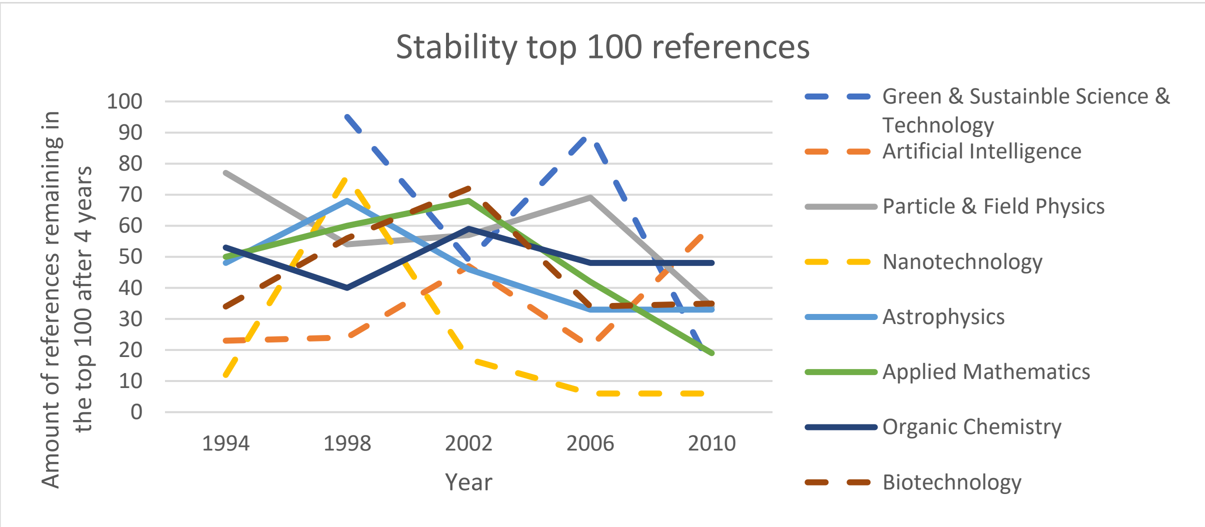

Figure 36: Stability top 100 references

Furthermore, differences are noticeable in the stability of the reference ranking per field (Figure 36). Lastly, it is argued that knowledge fields that can, proportionally, 'forget' more knowledge are higher in their knowledge accumulation. Fields that forget more knowledge, and therefor cite more recent references, debate less long about previous papers and therefore more uniformly move on faster. In addition, newer and more up to date knowledge has taken their place. A higher knowledge accumulation is associated with a lower (technical) task uncertainty (Heimeriks & Balland, 2015). Perhaps, one of the most intriguing findings of this study is that mature and emerging fields differ greatly in their rate of knowledge accumulation (Figure 37). More mature fields, generally speaking, have shrunk in their publication citation volume of the previous years and therefore seem to forget more publications. Emerging fields however, seem to show the opposite and even cite more papers from the past when time goes by. This pattern is confirmed by the reference publication year spectroscopies of all fields (Appendix 1). Mature fields show a spikier distributions. The citing mean-life (Appendix 7) and citing half-life (Figure 38) differ per field too. Mature fields tend to have a higher citing mean-life, making their knowledge bases older and therefore arguably more stable. Hence the association with a lower technical task uncertainty. Conclusively, fields differ in their knowledge base sizes, homogeneity, dominance, reliance and stability. Thus arguably vary in their technical task uncertainty.

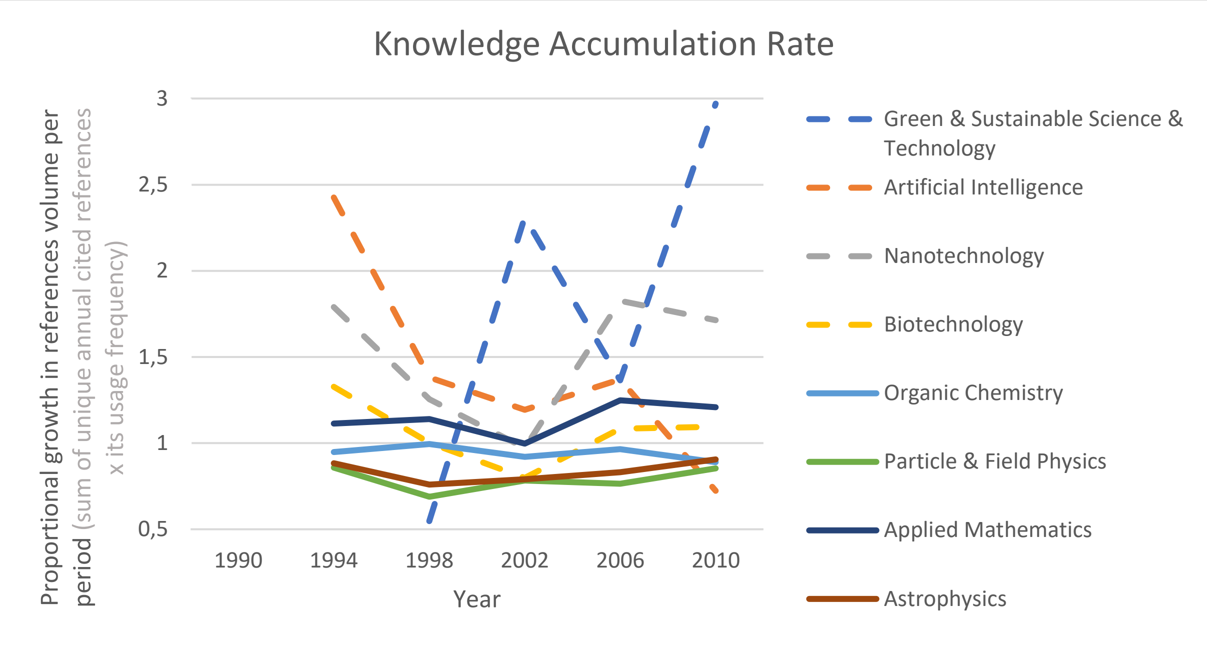

Figure 37: Knowledge accumulation rate per field (lower proportional growths represent a higher knowledge accumulation rate)

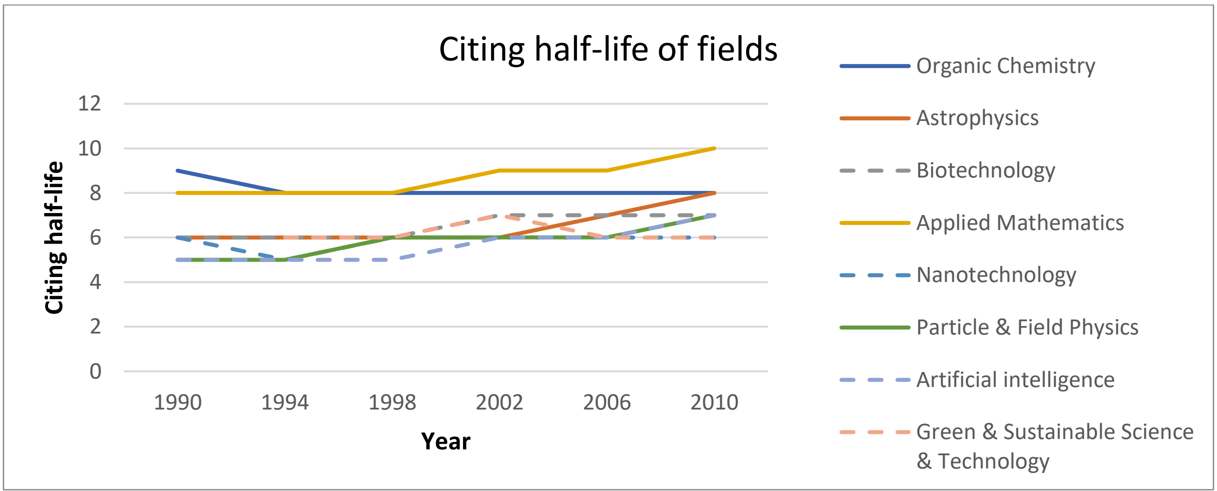

Figure 38: Citing half-life of fields

Lastly, we'll look at the strategic task uncertainty. It is found that fields vary in their top 10 keyword dominance (Appendix 7). Astrophysics, for example, has a top 10 of keywords (author keywords and keyword plus) that is at least twice as dominant as that of Applied Mathematics in some years. Based on the stability of the top 10 keyword plus, top 10 author keywords, top 100 keyword plus (appendix 7), and top 100 author keywords (Figure 39), we can conclude that there is a great stability difference between fields. Applied Mathematics and Astrophysics seem to be leading fields in terms of stability, while Nanotechnology and Green & Sustainable Science & Technology are much more turbulent. Subsequently, we can conclude that the inequality of author keyword-to-keyword connectivity differs per field (Figure 40). This means that some fields are much more directed in terms of research topics than others. The Big Sciences score highest in their topic connectivity inequality, while Nanotechnology and Organic Chemistry have a very egalitarian topic connectivity, implying a more scattered field.

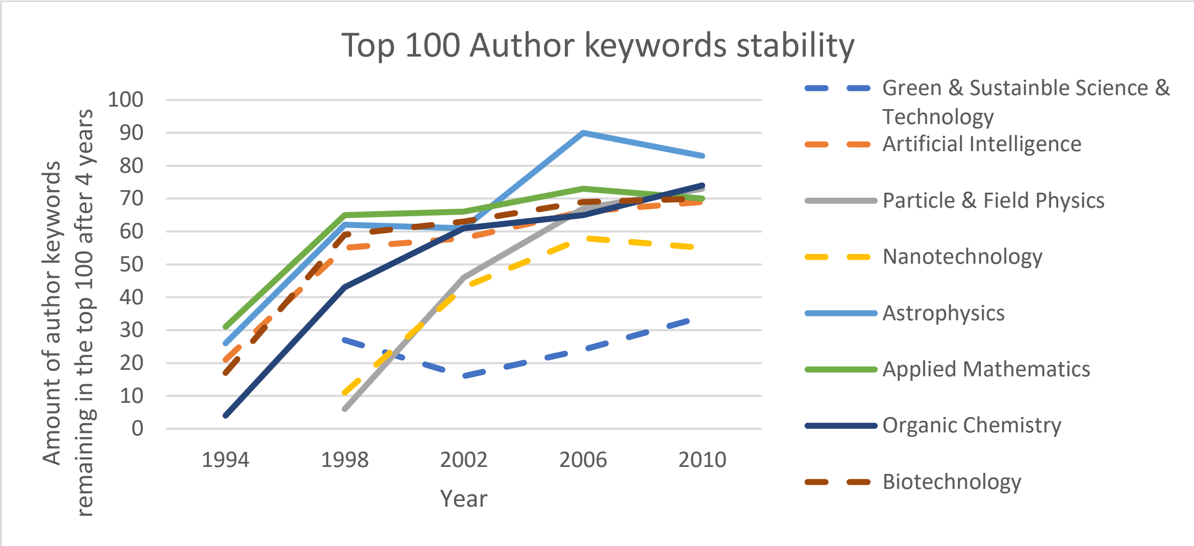

Figure 39: Top 100 author keyword stability

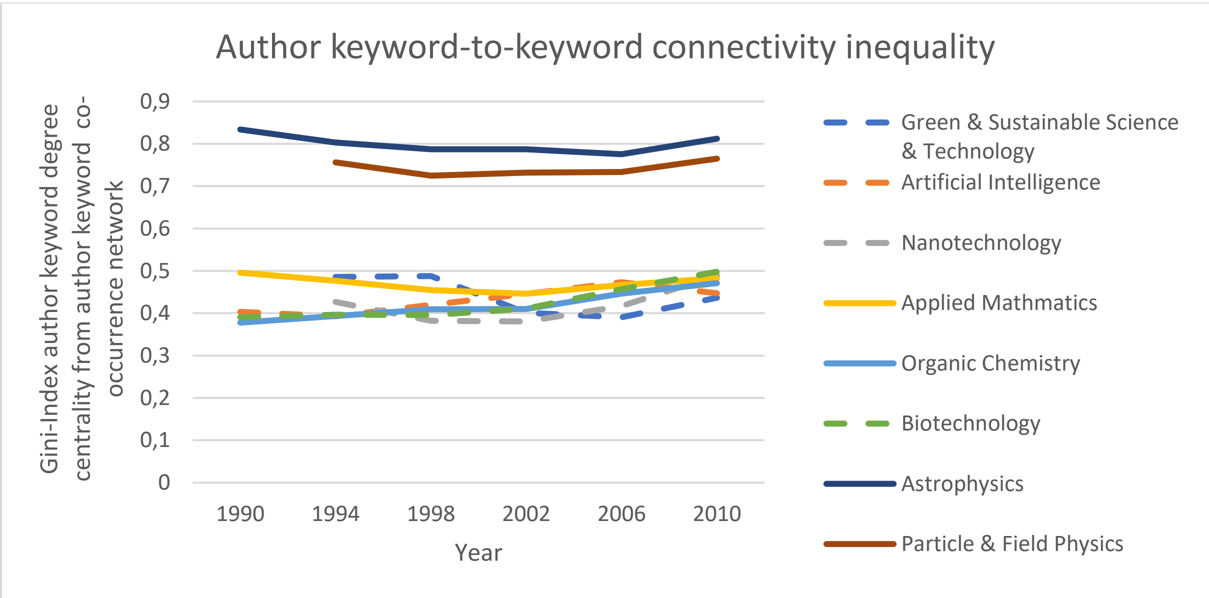

Figure 40: Author keyword-to-keyword connectivity inequality

To conclude, we have seen that fields differ greatly in their topic dominance, stability and connectivity. It is therefore concluded that field differ in their strategic task uncertainty.

With the prior findings we can partly answer sub question 2: ‘How can differences in task uncertainty characteristic levels between fields be quantitatively measured?’. This study has used reference homogeneity, stability and citing behavior to capture technical task uncertainty characteristics. This has appeared to be rather difficult due to the distance between theory and operationalization. The interpretation of reference homogeneity and connectivity for example can be quiet ambiguous. The knowledge accumulation indicator seems to show promising insights, but needs further validation for obvious epistemological reasons. When considering the strategic task uncertainty, the topic ranking and stability seem to show the most promising insights. Clear differences can be found, and this operationalization stands close to Whitley’s theory. Nevertheless, the variety of indicators combined has given a more in-depth insight in the task uncertainty of fields. Astrophysics, for example, is a case that is characterized by a low technical and strategic task uncertainty due to the high knowledge accumulation rate and stable topic ranking.

Dimension levels per field

The indicators within analytical aspects are aggregated to relative low, medium, and high levels. The relative scores of fields for their analytical aspect are all together presented in Table 42 & Table 43. Table 42 presents the scores of fields for the beginning of the time period while Table 43 presents those for the end of the period. Be aware that these results are relative to each other. A high mutual dependence, hence means that the field operates under a high mutual dependence compared to the other empirical cases.

Table 42: Dimension levels per field at beginning of period

Beginning of period				
Field	**Mutual Dependency**		**Task Uncertainty**	
	Functional Dependence	**Strategic dependence**	**Technical Task Uncertainty**	**Strategic Task Uncertainty**
Green & Sustainable Science & Technology	Low	Low	High	High
Artificial Intelligence	Medium	Low	High	High
Nanotechnology	Low	Medium/High	High	High
Biotechnology	Low	Medium/High	Low	Medium
Particle & Field Physics	High	High	Medium/Low	Medium
Applied Mathematics	Medium/High	Low	High	Medium/low
Astrophysics	High	High	Medium/Low	Low
Organic Chemistry	Low/Medium	High	Medium/Low	Medium/high

Table 43: Dimension levels per field at end of period

End of Period				
Field	**Mutual Dependency**		**Task Uncertainty**	
	Functional Dependence	**Strategic dependence**	**Technical Task Uncertainty**	**Strategic Task Uncertainty**
Green & Sustainable Science & Technology	Low	Medium	High	High
Artificial Intelligence	Medium	Low	High	Medium/high
Nanotechnology	High	High	High	Medium/high
Biotechnology	Medium	High	Low	Medium/low
Particle & Field Physics	High	High	Medium/Low	Low
Applied Mathematics	Medium	Low	High	Low
Astrophysics	High	High	Low	Low
Organic Chemistry	Low/Medium	High	Medium/low	Low

With these aggregation, we can try to answer the third sub question, SQ3: ‘To what extent can differences in analytical aspect levels of dimensions in knowledge fields be quantitatively identified?’. When one studies these levels, one can conclude that analytical aspects per dimension can differ greatly. It is true that a high and a low level are a rare combination within a dimension, but Applied Mathematics (End of period: Task Uncertainty) and Organic Chemistry (End of period: Mutual Dependency) are some of the cases that indicate its possibility. Conclusively, analytical levels can differ but this is rather rare, just like Whitley (1984, 2000) has argued.

Relative structure dynamics

As mentioned in the theory, we can distinguish two types of organizational characteristics dynamics; relative and absolute dynamics. Relative dynamics are fields specific changes over time in comparison to other fields which could be the result of a maturity process as well as contextual factors. Absolute dynamics refer to changes over time in structure characteristics that seem to effect all fields regardless of their maturity. Therefor these absolute changes are likely to be linked to the context in which it finds itself.

The next sub question that can be answered, is sub question four; SQ4: How have organizational structure characteristics of knowledge fields changed relative to each other over time?. This question can be answered in two ways. The first is by comparing emerging and mature fields in their relative levels. It is found that mature fields are likely to witness higher levels in their functional and strategic dependence. Mature fields are more stable in their author/institution ranking stabilities. In addition, the results suggest that mature fields demand for greater collaborations, but this could also be explained by specifically the presence of the ‘big science’ cases in our sample, and thus leaves questions related to the relative dynamics of the strategic dependency. Apart from collaboration size and frequencies, it is found that authors in mature fields are more unequal in the role of lead author. Mature fields thus seem to have established more stable and plausibly greater hierarchies which leave little room for new entrants. In addition, generally speaking, lower levels of technical and strategic task uncertainty are found for mature fields than for emerging fields. Mature fields show a higher knowledge accumulation rate and more stable topic rankings.

A second approach for answering this question is by analyzing holistic relative differences between fields throughout the time period. Here we find that emerging fields have witnessed a much greater shift in their relative levels for especially the analytical aspects of the mutual dependency dimension. This is mostly due to the convergence of levels of emerging and mature fields in collaboration frequency, and author/institution ranking stability.

Conclusively, fields tend to increase their mutual dependency while lowering their task uncertainty throughout the maturity process.

Absolute structure dynamics

The last sub question that can be answered is sub question five; SQ5: ‘What universal absolute changes in the organizational structure characteristics can be identified throughout the time period?’. Universal absolute dynamics in this study can be categorized in two groups; that is continuous absolute trends and sudden absolute trends. The first is a structural trend that returns in all fields throughout the whole period. The latter however, is a trend that all fields witness in a certain year. This distinction is important for the interpretation of the absolute trend, as will be elaborated on in the discussion.

Notable continuous absolute trends in the mutual dependency dimensions are, amongst other factors, the increasing fractionalized institution citation inequality in combination with the progressive increase in institution ranking stability. All fields show a continuous growth in citation inequality (except for Green & Sustainable Science & Technology) and increasing stability of this hierarchy. In addition, this mutual dependency shows continuous absolute increases in the average collaborations sizes and frequencies and an increase in the collaborative dominance inequality. Based on these trends, it seems that the sciences increasingly more seem to be heading towards a highly unequal oligarchy in which a small group of institutions are able to dominate fields for a longer period of time.

More continuous absolute trends have been identified for the task uncertainty dimension. The mean and median reference age has risen throughout the 20 year time period, showing that scholars increasingly more build forth on older knowledge. In addition, it is found that the reference density has slowly increased too. This might imply that the fields have become increasingly more complex (more references) and more fundamental (older references).

Although the reference density shows a continuous increasing trend for all fields in the time period, one can also identify a sudden, more radical, increase in density between 2006 and 2010. Subsequently, not only has the task uncertainty changed in its technical task uncertainty (refence density), but also in its strategic task uncertainty (topic stability). All fields (except for Green & Sustainable Science & Technology) have shown an inverse exponential trend in the topic ranking stability.

An additional sudden radical pattern change to be found is that of the author ranking stability. The stabilities of most fields have witnessed a dramatic increase as of 2006/2010. Organic Chemistry for example showed a rather stable stability in 1994-2006 stagnating around 16 authors remaining in the top 100 after every 4 years. In 2010, however, this increased to almost 40 authors remaining in the top. Also Nanotechnology, Artificial Intelligence, Applied Mathematics and Biotechnology show extraordinary changes in stabilities. As this may be, no obvious absolute change is to be found for the fractionalized author citation inequality, implying that the hierarchies became more stable but not greater.

To conclude, it is thus apparent that the 20 year time period is characterized by an absolute increase in the mutual dependency, especially on institutional level. Moreover, fields have become more reference dense and more stable in their topic ranking stability. These changes have returned in all fields and are therefore unlikely to be part of a maturity process. Instead, when reflecting on Whitley's theory, contextual factors are likely to be the cause of this (1984, 2000). It is unknown what contextual factors have caused these changes, but this period is characterized by an increase in globalization and by the introduction of ICT, which both could plausibly be the cause.

Conclusion

This explorative study examined the organizational structure of eight knowledge fields (i.e. Nanotechnology, Biotechnology, Artificial Intelligence, Green & Sustainable Science & Technology, Astrophysics, Applied Mathematics, Organic Chemistry and Particle & Field Physics). This is attempted by measuring the functional dependence, strategic dependence, technical task uncertainty and strategic uncertainty of these cases. Based on the results and answers on the sub questions presented in the results section, this paper will answer the main research question presented in the introduction:

'How do organizational structures of different knowledge fields change over time?'.

We concluded that the organizational structures between fields are different and that even the analytical aspects within dimension can greatly differ. Moreover, fields show different trends in their organizational structure. Be that as it may, generally speaking, it is found that mature fields operate under a higher functional (and possibly strategic dependence) while presenting lower levels of technical and strategic task uncertainty. Based on this finding, it can be argued that emerging fields tend to increase their mutual dependency while lowering their task uncertainty.

Moreover, absolute trends have been found that are unlikely to be linked to the 'maturity' of fields. Predominantly, fields in the period of 1990-2010 especially show a great increase in its mutual dependency. The institution citation distribution has become more unequal; its ranking has become more stable; and collaborations have intensified and become more frequent. Moreover, the task uncertainty seems to have decreased for all fields due to an increase in reference density and topic rankings stability.

The absolute organizational characteristics levels however, highly depend on the nature of the field. The 'big sciences' for example are highly unequal in their author/institution citations and stable in their citation ranking, while they are characterized by enormous research collaborations. This high level of mutual dependency is accompanied with a high rate of knowledge accumulation and a very directed research field in terms of topics. This uncertainty minimization and high dependency is likely linked to the expensive and scare research instruments in the field as discussed in the theory section. On the other hand a field like Applied Mathematics is mature and low in its task uncertainty, but is due to its nature also low in its (strategic) mutual dependence. The field does not need to heavily collaborate to mobilize resources.

Ultimately the truth is likely to lay somewhere in the middle when returning to the research question. Yes, fields seem to be prone to a certain maturity dynamic in its organizational structure as discussed earlier, but the time period in which it finds itself and the nature of the field highly influences the extend of this dynamic.

These conclusions might appear to be very surely, however there are quite some limitations and knowledge gaps that need to be addressed in the future, due to the exploratory nature of this research. These topics will be discussed in the discussion section.

Discussion

This section will discuss the limitations; practical and theoretical implications; and future research topics of interest.

Limitations

This study has aimed to broaden the horizon of research on the topic of organizational structures in knowledge fields. Consequently, it aimed to measure trends in a high amount of experimental indicators. This can be beneficial for readers that aim to explore new research opportunities in the field and would like to see a high variety of indicators and perspectives. However, it also brings along downsides. Due to this high number of indicators, it is not feasible to use statistical analyses for comparisons due to time restrictions. Instead, this study remained highly descriptive and is therefore less insightful and less robust than when one would conduct more statistical tests on it.

In addition, this explorative and experimental nature effects another element of the interpretation of the results. Within analytical aspects, multiple indicators are used. A correct aggregation and normalization to levels of an analytical aspects/dimensions has not been proposed. The reason for this is that no correct aggregation and normalization exists up to this date, and this paper does not aim to provide one. Its intention, however, is to provide a more holistic view and start the scientific debate on differences between fields; their dynamics; and how to quantitatively measure and interpret this. The conversion from indicator levels to dimension levels is therefore prone to interpretation. My interpretation of the data is given and should be considered in the light of these limitations. As that may be, the absolute levels of the indicators are reliable and are replicable with the code given in the appendix. This in combination with the reasoning given throughout the paper, makes up for a strong case that the empirical cases do differ in their organizational structure; their dynamics; and that it is likely that the chosen mature fields are higher in their mutual dependency while lower in the task uncertainty than the emerging fields. It is however, unclear whether this conclusion holds up for other cases outside of our sample. Therefore, the external validity is not claimed.

Moreover, the results are generally speaking in line with the expected levels based on the literature used in the theory section. However, this study has explored organizational structures of fields in mainly the natural sciences. Relative levels (i.e. high/medium/low) are likely to change when other categories of knowledge fields are included. Whitley argues that the social sciences are expected to be much higher in their task uncertainty (Whitley, 1984, 2000). Therefore, fields in this study that are associated with low levels, might actually be somewhere else in the spectrum when including other knowledge fields. The levels found in this study should therefore be taken with a grain of salt.

Lastly, the chosen indicators and sampling strategy are arguably unconventional or are already a topic of discussion. Construct validity questions might arise like; are keywords really suitable metrics for topics? Are fractionalized citation counts suitable metrics for prestige? What are the preferred ways to demarcate knowledge fields? And what might be a good metric for the rate of knowledge accumulation? This study has argued for the chosen approach, but they are definitely not perfect representations of the concepts of interest. Nevertheless, due to the reasoning discussed previously in this paper, it is believed that these decisions are justified. This does not change the fact that the field of scientometrics needs to keep finding novel ways of measuring concepts. Especially the analytical aspect of technical task uncertainty deserves more attention. References did not provide very clear trends that the theory suggests should be present. Perhaps that more advanced analytics like text mining could provide a solution to this challenge.

Theoretical contribution

The most evident theoretical contributions of this paper are that knowledge fields differ in their organizational structures and dynamics. This was already suggested or implied by some studies within the field, but never has there been a study that has explicitly aimed to research this. Furthermore, it is found that the empirical mature fields are operating under a higher degree of mutual dependency and lower degree of task uncertainty than the chosen emerging fields. Therefore, it is expected that over time, fields tend to increase this mutual dependency and lower their task uncertainty. Maturity is on the other hand not the defining element for the structure. It is argued, that the time period and nature of the field in combination with the maturity together influence its state.

Moreover, this study has proposed a variety of new indicators for theoretical concepts. Scientometrics for the organization structure of knowledge fields are barely developed and this study has aimed to use a collection of validated and experimental indicators to capture the organizational structure characteristics. For example, this study has used the economic Gini-index indicator to measure inequalities in citations and network characteristics. Inequalities imply hierarchies, and the research hereof in knowledge fields lacked the right indicator. Another indicator proposed is that for knowledge accumulation. Knowledge accumulation is a widely understood and accepted concept, but has not been quantitatively measured within the field of scientometrics. This paper proposes that this could be measured through identifying the proportion of 'forgotten' knowledge over time by looking at the frequency of annual unique references in the reference publication year spectroscopy and multiply this by its usage frequency. The comparison of this reference volumes between two empirical years is thus an abstraction of the amount and value of forgotten knowledge. It remains to be seen whether this abstraction is correct, and thus demands for further validation through triangulation. But if it does, then this offers the field of scientometrics and innovation sciences as a whole, a very much needed indicator since knowledge accumulation forms a central concept in the fields (Heimeriks & Balland, 2015). The knowledge accumulation rate indicator could, for example, be used in other contexts e.g. industrial/sectorial knowledge accumulation (patents) or corporate knowledge accumulation (knowledge management databases). Regardless of the new indicators proposed, based on this study, it seems evident that scientometrics for this topic are needed and hence demand for more attention.

One less obvious theoretical contribution of this paper is the insight that Whitley's theory might be too simplistic and ambiguous. Even a relatively straightforward analytical aspect like the strategic dependence seems to be too broad. Fields can, for example, conduct research in intensive collaborations, but the frequency of collaborations can ironically be low. Contradicting results of collaboration intensity and frequency thus raise the question of what a high or low level of strategic dependence entails, not to mention how to compare fields in their dependence. A similar challenge has been found for the functional dependence aspect, in which hierarchies can be great and unstable and vice versa. This brings us back to the aggregation challenge mentioned in the limitations section above. Perhaps, an aggregation becomes more straightforward once Whitley framework; its dimensions; and its analytical aspects are further broken down. This would help close the distant gap between theory and operationalization.

Contributions to other theories

Apart from these theoretical contributions to Whitley's theory, this study on knowledge field specific structures potentially also aids adjacent theories that this paper would like to further speculate on.

Subsequently, transition theories like the technological innovation system (TIS) (Hekkert, Suurs, Negro, Kuhlmann, & Smits, 2007) have predominantly viewed the scientific system and its dynamics as a black box and demands for a better understanding. System theory has not (or barely) been used in the scientific context. It is for example unclear how actors, institutions, and infrastructures interact and perform to achieve scientific goals in the context of technological development. Actor roles have not been introduced in this system although it is likely that different actors take on different roles under different organizational structures of scientific systems. Just like innovation systems, a distinction between actors can be made e.g. incumbents, entrepreneurs, brokers, publishers, etc., and the institutions and infrastructures of the scientific system are expected to influence them. This study has for example found great hierarchies that are more stable in mature fields. This probably influences the role scholars (system actors) take on. Well performing scholars thrive in the task technicalities and strategy (system institutions) of the field and are therefore likely to take on the role of an incumbent to defend their position. This is especially to be expected in mature fields where hierarchical positions are more stable. On the other hand, changing uncertainty levels, for example, imply a changing window of opportunity for scholars to diverge into novel topics and knowledge bases. When considering the conclusion of this paper, it means that eventually, further into the maturity process, fewer (risk accepting) scholars would be able to create knowledge branches for which the reputational payoff is more uncertain. This on its turn effects the degree of novelty of research and gives a new meaning to (institutional) entrepreneurship in the context of the sciences. These entrepreneurial scholars that aim for radically new research are faced with a high reputational uncertainty when they aim to branch off from a field with a low task uncertainty. These are just some of the actor roles within the scientific system that are poorly understood. However, these actors are vital for the performance of the functions of the TIS (F3, and arguably F4). In addition, such a 'knowledge innovation system' not only gives a more in-depth understanding of transition theories but also of the continuous evolutionary process in the sciences.

Although studies on the evolutionary process of scientific fields have mainly focused on the dynamics regarding the path- and place- dependency of topics (David, 1994; Heimeriks & Balland, 2015) (strategic dependence), other aspects of the organizational structure are generally neglected. This study, however, has shown that hierarchies, collaborations and knowledge bases also evolve. With this, in combination with assumptions regarding the dynamics of research standards (see future research; validating & replicating), we can place the evolutionary theory of Nelson and Winter (1982) in the context of the sciences. Scholars, from an evolutionary perspective, can be treated as motivated by prestige and engage in search for novel ways to increase their, among others, citations (variation). Their research routines (the manifestation of the technical and strategic task uncertainty) are expected to be increasingly standardized and new scholars/fields are, due to the reputational system, inclined to adopt these (inheritance). This increasing mutual dependency in the form of emerging stable hierarchies emphasize the tendency of scholars to gain influence in the system (selection). Thus, the found dynamics of this study possibly enable us to combine the stationary view of Whitley in combination with the Lamarckian perspective of Nelson and Winter. Hence, it allows us to better understand the behavior of scholars in specific organizational structures.

Lastly, the high mutual dependency and low task uncertainty found in mature fields is expected to stimulate intellectual conformity. Radical research and branching off is less 'allowed' by the mature reputational system. As mentioned in the theory section, this maturity process in the organizational structure of knowledge fields could explain the finding of Bonaccorsi (2008), who found that emerging fields show a greater diverging dynamics as opposed to classical mature fields. Especially the reference-to-reference inequality and topic stability results of this study, might imply that the knowledge bases of emerging fields can diverge to a greater extent than mature fields. The preliminary link between Whitley's theory of the organizational structure to the findings of Bonaccorsi could thus potentially explain this differences in degree of divergence found between mature and emerging fields.

Hopefully, the findings of this study on the dynamics of organizational structures in combination with existing theories of Whitley (1984, 2000), innovation systems and Nelson & Winter (1982) will create common ground for scholars for future research regarding this topic.

Practical contribution

This paper aimed to shed light on research fields for practical actors and provides a more comprehensive understanding of their structure. The results sections has shown how different field can be, and that fields therefore should be seen as independent and unique cases. This study has provided field specific knowledge regarding the stability and presence of intellectual leader; it has shown how fields collaborate; what knowledge bases and knowledge accumulation differences are present; and what fields are characterized by its shared topic research agenda or divergence. This could form input for actors in decision making processes.

Subsequently, with these trends and differences in organizational structures arise new questions. Fields differ in their mutual dependency and task uncertainty, but one can wonder what ideal levels of dependencies and uncertainties are. A higher mutual dependency for example is associated with greater hierarchies. This is likely to increase the intellectual conformity of researchers, which has positive and negative externalities on its turn. It can be expected that (especially monodisciplinary) fields due to this will converge in research priorities and that uniform standards will arise, making the field more accumulative (Towne et al., 2005; Whitley, 1984, 2000). This, however, is expected to hammer radical breakthroughs and diversification. Such a debate between right- and left-wing views has similarities to that of politics, for which this study does not provide answers. Nonetheless, the overall increased functional and strategic dependency found in all fields throughout this period does have consequences and demands further attention.

One specific topic that is interesting for policy makers is the increased mutual dependency, especially on institutional level. Institutions have become increasingly more unequal in their citation distribution. In addition, they have become increasingly more stable in their citation ranking. This in combination with an upsurge in research collaboration sizes, frequencies and a clear rise in the author collaboration dominance factor inequality could potentially be worrisome. This combination shows that hierarchies become more unequal and stable. These functional and strategic dependencies are expected to reinforce each other, creating even a stronger position for the 'intellectual elites' (Whitley, 1984, 2000). It seems therefore crucial to ask ourselves what the implications are of an organization that incrementally moves towards an oligarchy in which a small group of institutions dominate knowledge fields in the sciences. One implication that could be derived seems to be that mature fields are harder to excel in for new entrants. As Balland & Heimeriks (2015) pointed out, this could be a rationale for institutions, regions and nations to focus on specializing in emerging fields that are more turbulent in their ranking and therefore offer a window of opportunity. On the other hand, this forms also a rationale for an entity to pick the 'winners'. Meaning, investing and focusing more on the mature fields in which one excels, could be a wise choice since the stability of these fields naturally defend the entity's leading position. Logically and realistically, these (potentially successful) specialization options are fairly limited due to the path- and place-dependent nature of the respective region (Heimeriks & Balland, 2015) and thus forms a good guide for local/national policymakers.

As mentioned in the theory, another practical implication of this increasing mutual dependency is that it is likely that this will decrease the task uncertainty on its turn (Collins, 1998; Hoedemaekers, 2013; Whitley, 1984, 2000). Hence, the research priorities, standards and techniques will become more uniform by a reputational system that steers scholars into this form of 'good science'. Although this is expected to increase knowledge accumulation and to diminish research risks, it is also expected to hammer creativity and radical research. Actors are due to this faced with the question whether this shift is desirable and how to possibly enforce/counter this.

Ultimately, it is safe to assume that not all implications of this hierarchical power shift in knowledge fields are comprehensively understood. But regardless of this, this awareness seems essential for the management of the sciences.

Future research

Following this study, there are particular studies that are believed to need more attention. This would preferably be done in the order of validating & replicating results (the what: organizational structures); more comprehensively understanding the rationale behind organizational structures (the why: collective goals); and identifying influential contextual factors (the how: action/reaction). The above mentioned studies would give way, for a better understanding of the collective activities and the environment they are located in. These insights are essential for a system perspective (Hekkert et al., 2007) on the sciences which could play a prominent role in (technological) innovation systems. Moreover, 'the what', 'the why' and especially 'the how' are recognized to be key elements in mission-oriented innovation policy. This policy framework has become increasingly more popular in recent years, but its approach demands for 'directed' knowledge production in which organizational structures steer scholars into the desired direction of this policy (Goetheer, 2018; Mazzucato, 2017). Hence, the following proposed studies:

Validating & replicating

As discussed in the limitations, the research field on knowledge production and scientometrics are in need of novel, validated, and universally agreed upon metrics for organizational structure concepts. Especially the analytical aspect of the technical task uncertainty lacks suitable metrics and knowledge. References as input for the study of knowledge bases might be too distant from the theory. In retrospect, a more suitable approach could be text mining whole papers and identifying the homogeneity of returning keywords regarding standards, methods and norms. Interesting (sub)questions could be: what proportion of papers in the field rely on quantitative research?; What analysis methods return?; and how do fields differ in their research method variety? A more uniform research approach could imply a low technical task uncertainty. The dynamics of this aspect could in addition validate the suspected Lamarckian inheritance process for research standards, methods and techniques.

Besides further examining the technical task uncertainty, it would be interesting to compare more cases on the strategic dependency aspect. The 'big sciences' in our pool of mature empirical cases might have influenced the results and thus unfairly given the impression that the strategic dependence increase throughout the maturity process. More mature cases could thus reinforce this derived conclusion.

This iteration in combination with statistical comparisons between fields for relevant indicators would reinforce the results of this study.

Understanding the rationale behind organizational structures

Another interesting research topic could be the identification of scientific collective goals. If organizational structures are systems to direct activities into desired collective ambitions, and if these structures are different between fields, then one could question whether different organizational structures are present due to differences in the collective goals. It could, for example, be argued that certain fields are more driven by its context of application (e.g. Biotechnology and Nanotechnology) while other fields might have a goal more orientated towards fundamental knowledge production (e.g. Particle & Field Physics). Time dynamics of structures, could besides imply changes in collective goals over time. As this may be, it could also be argued that 'more roads lead to Rome' and that differences in structures do not per definition imply differences in collective goals. This would be insightful, because differences in goals would emphasize the need for unique policies per distinctive fields regarding their organizational structures. Hence, its goals could give input to dilemmas like when one should minimize technical and strategic task uncertainties of fields or when one should allow for more diversification. This is essential, because currently there is no clear answer on what state of the organizational structures are desirable for certain collective ambitions.

The influence of contextual factors

Lastly, this study has mostly focused on the relative levels of indicators between fields. However, universal absolute trends for indicators are occasionally present. It is unlikely that some of these are linked to the maturity of a field. Some mature fields have shown dramatic trends that cannot have been consistently present throughout their history of existence. Besides, trends have been found that are present in all fields. Thus, rather it is plausible, that this is the effect of external factors (e.g. technological change). However, to robustly conclude this, we would need more data from other years (pre and post-transition periods) to compare results. This would be accompanied with several technical research questions. One would be that many indicators and publications are not yet explicitly codified and stored in large databases for the pre-transition period (<1990). On the other hand, the data set might be too large for whole fields for the post-transition period (>2010). Some knowledge fields in this study have already resulted in an integer overflow caused by the limitations of the software program 'R' when using our sampling strategy. Especially the computation of great (sparse) matrices form issues when collecting data of this magnitude. Future developments in R or smaller sample sizes in combination with statistical analyses to guarantee the generalization of finding to whole fields could form some solutions here.

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Appendices

The following appendices are incorporated in this paper:

Appendix 1: Reference publication year spectroscopy (RPYS)

Appendix 2: Top 30 Author Keyword Dynamics

Appendix 3: Top 30 Keyword Plus Dynamics

Appendix 4: Top 30 Title words Dynamics

Appendix 5: Top 30 Abstract words Dynamics

Appendix 6: Mutual Dependency Graphs

Appendix 7: Task Uncertainty Graphs

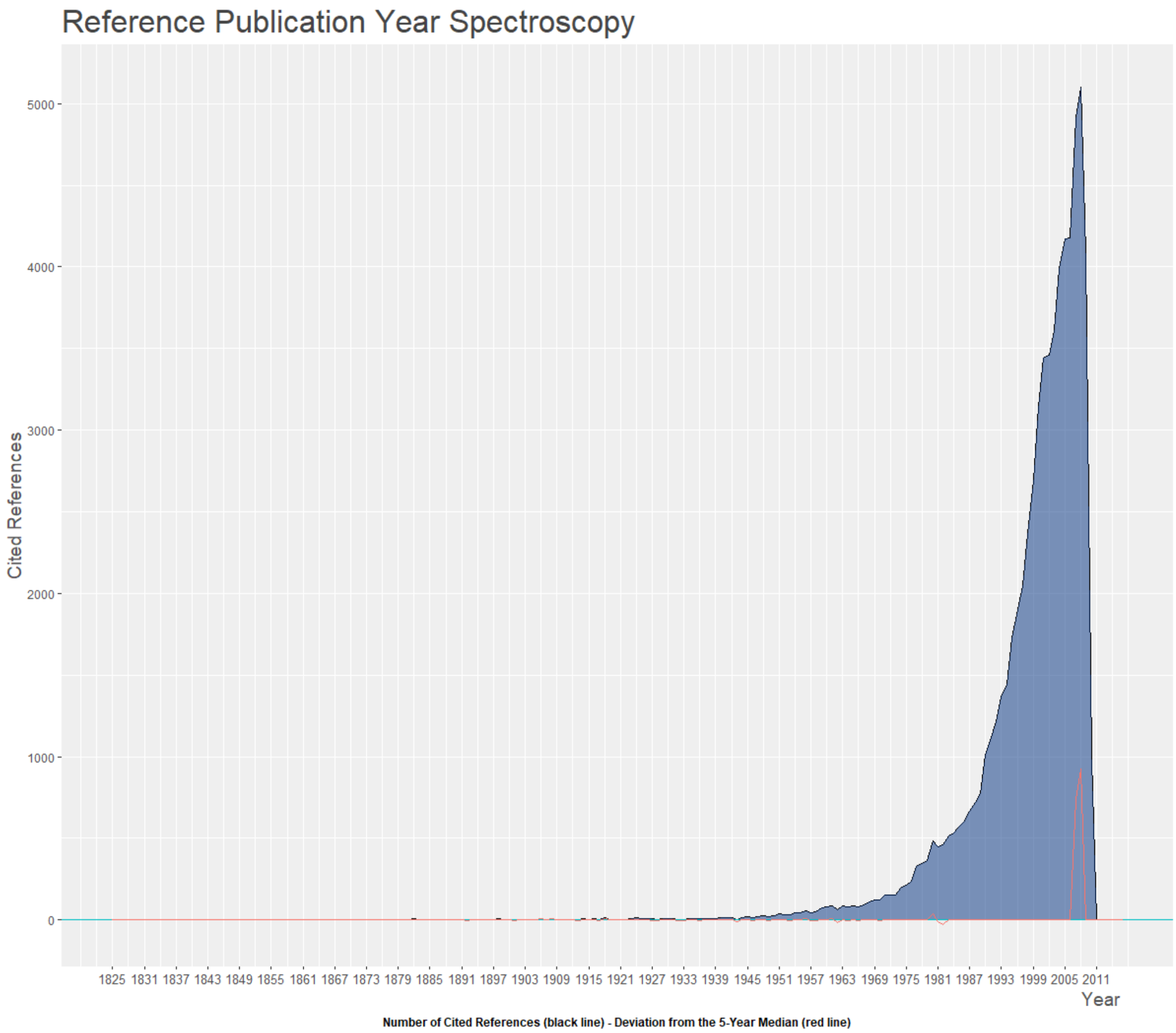
Appendix 8: Proposition Knowledge Accumulation Rate (KAR) Indicator

Appendix 9: Relative and absolute differences

Appendix 1 - Reference publication year spectroscopy (RPYS)

A RPYS shows the amount of unique references per year that have been found in a database or reference list. This appendix shows the cumulative RPYS per field, meaning that it shows the amount of unique references per year that have been used in 1990, 1994, 1998, 2002, 2006 and 2010.

Green & Sustainable Science & Technology



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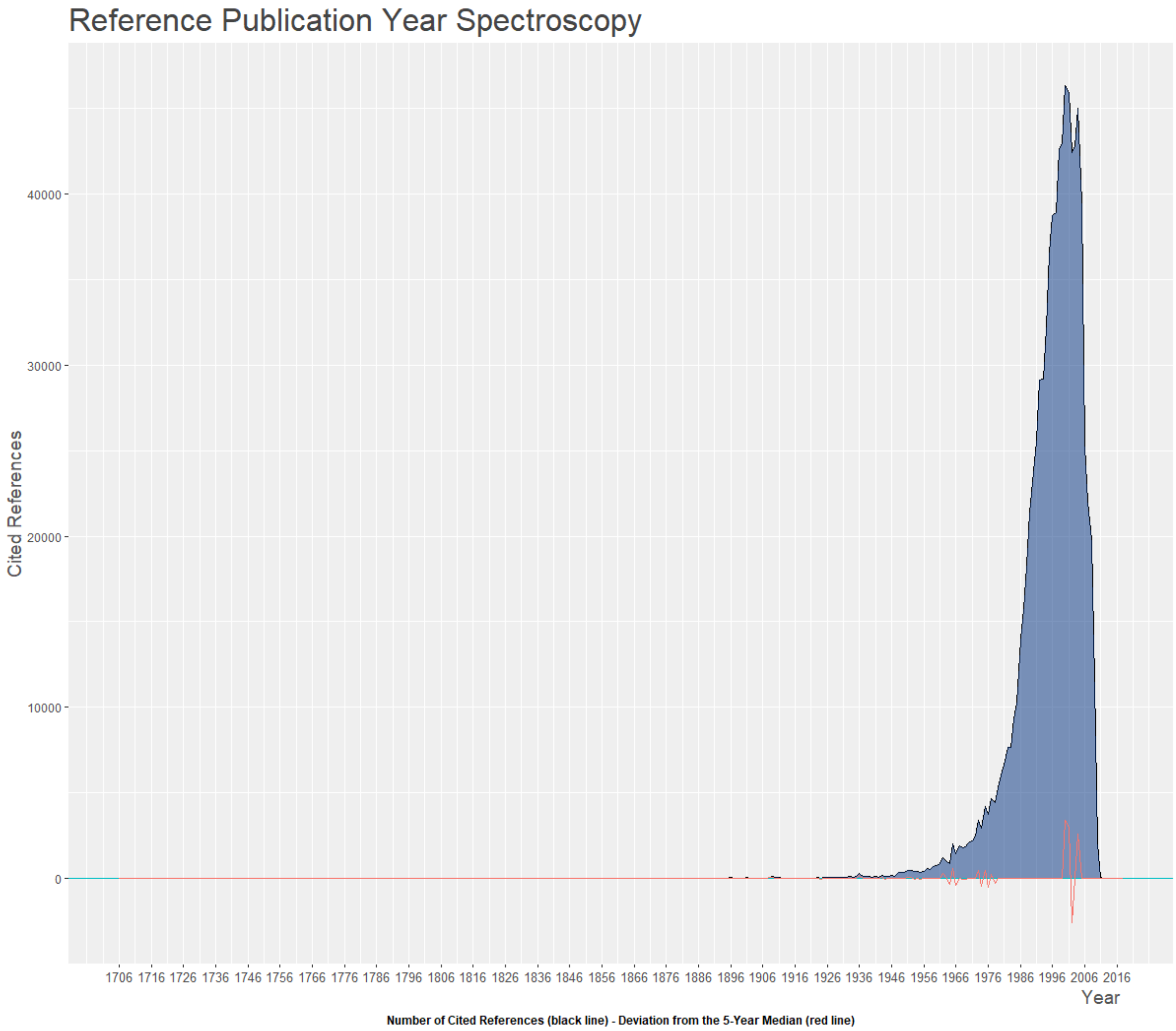

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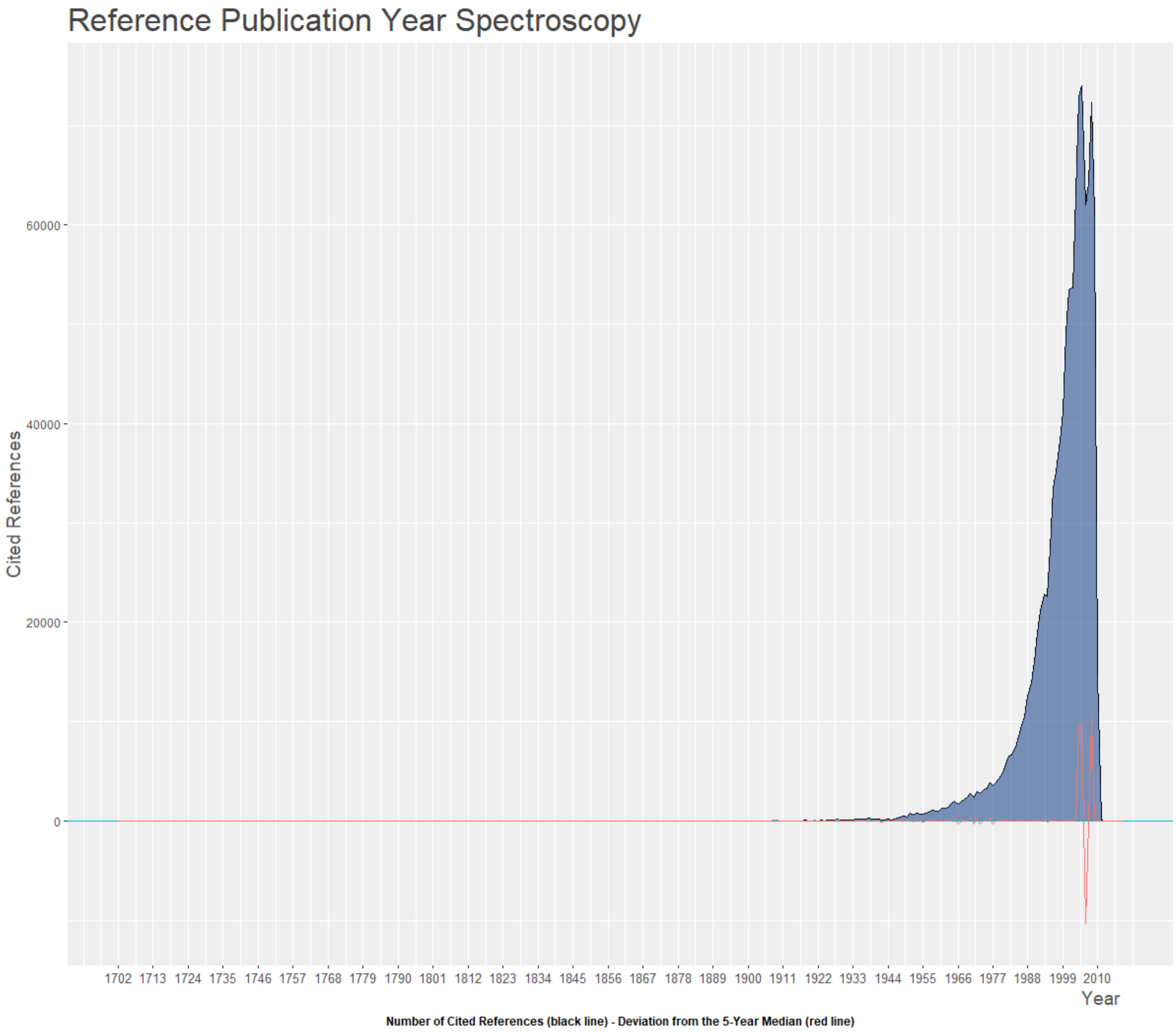

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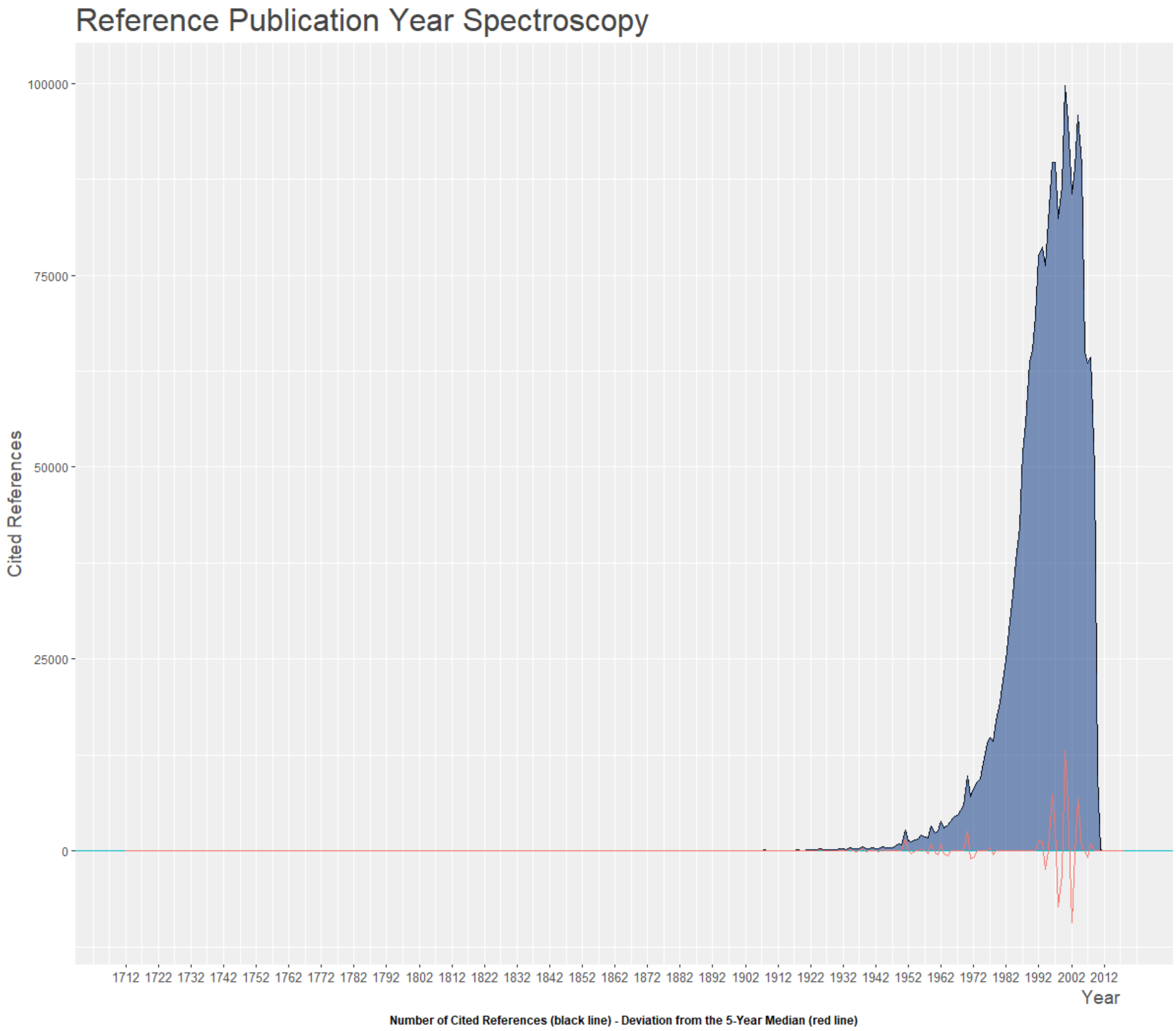

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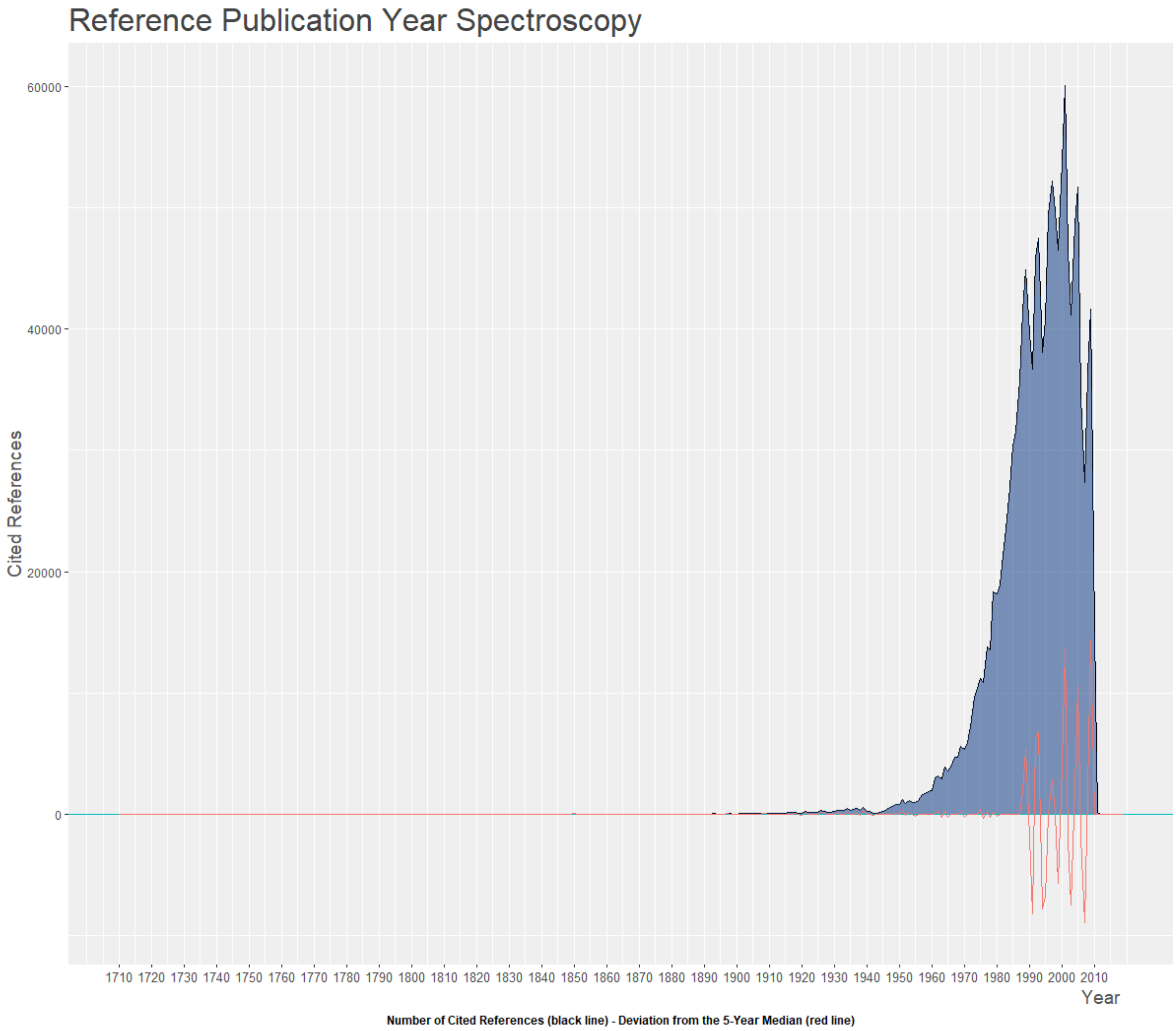
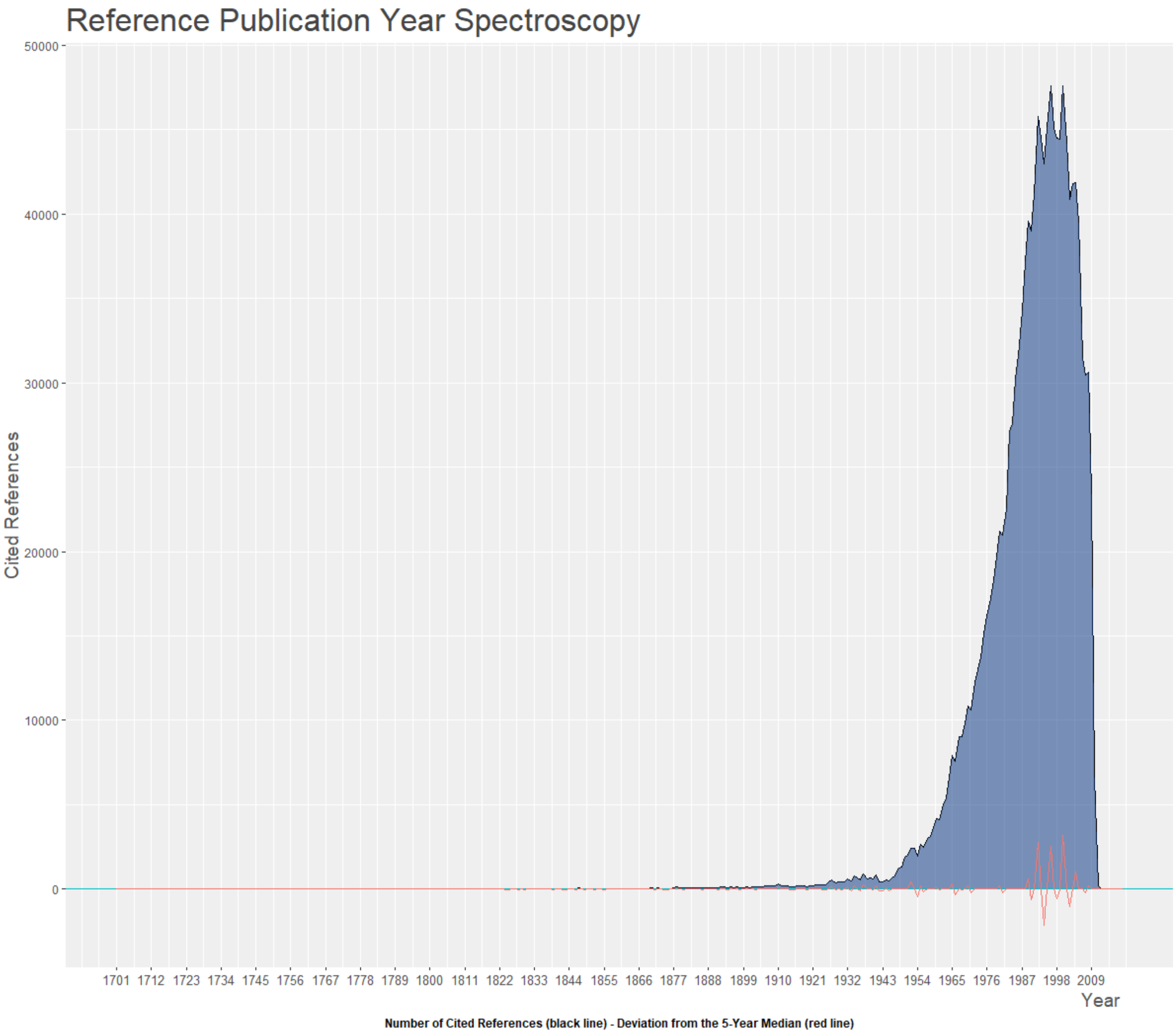
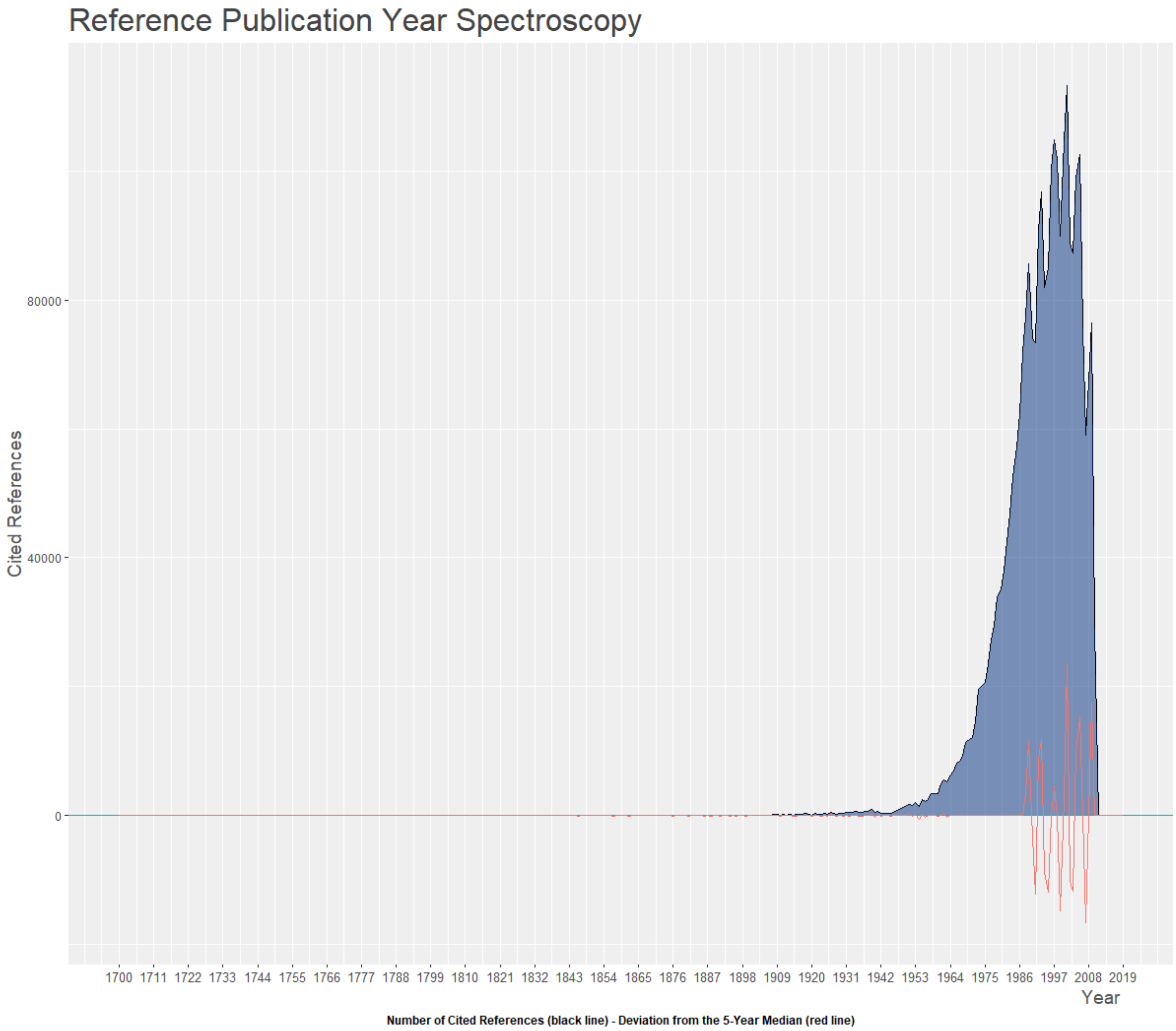
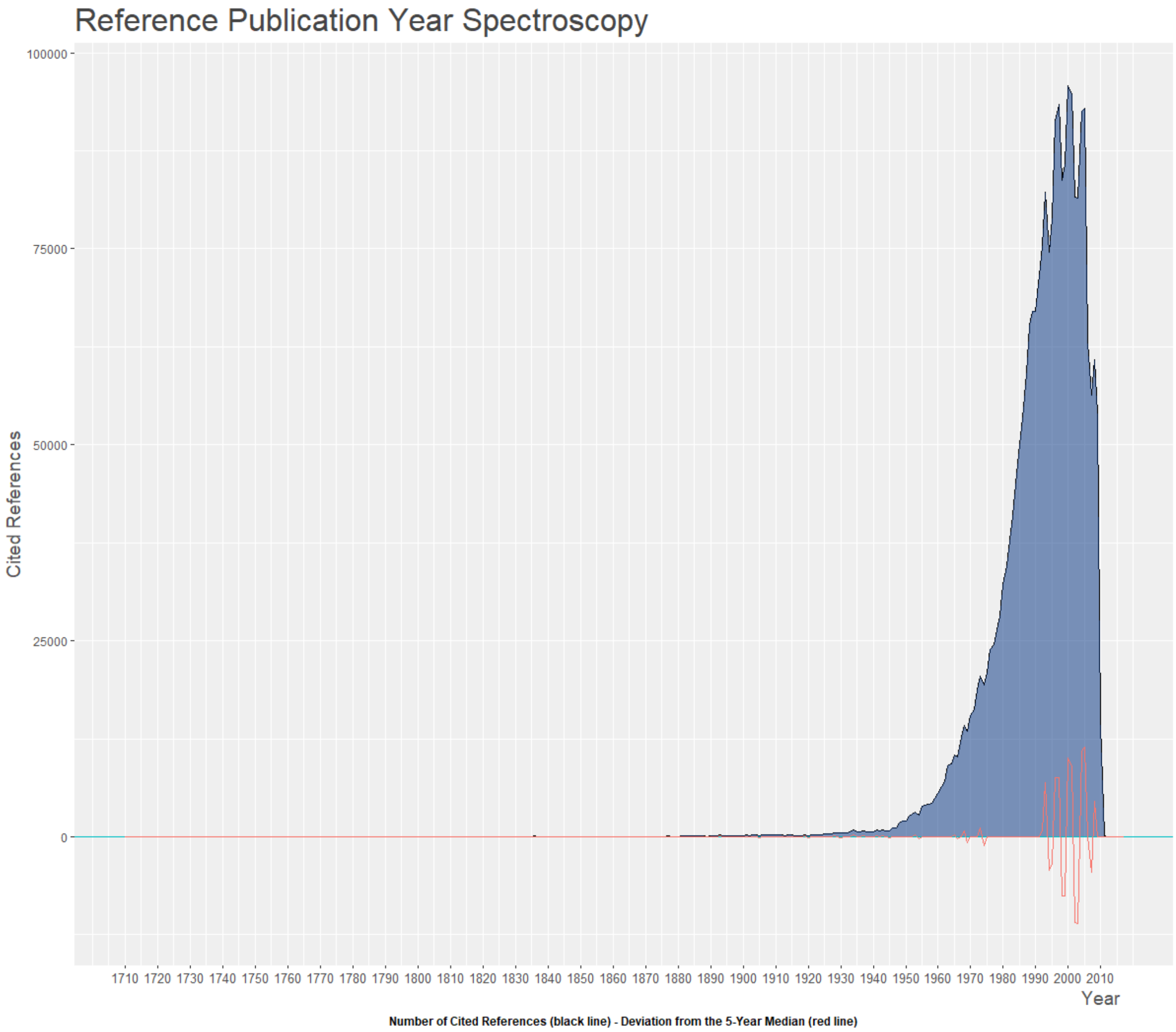


Applied Mathematics



Astrophysics




Reference Publication Year Spectroscopy
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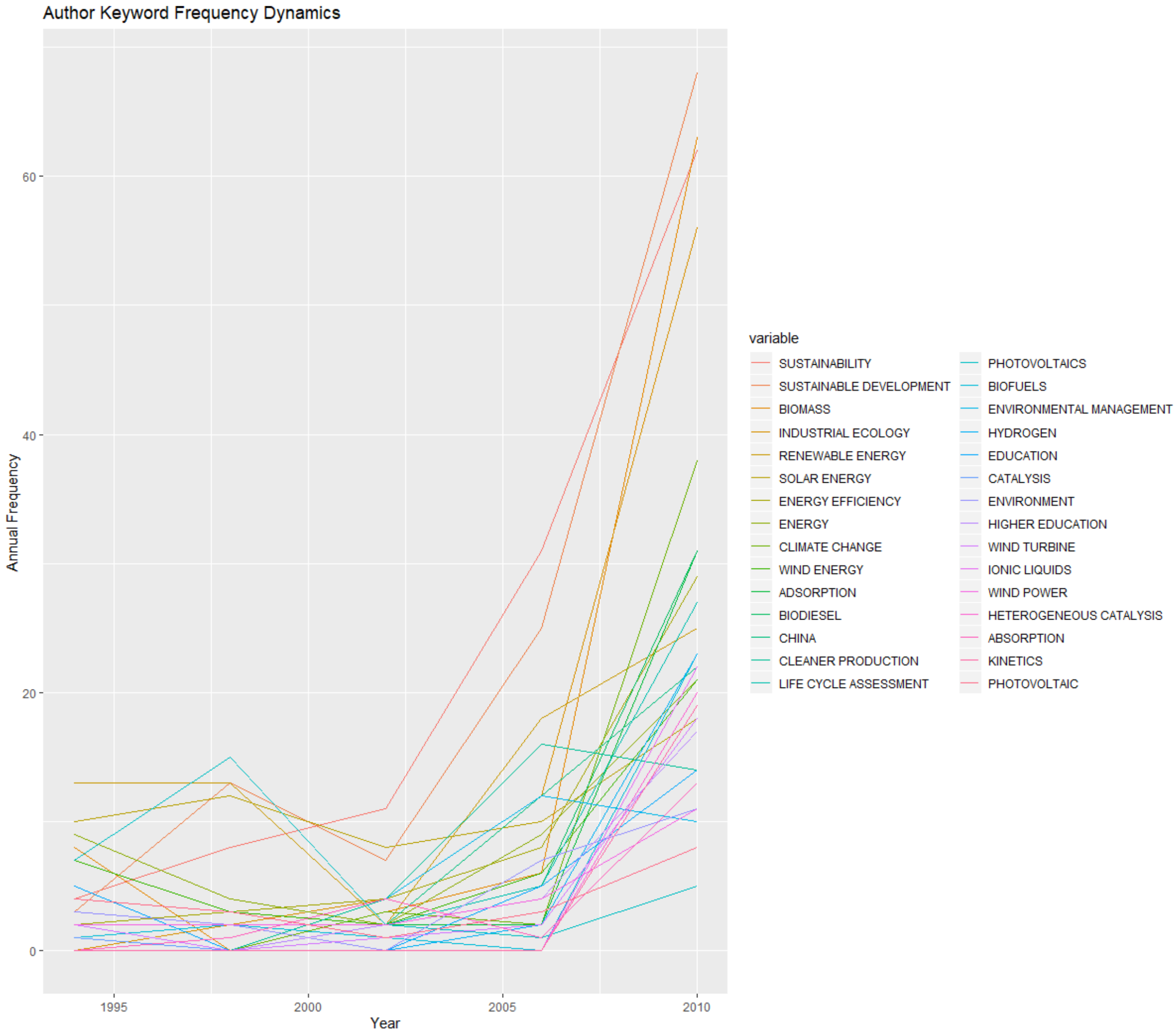
75000
50000
25000
0
Cited References
1710 1720 1730 1740 1750 1760 1770 1780 1790 1800 1810 1820 1830 1840 1850 1860 1870 1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010
Year
Number of Cited References (black line) - Deviation from the 5-Year Median (red line)

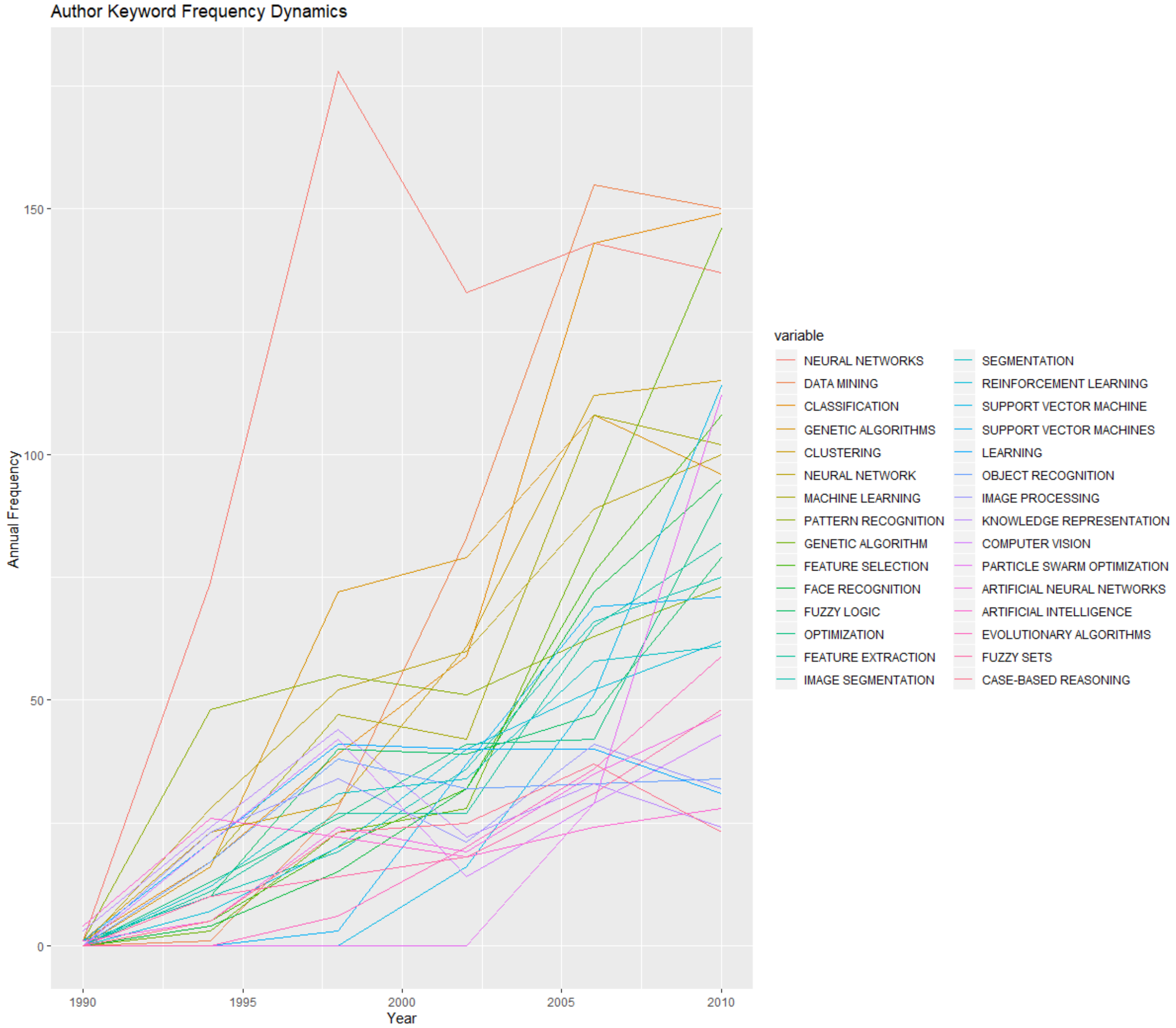
Appendix 2 - Top 30 Author Keyword Dynamics

Dynamics of the in 2010 top 30 author keyword over time.

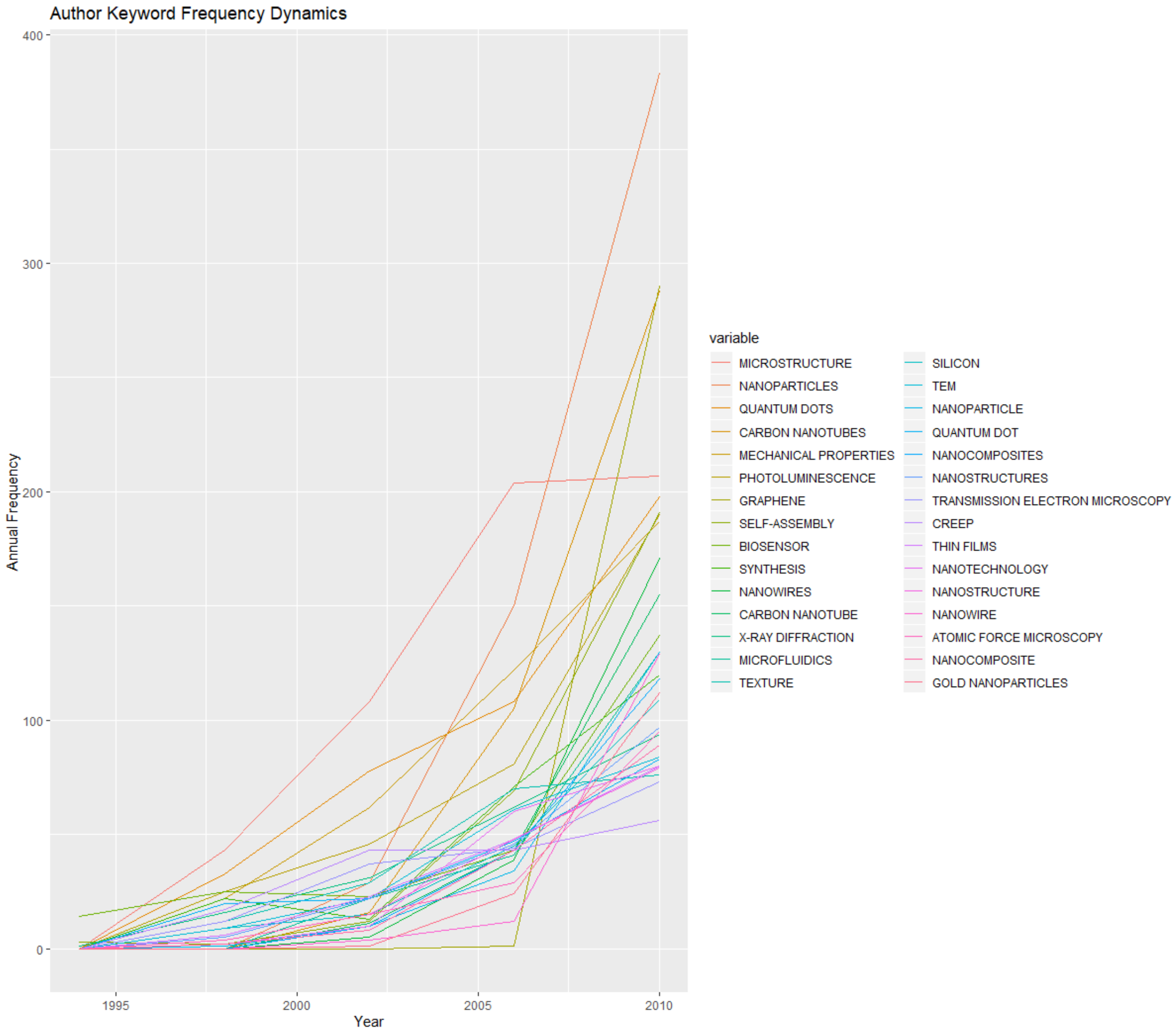
Green & Sustainable Science & Technology



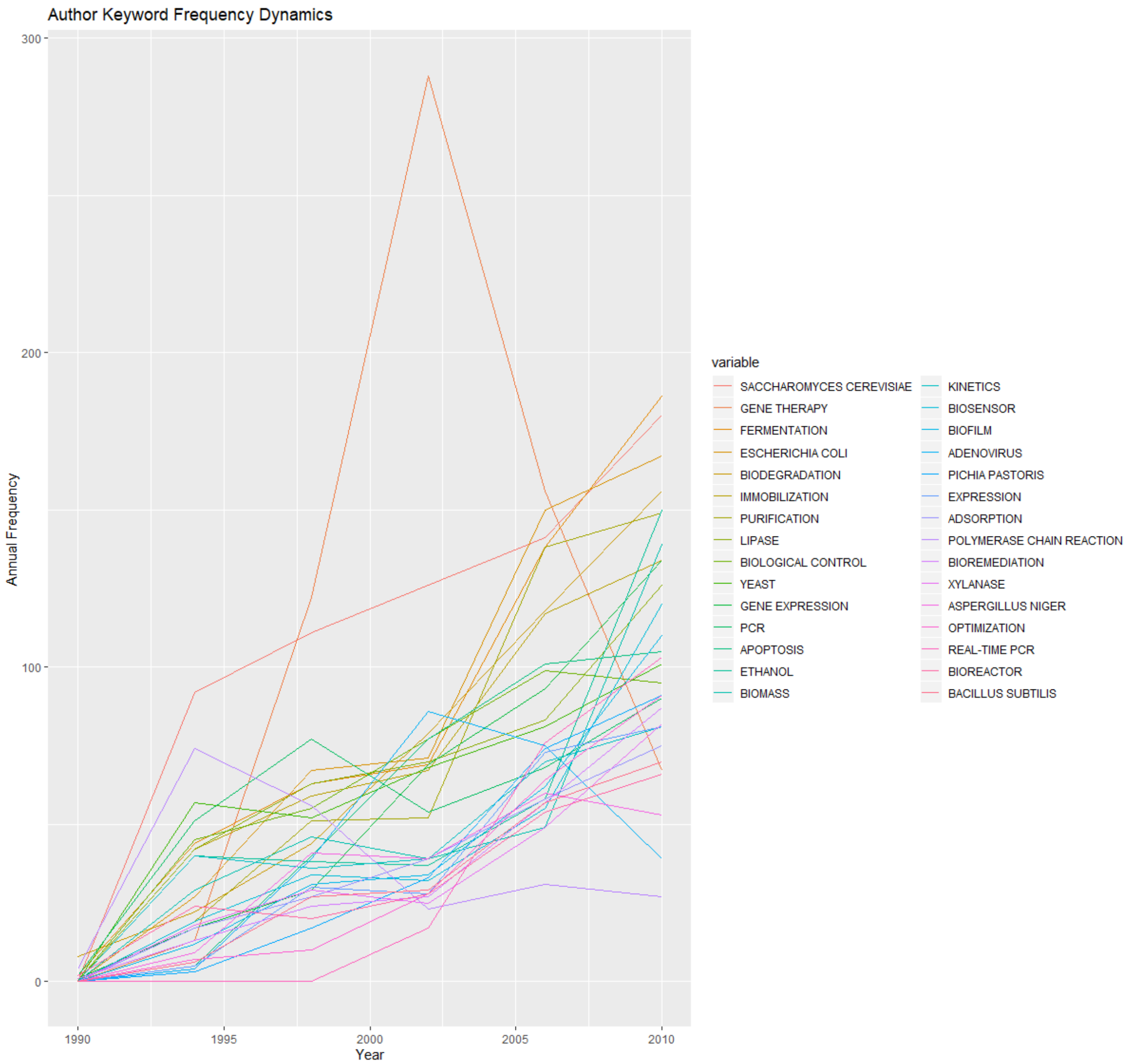
Artificial Intelligence



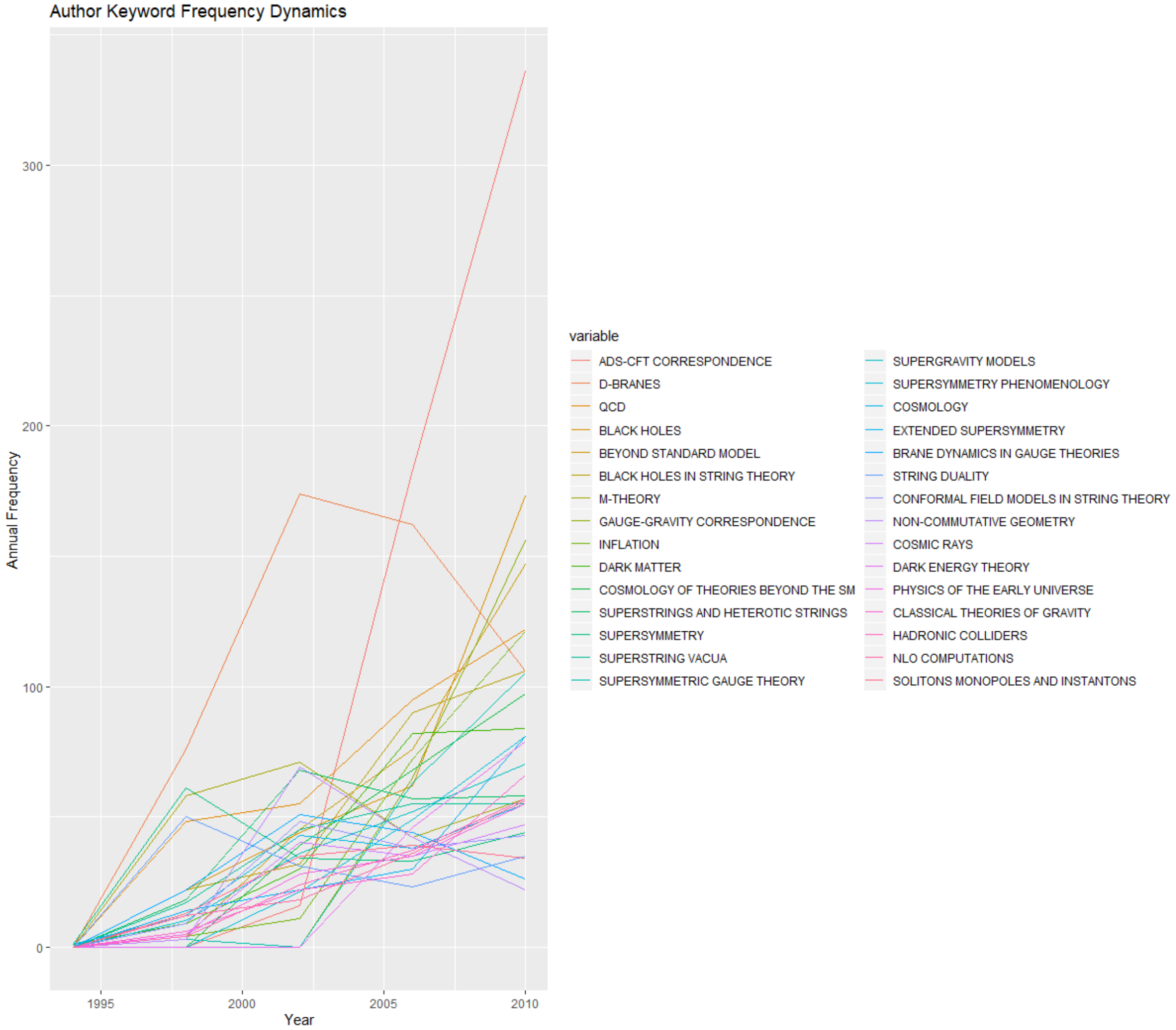
Nanotechnology



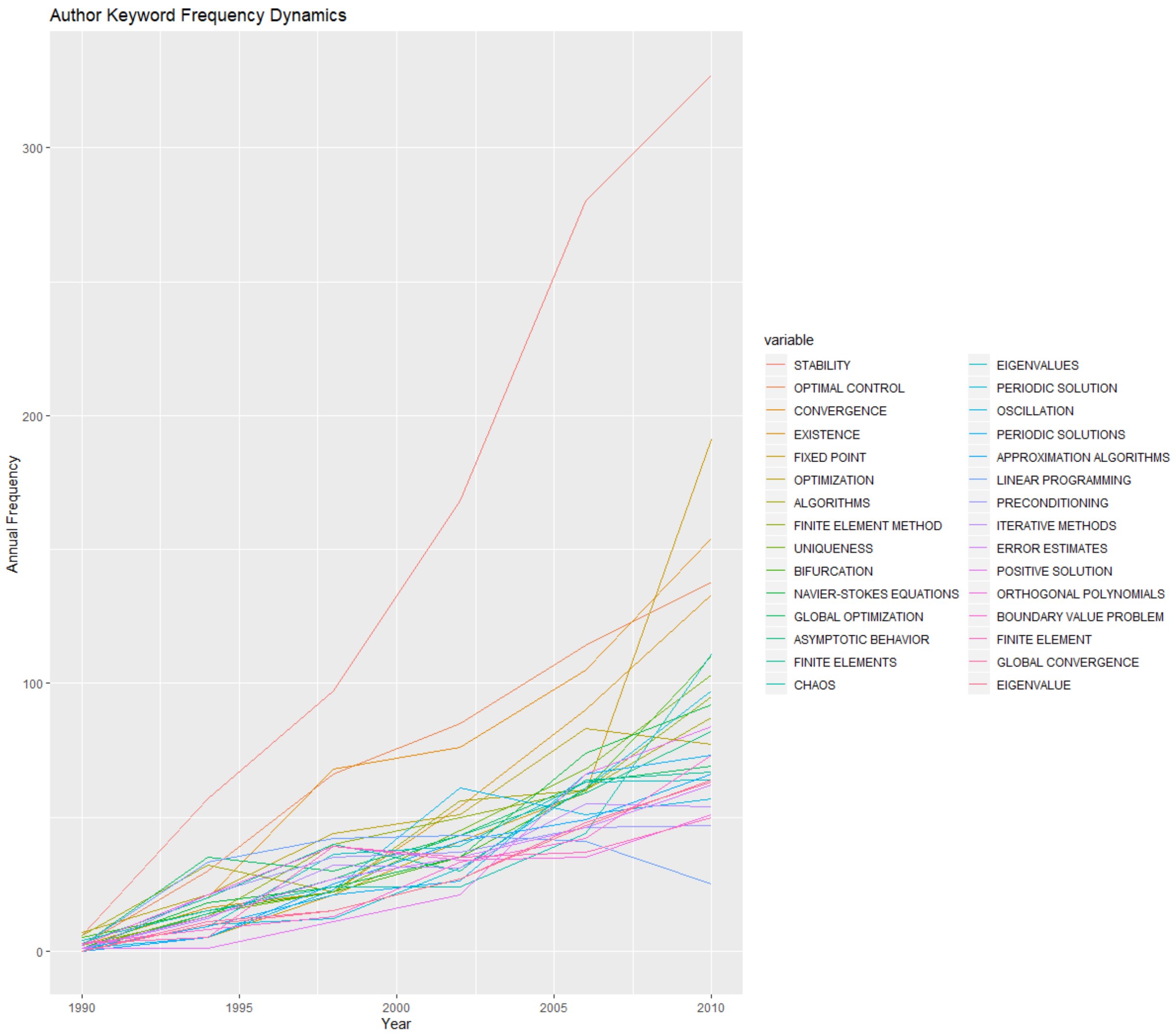
Biotechnology



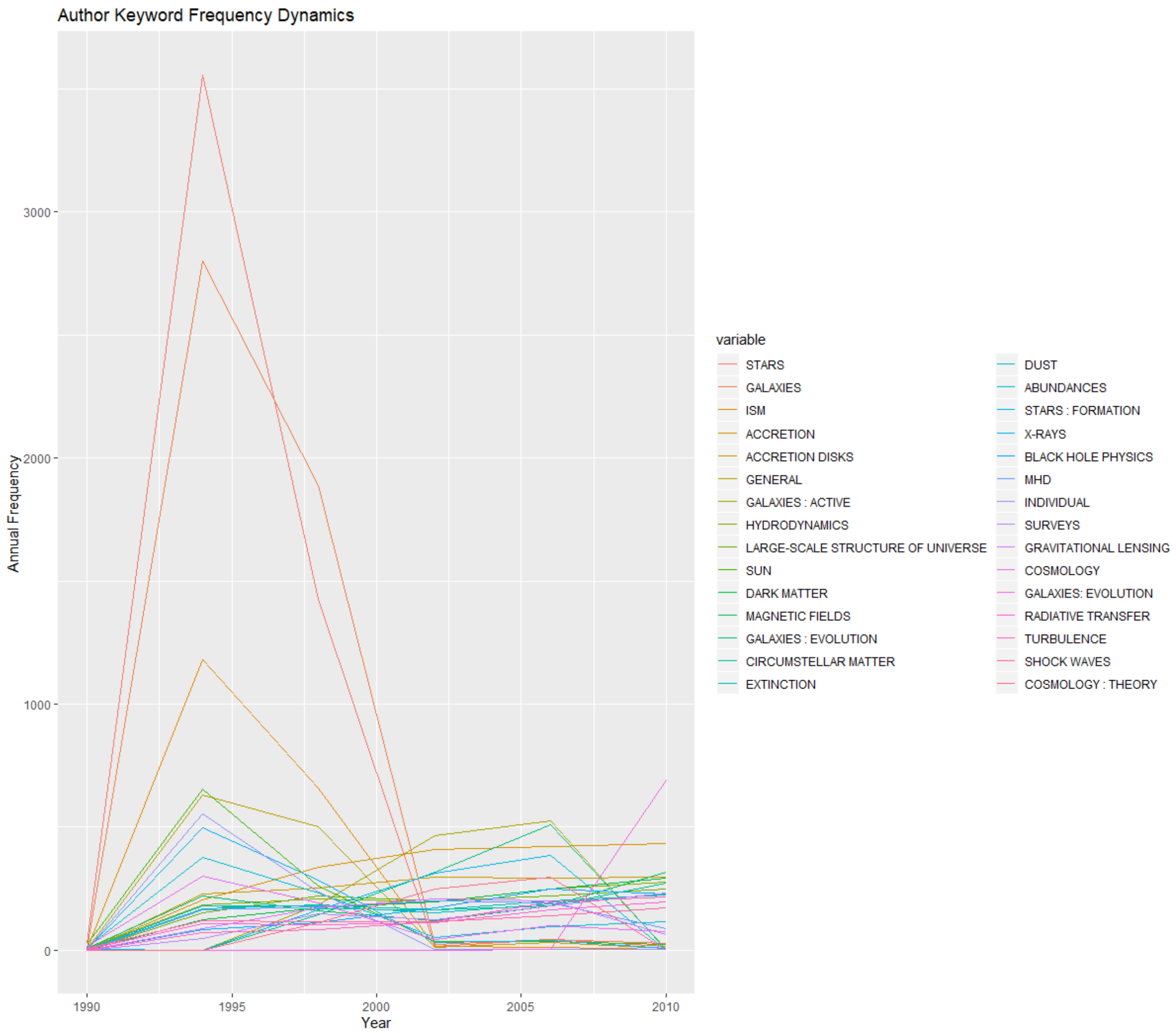
Particle & Field Physics



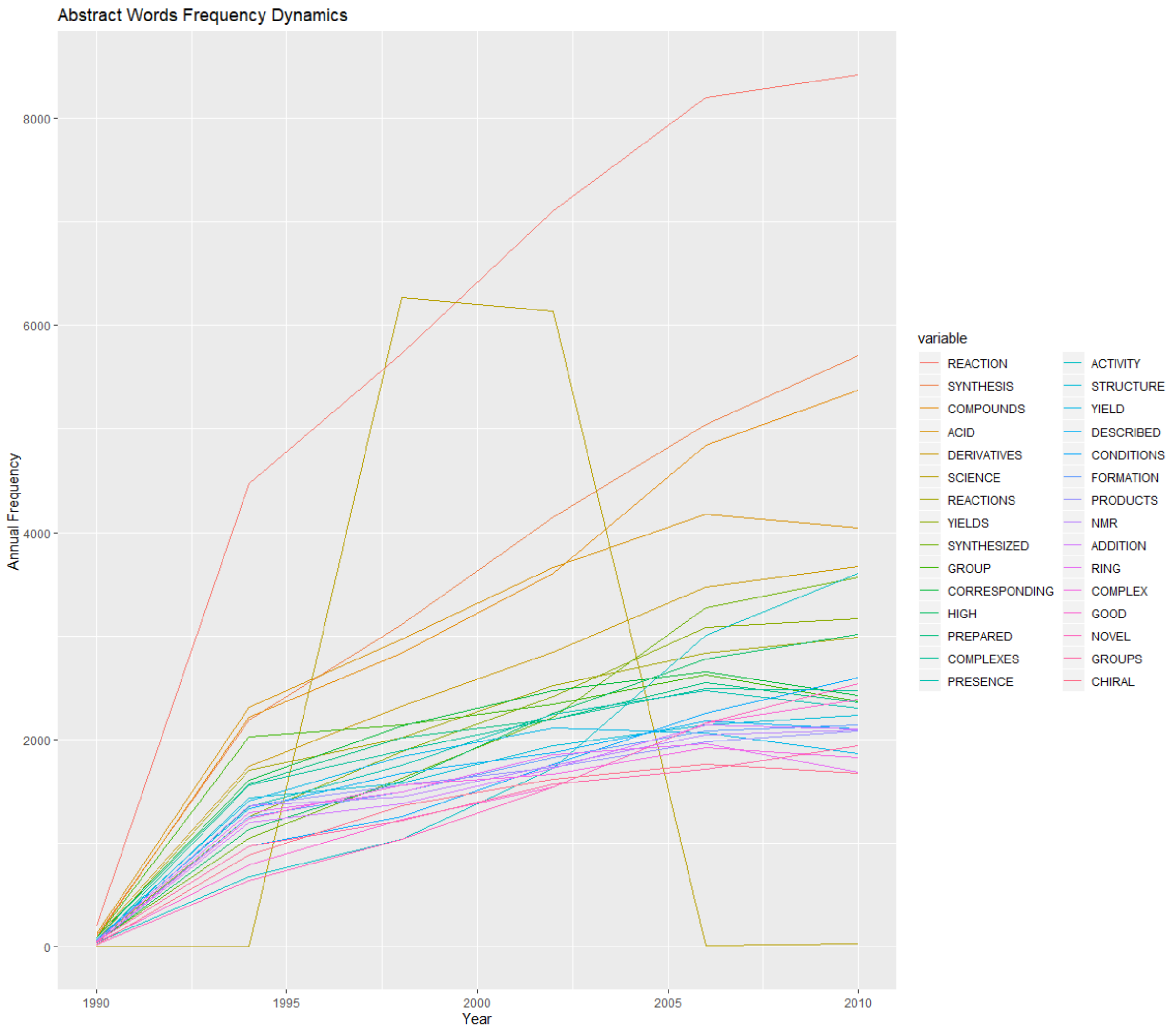
Applied Mathematics



Astrophysics



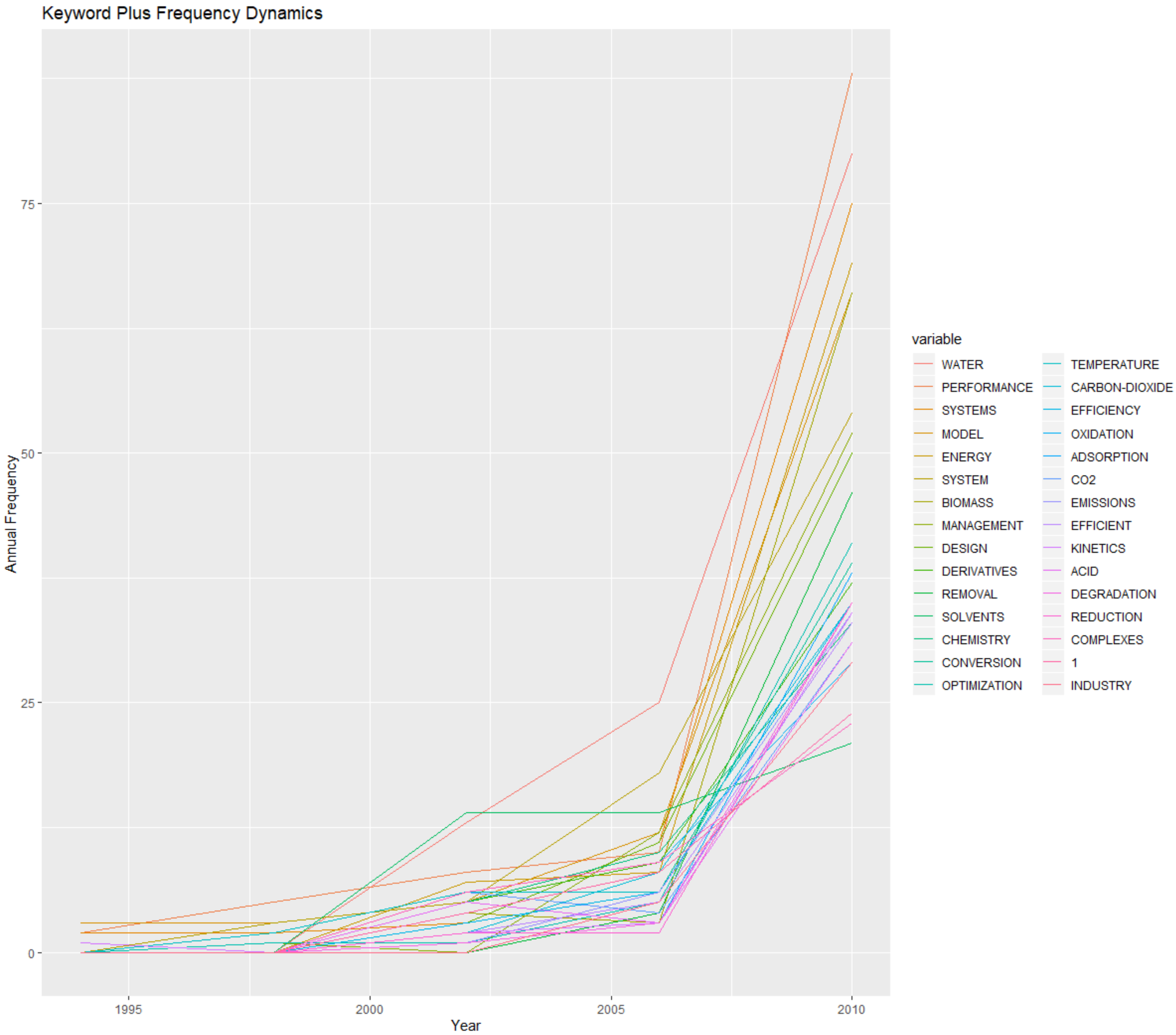
Organic Chemistry



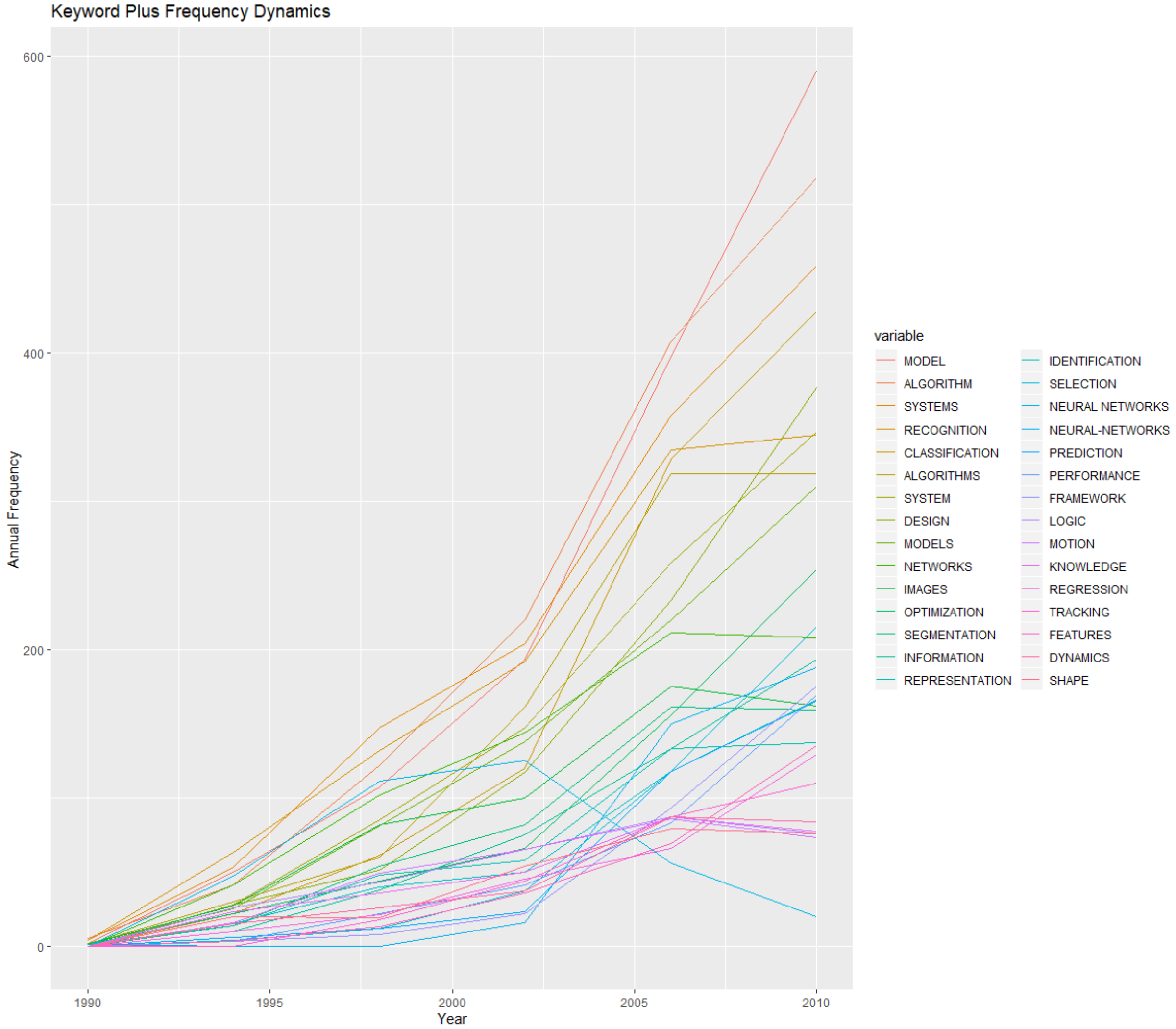
Appendix 3 - Top 30 Keyword Plus Dynamics

Dynamics of the in 2010 top 30 keyword plus over time.

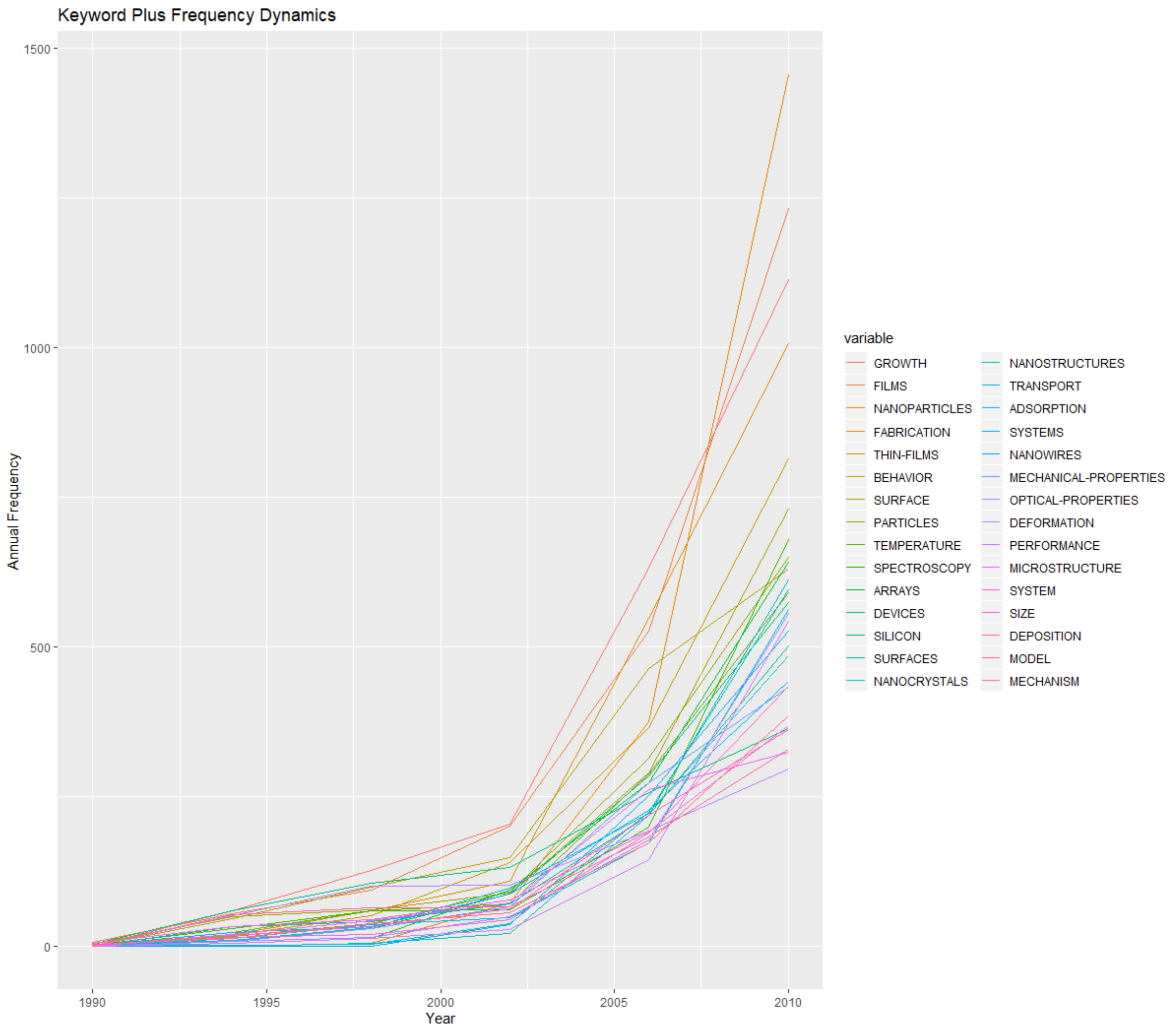
Green & Sustainable Science & Technology



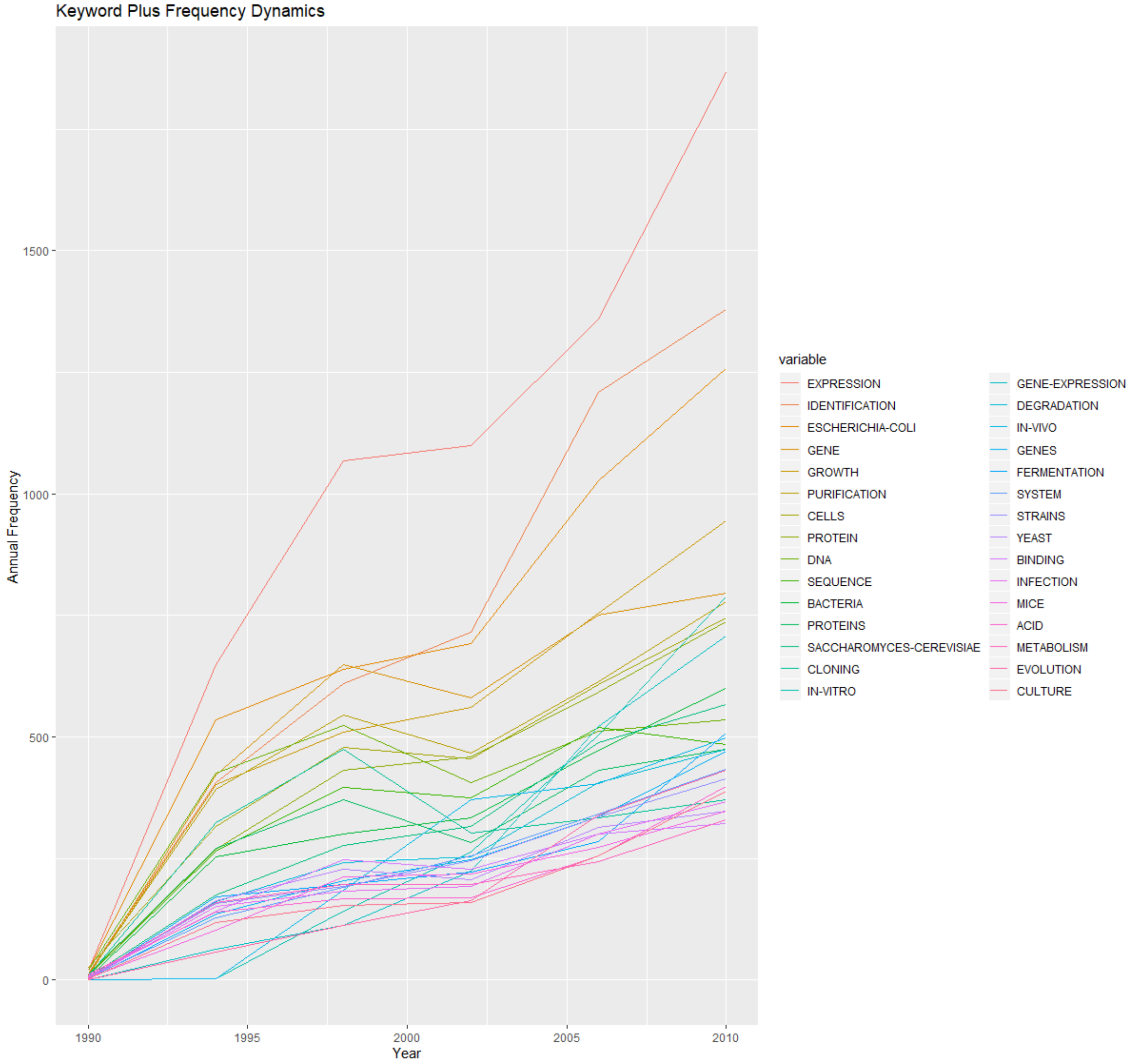
Artificial Intelligence



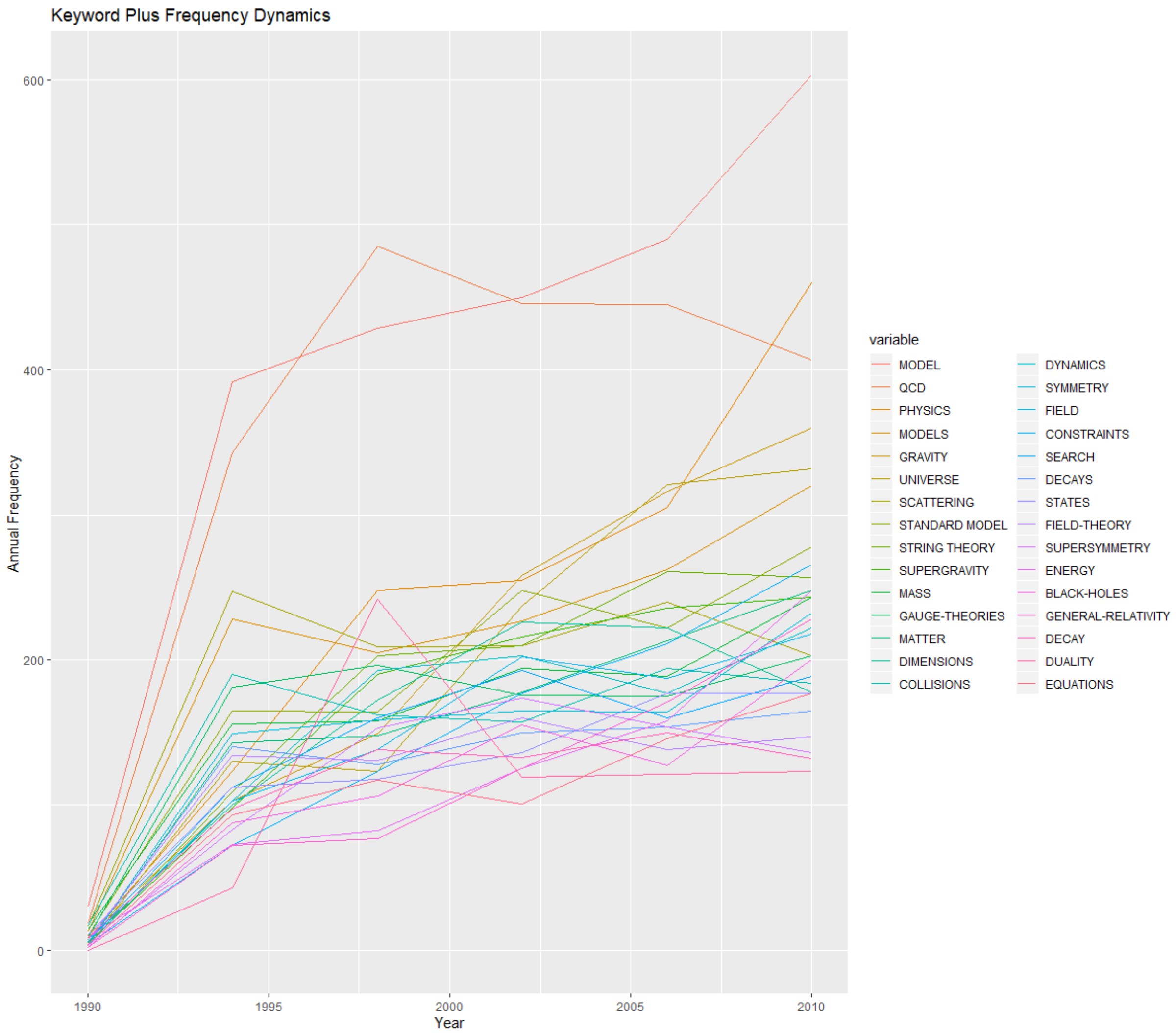
Nanotechnology



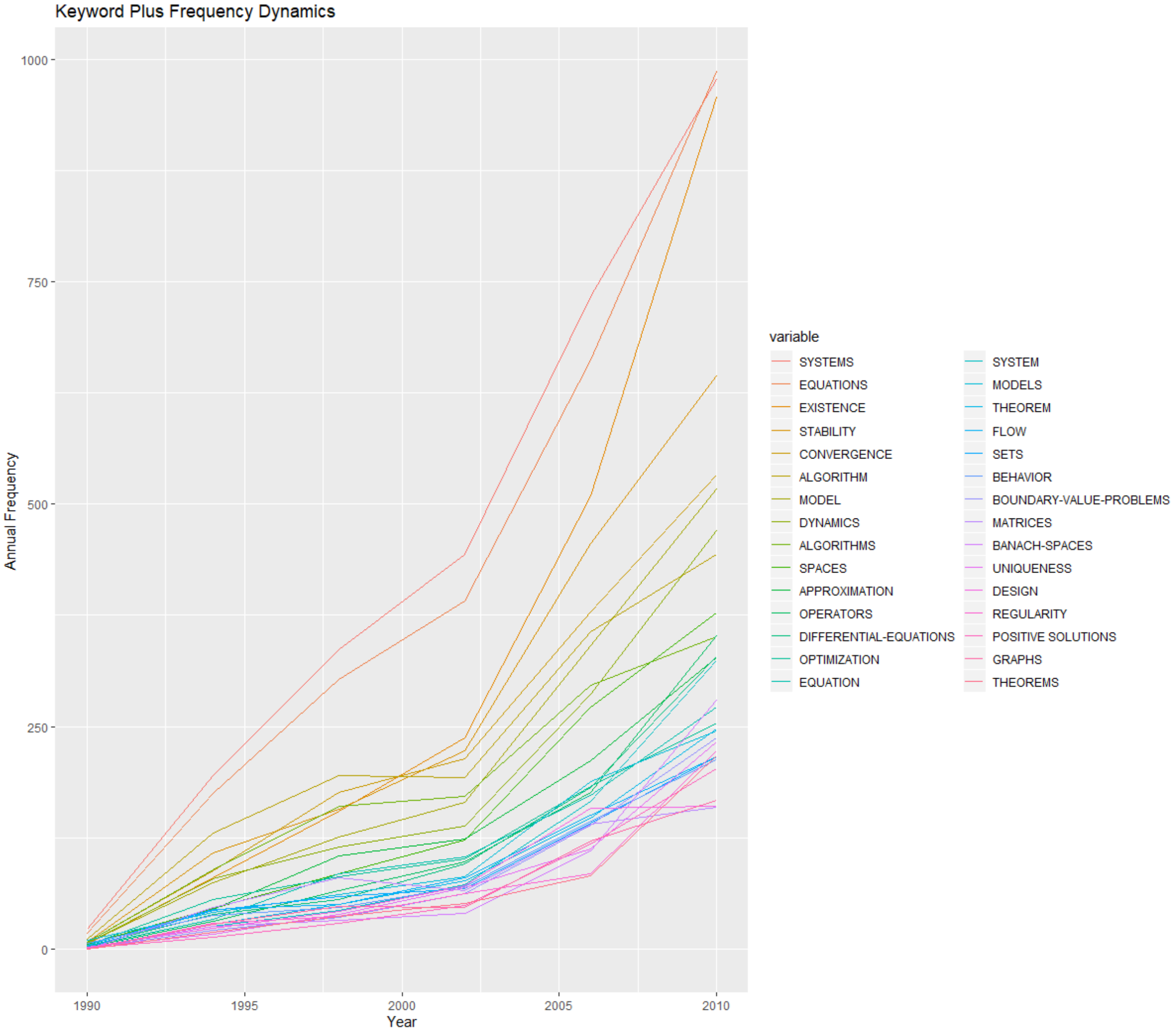
Biotechnology



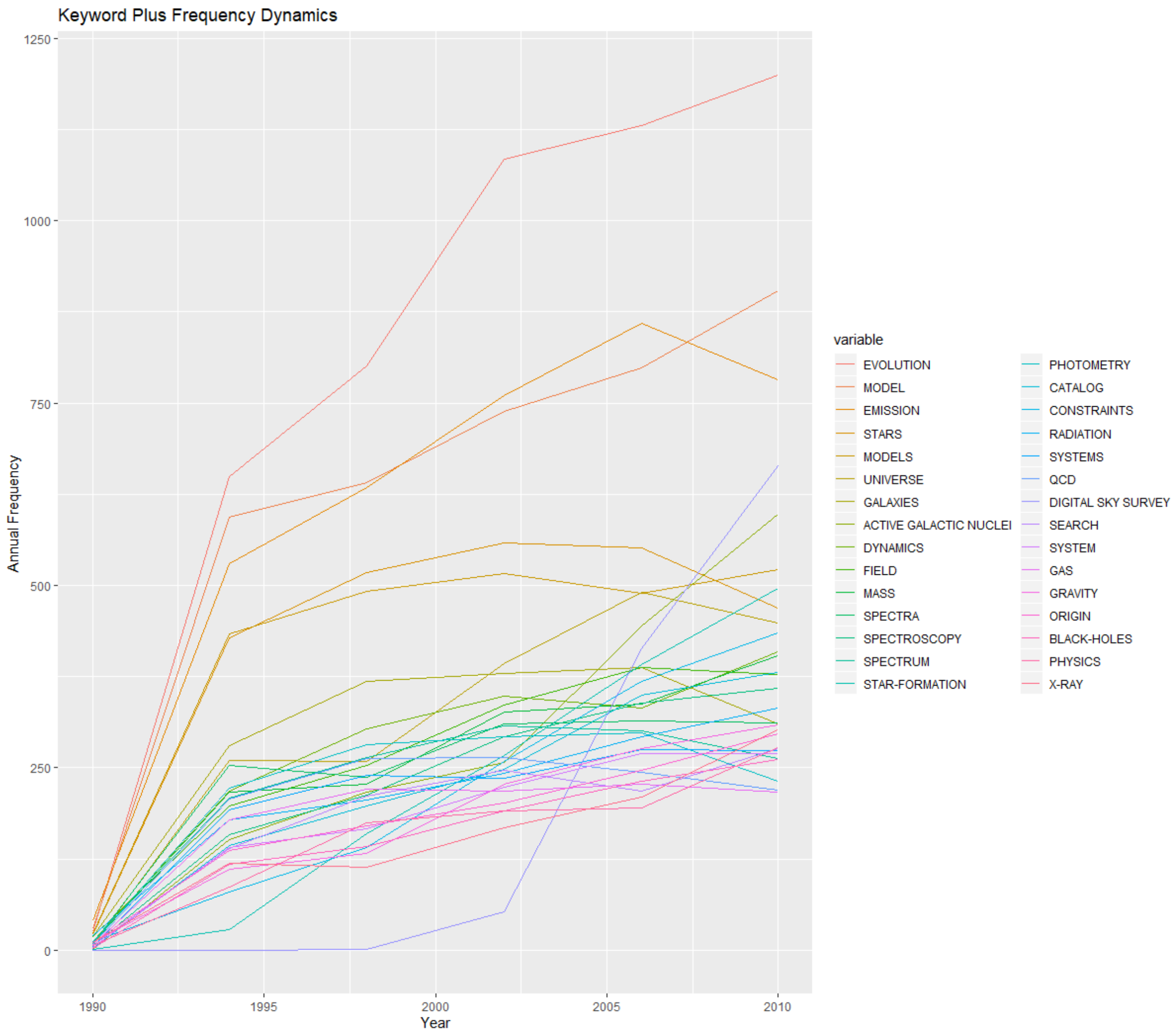
Particle & Field Physics



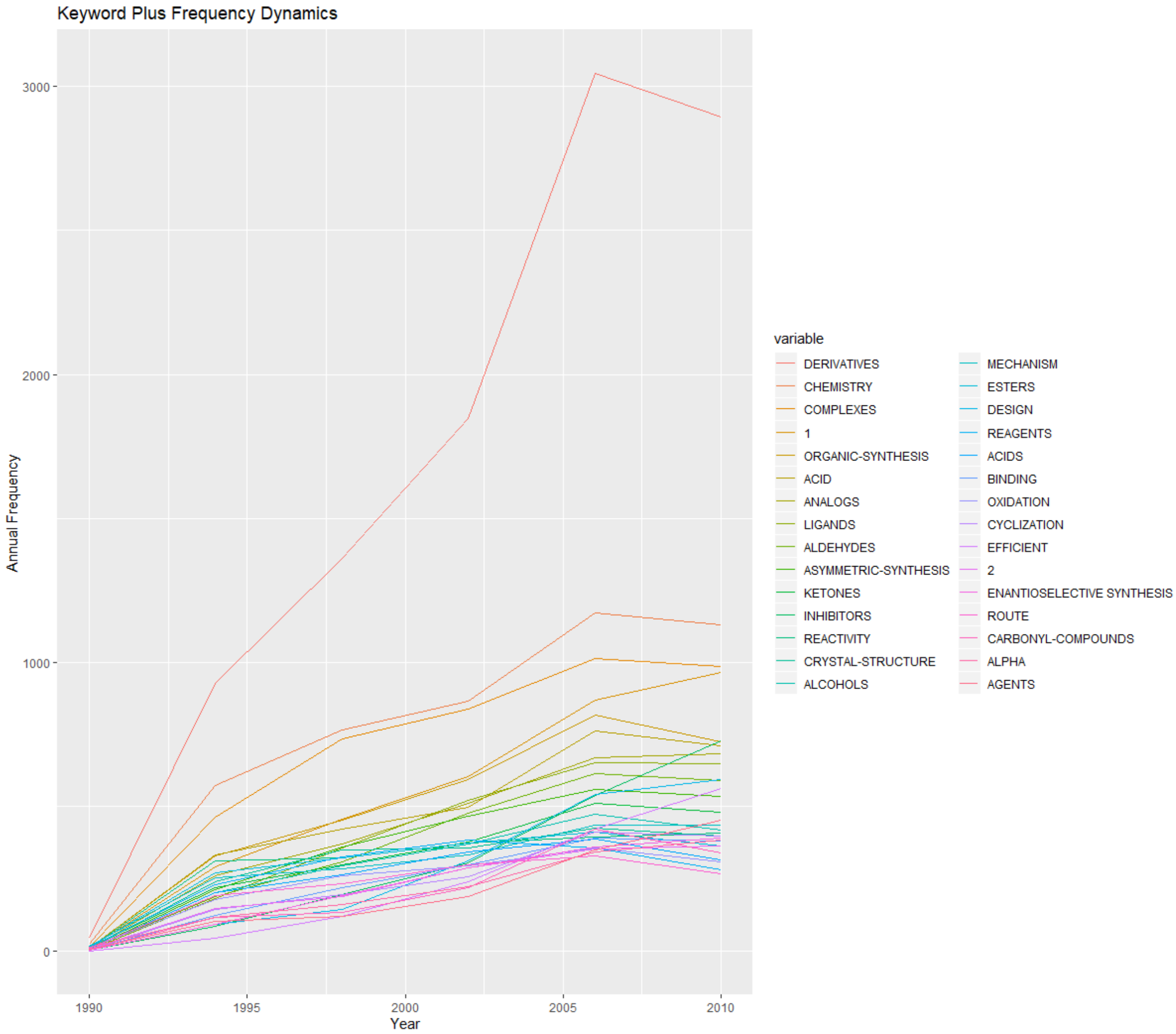
Applied Mathematics



Astrophysics



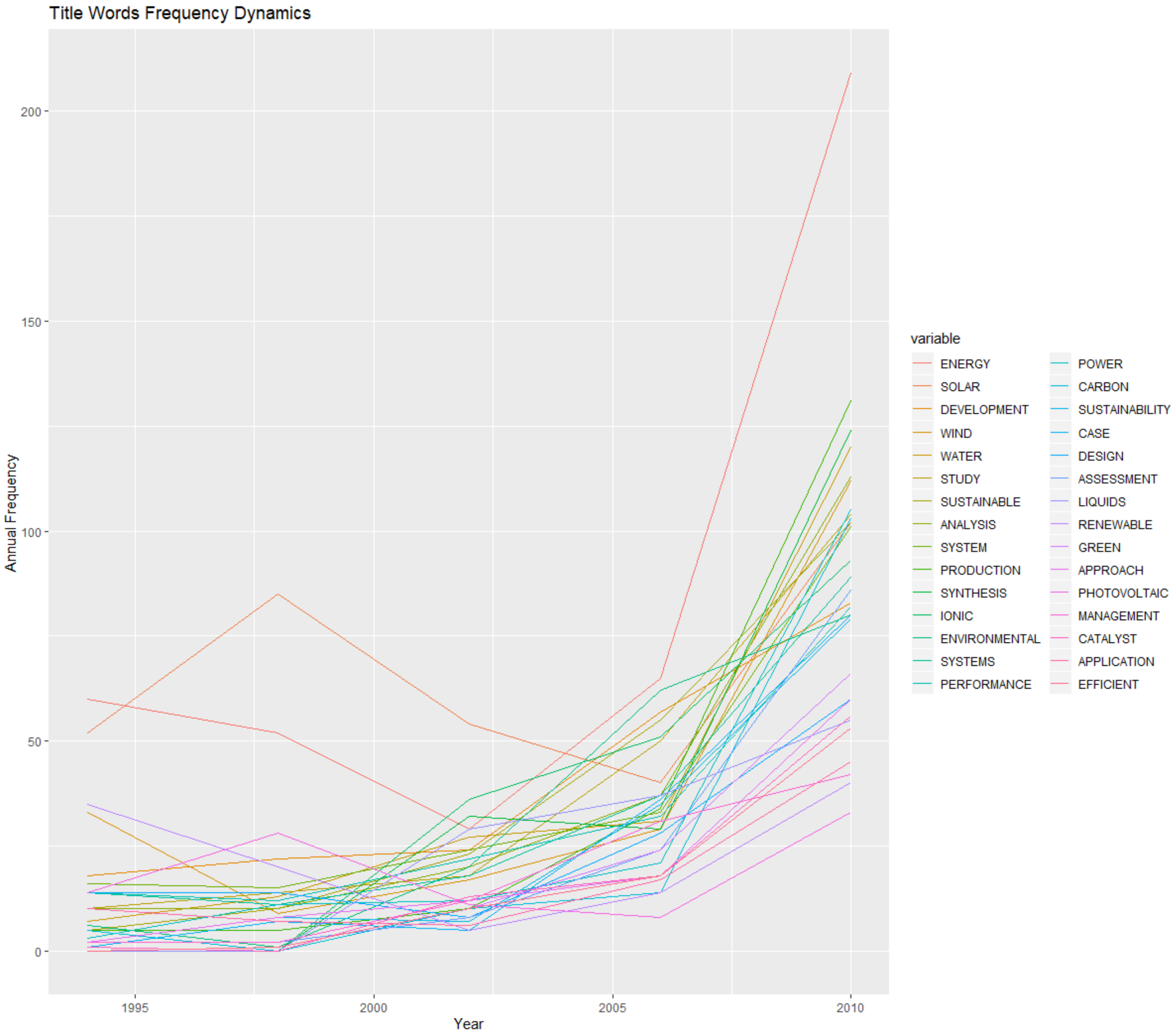
Organic Chemistry



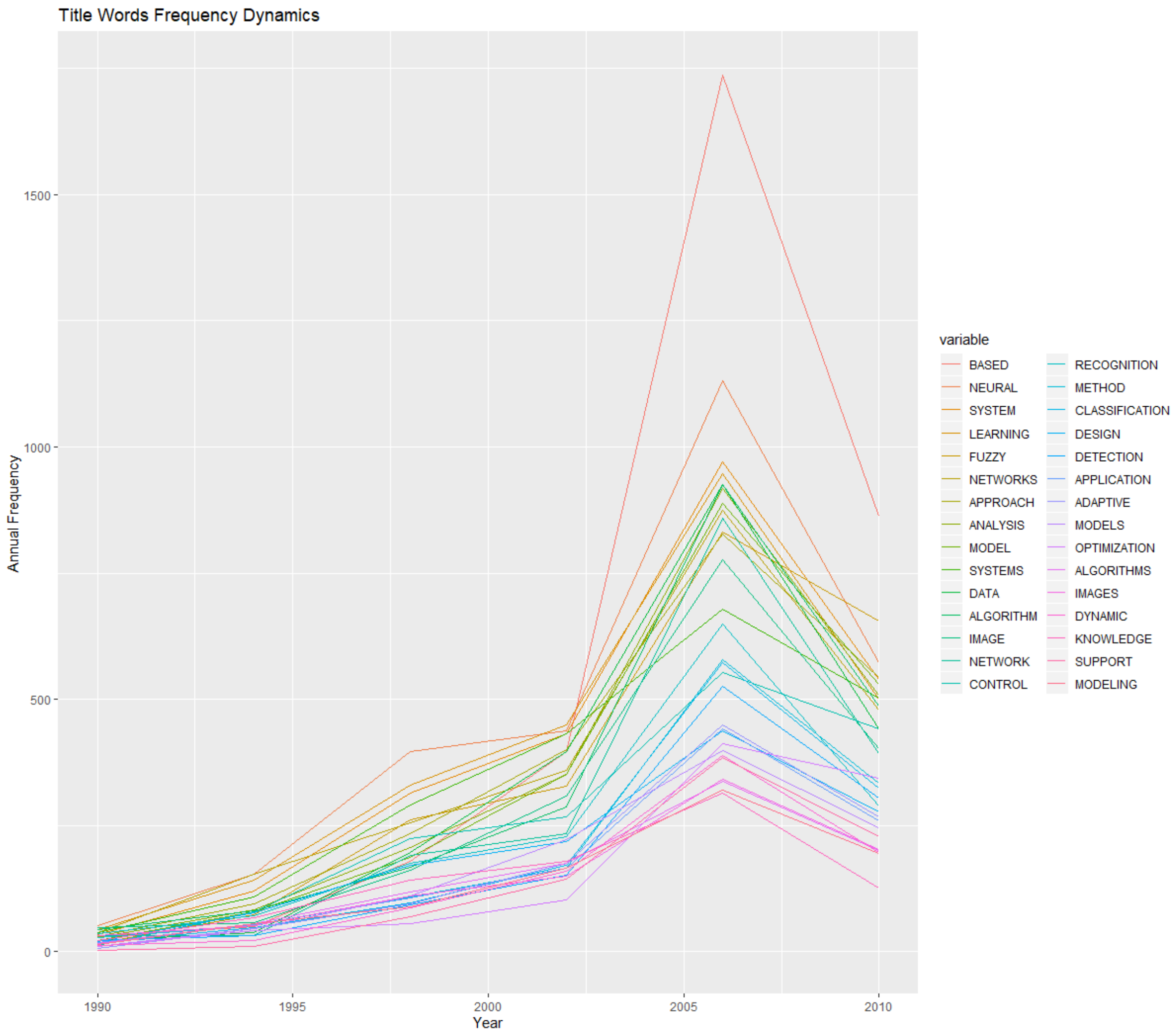
Appendix 4 – Top 30 Title Words Dynamics

Dynamics of the in 2010 top 30 title words over time.

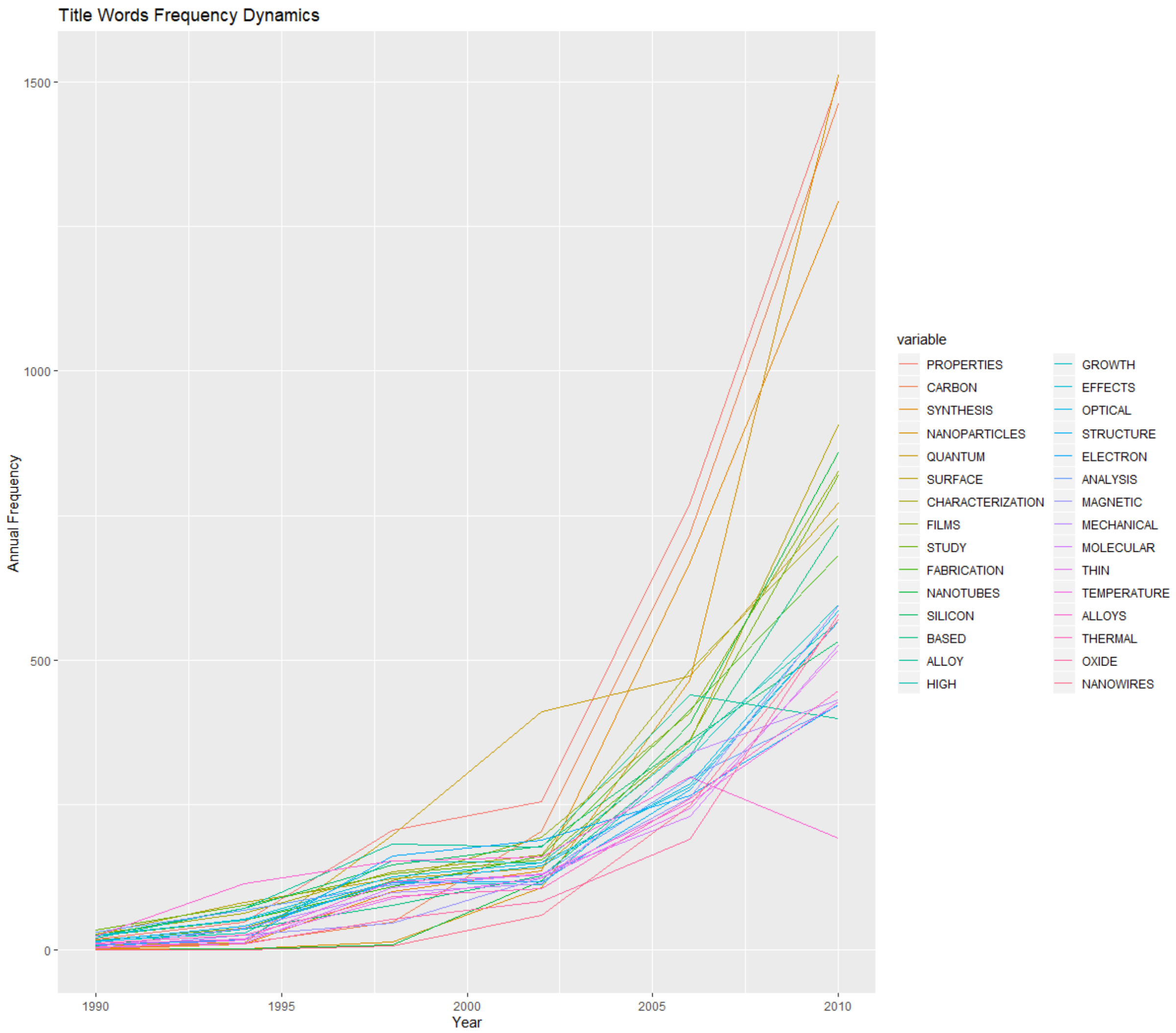
Green & Sustainable Science & Technology



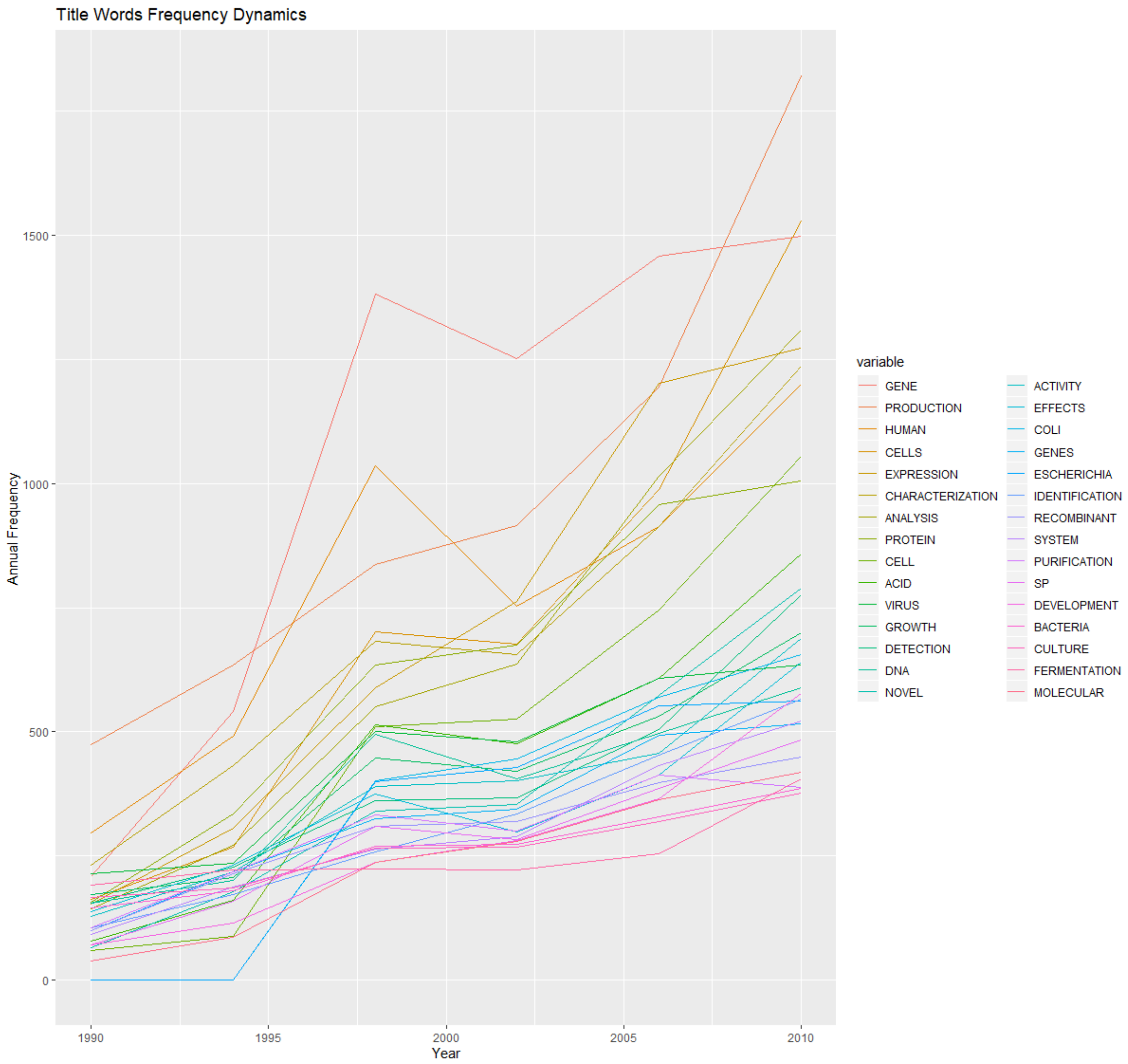
Artificial Intelligence



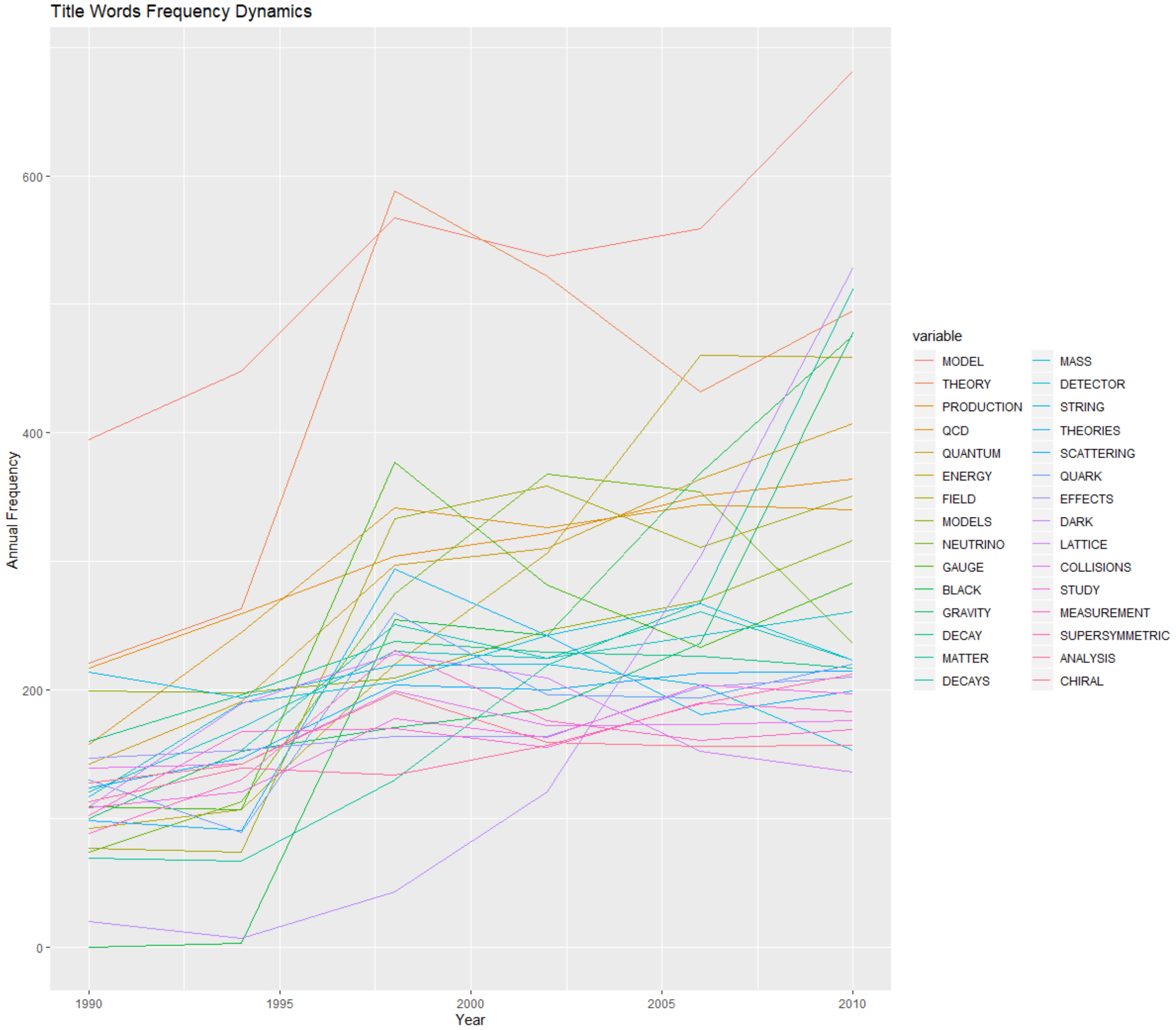
Nanotechnology



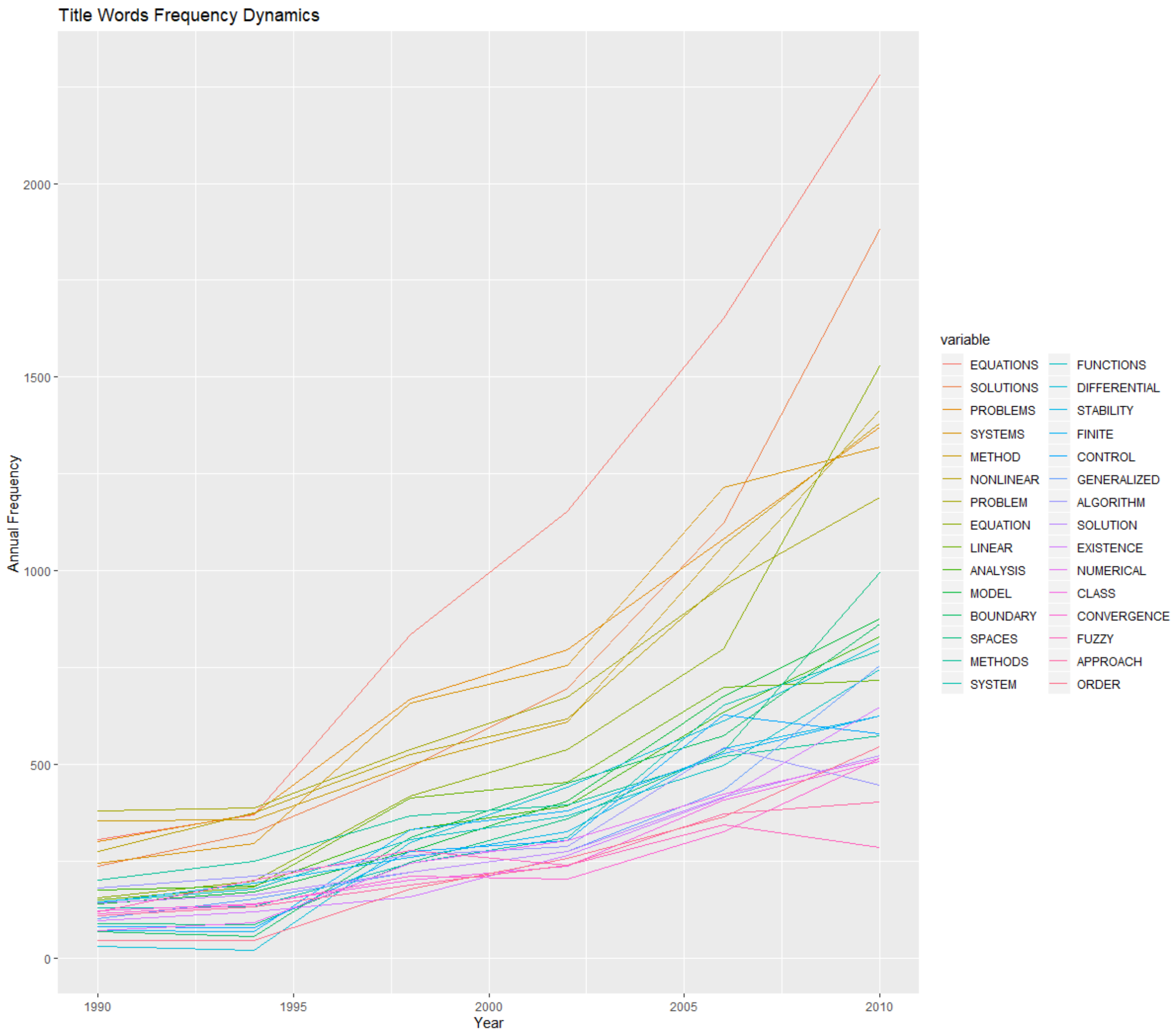
Biotechnology



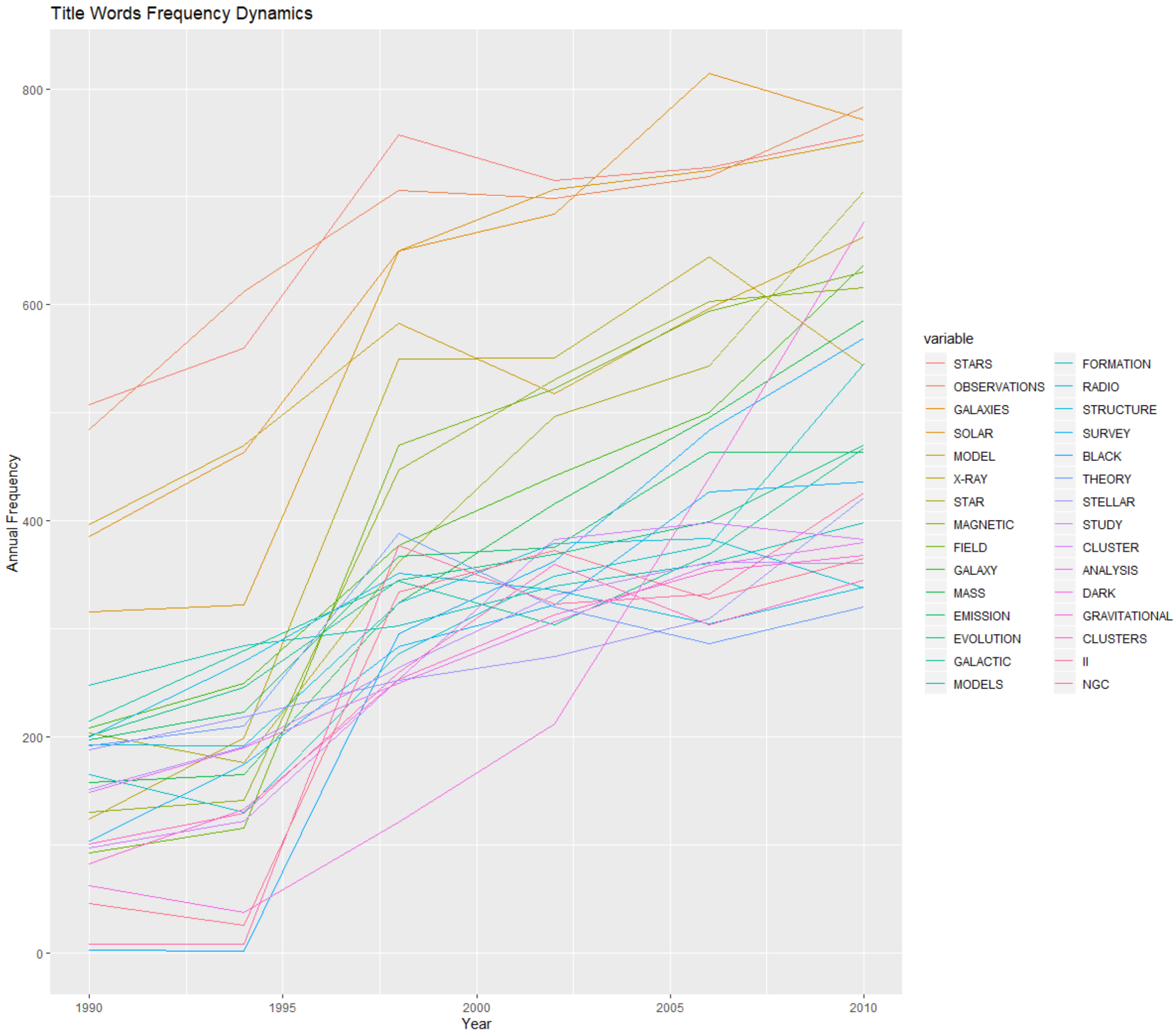
Particle & Field Physics



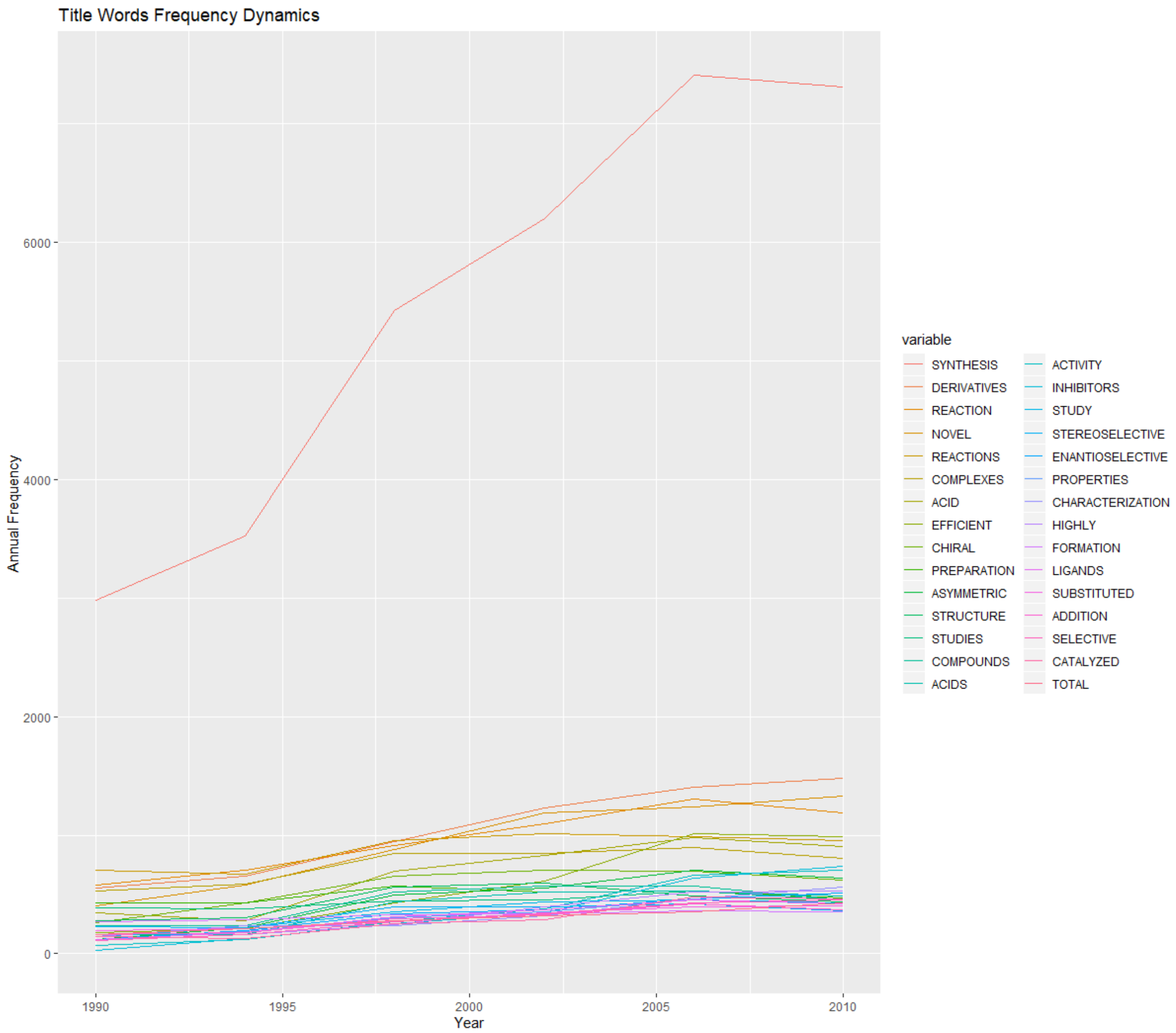
Applied Mathematics



Astrophysics



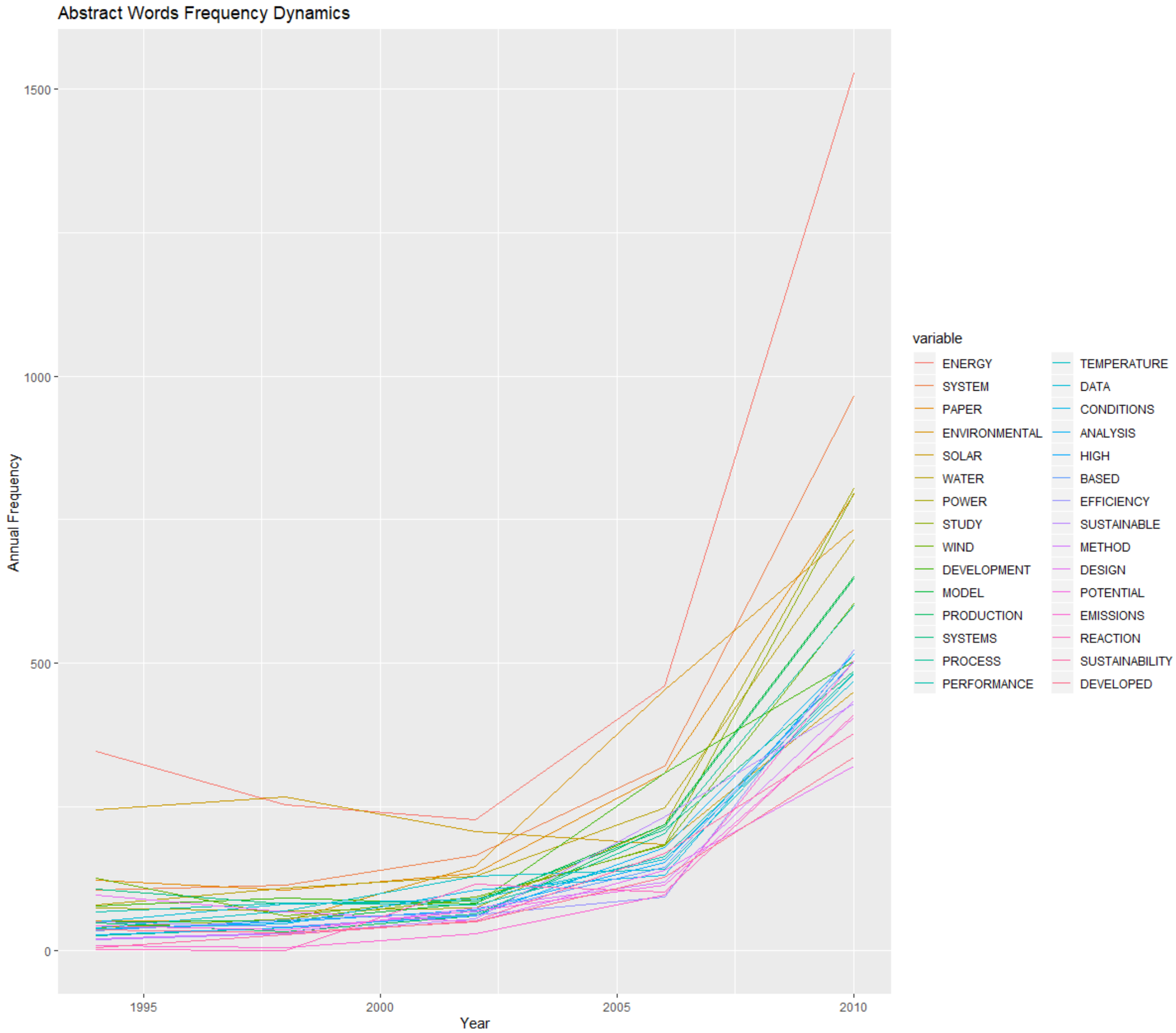
Organic Chemistry



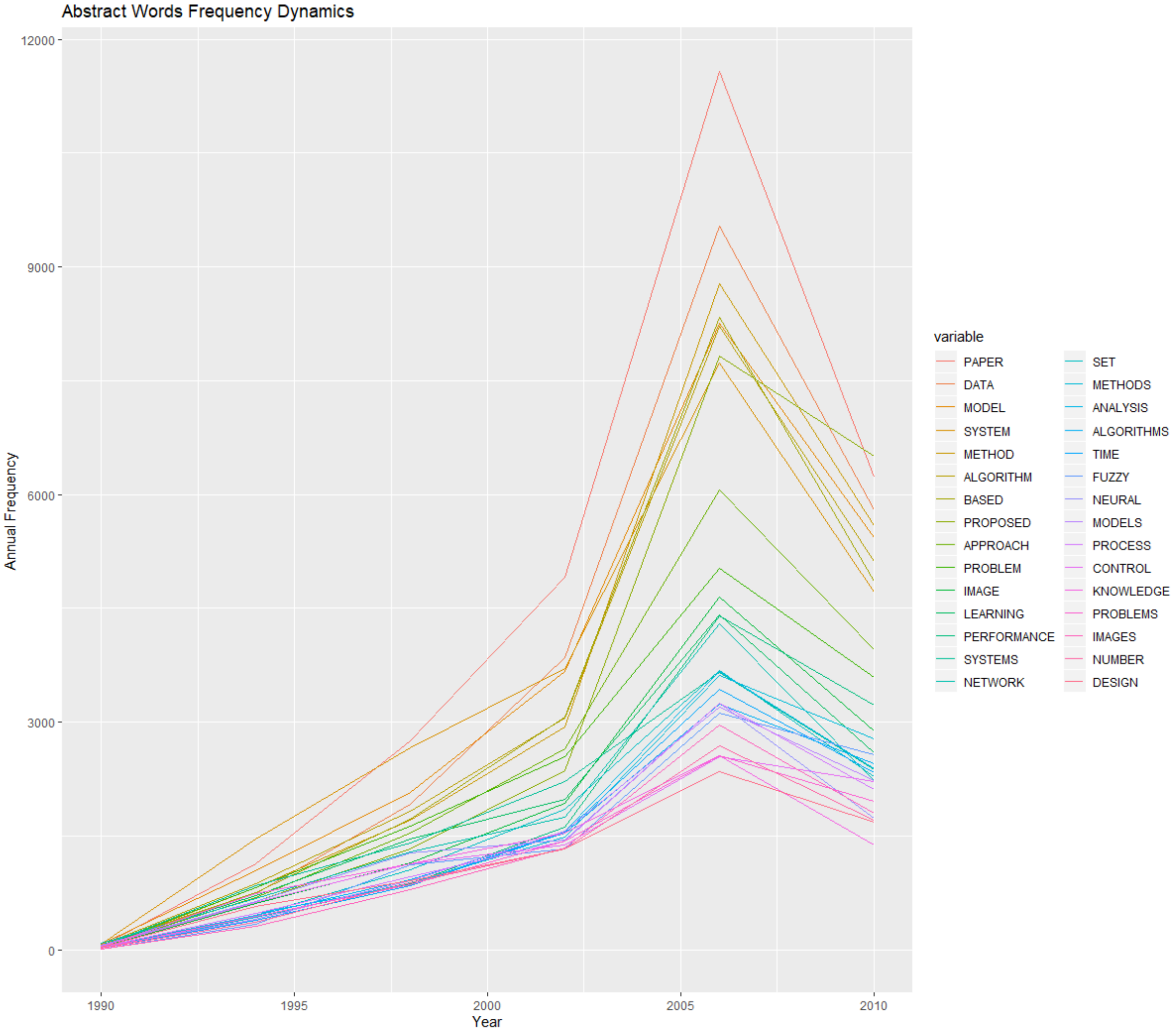
Appendix 5 - Top 30 Abstract Words Dynamics

Dynamics of the in 2010 top 30 abstract words over time.

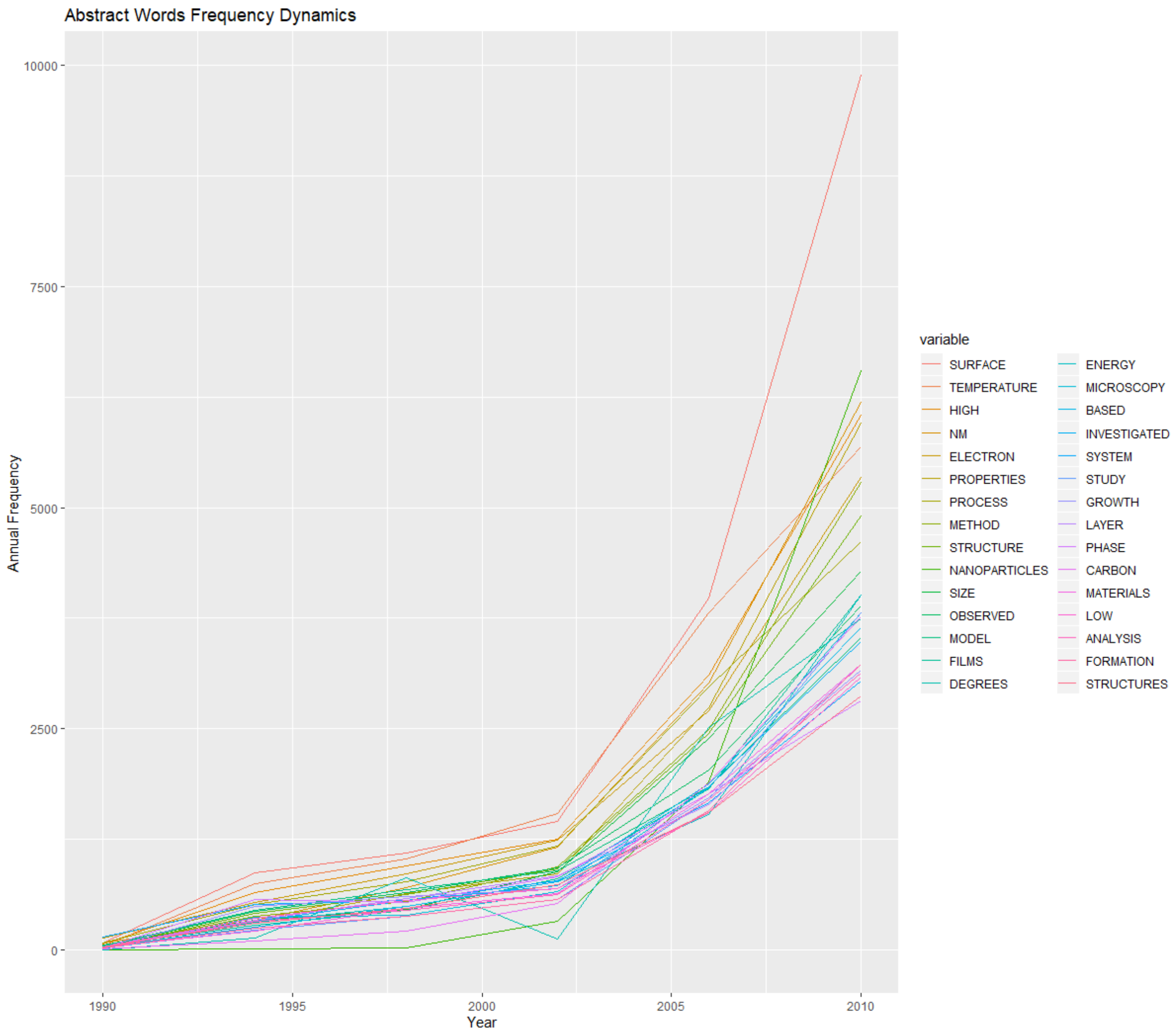
Green & Sustainable Science & Technology



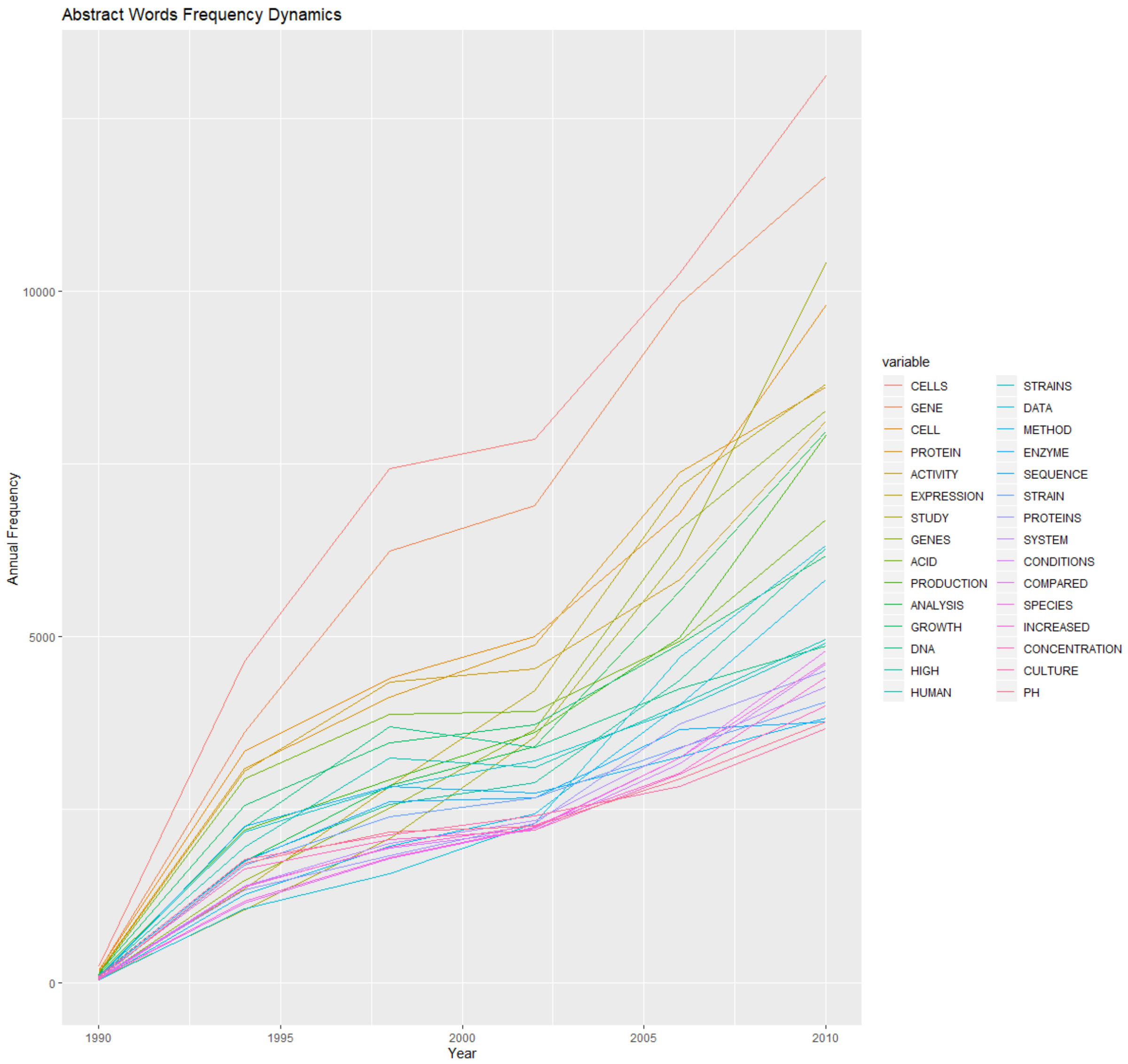
Artificial Intelligence



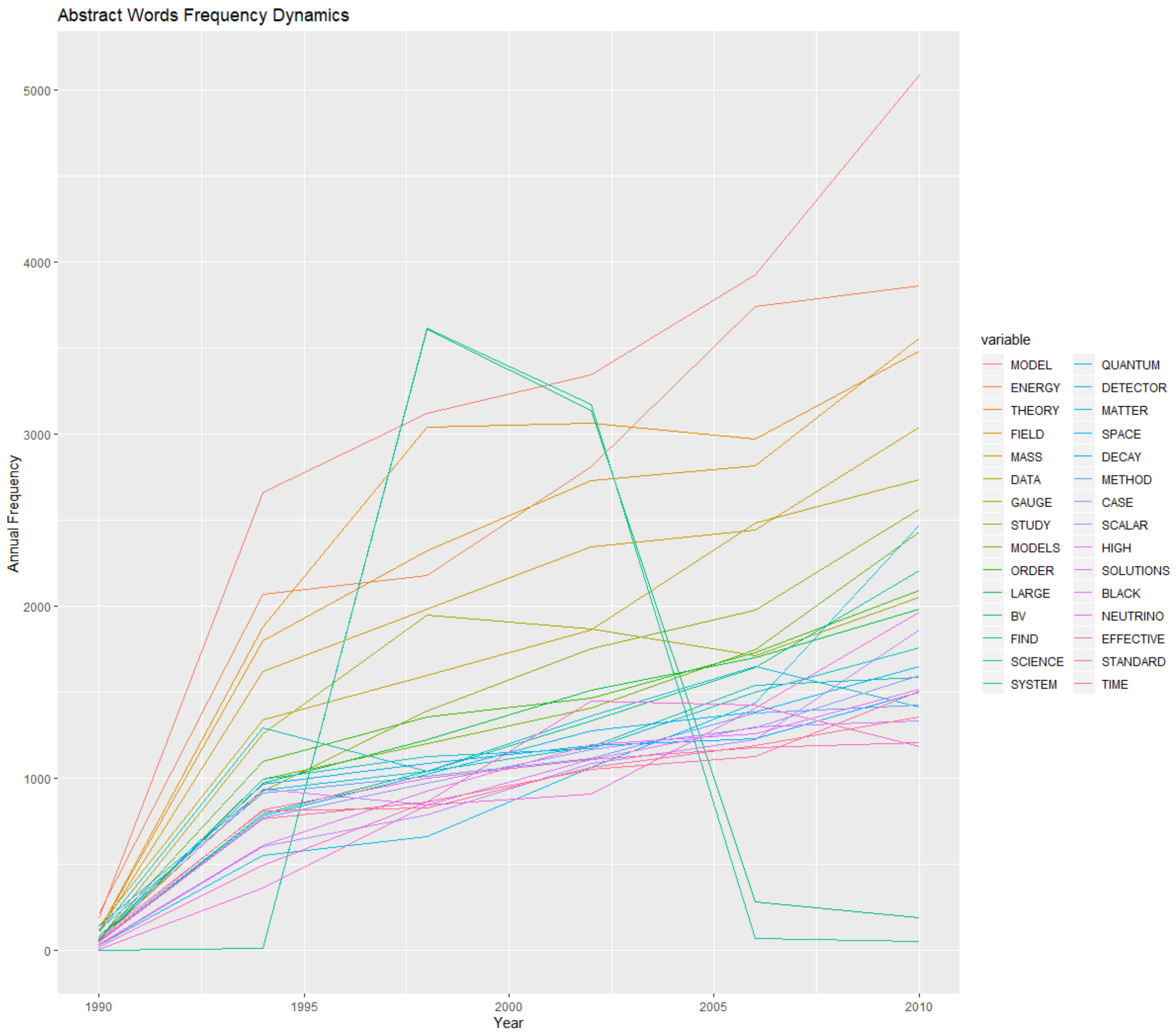
Nanotechnology



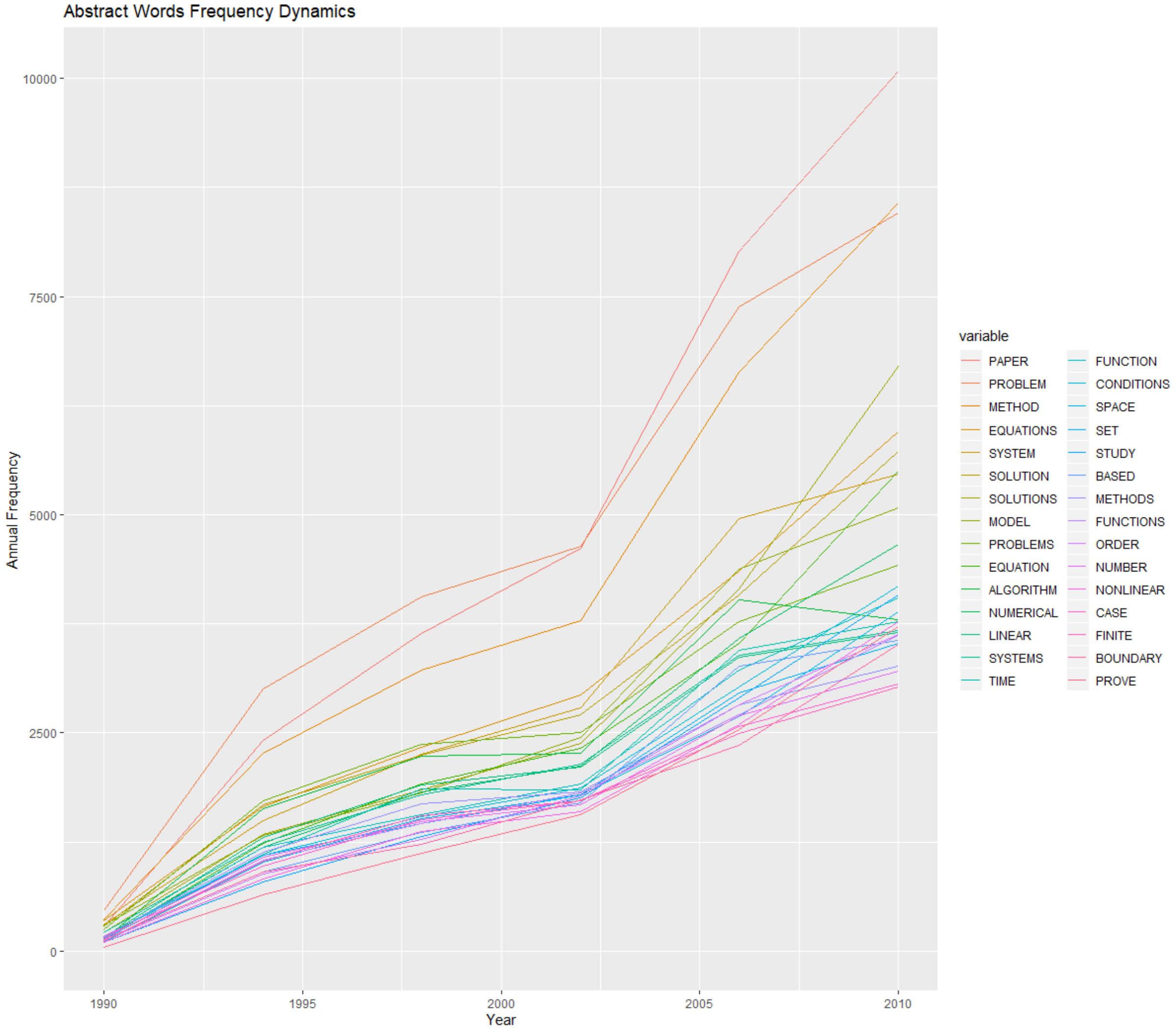
Biotechnology



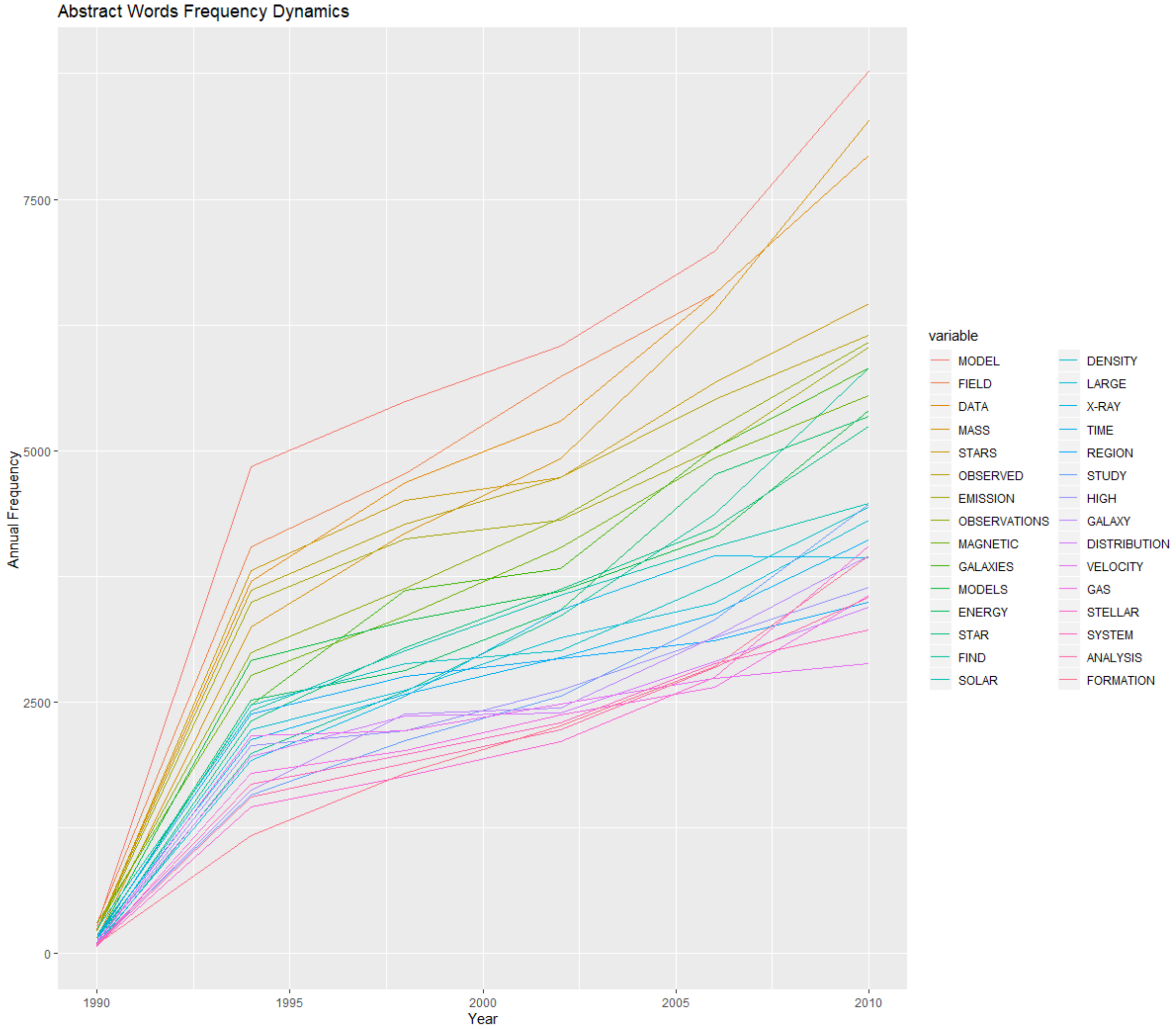
Particle & Field Physics



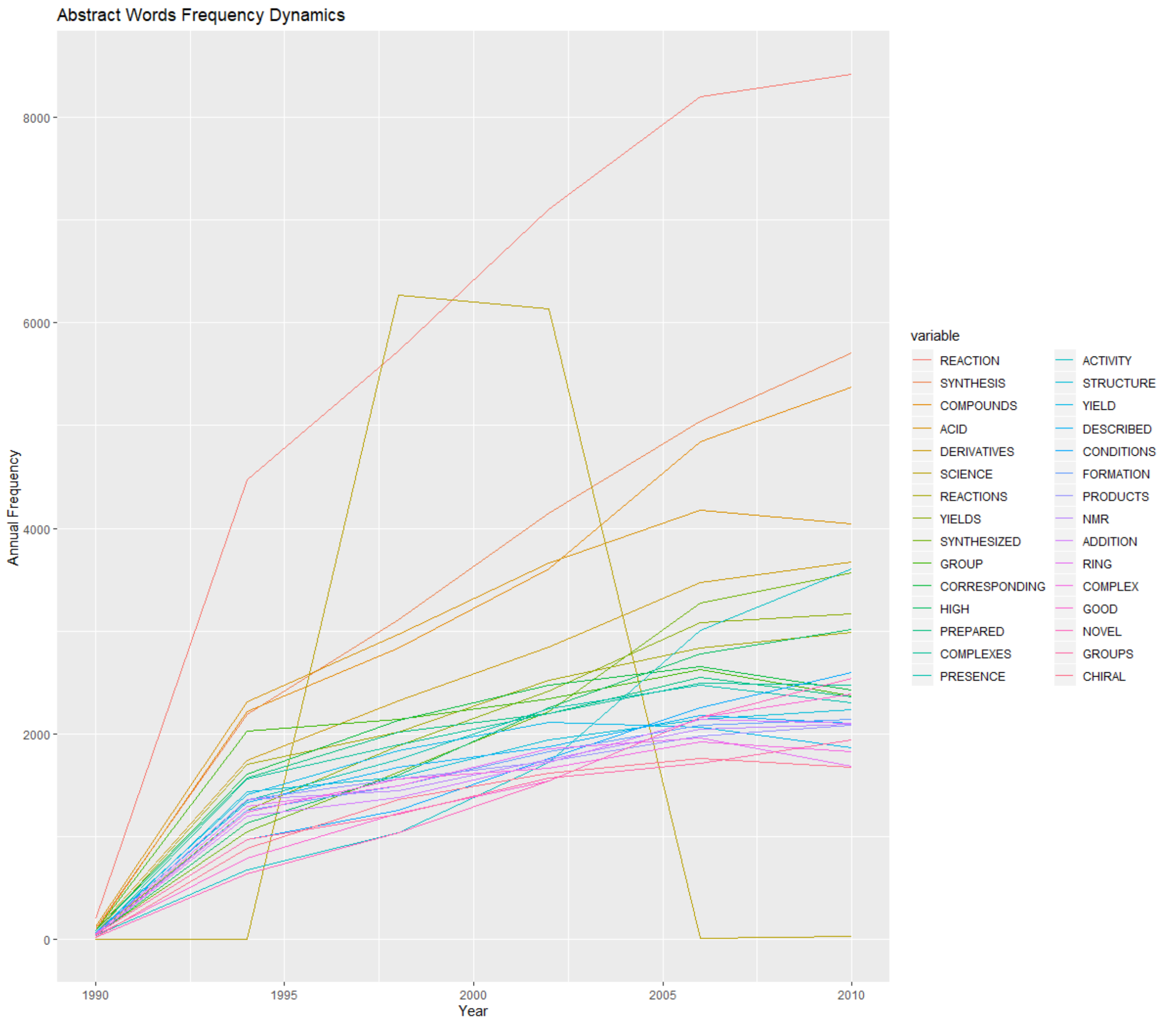
Applied Mathematics



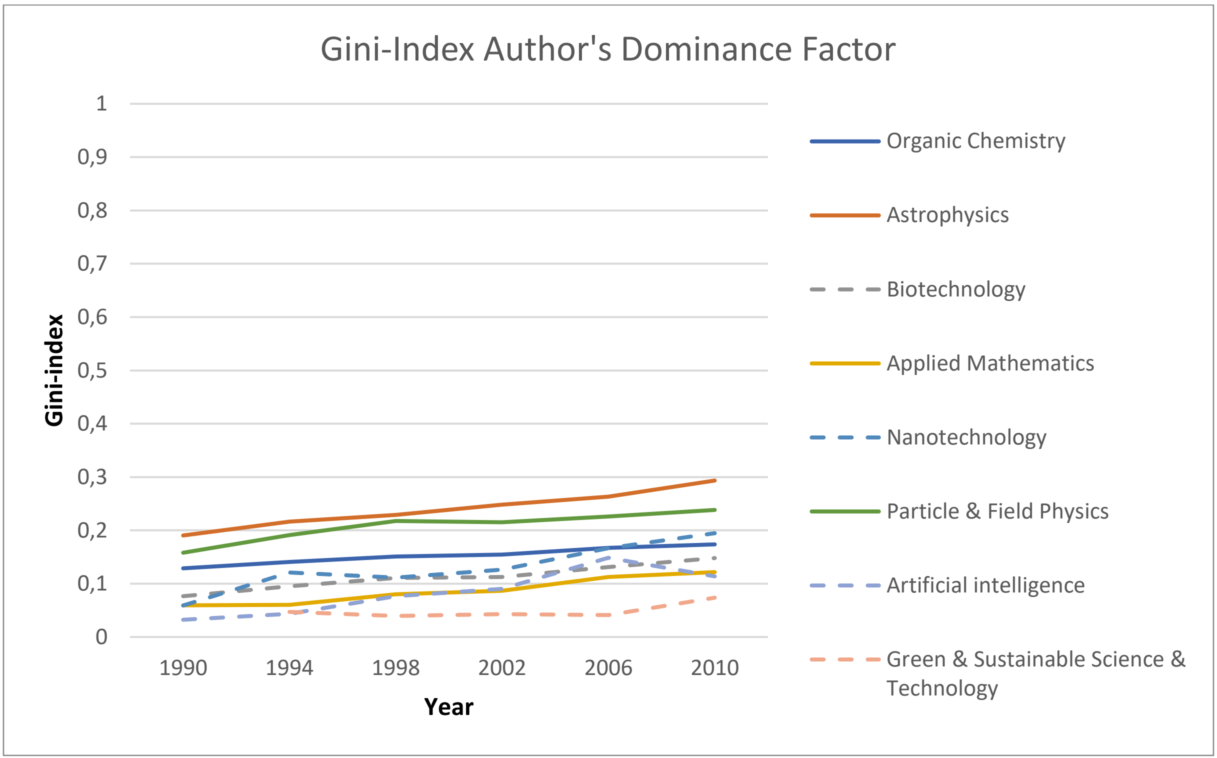
Astrophysics

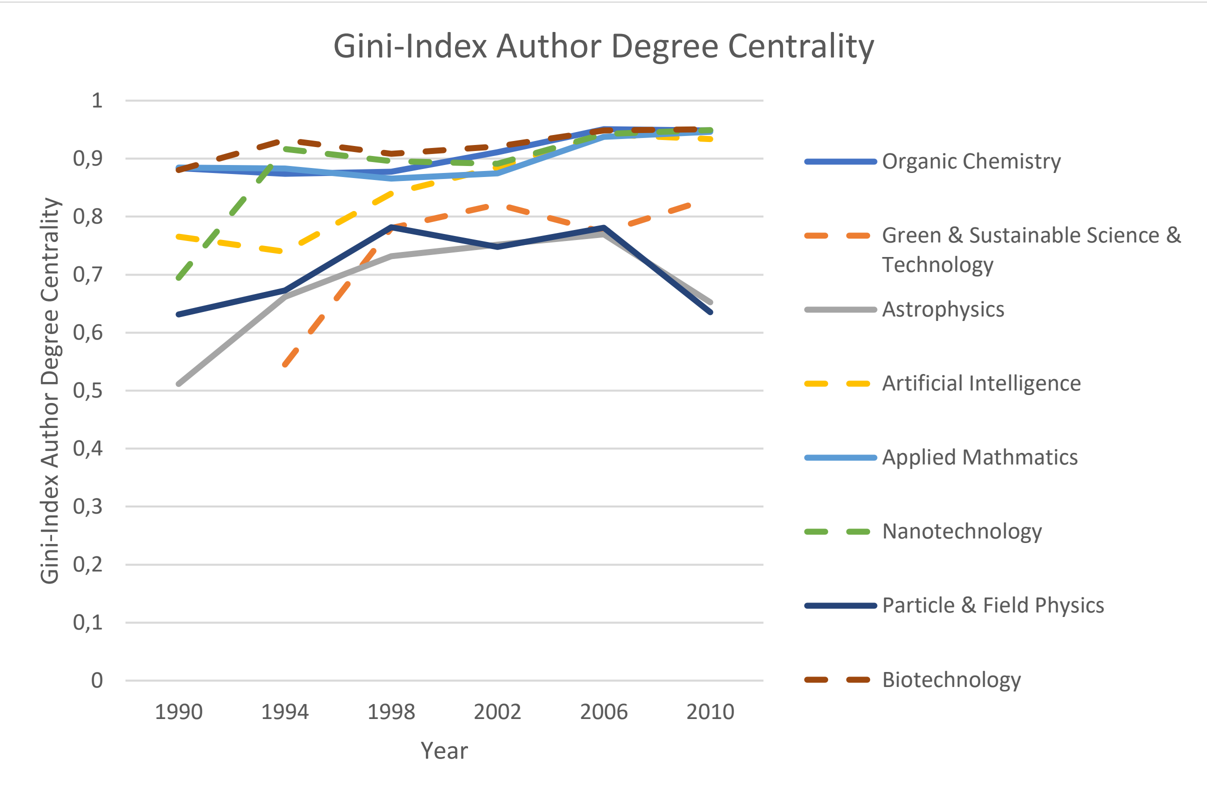


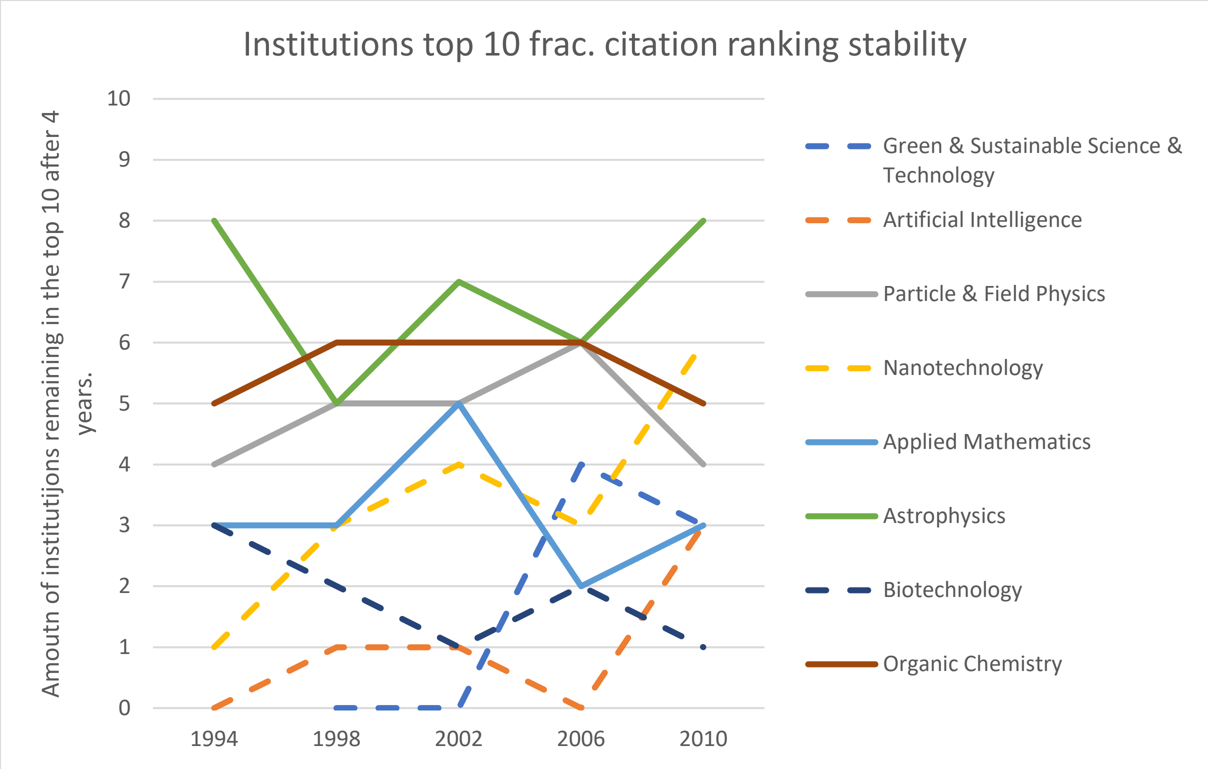
Organic Chemistry



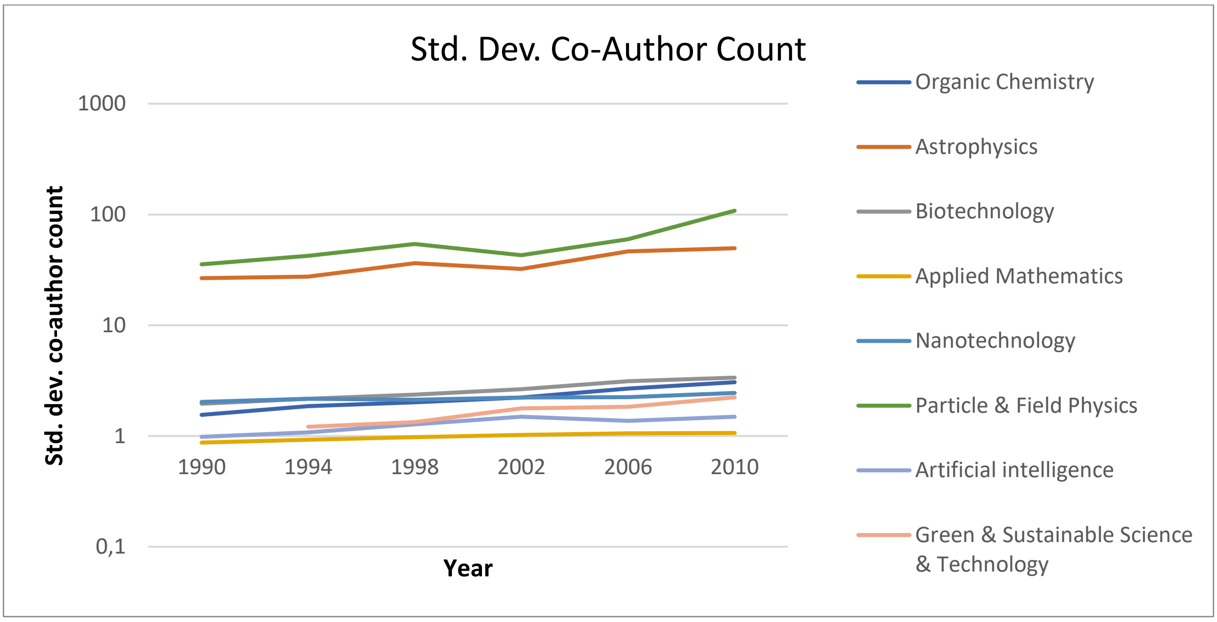
Appendix 6 - Mutual Dependency Graphs





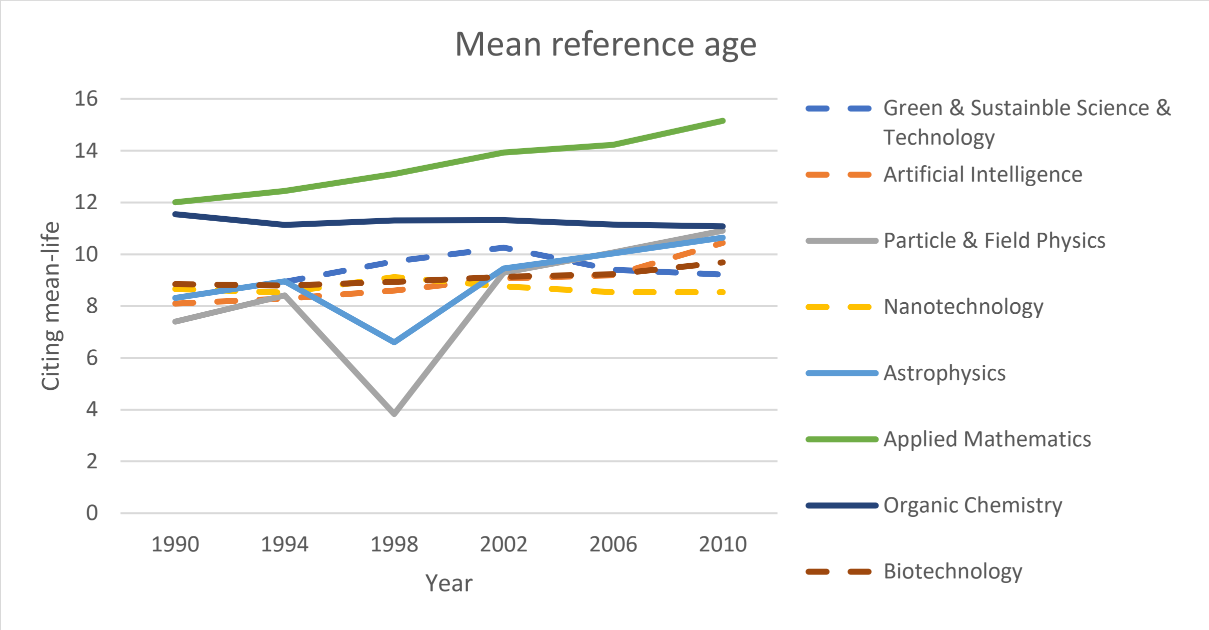


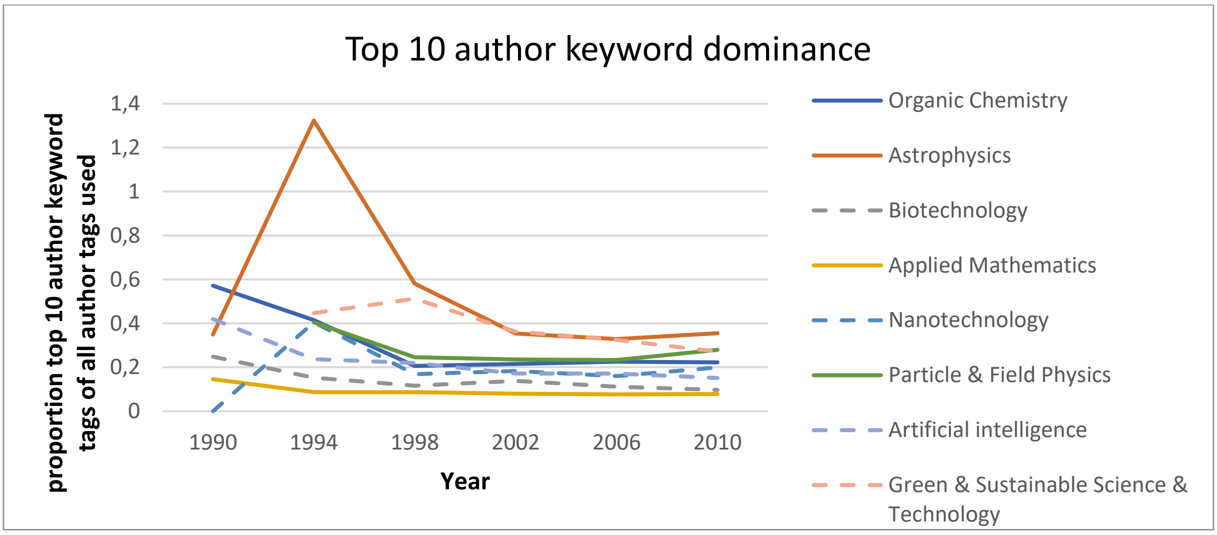
Institutions top 10 frac. citation ranking stability
Amoutn of institutijons remaining in the top 10 after 4 years.
10
9
8
7
6
5
4
3
2
1
0
1994
1998
2002
2006
2010
Green & Sustainable Science & Technology
Artificial Intelligence
Particle & Field Physics
Nanotechnology
Applied Mathematics
Astrophysics
Biotechnology
Organic Chemistry

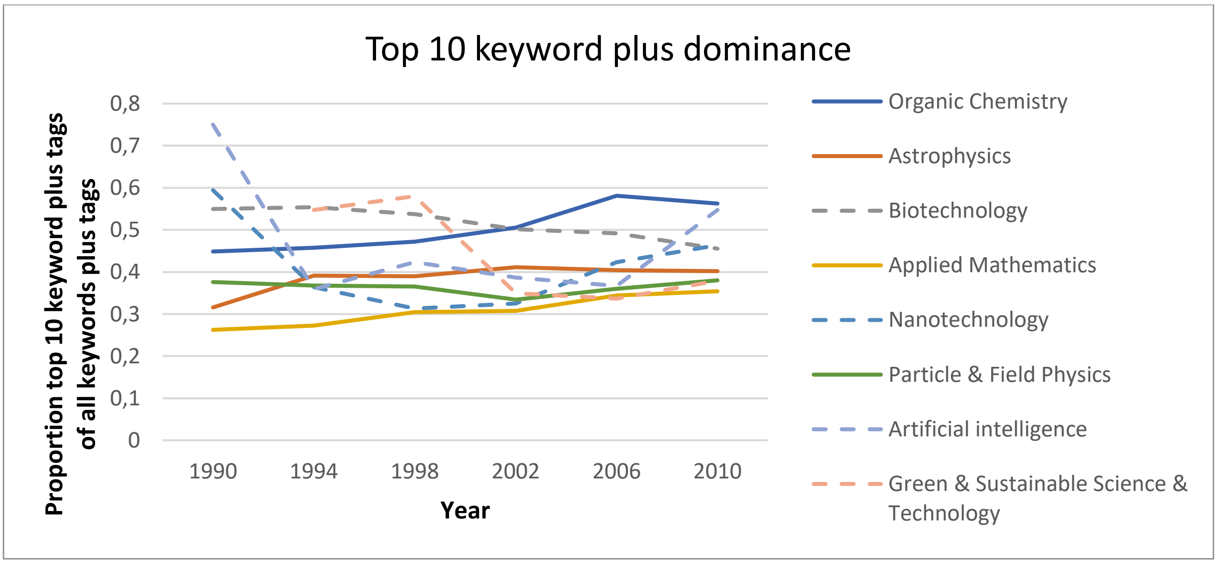


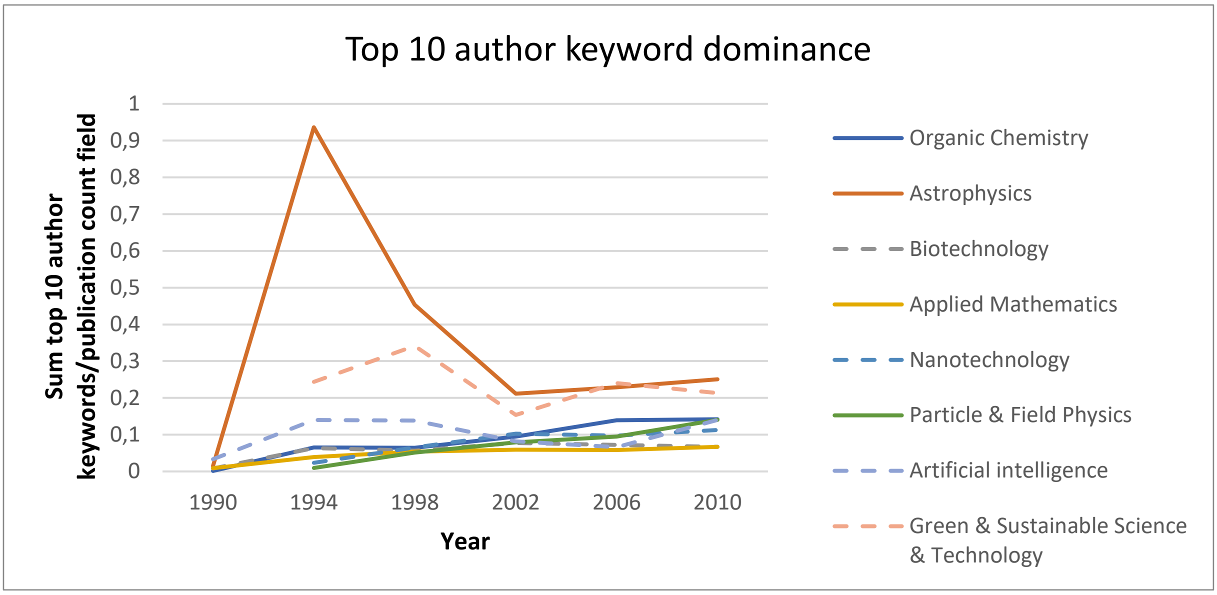
Std. Dev. Co-Author Count
Std. dev. co-author count
1000
100
10
1
0,1
1990
1994
1998
2002
2006
2010
Year
Organic Chemistry
Astrophysics
Biotechnology
Applied Mathematics
Nanotechnology
Particle & Field Physics
Artificial intelligence
Green & Sustainable Science & Technology

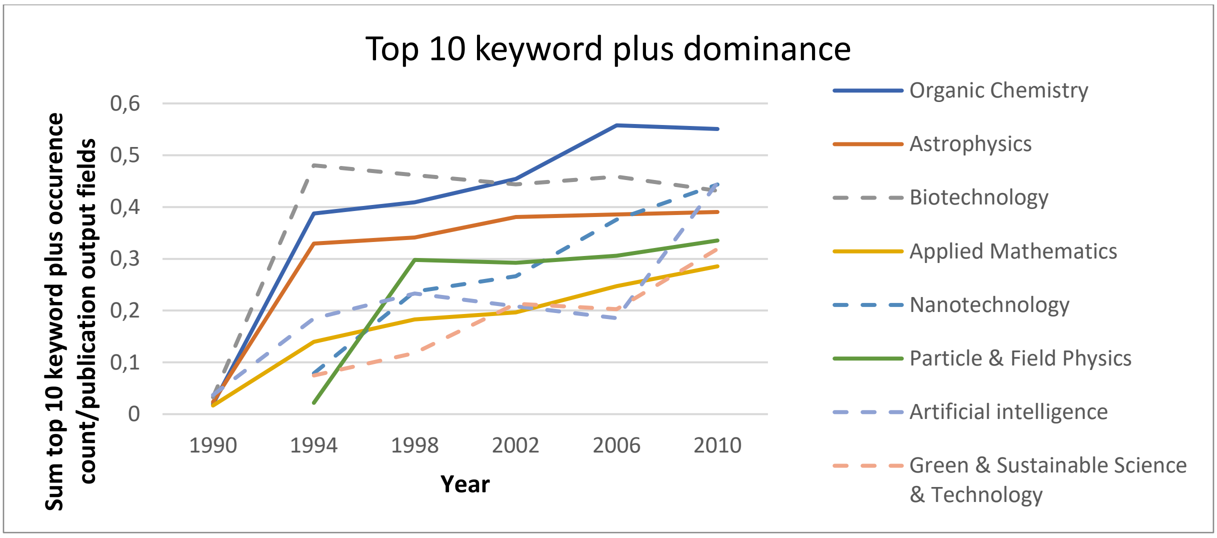
Appendix 7 - Task Uncertainty Graphs

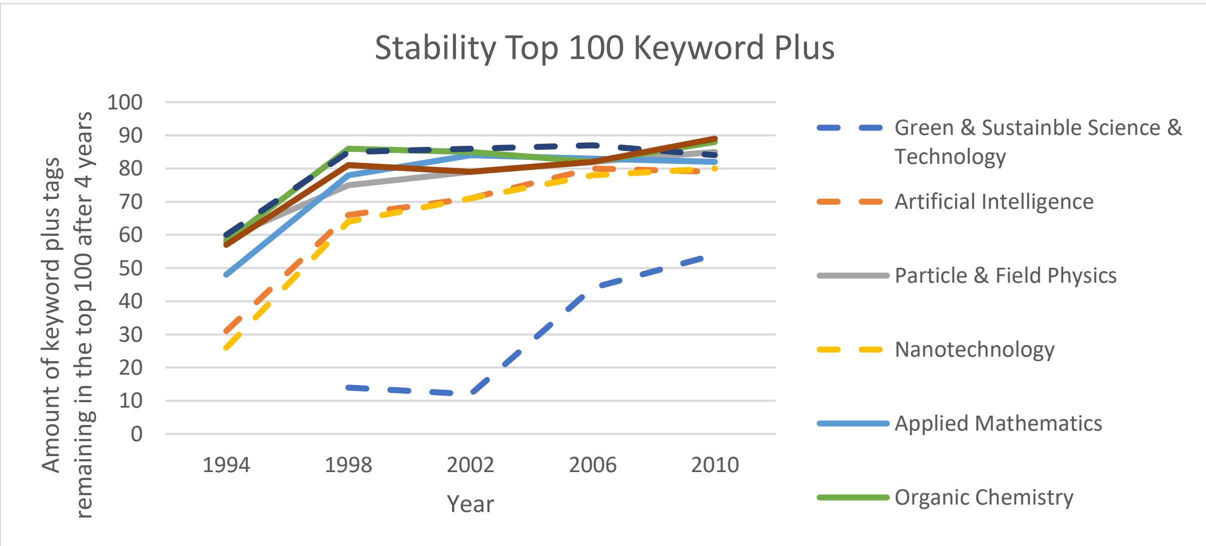


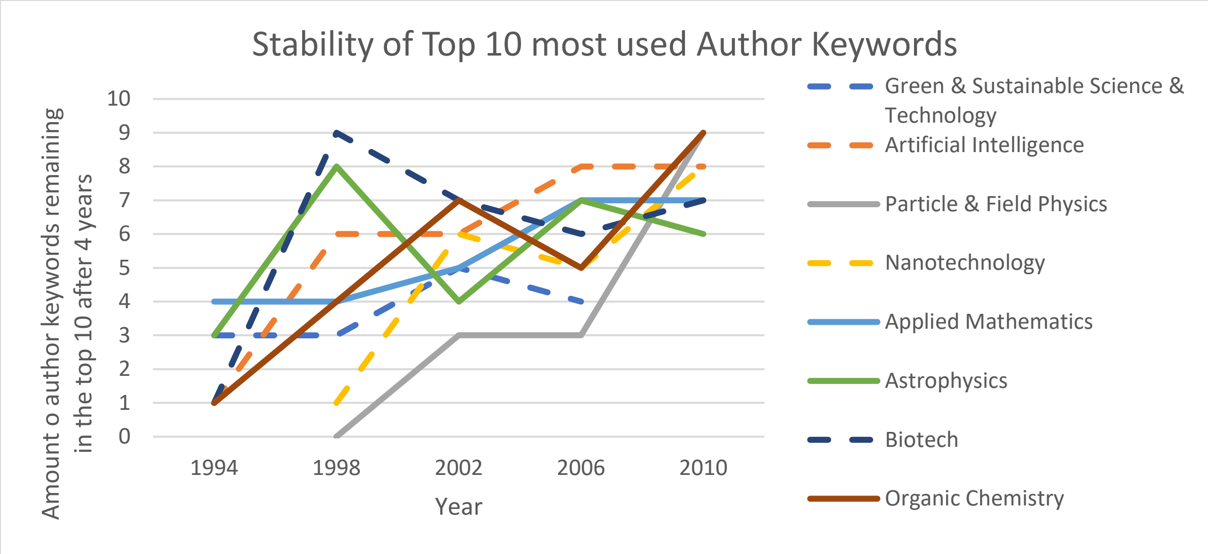




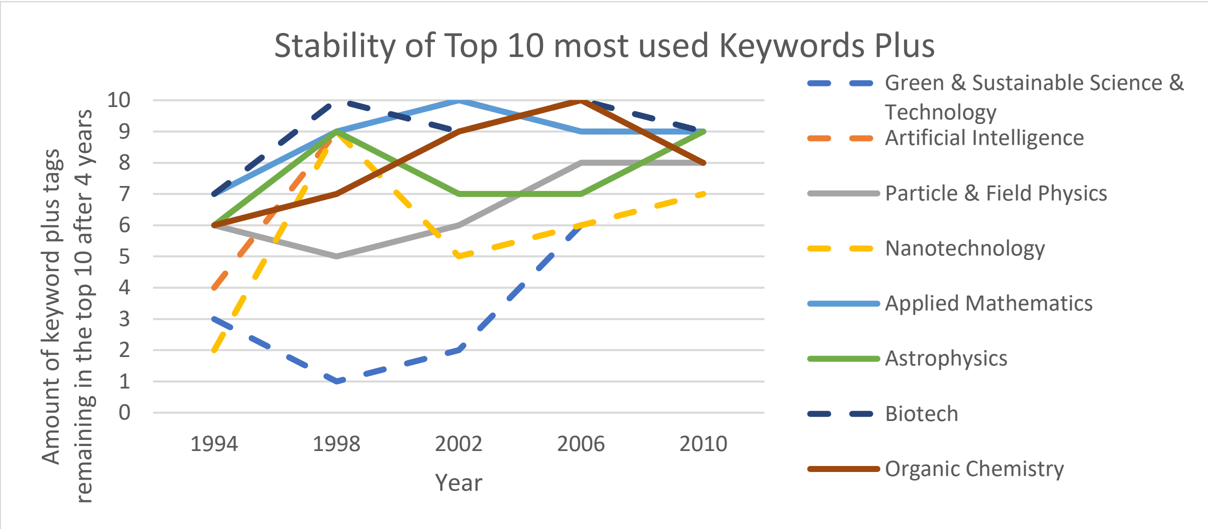

Top 10 author keyword dominance
Sum top 10 author keywords/publication count field
1
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
1990
1994
1998
2002
2006
2010
Year
Organic Chemistry
Astrophysics
Biotechnology
Applied Mathematics
Nanotechnology
Particle & Field Physics
Artificial intelligence
Green & Sustainable Science & Technology


Top 10 keyword plus dominance
Sum top 10 keyword plus occurence count/publication output fields
0,6
0,5
0,4
0,3
0,2
0,1
0
1990
1994
1998
2002
2006
2010
Year
Organic Chemistry
Astrophysics
Biotechnology
Applied Mathematics
Nanotechnology
Particle & Field Physics
Artificial intelligence
Green & Sustainable Science & Technology


Stability Top 100 Keyword Plus
Amount of keyword plus tags remaining in the top 100 after 4 years
100
90
80
70
60
50
40
30
20
10
0
1994
1998
2002
2006
2010
Year
Green & Sustainble Science & Technology
Artificial Intelligence
Particle & Field Physics
Nanotechnology
Applied Mathematics
Organic Chemistry



Stability of Top 10 most used Author Keywords
Amount o author keywords remaining in the top 10 after 4 years
10
9
8
7
6
5
4
3
2
1
0
1994
1998
2002
2006
2010
Year
Green & Sustainable Science & Technology
Artificial Intelligence
Particle & Field Physics
Nanotechnology
Applied Mathematics
Astrophysics
Biotech
Organic Chemistry



Stability of Top 10 most used Keywords Plus
Amount of keyword plus tags remaining in the top 10 after 4 years
10
9
8
7
6
5
4
3
2
1
0
1994
1998
2002
2006
2010
Year
Green & Sustainable Science & Technology
Artificial Intelligence
Particle & Field Physics
Nanotechnology
Applied Mathematics
Astrophysics
Biotech
Organic Chemistry

Appendix 8 - Proposition knowledge accumulation rate (KAR) indicator

Knowledge accumulation is a widely accepted and used concept which stands central in the field of innovation sciences and knowledge production. A quantitative indicator to measure this rate, however, has not been proposed yet.

This paper proposes to measure the rate of knowledge accumulation through 'forgotten' knowledge. This begins with arguing that knowledge builds forth on earlier knowledge, and that the knowledge root slowly tends to 'fade' away over time. This is also known as the replacement of the knowledge paradigm (Towne et al., 2005). Fields with a higher rate of knowledge accumulation can reject false theories faster and can build forth quicker on each other (Towne et al., 2005). Fields produce knowledge throughout their existence, but the majority of this knowledge in the form of publications will thus eventually not be directly cited anymore. This phenomenon can best be visualized with the help of a historical direct citation network (Figure 41).

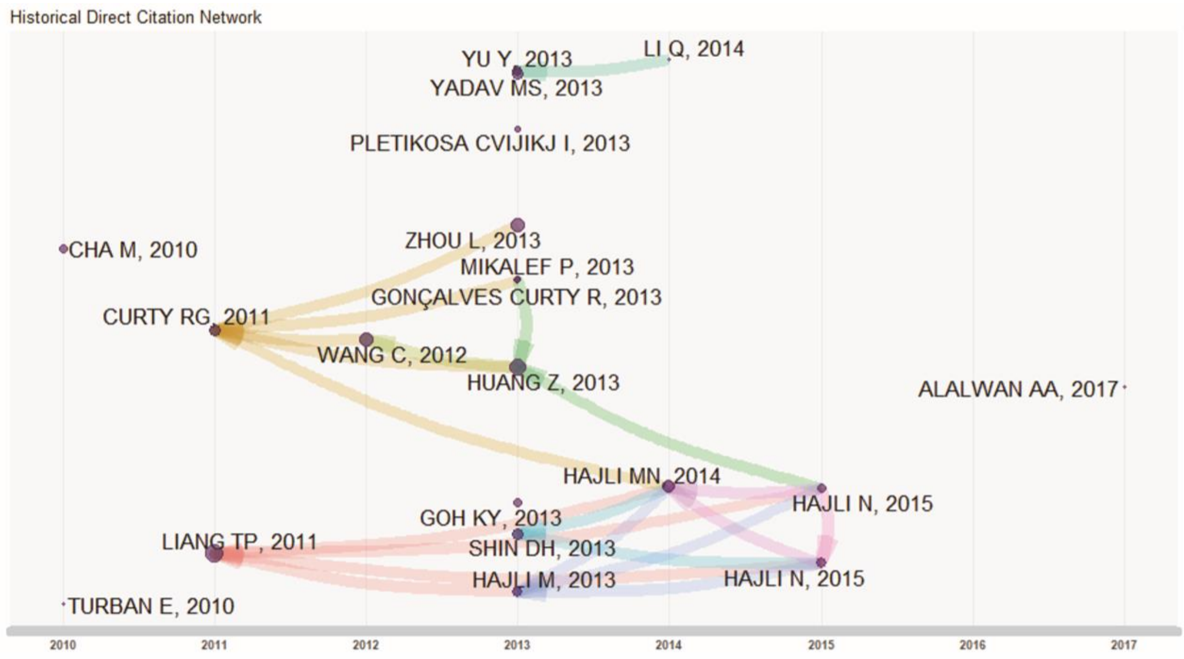


Figure 41: Historical direct citation network for research on social media and e-commerce(Javid, Nazari, & Ghaeli, 2019)

The above figure shows that Curty (2011) and Liang (2011) formed the 'root' of this new research paradigm in 2011. However, their papers were no longer cited after 2013 and can thus be considered 'forgotten knowledge' (Javid et al., 2019). Hence, the more knowledge a field can forget within a certain timeframe, plausibly the faster the knowledge accumulation rate.

For this, however, one first needs to quantifying the amount of knowledge through the frequency of unique references per year (see unique reference distribution in the reference publication year spectroscopy).

Not all publications in this distribution are equal in their significance for the field. Quantifying its value for the field of interest is thus essential. Overall gained citations do not form a reliable measure since one does not know which fields have cited the paper. In addition, the RPYS of more recent empirical years would therefor automatically increase the likelihood of higher citation rates since papers have had more time to acquire these. Instead, this paper argues that the value of references for the field should be measured through the frequency of which this specific field cites manuscripts in the empirical year. Thence, a manuscript that is cited twice in the reference list of Biotechnology in 2006 is in this case valued twice as much as a manuscript that is just cited once. Subsequently, these manuscripts can differ in their citation frequency for a specific field in other years. Biotechnology could for example only cite this manuscript once in 2010. Hence, the value of references for a field can thus change over time.

Ergo, one can now compute the knowledge base (KB) of a field in an empirical year (see equation). KB(t_1) is thus the volume of the reference publication year distribution for year t (e.g. 1990) as shown in Figure 42 (red).

$$f(x,t) = unique\ ref.count\ in\ year\ x\ \cdot its\ citation\ frequency, for\ emperical\ year\ t$$

$$KB(t) = Knowledge\ base\ of\ field\ in\ respective\ emperical\ year$$

$$KB\ (t_1) = \int_{-\infty}^{t1} f(x, t_1)dx$$

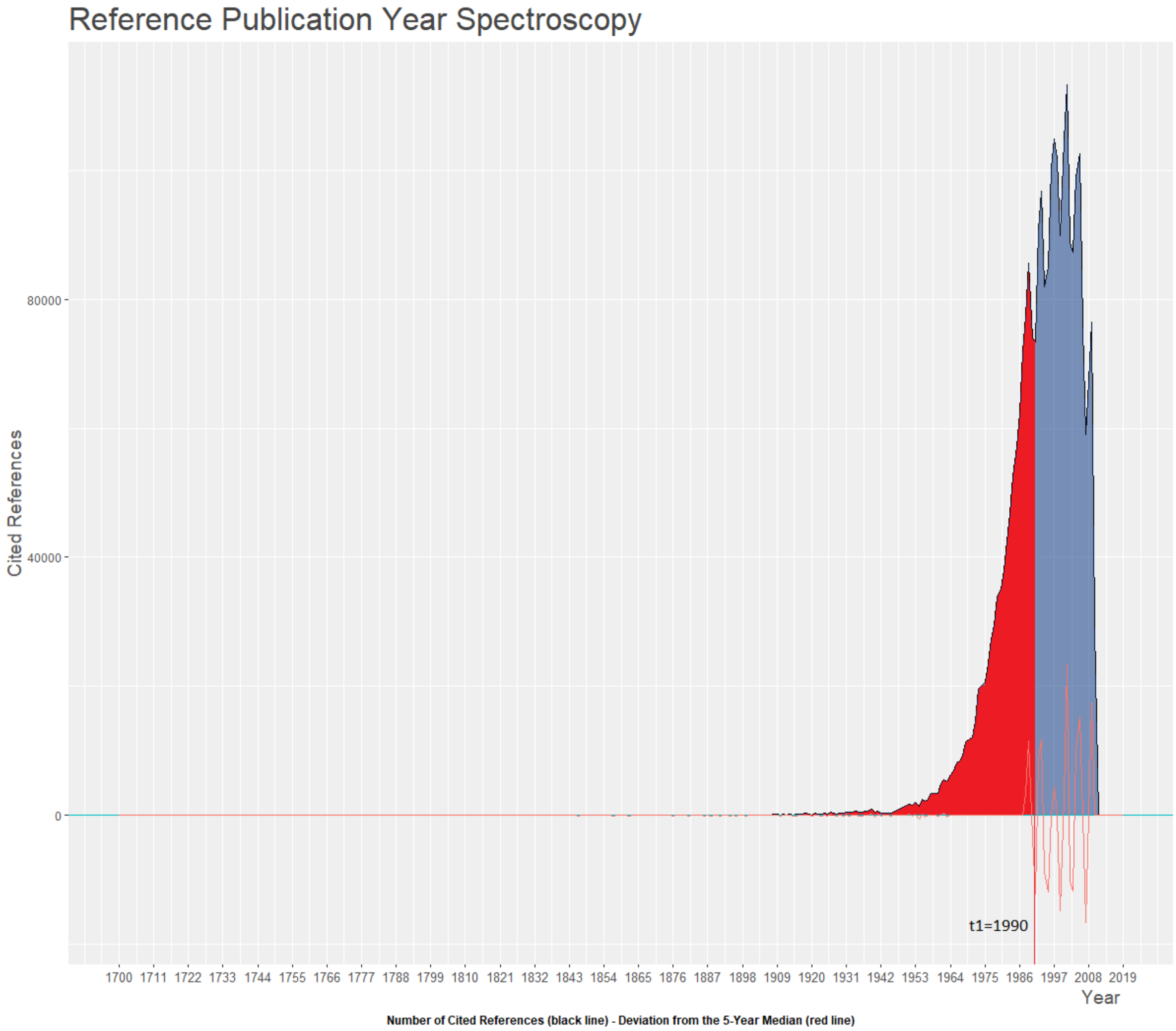


Figure 42: The accumulated RPYS of all 6 years in Astrophysics. The knowledge base volume of 1990 is marked red.

KB(t_1) can now be compared with KB (t_2) for the same period from the perspective of t_2 (e.g. 1994). This is made visual in in Figure 43. Here, KB(t_2) is the red volume of the respective period. The forgotten knowledge in t_2 in comparison to t_1 is the green volume. This is therefore the knowledge forgotten after the 4 year time period.

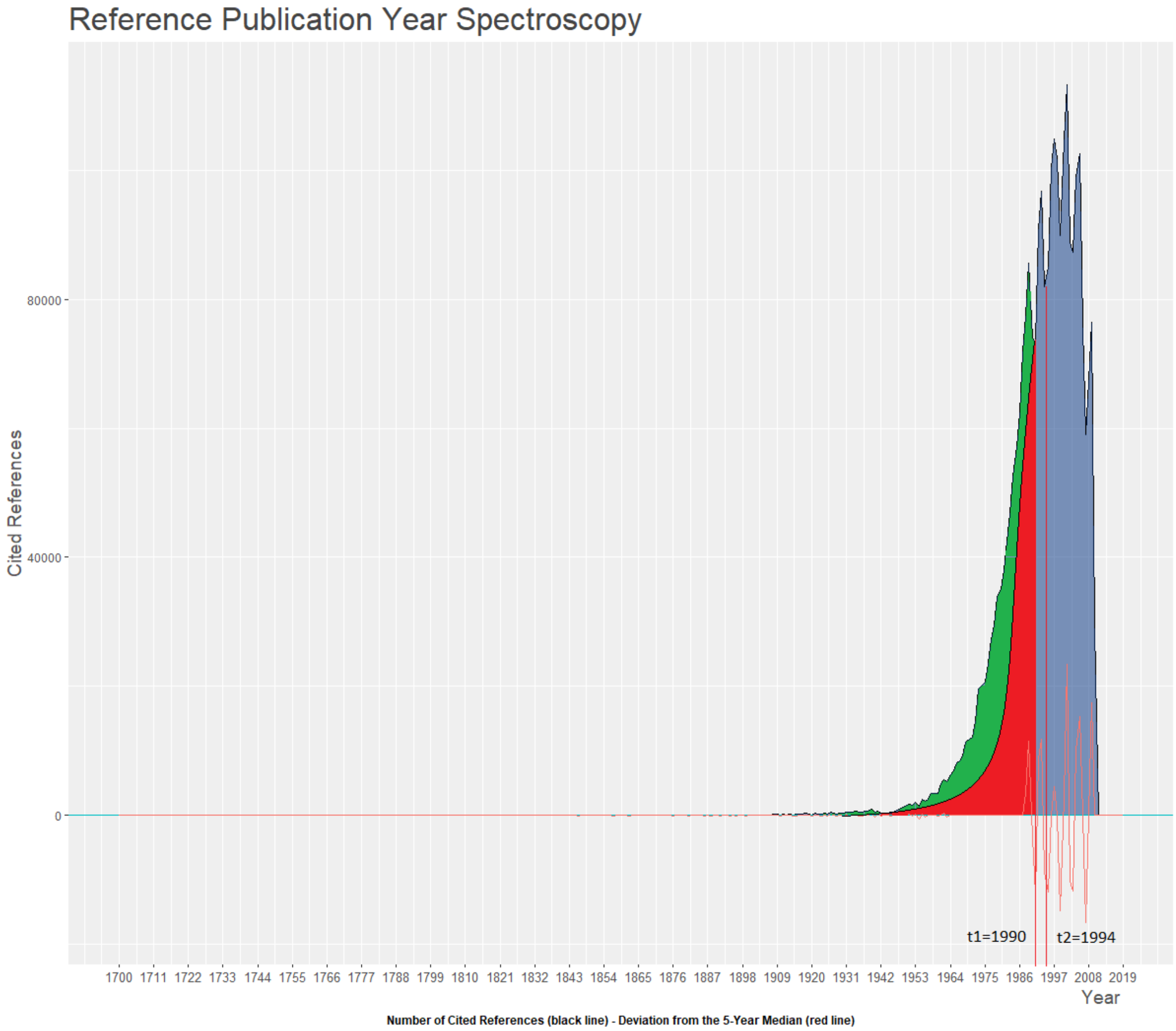


Figure 43: The knowledge base volume of 1990 (green + red); a sketched volume of 1994 (red); and the volume of forgotten knowledge (green)

It is important to compare volumes proportionally so that the knowledge accumulation rates (KAR) can be compared between fields and years. This is the case because fields and years differ in their annual publication output and reference density. Therefore, the equation for the KAR is as follows:

$KAR = Knowledge\ Accumulation\ Rate$

$$KAR = \frac{\int_{-\infty}^{t1} f(x, t_2)dx}{\int_{-\infty}^{t1} f(x, t_1)dx}$$

The larger the proportion of forgotten knowledge, the greater the knowledge accumulation rate will be. Conclusively, the lower the KAR value, the higher the knowledge accumulation rate. This can be measured over time by computing the KAR of 1990/1994, 1994/1998, 1998/2002, etc. Technically the same equation could be used for other contexts. This abstraction could for example be used for industrial/sectorial contexts (patents) and corporates (knowledge management systems).

Appendix 9 – Relative and absolute differences

This study frequently refers to the notions of relative and absolute differences. These terms can be confusing, therefore this appendix aims to briefly elaborate on these with the use of a visualization. For this, the graph of the collaboration frequency is used.

Relative differences are trend differences in variables over time between fields. In the graph below, it is seen that there is a difference between Green & Sustainable Science & Technology in comparison to Organic Chemistry. Not only has Organic chemistry relatively higher frequencies in comparison to Green & Sustainable Science & Technology, its relative change over time is also less dramatic. Relative differences are thus always to be considered in relation to other fields.

(Universal) Absolute differences are trend differences over time in relation to the y-axis. The graph, for example, clearly show that (all) fields show an increased frequency over time. This pattern returns in all fields regardless of their maturity, and is thus expected to relate to contextual factors which influence the overall scientific system.