FAKULTÄT FÜR !NFORMATIK
Faculty of Informatics

Doctoral Interdisciplinarity

A Multi-Method Analysis Based on Bibliometrics and Empirical Approaches

DISSERTATION

zur Erlangung des akademischen Grades

Doktorin der Technischen Wissenschaften

eingereicht von

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Matrikelnummer 1128447

an der Fakultät für Informatik

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Wien, 30. November 2016

María del Carmen Calatrava Moreno

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Erklärung zur Verfassung der Arbeit

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Wien, 30. November 2016

María del Carmen Calatrava Moreno

Acknowledgements

I would like to extend my gratitude to several people for their contributions to the refinement of my ideas and their support for my personal growth throughout this PhD journey.

I am grateful to my two supervisors. Prof. Hannes Werthner, my supervisor in computer science, who enrolled me as a PhD student and provided me with the opportunity to become a member of his group. During my PhD studies he has entrusted me with various academic activities that have contributed to my professional development. He has had the deepest impact on shaping my education and career. I also wholeheartedly thank Prof. Mary Ann Danowitz, my supervisor in the field of education science. She has always optimistically supported my own efforts, while gently keeping me on track. Her sound advice was an encouragement for me throughout my doctoral studies. She encouraged me to conduct important and purposeful research—something that means more to me than I can express.

An important part of my scientific development took place in other universities. Therefore, I would also like to express my gratitude to the scholars that have welcomed me in their institutions as a visiting researcher. Prof. Sotaro Shibayama, at the University of Tokyo, accepted me as a member of his group, supported my research and invited me to collaborate in his projects. I am also exceedingly grateful to Prof. Lynn McAlpine for her guidance and support during my research visits to the Department of Education at the University of Oxford. Her attitude towards research and her commitment to enhancing the learning experience of early-career researchers have been a source of inspiration. These research visits have evolved into fruitful on-going collaborations

I would also like to thank all the participants who took part in this study, in particular the doctoral researchers who agreed to be interviewed. I remain appreciative for the frankness and honesty with which each shared their time and experiences with me.

This journey would have been incomplete without my colleagues at the TU Wien. I am very fortunate to be able to thank so many people, including: Amra Delič, Katja Hildebrandt, Birgit Hofreiter, Elisabeth Kotvojs, Worarat Kratu, Julia Neidhardt, Natalia Rümmele, Michael Schadler, Clarissa Schmid, Maria Schweikert, Stephanie Wogowitsch and Natascha Zachs. This list is by no means exhaustive and I extend my gratitude to many other people not explicitly mentioned here. At different times and in different ways, each provided an attentive ear, inquired about my progress, offered good advice and willingly performed a much-needed favor. Inevitably they became friends.

In Austria, I was fortunate to know the family Auzinger. From very early on in our relationship, Hermine, Walter and Martin made me feel very welcome. They shared their traditions with me, helped me improve my German language skills, and unconditionally assisted me whenever needed. More importantly, they have supported and loved me as a new member of their family.

I am immensely thankful to my parents for their endless love and for giving me tremendous freedom and for supporting all my choices. I have always felt loved, trusted and supported no matter what I attempt. I am grateful to my mother, who always motivated me to be both a good-hearted and strong person. She instilled in me the desire and appreciation for learning and the drive to give all I have to making the most out of my educational opportunities.

Finally, a sincere and special thank-you goes to Thomas Auzinger. He has been a never-ending source of support, unremitting encouragement, instrumental knowledge and endless love. We often discussed our research with each other. These were the most reassuring, motivating and inspiring conversations. Together, we kept smiling through our doctoral studies and time fleeted fast.

Abstract

Interdisciplinary research is a mode of research that integrates two or more bodies of specialized knowledge, to solve problems whose solutions are beyond the scope of a single discipline. This form of research has become an important issue in doctoral education to prepare new generations of scientists to address complex real-world problems. European doctoral education has been subject to policy reforms resulting in new forms of doctoral education. This thesis provides a comprehensive analysis of the doctoral interdisciplinarity in three different kinds of programs in computer science: a traditional doctoral program and two structured programs. This is achieved with three interconnected approaches that aim to measure, understand and assess doctoral interdisciplinarity.

Firstly, a bibliometric method is used to measure the interdisciplinarity of publications. The Rao-Stirling diversity index quantifies the interdisciplinarity of a publication based on the disciplines that are integrated into it through its references. Therefore, this approach necessitates the categorization of all references into disciplinary fields, which is a prerequisite rarely fulfilled. As a methodological contribution, this thesis proposes an extension of the index, based on discrete and continuous optimization as well as graph-based pruning, in order to acknowledge the inaccuracies introduced in the measurement by missing bibliographic data. This bibliometric method is subsequently utilized for measuring the interdisciplinarity of doctoral researchers in the three doctoral programs where this investigation is conducted.

The second approach aims to understand how and why doctoral researchers conduct interdisciplinary research. Doctoral researchers identified as interdisciplinary through the bibliometric analysis participated in semi-structured interviews. The analysis of their accounts reveals that doctoral interdisciplinarity depends on far more than on explicit strategies implemented to facilitate interdisciplinarity. Personal attributes that emerge prior to the start of doctoral studies influence doctoral researchers' inclination to conduct research in one or multiple disciplines. Additionally, policy and structural factors as well as collaboration processes also influence the degree of disciplines integration conducted by doctoral researchers. These findings lead to the identification of patterns of doctoral interdisciplinarity which contribute to the theory of interdisciplinary education.

The third approach assesses how the fulfillment and importance of doctoral interdisciplinarity is perceived by different academic stakeholders. This approach utilizes the

360-degree feedback survey methodology to gather their assessment of factors and processes relevant for interdisciplinarity, which are selected based on a literature review and interviews with interdisciplinary doctoral researchers and professors. Their answers are analyzed using statistical methods in order to investigate the alignment of opinions between groups of stakeholders as well as single-disciplinary and interdisciplinary doctoral researchers. The findings provide useful insights for identifying discrepancies between stakeholders, revealing problematic issues and suggesting actions for improvement.

The three approaches (and their respective substantial amounts of information) are mutually complementary and validatory, and therefore strongly corroborating the findings of the investigation. This thesis also contributes to raising the awareness on facilitators and obstacles to doctoral interdisciplinarity and offers recommendations for supporting young interdisciplinary scientists.

Kurzfassung

Interdisziplinäre Forschung ist eine wissenschaftliche Herangehensweise, die zwei oder mehr spezialisierte Wissensgebiete zusammenführt um Fragestellungen zu behandeln, deren Umfang eine einzelne Forschungsdisziplin übersteigt. Diese Art der Forschung gewinnt im Bereich der Doktorratsausbildung zunehmend an Bedeutung um zukünftige Generationen an ForscherInnen auf die Behandlung komplexer, anwendungsbezogener Probleme vorzubereiten. Dies hat zur Folge, dass die europäische Doktorratsausbildung Reformen unterzogen wurde, die neue Formen der selbigen hervorbrachten. Die vorliegende Arbeit präsentiert eine umfassende Analyse der Interdisziplinarität dreier unterschiedlicher Doktorratsprogramme in der Informatik: einem traditionellen und zwei strukturierten Programmen. Dies geschieht mittels dreier ineinandergreifender Forschungsansätze um Interdisziplinarität nicht nur zu messen, sondern auch zu verstehen und zu bewerten.

Zu Beginn wird eine bibliometrische Methode eingesetzt um die Interdisziplinarität akademischer Publikationen basierend auf dem Rao-Stirling Diversitätsindex zu messen. Dieser Index quantifiziert die Interdisziplinarität einer Publikation aufgrund der Anzahl der Forschungsfelder, die sie mittels ihrer Referenzen zusammenführt. Dies setzt allerdings eine Kategorisierung aller Referenzen in ihre jeweiligen Felder voraus, was selten erreicht werden kann. Als einen methodologischen Forschungsbeitrag präsentiert die vorliegende Arbeit eine Erweiterung des obengenannten Index, die, basierend auf diskreter und kontinuierlicher Optimierung sowie der Reduktion von Graphen, die Ungenauigkeiten der Indexberechnung aufgrund unvollständiger bibliografischer Daten aufzeigt und quantifiziert. Diese Methode wird anschließend dazu verwendet um die Interdisziplinarität von JungforscherInnen der drei Doktorratsprogramme zu bestimmen.

Der zweite Forschungsansatz beschäftigt sich mit der Frage, wie und warum Doktorratsstudierende interdisziplinäre Forschung betreiben. Dazu wurden die durch die bibliometrische Methode als interdisziplinär eingestuften Studierenden mittels Leitfadeninterviews befragt. In der darauffolgenden Analyse stellte sich heraus, dass Interdisziplinarität im Doktorratsstudium von deutlich mehr Faktoren abhängt als nur von einer strategischen Ausrichtung zur Förderung von Interdisziplinarität. Einerseits haben persönliche Eigenschaften, die bereits vor Beginn des Doktorratsstudiums zu Tage treten, Einfluss auf die Bereitschaft des oder der Doktorratsstudierenden sich mit einer oder mehreren Disziplinen zu beschäftigen. Anderseits bestimmen sowohl politische und strukturelle Faktoren als auch die Gestaltung von Kollaborationsprozessen den Grad der Interdiszi-

plinarität. Diese Resultate führten zur Identifizierung von Interdisziplinaritätsmustern von Doktorratsstudierenden, und stellen einen Beitrag zur Theorie der interdisziplinären Bildung dar.

Der dritte Forschungsansatz untersucht, wie VertreterInnen verschiedener Interessensgruppen im Zusammenhang mit den obengenannten Doktorratsprogrammen das Vorhandensein und die Relevanz von Interdisziplinarität bewerten. Basierend auf der Methode der 360-Grad Beurteilung als Befragungsmodell, bewerteten die VertreterInnen wichtige Faktoren und Prozesse, die mittels eingehender Literaturrecherche und Interviews mit interdisziplinären Doktorratsstudierenden und ProfessorInnen identifiziert wurden. Mit Hilfe statistischer Methoden wurden Übereinstimmungen verschiedener Interessensgruppen sowie Studierender einer Disziplin als auch interdisziplinärer Studierender untersucht. Als Ergebnis werden wichtige Erkenntnisse präsentiert, die Diskrepanzen zwischen den Interessensgruppen aufzeigen und generelle Problemfelder identifizieren, aber auch Verbesserungsmöglichkeiten skizzieren.

Diese drei Forschungsansätze (und das jeweils zugehörige, umfassendes Datenmaterial) komplementieren sich nicht nur, sondern stellen auch eine gegenseitige Validierung dar, die die Gültigkeit der hier präsentierten Schlussfolgerungen untermauert. Die vorliegende Arbeit möchte außerdem bewusst machen, welche Faktoren für eine interdisziplinäre Doktoratsausbildung begünstigend wirken oder ein Hindernis darstellen, und macht Vorschläge, wie interdisziplinären JungforscherInnen unterstützt werden können.

Contents

CHAPTER 1

Introduction

The concept of academic disciplines developed at the end of the eighteenth century as demarcated domains of specialized knowledge (Weingart, 2010). The growing need to order an increasing and unmanageable complexity of available knowledge instigated scholars with similar concepts and methods, to unite, forming a community. In the nineteenth and twentieth centuries, disciplinary associations soon became the structuring principle of knowledge formation. However, over the latter half of the twentieth century, this approach led to the fragmentation of knowledge into an ever-growing number of specialties that has softened the once rigid boundaries of disciplines (Klein, 2010). This proliferation of specialized fields resulted in the need to bring together different knowledge areas in order to address problems that escape the domain of a single, narrow, although deep field of expertise. InterDisciplinary Research (IDR), the combination of two or more bodies of specialized knowledge to advance fundamental understanding, emerged out of such a need.

Since then, IDR has increasingly been viewed as a means of providing greater insight and success at investigating complex problems (Domik and Fischer, 2010; Newswander and Borrego, 2009; Pisapia et al., 2013). Numerous researchers and institutions of higher education advocate interdisciplinarity as a necessary form of research in order to tackle the increasing complexity of present day scientific problems (Klein, 1990; Lattuca, 2001). This growth in complexity also coincides with a collective shift of opinion on the purpose of science: from the assumption that knowledge is inherently beneficial and its pursuit can be justified in terms of curiosity, to the opinion that knowledge should have a larger purpose and contribute to the improvement of society. IDR contributes to the latter case and is regarded as the modus operandi to address problems in a complex, global, and rapidly innovating society.

IDR is becoming increasingly popular within the academic and scientific communities. It is frequently referred to in public discourses, academic discussions, project proposals, and other communication, even forming in part of strategic research policies. Brint

(2005) argued that while some universities have taken a familiar path towards recognition strengthening their standings in traditional fields of knowledge, others are attempting to gain recognition by creating new paths outside the single-disciplinary structure by encouraging interdisciplinary efforts.

The importance given to IDR, however, contrasts with the lack of consensus on its precise definition. There is no detailed prescriptive catalog of its defining criteria nor the procedures involved. Similarly, there is no agreement about how to identify and measure IDR (Wagner et al., 2011). In the absence of a full agreement on the concept of interdisciplinarity, it is essential to understand more fully its characteristics, qualities, processes and outcomes. The literature on interdisciplinarity offers comprehensive descriptions of interdisciplinary initiatives and strategies. Conversely, there is limited research examining the processes and outcomes of IDR (Jacobs and Frickel, 2009; Klein, 1990; Lattuca, 2001), and even fewer analyses have been conducted on interdisciplinarity during the first stages of research careers.

This dissertation is an effort to address some of the above issues. It investigates IDR without presuming it be either superior or inferior to other kinds of research, but rather as a complementary and necessary form of advancing knowledge; one which often faces more obstacles and disincentives than single-disciplinary research (Brandt et al., 2013; Institute of Medicine and National Academy of Sciences and National Academy of Engineering, 2005; Winskel et al., 2014). The investigation focuses on interdisciplinarity at a doctoral level, as early career researchers are central to increasing the interdisciplinarity research capacity of higher education institutions (Golde and Walker, 2006). Moreover, the integration of knowledge from distinct disciplinary traditions has become an important issue in doctoral education as programs aim to prepare graduates to solve complex real-world problems. This has been especially so in Europe, where doctoral education has been subject to policy reforms by the European Union (European University Association, 2007; 2010); and at national levels too (Kehm, 2006; Nyhagen and Baschung, 2013). To respond to nation-states' and industry employers' claims that doctoral researchers are educated too narrowly (Stewart and L. Chen, 2009), European universities developed new doctoral structures to prepare interdisciplinary early career scientists (European Union Research Advisory Board, 2004; Reichert et al., 2005). These doctoral programs have structured curricula with general and subject-related courses (Kehm, 2006). They were established as alternatives to the traditional doctoral model, where doctoral researchers are not necessarily integrated into a formal study program (Pecher and Thomas, 2004). These new programs introduce significant innovations to the academic culture. The success of their strategies to effectively facilitate and promote interdisciplinarity, however, depends on the advancement of our knowledge on the factors that contribute to IDR, how it can be measured, and the opinions of individuals involved in the training of interdisciplinary young researchers—issues that this thesis addresses.

1.1 Research Questions

The purpose of this dissertation has three main objectives:

First, it aims to provide a method that allows research institutions to monitor their interdisciplinary scientific endeavors. The method should fulfill a series of fundamental requirements for its use: It should be (i) operationally reliable; (ii) deliver clear and conclusive results; (iii) facilitate periodical monitoring; (iv) employ data either already available or easy to gather at the institution; (v) deliver robust results in the presence of missing data. Taking these requirements into account we address the following research question:

1. *How to efficiently and effectively measure interdisciplinarity in a research institution?*

Second, this thesis aims to provide insight into interdisciplinarity in the context of different doctoral structures and approaches to manage specialization. This analysis focuses on individuals who are either nearing or have recently completed their doctoral degrees. They are likely to be among the early generation of scholars trained in different kinds of doctoral programs and during a time when IDR has become important. Therefore, they are in a unique position to assess the nature of this process. Two main questions guide the research:

2. *What dispositions and experiences are associated with doctoral researchers becoming interdisciplinary early career scientists?*
3. *What are the factors and facilitators of interdisciplinary doctoral research that stem from traditional and structured doctoral programs?*

Finally, this dissertation aims to provide an overview on how interdisciplinarity at the doctoral level is perceived not only by doctoral researchers, but by individuals with different roles in academia—from researchers, over directors of higher education institutions, to funding institutions—, and also by those with varying degrees of involvement with interdisciplinarity. Therefore, we address the following question:

4. *How do perspectives on doctoral IDR of different university stakeholders coincide?*

While these research questions are applicable to doctoral education in general, this thesis focuses on Computer Science (CS) as explained below.

1.2 Significance of the Investigation

Previous literature on interdisciplinary graduate education have investigated interdisciplinarity mostly utilizing a single method of analysis (Wagner et al., 2011). Nevertheless, given the complexity of the processes and factors involved in IDR, a multifaceted and multi-method approach is required (Huutoniemi, 2010). Schilling (2001) referred to this complexity in the evaluation of higher education interdisciplinary programs: “The hope for one single measure that will make our case is inappropriate for programs that embrace complexity and ambiguity as part of their core identity”. This dissertation applies such a multifaceted and multi-method approach. It investigates doctoral programs from different perspectives: (i) quantifying interdisciplinarity; (ii) understanding interdisciplinary dispositions, experiences, factors and facilitators; and (iii) assessing opinions of university stakeholders. It combines CS methods to efficiently analyze large amount of data, and qualitative and quantitative empirical methods to obtain a deeper insight on factors, processes and individuals’ opinions.

The investigation of this thesis focuses on interdisciplinarity in CS. The field of CS is ideal to experiment with curricular innovations and ways of preparing doctoral researchers to engage with interdisciplinarity (Abernethy and Treu, 2015). It is a young field with interdisciplinary origin but has established itself a distinct field conducting both basic and applied research (Tedre, 2014). Moreover, computer technology is often central to much scientific research of other disciplines. There have been continuous efforts to improve and update CS academic programs and incorporate interdisciplinarity including teaching of basic CS concepts (Smarkusky and Toman, 2009), supporting interdisciplinarity collaborative learning (Muterspaw et al., 2015), and providing an understanding of the complexities of systems for real-world problems (desJardins, 2013). Undergraduate and graduate programs have been re-designed to incorporate interdisciplinarity (Abernethy and Treu, 2015; Mielke et al., 2008; Sobiesk et al., 2006). Additionally, interdisciplinarity is often discussed at major conferences (Aparac-Jelušić et al., 2013; Friedman, 2013; Wolz and Cassel, 2012). This leveraging of interdisciplinarity with computing is taking place in highly interdisciplinary areas of CS (Abernethy and Treu, 2015; Blackwell, 2015) and in areas where basic research predominates (Chi-Chih Yao, 2015).

Although interdisciplinarity is receiving increasing attention in CS, there is limited knowledge about its forms and processes. While there is a wealth of informative literature on interdisciplinary education in the social sciences and humanities, it is not so common for science and engineering academics to publish on IDR processes. An indication of this is the methodological approaches that Borrego and Newswander (2010) had to utilize to analyze definitions of IDR from the perspective of humanities, sciences and engineering. They analyzed concepts and definitions of interdisciplinarity in the humanities from a large body of literature. However, since the literature on interdisciplinarity in science and engineering was sparse, they identified concepts and definitions from a content analysis of successful U.S. National Science Foundation project proposals. This situation is an indication that information is lacking about the kind of interdisciplinary work that is done in CS, and more specifically what doctoral researchers do and how diverse experiences relate to various forms of interdisciplinarity.

A further understanding of interdisciplinarity within CS is advantageous and important for defining academic policy and program changes in order to promote high-quality IDR within this field. Therefore, this investigation contributes to interdisciplinary studies, CS and higher education research.

Theories, concepts, and methods from the three fields are comprised in this thesis. However, part of its readership may only have expertise in one of these fields. In order to facilitate the understanding of a broad readership, concepts that are well-known only by experts of a given field, are described to facilitate the understanding of experts in the other disciplines.

1.3 Structure of the Thesis

This thesis is organized into the following chapters:

Chapter 2 introduces fundamental concepts and provides the context of this thesis by embedding it in relevant bodies of literature.

Chapter 3 provides a description of the environment under which this study was conducted, makes particular reference to the doctoral programs.

Chapter 4 introduces the methodological approaches employed in this research. The methods of data collection and analysis are described. The reliability and ethical considerations of this study are also discussed.

Chapter 5 presents an existing method for measuring the interdisciplinarity of publications according to the integration of different disciplines using references. Theoretical extension of this method is offered in order to account for the uncertainty from missing data resulting from references not being categorized into disciplinary fields, which is a common deficiency of available bibliographic data repositories. An implementation of this method is presented and evaluated. Subsequently, it is used to measure the interdisciplinarity of doctoral researchers in CS.

Chapter 6 utilizes the method presented in Chapter 5 in order to identify interdisciplinary doctoral researchers. Based on personal interview data, the chapter presents efforts to identify what factors, processes and predispositions contribute to the interdisciplinarity of early career researchers. Patterns of doctoral interdisciplinarity within the field of CS are also presented.

Chapter 7 presents an analysis of the opinions of doctoral interdisciplinarity held by different academic stakeholders including doctoral researchers, post-doctoral researchers, professors, department directors and research funding agencies. A 360-degree methodology was employed to gather their opinions on interdisciplinary factors and processes identified in the literature and prior interviews with doctoral researchers and professors. The method and its implementation are explained, and the results are presented.

Chapter 8 summarizes the thesis research. It discusses its limitations, possible implications and directions for future research.

1.4 Publications

During the period of this thesis, an interdisciplinary record of articles have been published in renowned conference proceedings and journals both in fields of CS and higher education.

This thesis is based on the following peer-reviewed publications:

Calatrava Moreno, M. C., Auzinger, T., and Werthner, H. (2016). "On the uncertainty of interdisciplinarity measurements due to incomplete bibliographic data". In: *Scientometrics* 107.1, pp. 213–232. DOI: 10.1007/s11192-016-1842-4.

Calatrava Moreno, M. C. and Danowitz, M. A. (2016a). "Becoming an interdisciplinary scientist: An analysis of students' experiences in three computer science doctoral programmes". In: *Journal of Higher Education Policy and Management* 38.4, pp. 448–464. DOI: 10.1080/1360080X.2016.1182670.

— (2016b). "Interdisciplinarity in computer science: Emergent patterns from doctoral experiences". In: *ACM Transactions on Computing Education*. Conditionally accepted.

Calatrava Moreno, M. C., Kynčlová, P., and Werthner, H. (2016). "A Multiple-Perspective Analysis of Doctoral Interdisciplinarity". In: *IEEE International Conference on Information Technology based Higher Education and Training (ITHET)*. IEEE. Istanbul, Turkey.

Calatrava Moreno, M. C. (2014). "A 360-degree evaluation framework for doctoral programs". In: *IEEE Global Engineering Education Conference (EDUCON)*. IEEE, pp. 850–853. DOI: 10.1109/EDUCON.2014.6826195.

— (2013). "Towards a flexible assessment of higher education with 360-degree feedback". In: *IEEE International Conference on Information Technology based Higher Education and Training (ITHET)*. IEEE. Antalya, Turkey. DOI: 10.1109/ITHET.2013.6671041.

During the time period of this thesis, the following loosely related or unrelated peer-reviewed articles were published:

Calatrava Moreno, M. C. and Kollanus, S. (2013). "On the motivations to enroll in doctoral studies in Computer Science—A comparison of PhD program models." In: *IEEE International Conference on Information Technology based Higher Education and Training (ITHET)*. IEEE. DOI: 10.1109/ITHET.2013.6671028.

Calatrava Moreno, M. d. C. and Auzinger, T. (2013). "General-Purpose Graphics Processing Units in Service-Oriented Architectures". In: *2013 IEEE 6th International Conference on Service-Oriented Computing and Applications*. SOCA '13. IEEE, pp. 260–267. ISBN: 978-1-4799-2701-2. DOI: 10.1109/soca.2013.15.

Pobiedina, N., Neidhardt, J., Calatrava Moreno, M. C., Grad-Gyenge, L., and Werthner, H. (2013). "On successful team formation: Statistical analysis of a multiplayer online game". In: *IEEE Conference on Business Informatics (CBI)*. IEEE, pp. 55–62. DOI: 10.1109/CBI.2013.17.

Pobiedina, N., Neidhardt, J., Calatrava Moreno, M. C., and Werthner, H. (2013). "Ranking Factors of Team Success". In: *Proceedings of the 22nd International Conference on World Wide Web*. WWW '13 Companion. Rio de Janeiro, Brazil: ACM, pp. 1185–1194. ISBN: 978-1-4503-2038-2. DOI: 10.1145/2487788.2488147.

The following additional publications were also produced in the period of this thesis:

Calatrava Moreno, M. C. (2016). *Quantifying Interdisciplinarity in the Face of Uncertainty*. http://era.ideasoneurope.eu/2016/06/10/quantifying-interdisciplinarity-face-uncertainty/. Blog post for Europe of Knowledge. The official blog for ECPR Standing Group on the Politics of Higher Education, Research and Innovation.

Calatrava Moreno, M. C. and Auzinger, T. (2016). *robustrao: An Extended Rao-Stirling Diversity Index to Handle Missing Data*. https://cran.rstudio.com/web/packages/robustrao/index.html. Accessed: 15-09-2016.

Calatrava Moreno, M. C. (2012). "A Qualitative Framework for Comparison and Evaluation of Computer Science Doctoral Programs". In: *Proceedings of the 17th ACM Annual Conference on Innovation and Technology in Computer Science Education*. ITiCSE '12. Poster. Haifa, Israel: ACM, pp. 398–398. ISBN: 978-1-4503-1246-2. DOI: 10.1145/2325296.2325414.

Calatrava Moreno, M. C. and Werthner, H. (2012). "The Vienna PhD School of Informatics. Design, Implementation and Experiences". In: *Proceedings of the 8th European Computer Science Summit*. Barcelona, Spain.

The findings of this research have also been presented at the following conferences with proceedings and venues for discussion:

ÖZBF-Kongress, 2016 (Salzburg, Austria). Österreichische Zentrum für Begabtenförderung und Begabungsforschung: *Measuring and understanding interdisciplinarity: An analysis of three computer science doctoral programs.*

Open Evaluation, 2016 (Vienna, Austria): *Measuring and understanding interdisciplinarity in computer science doctoral programs.*

IEEE ITHET, 2016 (Istanbul, Turkey). International Conference on Information Technology based Higher Education: *A multiple-perspective analysis of doctoral interdisciplinarity.*

EAIR Forum, 2016 (Birmingham, UK). The European Higher Education Society: *Interdisciplinarity in computer science: Emergent patterns from doctoral experiences.*

UKCGE International Annual Conference Doctoral Training Structures—form and functionality, 2014 (Dublin, Ireland): *Contrasting approaches to interdisciplinarity at doctoral level—Students experiences.*

IEEE EDUCON, 2014 (Istanbul, Turkey). Global Engineering Education Conference: *A 360-degree evaluation framework for doctoral programs.*

IEEE ITHET, 2013 (Antalya, Turkey). International Conference on Information Technology based Higher Education: *Towards a flexible assessment of higher education with 360-degree feedback.*

CHAPTER 2

Background and Previous Work

This chapter presents an overview of the different interdisciplinarity typologies and the employed for its analysis. These related works provide the background information on this thesis.

Firstly, it is important to explain what is meant by “discipline” and “interdisciplinarity”. Research and researchers within a given discipline follow similar canons of rigor, theoretical assumptions, methodological approaches and sets of problems. However, the definition of a discipline is subject to certain granularity. Biology, for example, can be considered as a single discipline or as consisting of several (sub)-disciplines, such as ecology, genetics or molecular biology. Moreover, there may be competing theoretical and methodological approaches within a discipline. For instance, within Computer Science (CS), software engineering heavily relies on CS methods, while artificial intelligence also draws upon mathematics, psychology, linguistics, philosophy and neuroscience. Additionally, the term “discipline” may be used to refer to both academic knowledge and non-academic practical activities. In this thesis, “discipline” will be used to designate broad fields of knowledge and practice according to the administrative classification of higher education institutions, such as departments of biology, CS, mathematics, etc. As a consequence, sub-disciplines will not be regarded as independent disciplines, nor will their integration be considered interdisciplinarity. For example, research integrating both software and computer engineering will be considered single-disciplinarity in CS.

The most straightforward definition of the term “interdisciplinarity” implies the involvement of two or more different disciplines or areas of knowledge. Nevertheless, there is extensive literature that supports the differentiation of interdisciplinarity, which is presented in the following section. The use of the term “interdisciplinarity” might lead to confusion because it is used to designate all forms of integration of knowledge, while it can also be used to refer to a particular type of knowledge integration. In this thesis, we generally use the broader meaning of interdisciplinarity and refer to “interdisciplinary research” as describing research where two or more disciplines work together, integrating information, data, techniques, tools perspectives, concepts and theories. However, in this chapter we also use the more specific connotation of "interdisciplinarity" in order to explain the different forms of knowledge integration. These two interpretations can be differentiated according to the context, but the ambiguity of this term should be kept in mind.

2.1 Typologies of Interdisciplinarity

Multiple kinds of knowledge integration exist. Klein (1996), an internationally recognized expert on InterDisciplinary Research (IDR), describes these with a continuum of interdisciplinarity:

> "from simple borrowings and methodological thickening to theoretical enrichment, converging sites, and a general shift ... to new 'cross-' 'counter-' and 'antidisciplinary' positions that front the problem of how meaning is produced, maintained, and deconstructed." (p. 153)

This section presents different categorizations of interdisciplinarity based on varying dimensions of IDR. Firstly, theoretical typologies of interdisciplinarity will be presented. These are grounded on the degree of discipline integration. Subsequently, typologies based on the underlying interdisciplinarity practices and rationales will be covered. These are more recent typologies that utilize empirically grounded accounts, shifting from hierarchical classifications of interdisciplinary to more descriptive typologies, and from the science scale to the sites of knowledge production (Huutoniemi et al., 2010).

2.1.1 Degrees of Disciplinarity and Integration

The first major interdisciplinarity typology was provided by the Organization for Economic Co-operation and Development (OECD) (1982). It distinguishes the three most widely used terms that define the forms of discipline integration: *multidisciplinarity*, *interdisciplinarity*, and *transdisciplinarity*. The OECD classification defines multidisciplinarity as an approach that juxtaposes disciplines. Juxtaposition involves wider methods, knowledge, and information while the disciplines remain separate and the disciplinary elements retain their original identity. The line between multidisciplinarity and interdisciplinarity is crossed when information from different disciplines is integrated to construct a more comprehensive understanding. In interdisciplinary research the different disciplines do not remain separate; instead concepts, methodologies, or epistemologies are explicitly exchanged and integrated, resulting in a mutual enrichment (Klein, 1990). Transdisciplinarity requires the greatest synthesis. In the OECD typology, this term was defined as a common system of axioms that transcends the narrow scope of disciplinary world-views through an overarching synthesis. In this mode, the disciplines involved not only share a common question but also borrow methods, create a common conceptual framework, and either learn each other's disciplinary language or create a new common one (Aboelela

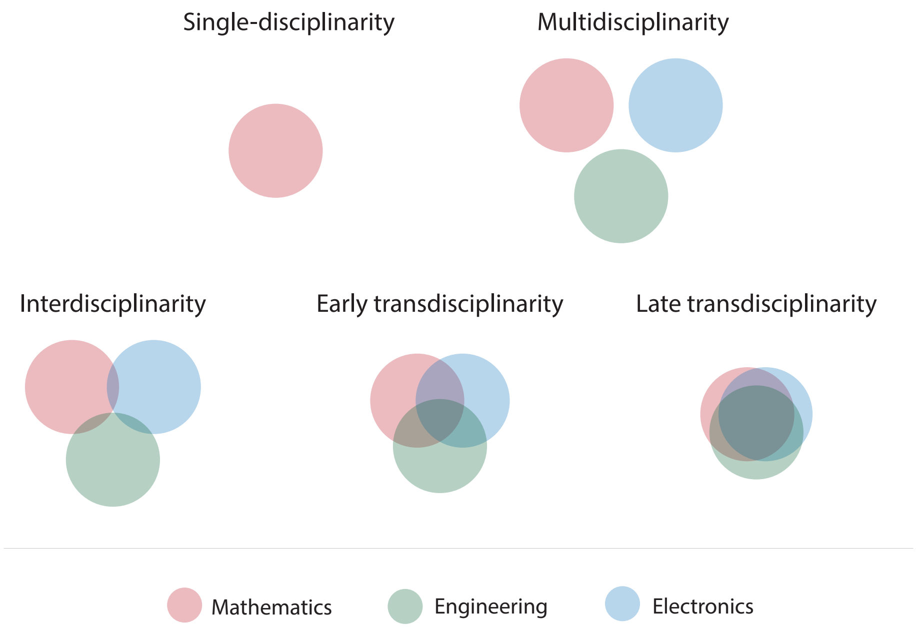

Figure 2.1: Graphical representation of the OECD taxonomy of interdisciplinarity.

et al., 2007), eventually giving rise to a new field of knowledge. Figure 2.1 graphically represents the above-described variants of knowledge integration with the example of the origin of CS: initially, an integration of the fields of mathematics and engineering allowed the construction of mechanical computers (e.g., Charles Babbage's difference engine); the later integration of electronics led to the creation of electromechanical computers (e.g., the Torpedo Data Computer) followed by electronic computers (e.g., ENIAC). Therefore, this knowledge integration process ultimately resulted in the establishment of CS as a new separate discipline.

Other classification schemes have also differentiated forms of disciplinary interactions, broadly referred as Interdisciplinarity (ID)—which have a greater degree of subtleties and complexities. An early example, presented by Heckhausen in a OECD conference (1972), is the categorization of ID according to the maturation of the disciplines involved. He defined *indiscriminate ID* as an encyclopedic form in which the individual is familiar with multiple disciplines. As an example, he cited the *studium generale* of the German vocational training which prepared workers to handle a variety of problems with "enlightened common sense" and exposure to different disciplines during their professional education. A second form of disciplinary interaction, *pseudo ID*, occurs in disciplines that share analytical tools. *Composite ID* refers to the use of complementary skills and methods to address complex problems or to achieve a shared goal. If the employment of such skills and methods does not result in a significant change of the disciplines involved, the relationship is *auxiliary*; if instead, an enduring dependence of skills and methods develops, the relationship becomes *supplementary*. Finally, *unified ID* occurs when the skills and methods become part of the disciplines involved.

Boden (1997) defined six categories of disciplinary integration according its strength: *encyclopedic ID*, *contextualizing ID*, *shared ID*, *cooperative ID*, *generalizing ID* and *integrated ID*. She designated *encyclopedic ID* as an enterprise covering many disciplines within a wide range but with no need for exchange between them. In this kind of interdisciplinarity, the researchers do not consult any of the disciplines available except their own. In *contextualizing ID* the researcher takes other disciplines into account, but without active co-operation with those disciplines. As an example she cites the engineering profession's effort to include social contexts of practice. In *shared ID*, Boden designates different aspects of a complex problem as being tackled by different groups with complementary skills. Their results are communicated and the overall progress is monitored. However, this approach does not involve daily cooperation. In contrast, *cooperative ID* entails several groups with complementary skills cooperating actively to work towards a common goal. Consequently, researchers in a particular discipline may find their methods and theoretical concepts modified as a result of this cooperation. *Generalizing ID* occurs when a single theoretical perspective is applied to a wide range of previously distinct disciplines. Cybernetics is an example of it, as it is a discipline that not only involved cooperation of experts from many disciplines (mathematics, control-engineering, CS, physiology, psychology, anthropology, sociology), but also represents a concerted effort to apply the same theoretical approach to all of them. The highest level of the genus interdisciplinarity is *integrated ID*, in which some of the concepts and insights of one discipline contribute to the problems and theories of another (preferably being a mutually applicable process). This not only modifies original methods and theories of the disciplines involved, but also fosters new concepts and unifies methodologies. For Boden, this is "the only true interdisciplinarity", and also the rarest.

Yet another perspective to categorize forms of interdisciplinarity is proposed by Karlqvist (1999), and is based on the distance between fields which he categorizes into 5 modes. *Mode 1* is defined as the *unification of knowledge*. This occurs when two theories from different disciplines are different manifestations of the same underlying structure. Given such a relationship, the two theories can be subsumed under a new theory, new methods may be developed, producing eventually a new discipline. *Mode 2* is referred to as *accumulation of knowledge*. This occurs when knowledge from different disciplines is added to solve a common problem rather than interrelating aspects from various disciplines which share a common set of underlying principles. This mode is analogous to multidisciplinarity as it describes the situation where experts from different disciplines contribute without interfering or challenging each other's theories and methods. The disciplines involved in *Mode 3* are less compatible than in the previous modes. This mode is referred to as *doing different things*, and these "different things" cannot be combined without an additional framework that enables the integration of such disciplines to become meaningful. In

Mode 4, *doing things differently*, describes a combination of disciplines with not only disparate theories, but also with distinct basic underlying assumptions and paradigmatic bases for theories. Karlqvist presents the example of a project between natural scientists and social scientists where mechanistic models are placed against behavioral ones. The largest gap between disciplines is illustrated by *Mode 5*: *thinking differently*. In this case, the theories and methods and different; additionally, fundamental interpretative and conceptual differences also exist. According to Karlqvist, knowledge can no longer be combined and must be treated as complementary.

The typologies described above constitute important contributions to the definition of interdisciplinarity and the categorization of its forms. For the completeness of this literature review, further typologies are summarized in Table 2.1.

Table 2.1: Further categorizations of IDR according to the degrees of disciplinarity and integration.

Author	**Rationale for categorization**	**Categories**
R. C. Miller, 1982	Degree of conceptual order	Topical focus, professional preparation, life experience perspective, shared components, cross-cutting organizing principles, hybrids, grand synthesis
Stember, 1991	Responses to dissatisfaction with disciplines	Intradisciplinarity, cross-disciplinarity, multidisciplinarity, interdisciplinarity, transdisciplinarity

2.1.2 Interdisciplinary Practices

Several practice-based categorizations of interdisciplinarity have been discussed in the literature. Lattuca (2003) investigated forms of interdisciplinarity grounded in the work of faculty members who conduct interdisciplinary scholarship. Through the examination of their explicit and implied definitions of interdisciplinarity she identified four forms: *informed disciplinarity*, *synthetic ID*, *transdisciplinarity* and *conceptual ID*. Lattuca describes *informed disciplinarity* as a single-disciplinary enterprise and therefore, motivated by a single-disciplinary question. However, the researcher makes use of examples from other disciplines to facilitate the understanding of connections with other disciplines. The research question may also be informed by concepts of theories from other disciplines, but these contributions are made in the service of a single-disciplinary question. The second type of interdisciplinarity, *synthetic ID*, occurs when the research question bridges two or more disciplines but the contributions to the individual disciplines are still identifiable.

She defines *transdisciplinarity* as the application of theories, concepts or methods across disciplines with the aim of developing an overarching synthesis. This practice differs from *informed disciplinarity* and *synthetic ID* in that the theories, concepts, or methods are not borrowed and applied from one discipline to the other, but rather, they transcend the disciplines involved which become subordinate to a larger framework. The last category of Lattuca's typology is *conceptual ID*. In this form of interdisciplinarity research, questions are not grounded on a compelling disciplinary basis, and can only be answered by using a variety of disciplines.

Alternatively, Lengwiller (2006) proposes a typology of interdisciplinarity based on a study of research practices—namely, the underlying organizational structures and cognitive factors. In the latter, he defines *cognitive coupling* as the mutual dependence between the different disciplines involved in IDR. He distinguishes four forms of interdisciplinarity: *methodological ID*, *charismatic ID*, *heuristic ID* and *pragmatic ID*. *Methodological ID* occurs in organizations with a highly formalized structure of institutes and a consistent methodological and theoretical framework, leading to a tight cognitive coupling within interdisciplinary cooperations. Conversely, *charismatic ID* is found in institutes with a decentralized structure lacking the organizational elements necessary for fostering interdisciplinary cooperation. As with *methodological ID*, cognitive coupling is also high in *charismatic ID*, although in the latter, researchers rely on personal contacts and informal networks to establish interdisciplinary projects rather than on the structure of their institutes. The third form of interdisciplinarity, *heuristic ID*, occurs in applied and contract research projects subject to time pressure and budget constraints. These are projects in which the methodological approach and the expected results vary according to the source of funding and customer expectations. Since researchers need to adapt their methodological approaches accordingly, the cognitive coupling of *heuristic ID* tends to be weak. Finally, *pragmatic ID* is characterized by low organizational support for interdisciplinarity, and low interest in (or even opposition to) methodological and theoretical integrations with other disciplines. The reason for engaging in interdisciplinary cooperation are mainly external or pragmatic, such as the need to fulfill the requirements of funding institutions. Lengwiller describes *pragmatic ID* as the most fragile of the four research types.

Further typologies based on research practices are summarized in Table 2.2.

2.1.3 Rationales of Interdisciplinarity

A third typology regards interdisciplinarity as purposeful. Its categorization is based on the reasons that prompt researchers to combine of knowledge and modes of thinking that stem from various disciplines.

The work of Mansilla (2006) follows this line of analysis. She investigated how researchers integrate disciplinary perspectives for the advancement of their work, and identified three epistemological approaches to interdisciplinary inquiry: *conceptual bridging*, *comprehensive* and *pragmatic*. A *conceptual bridging* approach examines single concepts,

Table 2.2: Further categorizations of IDR according to interdisciplinary practices.

Author	**Rationale for categorization**	**Categories**
Rossini and Porter, 1979	Socio-cognitive frameworks for integration	Common group learning, modeling, negotiation among experts, integration by leader
Lenoir et al., 2000	Social representations of ID	Eclecticism, pseudo-ID, hegemony, holism
Palmer, 2001	Cognitive strategies for ID	Team leader, collaborator, generalist
Bruun, Hukkinen, et al., 2005	Interactions between fields	Encyclopedic, contextualizing, composite, empirical, methodological, theoretical
Bruun, Langlais, et al., 2005	Knowledge networking	Modular, translational, pioneering

principles, or mechanisms that can account for phenomena studied within a broad variety of disciplines. An example of *conceptual bridging* is the different use of network behavior in diverse fields such as biology (e.g., metabolic networks), electrical engineering (e.g., power grids) or neurobiology (e.g., neural networks). Mansilla describes the integration mechanism of *conceptual bridging* as a process in which the cross-disciplinary analogies are established, and knowledge from one field is translated to inform the other field. A *comprehensive* approach to IDR occurs when perspectives of the same phenomenon are studied by different disciplines. In this case, the disciplinary perspectives are interwoven to account for the phenomenon in full complexity. The integration mechanism consists firstly in defining the dimensions of the problem, then reformulating of findings of one discipline as hypothesis for further exploration in another, and finally, integrating their insights. Mansilla refers to the third approach as *pragmatic*. This is an outcome-centered approach, in which the choice of the disciplines to be integrated is strategic; it depends on the envision of an effective solution to a problem. The integration mechanism comes into play when researchers have a clear sense of the desired outcome, which informs the selection of the participating disciplines. Theories, concepts and methods from the different disciplines are borrowed in order to produce a solution—one which is assessed against standards of relevance, viability, and effectiveness.

Barry et al. (2008) outline three distinctive motivations for IDR and refer to these as *logics of interdisciplinarity*. They are: *accountability*, *innovation* and *ontological change*. The first logic, *accountability*, is where interdisciplinarity is guided by the idea that it helps to audit and legitimize scientific results. An example of this logic would be the incorporation of the social sciences in natural science projects in order to monitor and advise on investigations involving human subjects. The second logic, *innovation*, is exemplified by Barry et al. by the use of ethnography (a systematic study of people and cultures) in the development of technological artifacts in order to capture the "unarticulated desires" of the users. The third logic, *ontological change*, refers to a shift on the grounds of what a project or discipline is or can be. This change is represented by the aims of re-conceiving the object of research and the relations between disciplines. Although Barry et al. acknowledge that the three logics are neither autonomous nor exhaustive, their work aims to question the idea that interdisciplinarity should be portrayed exclusively in terms of the synthesis of disciplines.

A summary of further categorizations of interdisciplinarity according to the rationales of interdisciplinarity can be found in Table 2.3.

Table 2.3: Further categorizations of IDR according to the rationales of interdisciplinarity.

Author	**Rationale for categorization**	**Categories**
OECD, 1982	Demands for ID	Endogenous ID, exogenous ID
Klein, 1985	Motives for ID	Instrumental ID, conceptual ID
Bruun, Hukkinen, et al., 2005	Types of research goals	Epistemological ID, instrumental ID, mixed goals

2.1.4 Conclusion

Although academics' definitions of interdisciplinary differ, the distinction between multi-disciplinarity as a juxtaposition of disciplinary components, and interdisciplinarity as a more synthetic approach of knowledge integration, has been the most influential typology. As can be observed from the review of typologies presented in this section, the term "interdisciplinarity" not only has this specific meaning, but is also used a generic word to describe all activities that juxtapose, apply, combine, synthesize, integrate or transcend two or more disciplines (Huutoniemi et al., 2010; R. C. Miller, 1982).

2.2 Analyses of Interdisciplinarity: Measuring, Understanding and Assessing

This section explains the various methods utilized for analyzing IDR. Depending on the purpose of the analysis, different methods may be employed. We distinguish three purposes: (i) measurement, as a quantification of the degree of research interdisciplinarity; (ii) understanding, as a comprehension of the phenomenon of interdisciplinary; and (iii) assessment, as an evaluation of interdisciplinarity which can be both qualitative and quantitative.

2.2.1 Measuring Interdisciplinarity

The literature on measuring IDR examines interdisciplinarity based on different professional facets such as (i) teaching, e.g., cross-departmental, co-teaching (Haines et al., 2011); (ii) collaborations, e.g., projects with experts from other disciplines (Karlovčec and Mladenić, 2015; Mâsse et al., 2008; Wagner, 2005); and (iii) scientific writing, e.g., publications, research proposals (Mutz et al., 2015; Porter and Chubin, 1985; Rinia et al., 2002). The most common approach is the analysis of publication data, also known as bibliometrics. This approach is based on the widely-held view that the publication of research findings is one of the main activities of the scientific research process.

Bibliometric Approaches

Bibliometric-based measures of interdisciplinarity can be classified according to two main criteria: (i) their approach to locate units of analysis (e.g., publications) in the global map of science, and (ii) their definition of what indicates an interdisciplinary activity (e.g., researcher collaboration, references to other disciplines).

Regarding the first criterion, two main kind of approaches exist: *top-down* and *bottom-up*. The top-down approach, also called classification-based or structural approach, relies on a pre-defined taxonomy of disciplines which is used to categorize the units of analysis. Since there is no consensus on a list of disciplines that accurately describes the landscape of knowledge and science, this approach is biased by the use of different taxonomies (National Research Council, 2010; Rafols and Leydesdorff, 2009). Instead, the categorization of units of analysis in the bottom-up approach is based on clusters formed during their analysis (e.g., co-authorship networks, co-citation clusters). These clusters can be studied with statistical methods and visualized with graphs to provide an insight into their structure. While the latter is ideal for capturing emerging developments and innovative lines of research that do not fit into the current taxonomy of disciplines, top-down approaches are especially useful at large-scale explorations, such as the disciplinary breadth of universities (Wagner et al., 2011).

With regards to indicators of IDR, two main types of approaches can be distinguished: *citation-based* and *non-citation-based* analyses. Citation analysis is the most accepted method for measuring the interdisciplinarity of scientific output. Within this method, an exchange or integration between fields is revealed by discipline-specific citations pointing to other fields. According to Rafols and Meyer (2010), the percentage of citations outside the discipline of the citing paper is the most common indicator of IDR. This is suggested in the earliest work of Garfield et al. (1978) and is the basis of more sophisticated measures of IDR—which are described later in this section. Alternatively, non-citation based analyses are grounded on other information contained in publications, such as co-authorship, affiliations and text.

The approaches described above and their most important methods are presented in Table 2.4. In the following each method is explained in detail.

Table 2.4: Overview of bibliometric approaches to evaluate research interdisciplinarity.

		INDICATORS	
		Non-citation based	**Citation-based**
APPROACHES	**Bottom-up**	Co-authorship and affiliation Co-words	Bibliometric coupling Author bibliometric coupling Co-citation Author co-citation
	Top-down	Networks of publications' disciplines	Networks of citations' disciplines Shannon index Simpson index Gini index Rao-Stirling diversity index

Co-authorship and Affiliation Analysis has been employed to quantify collaboration through counts of co-occurrences of disciplinary affiliations, as well as to explore scientific collaboration with social network methods. This method assumes that the disciplinary affiliations of the co-authors constitute an indicator of which disciplines are integrated in the document. Although methods based on co-authorship and affiliation have been used to analyze interdisciplinarity (Schummer, 2004), it is infrequently used and increasingly regarded to be invalid, as noted by Katz and Martin (1997), as well as Lundberg et al. (2006). This is due to the fact that institutions do not always fit the concept of disciplines and the affiliation of an individual does not necessarily reflect his/her disciplinary field; researchers often have expertise in fields different to the main research focus of their department. For example, they might be no longer working in the research field in which they took their degree. Moreover, the co-authorship analyses require a more complicated process of data collection because affiliation data is not provided in the citation information of publications. It needs to be collected directly from the manuscripts. This reduces the usefulness of this method as an IDR indicator for large number of publications (Wagner et al., 2011).

Co-word Analysis is a bibliometric technique that is not based on citation relationships or a taxonomy of disciplines. It is used to create a map of knowledge that describes the development of science. It is based on the assumption that a document's words, keywords or phrases constitute an adequate description of its content. The co-occurrence of pairs of such items within the same document is an indication of a link between the subjects to which they refer (Cambrosio et al., 1993). Indices based on the co-occurrence of items are used to measure the strength of the relationships between items. Examples of indices are inclusion, proximity, density and centrality. Based on these indices, items are clustered into groups and displayed in network maps that represent the structure of the concepts mentioned in the documents. For instance, an inclusion map is used to highlight the central subjects in a domain, a proximity map reveals the connections between areas, while density and centrality maps are employed to evaluate the shape of each map, showing the degree to which each subject is centrally structured and the extent to which each subject is central to others (He, 1999). A time-series of such maps describes the evolution of subjects in the map of science.

The co-word analysis method was first developed during the 1980s in a collaboration between the Centre de Sociologie de l'Innovation of the École Nationale Superiore des Mines of Paris and CNRS (Centre National de la Recherche Scientifique) in France. A few years later the book *Mapping the Dynamics of Science and Technology* (Gravetter and Forzano, 2011) introduced the theoretical foundation of co-word analysis and provided examples of its use. Since the publishing of this book, co-word has spread and improved. Co-word analysis offers more perspectives on the data through the different indices and provides varying degrees of granularity: from the analysis of single co-word traces, to the overview of the overall structure of the co-work network using graph visualization. The main limitation of this method is that it has no information on the disciplines of the items. Since items are not associated to disciplines, this method is not adequate for a quantitative evaluation of the integration of disciplines in a document or a set of documents. Instead, it provides a description of the linkages among subjects mentioned in a bibliographic dataset.

Bibliographic Coupling aims to provide a similarity measure between documents, for which it utilizes citation analysis. Bibliographic coupling occurs when two documents reference a common third in their list of references (see Figure 2.2). The strength of the coupling is higher the more citations they share to other documents.

The concept of bibliographic coupling was introduced by Kessler (1963), who demonstrated the existence of the phenomenon and argued for its usefulness as an indicator of subject relatedness. Soon after, Martyn (1964) stated the major theoretical criticism of this method: it does not guarantee that two coupled documents cite the same piece of information in the third document. He also observed that even if two coupled documents (A and B) cite the same information in the third document (E), the size of that conjunction remains unknown. If in addition to such three documents (A, B and E) another two coupled documents (M and N) also reference the same third document (C), the conjunction of both pairs (A-B and M-N) might not be the same. These observations were empirically supported in a validation study of Vladutz and Cook (1984). As a consequence, the results of this method should only be regarded as an indication that there is a certain probability that the two or more documents treat a related subject matter. A characteristic of bibliographic coupling is that it is a retrospective similarity measure in the sense that the information used to establish the similarity relationship between two documents lies in the past and is static (i.e., bibliographic coupling strength cannot change over time since outgoing citation counts are fixed). Such a characteristic is useful in finding related research carried out in the past, and it has been used to examine relations between

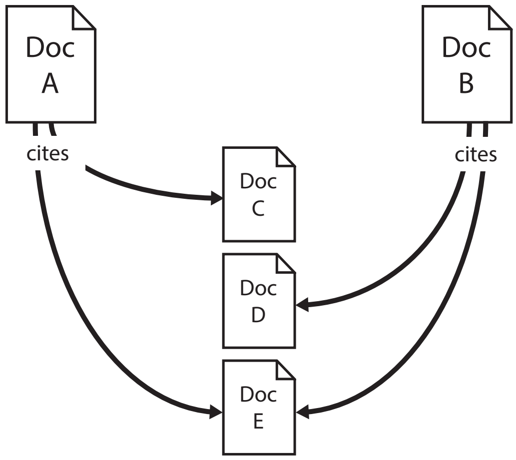

Figure 2.2: Documents A and B are bibliographically coupled through document E, but not through documents C and E.

disciplines and identify research specialties (Rafols and Meyer, 2010).

Author Bibliographic Coupling was proposed by Zhao and Strotmann (2008) as an extension of the work of Kessler (1963) on bibliographic coupling. Authors are bibliographically coupled if the cumulative reference lists of their respective works contain a reference to a common document. Their coupling strength also increases with a higher number of shared citations to other documents. Similar to bibliographic coupling, the result of author bibliographic coupling indicates a probability that two or more authors work on related topics.

Co-citation Analysis is a variation on bibliographic coupling that also measures similarity between documents. Two documents are said to be co-cited if they appear simultaneously in the reference list of a third document (see Figure 2.3). Co-citation frequency is defined as the frequency with which two documents are cited together by other documents (Small, 1973). The more co-citations two documents receive, the higher co-citation strength, and the more likely they are semantically.

Co-citation analysis, introduced by Small (1973) and Marshakova (1973), addresses the above-mentioned characteristic of bibliometric coupling as being a retrospective similarity measure. The main difference is that similarity is assessed based on incoming citations, the frequencies of which change over time according to the evolution of the academic field. However, the limitations of bibliographic coupling also apply to co-citation analysis (J. R. Cole, S. Cole, et al., 1974).

An improvement of co-citation analysis was proposed by Gipp and Beel (2009): co-citation

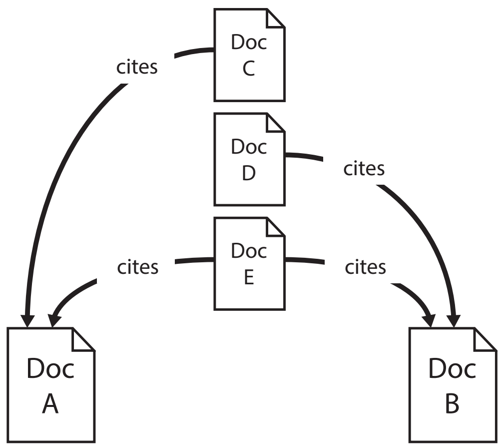

Figure 2.3: Documents A and B are co-cited by document E, but not by documents C and D.

proximity analysis. This method assumes that within a document's full-text, citations in close proximity to each other have a greater tendency to exhibit a stronger similarity than those cited further apart. This approach has the same limitations as co-citation analysis, but allows a more granular classification of related documents.

Author Co-citation Analysis uses authors as the main unit of analysis and the co-citation of pairs of authors (the frequency they are cited by a third party) as the variable that indicates their "distance" from each other. This approach was introduced by White and Griffith (1981) with the underlying assumption that the more often a pair of authors is cited together, the closer the relationship between them.

This method is useful in identifying influential authors and displaying their interrelationships from the citation records using graph visualization techniques. However, it has the same limitations as the other co-citation methods described above.

Networks with a Taxonomy of Disciplines. Some studies build on both top-down and bottom-up approaches to increase the descriptive power of their analysis. They combine networks and clusters obtained with bottom-up approaches such as citation and co-authorship networks with a pre-defined taxonomy of disciplines. While bottom-up approaches are more accurate for describing direct knowledge flows or explicit relations, they cannot capture the position of local elements in the global map of science. Therefore, they miss the large-scale perspective of the integration process. When combined with a taxonomy of disciplines, the visualization of diversity and interdisciplinary relationship are significantly improved.

The use of a taxonomy of disciplines with a bottom-up approach is possible for both citation-based and non-citation based methods. An example of the combination of bottom-up citation-based methods with a taxonomy of discipline is the work of Rafols and Meyer (Rafols and Meyer, 2010). They combine the use of a taxonomy of disciplines with bibliographic coupling to analyze individual publications in the same field in an attempt to illustrate different aspects of interdisciplinarity. A combination of taxonomies of disciplines with co-citation networks was performed by Leydesdorff et al. (2013) who visualized global maps of science based on the taxonomy of disciplines provided by the Web of Science (WoS). The purpose was to identify the disciplinary structure of scientific articles indexed by WoS. An example of the use of taxonomies with non-citation-based methods can be represented by Taşkın and Aydinoglu's work (2015) on the research interdisciplinarity of a NASA research institute. They used social network analysis on a set of publications, where each publication was categorized with one or more disciplines of the taxonomy of the WoS. They created a network where each node represented a discipline. Links between nodes were formed if two disciplines were used to categorize the same publication.

Diversity Indices are compound measures that aggregate multiple indicators of interdisciplinarity. Indices are useful to quantify the interdisciplinary of publications, as well as researchers and institutions, by aggregating the results of the index over their publications or members. In this thesis, a diversity index is utilized to quantify the integration of disciplines in the publications of doctoral researchers. Formalizations and definitions of diversity indices are described in detail below.

In order to quantify the diversity of a dataset, two main characteristics have to be taken into account: (i) the number R of possible disciplines to which the dataset's items can assigned; and (ii) how evenly the items are distributed among the disciplines. The latter can be conveniently quantified in terms of proportions, which yield the relative amount p_i of items that belong to discipline i and which satisfy $\sum_i p_i = 1$. A good diversity measure should increase with both the number of disciplines and with increased evenness of the individual proportions.

When placing all emphasis on the first or the second of the two characteristics, the following simple diversity measures can be utilized: (i) the number R of possible disciplines itself; and (ii) the inverse of the largest proportion among all disciplines, which encodes the largest deviation from complete evenness (characterized by uniform proportions for all disciplines). In practice, such simple measures are unsuitable since they focus on only a single aspect of the dataset's diversity. A more comprehensive measure, which takes all characteristics of the dataset into account, is highly preferable.

Indeed, there exists a family of diversity indices ${}^qD$ that provides a parameter q which smoothly interpolates between the two aforementioned characteristics. This is also referred to as *true diversity*, formally expressed as

$$ {}^qD = \left(\sum_{i=1}^{R} p_i^q \right)^{\frac{1}{1-q}} \tag{2.1} $$

where the edge cases ${}^0D = R$ and ${}^\infty D = (\max_i p_i)^{-1}$ can be obtained by choosing the corresponding values $q = 0$ and $q = \infty$ for the parameter (Hill, 1973; Jost, 2006). The latter was utilized by Berger and Parker (1970) in ecological studies . Note that $1 \leq {}^qD \leq R$ for all q and all p_i. In practice however, an intermediate value for q is generally chosen. Consequently, there is a multitude of diversity indices that have been proposed throughout the years and most of them are variants of ${}^qD$ for the values $q = 1$ and $q = 2$. In the following, an overview is provided.

Already in 1949, the *Simpson index* λ—named after its creator —was proposed to measure the degree of concentration when categorizing persons (Simpson, 1949), and expressed as

$$\lambda = \frac{1}{{}^2D} = \sum_{i=1}^{R} p_i^2.$$

This was independently proposed by Herfindahl (1950) and Hirschman (1945) (originally as $\sqrt{\lambda}$) in the field of economics; it is also referred to as the *Herfindahl-Hirschman Index (HHI)* index, used to describe the size of enterprises in comparison to the industry. Since the actual numeric value of the Simpson index decreases with increasing diversity, simple corrections were proposed in order to generate more intuitive results. Among them are the *inverse Simpson index* $\lambda^{-1} = {}^2D$ and the *Gini-Simpson index* $1 - \lambda = 1 - {}^2D^{-1}$.

The most prominent diversity index in CS is the *Shannon entropy* H, given by

$$H = \log\left({}^1D\right) = -\sum_{i=1}^{R} p_i \log p_i,$$

which was used by Claude Shannon (1948) in his seminal work that founded the field of information theory, where the entropy was used to quantify uncertainties regarding information transfer during communication. This approach was later generalized by Rényi (1961) to a parametrized family ${}^qH$ of entropies, mirroring the true diversities, and given as

$${}^qH = \log\left({}^qD\right).$$

Prominent examples include: the *Hartley entropy* ${}^0H$ (mirroring the cardinality) (Hartley, 1928), the *collision* (or *Rényi*) *entropy* ${}^2H$ (mirroring the inverse Simpson index), and the *min-entropy* ${}^\infty H$ (mirroring the Berger-Parker index).

To illustrate the qualitative behavior of different diversity indices, their application to a simple test case is shown in Figure 2.4. For a dataset with two disciplines, the corresponding proportions of items in disciplines one and two are given by p_1 and $p_2 = 1 - p_1$. The diversity values for the true diversity indices with parameter $q = 0, 1, 2, \infty$ as well as a rescaled version of the Gini-Simpson index $1 - \lambda$, which maps its value range linearly from $[0, 1 - R^{-1}]$ to $[1, R]$, are shown. As required, all diversity indices assume their maximum value of $\frac{1}{2}$ for an even distribution of the items (i.e., $p_1 = p_2 = \frac{1}{2}$). Apart from the cardinality index ${}^0D$, rather similar behavior can be observed in the true diversity indices with $q \geq 1$ and the rescaled Gini-Simpson index.

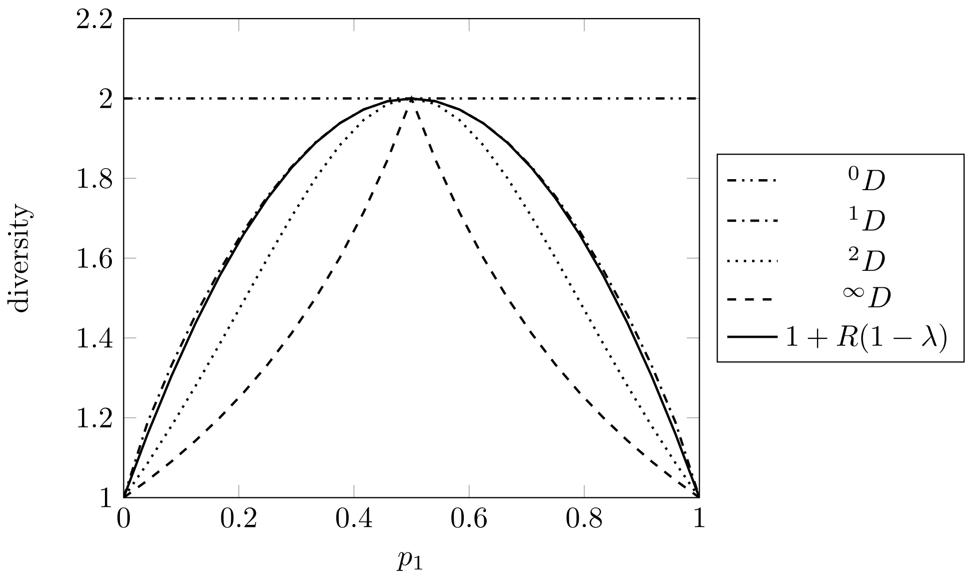

Figure 2.4: Comparison of different diversity measures. Five diversity indices are plotted for a dataset with two disciplines over the proportion p_1 of the first discipline. Consequently the proportion of the second discipline p_2 is given by $1 - p_1$.

In our work (see Chapter 5), we employ a modified version of the Gini-Simpson index – the *Rao-Stirling diversity index* (Porter and Rafols, 2009; Stirling, 2007). It augments the index by taking into account the actual similarity between the different disciplines. Therefore, a publication that integrates two disparate disciplines (e.g., CS and zoology) will have a higher diversity index than one that integrates more similar disciplines (e.g., CS and engineering). In order to achieve this, the index relies on a specific metric of distances (or similarities) between pairs of disciplines. The Gini-Simpson index can be interpreted as a special case of the Rao-Stirling diversity index where all disciplines are completely dissimilar. This can be seen by the fact that the maximal diversity is reported for even proportions. In the case where all but one discipline are so similar as to be considered identical, the maximal diversity will not be achieved by having the same amount of items in each discipline; whereas having half the items in the dissimilar discipline will yield a higher diversity. Formally, this is realized with a similarity matrix s_{ij}, which encodes the similarities between the disciplines i and j, where $0 \leq s_{ij} \leq 1$ and $s_{ii} = 1$. Thus, the Gini-Simpson index

$$1 - \lambda = 1 - \sum_{i=1}^{R} p_i \, p_i = 1 - \sum_{\substack{i=1 \\ j=1}}^{R} p_i \, \delta_{ij} \, p_j$$

with the Kronecker delta

$$\delta_{ij} = \begin{cases} 1 & \text{if } i = j \\ 0 & \text{otherwise} \end{cases}$$

becomes the Rao-Stirling diversity index I given by

$$I = 1 - \sum_{\substack{i=1 \\ j=1}}^{R} p_i \, s_{ij} \, p_j.$$

For its detailed description we refer to Section 5.2.

Limitations of Bibliometric Methods

The literature reviewed in the section takes different approaches to measure and evaluate interdisciplinarity, though all of them exhibit different limitations Those methods analyzing IDR as a teaming process (i.e., co-authorship and affiliation) employ measures that reflect the underlying social dynamics and fail to grasp the integration of disciplines in the content of publications. Although cross-disciplinary collaboration may take place in some IDR endeavors, it is not a prerequisite for all IDR projects. Although citation analysis does not presume interdisciplinary collaboration, it is, in its several forms, the most accepted basis to develop measures of IDR. In the application of these methods and the interpretation of their results, one needs to take into account the shortcomings of each bibliometric method.

Within citation analyses, the use of a predefined taxonomy of disciplines is useful for measuring IDR with diversity indices and for enhancing map visualization of large areas of science. Nevertheless, the use of a given scheme to categorize publications into disciplines is problematic because of the lack of consensus on an adequate categorization. As a result, measures of interdisciplinarity yield different results depending on the classification system chosen for analysis.

Existing bibliographic databases also have limitations that raise questions about their use for evaluating IDR. Bibliometric studies assume that the most important research studies form part of the international literature published in academic journals. While this assumption might apply to the physical and medical sciences, some fields of science mainly publish in conferences (as in the case of CS), books, book chapters and regional non-English journals, in which authors from the social sciences, humanities, and some technical fields publish. Therefore, the literature indexed by bibliographic databases is not evenly distributed over the fields of science.

Such limitations affect the accuracy of the results of bibliometric analyses, which should be interpreted as proxy indicators of interdisciplinarity. Moreover, the exclusive use of bibliometrics for the analysis of interdisciplinarity is itself a major limitation. The dynamic processes involved in IDR that also operate at other levels, such as social or cognitive, are difficult to grasp by the sole utilization of bibliometric methods (Wagner et al., 2011).

2.2.2 Understanding Interdisciplinarity

A challenge to assessing interdisciplinarity is the multiple ways interdisciplinary interactions can be conceived. Bibliometric approaches analyze the interdisciplinarity content of the work itself, however, they cannot properly identify research that is interdisciplinary in an epistemological or cognitive sense, let alone differentiate the various types of interdisciplinarity (Huutoniemi et al., 2010). In order to perform a rigorous assessment of interdisciplinarity, methods alternative to bibliometrics are required. These are mainly qualitative methods, mostly interviews but also focus groups and case studies. These methods delve deeply into the individuals, settings, culture and context in order to generate an understanding of interdisciplinarity, from the accounts of a representative number of people. Although quantitative methods allow for the gathering of opinions from a considerably higher number of participants, they are generally not employed to understand interdisciplinarity because they capture a shallow band of information.

An important difference between studies that aim to measure interdisciplinarity and those that aim to understand it, is the stronger reliance of the latter on a conceptual or theoretical framework. Such framework is not just a literature review. Instead, it provides an outline of the theory or hypotheses underpinning the study. It dwells on tested theories that embody the findings of numerous investigations on how phenomena occur, and offers a general representation of relationships between elements in a given phenomenon. Examples of theoretical frameworks often used in the analysis of interdisciplinarity are *professional socialization* and *sociocultural perspectives*.

Professional socialization refers to the process in which individuals learn the cultural norms, language, and behaviors of a community (Tinto, 1997; Weidman and Stein, 2003). Doctoral researchers engage in one or more academic communities through the process of socialization, developing their academic identity (Atkinson and Parry, 2000). Example of mechanisms that aim to facilitate doctoral socialization are the formal curriculum, which offers a normative perspective of the discipline (e.g., to master methods and theories), and the engagement with other scholars (e.g., to learn the language and behaviors). Socialization at the doctoral level is useful for the investigation of various processes, including socialization to the discipline, the profession and the role of doctoral researcher (Golde, 1998). Nevertheless, it is criticized as a rigid top-down approach that regards the individual as recipient of information without taking into consideration what the individual contributes to the process. Furthermore, it ignores the larger context in which the development of the individual takes place (Nerad, 2012).

Conversely, sociocultural perspectives emphasize the interdependence of social and individual processes in the construction of knowledge. This framework is used to describe the individual's awareness of the circumstances of the context and how the behavior is affected by the surrounding, social and cultural factors (Lattuca, 2002). In contrast to professional socialization, sociocultural perspectives extend the understanding of context by including not only the immediate context (e.g., the task of learning a specific concept), but also the larger contexts (the social, cultural settings where the learning takes place). Sociocultural perspectives also highlight the importance of understanding relationships within the context of the particular situations in which individuals find themselves. Moreover, it is utilized to understand doctoral researchers' engagement in formative practices with respect to their personal intentions (Hopwood, 2010). This is the framework used in this study (see Chapter 6).

2.2.3 Assessing Interdisciplinarity

Assessment in higher education has been receiving ever-increasing attention over the past three decades. This has been motivated by the widespread view that teaching and researching can be informed and improved with insights on educational processes and outcomes (Astin, 1985; Ewell, 1984). More recently, concern about accountability (Ewell, 1991) has led to a growing array of quality measurement tools. Today, the field of assessment in higher education is characterized by its multiplicity of purposes, approaches, units of analysis, and stakeholders (Boix Mansilla and Duraisingh, 2007). This broad array can also be applied to the assessment of interdisciplinary education and research.

Assessments of interdisciplinarity have been conducted with quite diverse focuses and goals. The qualities, processes, and influence of coursework and teaching programs (Crisp and Muir, 2012; Misra et al., 2009), research mentoring (Lyall and Meagher, 2012) and initiatives to facilitate doctoral researchers' interdisciplinarity such as collaborative learning (Miles and Rainbird, 2015), have been analyzed to inform teaching and provide learning support. Other focuses include the certification of interdisciplinary research centers and programs (Eckstein et al., 2006), as well as the review of research policies (Bruce et al., 2004; Winskel et al., 2014).

Given the variety of purposes of interdisciplinary assessments, it is natural that different approaches, both qualitative and quantitative, should be utilized. Mitrany and Stokols (Mitrany and Stokols, 2005) present two main methodological strategies for evaluating the transdisciplinary qualities and outcomes of doctoral training programs and dissertations. On the one hand, process measures include self-reports of the influence of coursework, research mentorship and scholarly exchanges along with one's intellectual values, attitudes and behaviors. On the other hand, product measures include external, objective appraisals of the transdisciplinary qualities of published papers, theses and dissertations. One method is the use of surveys (Crisp and Muir, 2012; Millar, 2013; Winskel et al., 2014) which has been used to examine both processes and products. Bibliometric methods have been used to quantitatively assess the extent of the interdisciplinarity of publications of research centers and programs (Amir, 1985; Cassi et al., 2014). Another method based on scientific writing is proposed by Mitrany and Stokols (2005). They suggest a composite scale designed to measure the transdisciplinary qualities of doctoral dissertations. Their evaluation is carried out by independent reviewers that rate multiple dimensions of transdisciplinary integration and scope. In order to analyze processes, interviews as well as discussions and focus groups have been used to gain a deeper understanding of interdisciplinary experiences and processes (Boix Mansilla, 2006b; Boix Mansilla and Duraisingh, 2007). Moreover, both qualitative and quantitative methods have also been combined so as to obtain complementary insights. For instance, a study on the Fifth Framework Program of the European Community for Research (Bruce et al., 2004) combines the input of discussions in workshops, a questionnaire and the analysis of case studies. Another example is provided by the study on the promotion of interdisciplinarity by the Academy of Finland (Bruun, Hukkinen, et al., 2005), the assessment of which is based on a qualitative analysis of research proposals, a survey and interviews.

These methods are used to investigate different units of analysis from individuals to disciplinary communities/fields over groups of individuals and institutions. Therefore, assessments of interdisciplinarity might include a single kind of participant/respondent (e.g., doctoral researchers) or diverse stakeholders (e.g., academics, states, research funding agencies, directors, etc.). This wide range of different approaches in the literature about how to define indicators of interdisciplinarity is not unexpected. A substantive assessment of interdisciplinarity is shaped by the variability of the goals, indicators, actors, and available data.

2.2.4 Conclusion

In this section, the existing methods for measuring, understanding and evaluating IDR have been presented. Nonetheless, there is no convergence towards a single type of measure—each one has benefits and drawbacks for representing and measuring IDR (Wagner et al., 2011). The strengths of one method over another are relative to the purpose of the measurement. Therefore, differing needs require different data and analyses.

2.3 Analyses of Interdisciplinary Doctoral Education

This section presents higher education studies with a focus on doctoral interdisciplinarity, which is the topic of investigation of this thesis. Although the bibliometrics literature presents a wide range of measurements of interdisciplinarity in higher education institutions, a focus on doctoral level is uncommon. Assessments of the interdisciplinarity of doctoral programs are also infrequent in the literature, even if methodological strategies have been suggested (Mitrany and Stokols, 2005). Instead, the great majority of analyses of interdisciplinarity at the doctoral level aim to understand the characteristics and processes in interdisciplinary doctoral programs. Two major lines of research can be distinguished: one that investigates the purpose, organization, and content of interdisciplinary doctoral structures, and another that mainly focuses on how interdisciplinary doctoral researchers experience and engage with interdisciplinarity. In the following, the most relevant works from both lines of research are presented.

2.3.1 Interdisciplinary Doctoral Structures

Interdisciplinary doctoral programs implement an interdisciplinary curriculum and structure that move beyond the single-disciplinary focus to integrate various perspectives on a research area or a research question. The literature on interdisciplinary doctoral programs has mainly analyzed U.S. graduate schools in both traditional departments and interdisciplinary centers. The structure of such programs has been analyzed by Holley (2009) and Manathunga et al. (2006). Their work identified common characteristics of interdisciplinary doctoral schools: interdisciplinary courses, elective courses from different disciplines, rotation between research groups, seminar curricula, follow-up and evaluating committees. Their successful implementation is not simple (e.g., due to conflicting interests from scholars in different disciplines) and it does not necessarily ensure doctoral IDR (Holley, 2009).

Interdisciplinary programs normally include interdisciplinary courses in their curriculum. Their aim is to expose doctoral researchers to multiple and sometime conflicting perspectives and to encourage them to construct connections between various disciplinary fields. Such courses enable doctoral researchers to develop the understanding of high-order relationships and organizing principles of various disciplines (Ivanitskaya et al., 2002). However, their implementation might be challenging and contentious, as described by Holley (2009). These are typically first-year courses that aim to provide a broad understanding of basic concepts from different disciplines. Since the content of such a course is rather broad, the learning of each discipline is more superficial than in a dedicated single-disciplinary course. As a consequence, faculty members remained strongly divided over the content, structure and implementation of such courses.

Another curricular strategy of interdisciplinary doctoral programs includes elective courses from different disciplines. The electives are advanced courses on a particular subject. They serve to provide doctoral researchers with a range of deep exposure to diverse fields. Nevertheless, they conflict with the importance of the early immersion of doctoral researchers in the research activity. Similar to single-disciplinary doctoral researchers, interdisciplinary ones are also pressured to an early commitment to the work of a specific research agenda, which often eliminates connections to other related topics (Holley, 2009).

Doctoral researchers' rotations between research groups are an alternative approach for cultivating an integrated awareness of the field through research work. Such rotations are a common practice in science and technology disciplines, allowing doctoral researchers (i) to experience different research topics before committing to a permanent supervisor; (ii) to understand different disciplinary perspectives; and (iii) to interact with faculty members from multiple disciplinary backgrounds. This practice is time-demanding, and therefore, considered to have a negative impact in the pace of the overall development of doctoral researchers (Holley, 2009).

The only curricular initiative that the literature unanimously regards as having a positive influence on interdisciplinary training is seminar curricula (Graybill et al., 2006; Manathunga et al., 2006; Newswander and Borrego, 2009). Seminars are commonly implemented on a weekly basis and have the format of a discussion forum through which doctoral researchers, professors, and others, share interdisciplinary knowledge. These meetings provide opportunities for doctoral researchers to interact and learn from experts in different but related fields (Manathunga et al., 2006).

Specific policy practices characteristic of successful interdisciplinarity have also been identified in the literature, such as the intentional inclusion of both doctoral researchers and professors from different disciplinary backgrounds (Newswander and Borrego, 2009). On the one hand, during the recruiting process of doctoral researchers, it is essential to select the most engaged doctoral candidates who offer the most promising compatibility with the program. Since IDR is often problem-driven, it is important that doctoral researchers understand the importance of the research problem and are committed to its solution (Klein, 2001). On the other hand, it is crucial to involve professors with interdisciplinary research agendas rather than a single-disciplinary research focus. It is emphasized that both doctoral researchers and professors should be matched to the appropriate structure rather than forcing them to be more interdisciplinary than it naturally suits them (Newswander and Borrego, 2009).

Finally, previous studies agree on the need of locating adequate resources in order to support interdisciplinarity, not only for doctoral researchers but also for their supervisors and interdisciplinary projects. Resources might have different forms (e.g., funding, space) and can manifest in many ways (e.g., policies, organizational structures); however, the ultimate goal remains invariable: to facilitate and encourage IDR (Graybill et al., 2006; Holley, 2009; Nash, 2008; Newswander and Borrego, 2009).

2.3.2 Interdisciplinary Doctoral Experiences

The literature on the experiences of interdisciplinary doctoral researchers present two major groups of studies: one which focuses on the challenges of becoming an interdisciplinary scholar, and a second one that analyzes the identity and socialization processes of young researchers into interdisciplinary communities and research practice. Both groups are typically conducted by researchers external to the doctoral programs. A third, but uncommon kind of study is the examination of interdisciplinarity is provided by doctoral researchers themselves, who offer a first-hand reflection on their doctoral programs and experiences. In the following, we present an overview of these three types of studies.

Several authors agree that the disciplinary structure of the university ties doctoral researchers to a single home department, discipline and academic supervisor. Consequently, the traditional university structure is believed to constrain IDR. Golde and Gallager (1999) discuss the challenges that doctoral researchers who desire to undertake interdisciplinary work face in traditional programs. Some of these observations are also discussed in the work of Lyall and Meagher (2012), this time based on evaluations of a number of interdisciplinary studentship and fellowship schemes and with a focus on the development of interdisciplinary research skills in early career researchers. In order to counteract such challenges, Nash(2008) proposes a meta-training on IDR that helps doctoral researchers understand and navigate aspects and challenges that are unique to IDR. In addition to other considerations, this meta-training could cover aspects such as: (i) learning how to manage obstacles and capitalize the facilitators at institutional, program, and individual level; (ii) learning how to manage career-development; and (iii) the development of strategies to facilitate shifting in and out of disciplinary frameworks as well as working between frameworks that follow different paradigms.

A second major line of research investigates the socialization of interdisciplinary doctoral researchers in the academic community. A conclusion from several studies is that with the current educational structures, socialization into IDR develops from the practice of interdisciplinarity itself and relationships with other scholars, rather than on a slate of interdisciplinary doctoral courses (Gardner et al., 2014; Holley, 2015). The academic supervisor, as a master of the research practice, is therefore a person of great influence, if not the most influential, in developing doctoral interdisciplinarity. The conclusions of several studies corroborate the importance of the academic supervisor: although their research questions relate to doctoral researcher socialization, most conclusions relate to academic supervision (D. Boden et al., 2011; Gardner et al., 2014; Holley, 2015). For example, Boden et al. (2011) found the relationship between doctoral researchers and supervisors influential from the beginning. In many doctoral programs, interdisciplinary doctoral researchers are mainly integrated into their program through the relationship with the supervisor. Later, the doctoral researchers have the opportunity to be integrated into other communities again by their supervisors. However, they noted that some supervisors do not take into account the importance of building a stable interdisciplinary culture in which to socialize the doctoral researchers. In order to prevent the undermining of the interdisciplinary efforts of programs and policies, they suggest the participation of professors who are passionate about IDR.

Finally, two studies stand out in the literature where interdisciplinary doctoral researchers reflect on their own experiences and from their own perspective. One is written by doctoral researchers in an Australian program on health sciences (G. E. Carey and Smith, 2007). Their insights aim to inspire other doctoral researchers towards interdisciplinarity and to provoke reflection on the intellectual challenges they face. A second one was written by doctoral researchers of an Integrative Graduate Education and Research Traineeship (IGERT) [1] program in the field of urban ecology (Graybill et al., 2006). They reflect on their experiences and identified three stages of their intellectual development and the questions that arose from each stage: (i) *naissance* (where is my home?), (ii) *navigation* (what do I prioritize?), and (iii) *maturation* (how do I integrate and represent my scholarship?). Additionally, they provide recommendations for interdisciplinary doctoral researchers and programs.

[1] IGERT is a national U.S. American program initiated in 1997 by the National Science Foundation (NSF) to develop a new generation of interdisciplinary scientists and professionals.

2.3.3 Conclusion

The analyses of doctoral interdisciplinarity described in this section exclusively rely on qualitative data (i.e., interviews and focus groups). Combinations of quantitative measures and qualitative assessments are uncommon. Even more exceptional is the combination of bibliometrics and qualitative methods. As Wagner et al. (2011) state, such combinations carry burdens of expense, intrusion, and lack of reproducibility year-upon-year, but have the potential to be more revealing of the actual working processes and the outputs of IDR.

Studies that conduct qualitative analyses of interdisciplinarity are conducted on interdisciplinary programs with the assumption that interdisciplinary doctoral researchers are enrolled in such programs. While this could be a valid assumption, interdisciplinary doctoral researchers enrolled in traditional programs are left out of the analyses. Although the proportion of interdisciplinary doctoral researchers may be larger in interdisciplinary programs, traditional programs usually have a significantly higher total number of enrolled doctoral researchers. In the traditional program, however, the identification of interdisciplinary doctoral researchers among a large number of single-disciplinary researchers is more complicated. Sampling approaches, such as preliminary surveys or referral sampling (Holley, 2015), commonly known as snow-ball sampling, could be used but they lack definite information on whether or not the sample is an accurate reading of the target population. Instead, bibliometric methods of analysis provide a more accurate measurement of the doctoral researchers' interdisciplinarity, and could be utilized to identify potential participants in all programs. This is the approach followed in this thesis to analyze interdisciplinary factors, processes and patterns in both kind of programs.

An important gap in the higher education literature arises from the insufficient attention that European doctoral interdisciplinary has received. Previous literature is concerned mainly with analyses conducted in U.S. institutions, and to a lesser extent, in British and Australian institutions. It is desirable to place more attention on the European programs, especially taking into account the new structures, alternative to the traditional program, that have proliferated during the past decade in order to prepare interdisciplinary early career researchers (Kehm, 2006; Lindner and Taddei, 2007; Pechar and Thomas, 2004).

This thesis addresses the aforementioned limitations and literature gap. Moreover, it conducts a comprehensive investigation on doctoral interdisciplinarity combining the three approaches of analysis discussed in this chapter: measuring, understanding and assessing.

CHAPTER 3

Research Context

This study was conducted at the *Faculty of Informatics of the Technische Universität Wien* (TU Wien), which is Austria's largest research and teaching institution in Computer Science (CS). This academic department[1] plays an active role in national and international research, and is highly ranked in the field of CS. The department defines as its core functions research (both applied and basic research), teaching and innovation.

The department has about 6,000 registered students—of which only approximately 2,500 are active students—in bachelor's, master's and PhD programs. Active students are those who obtain at least 16 ECTS credits in the previous study year. The difference in the number of registered and active students can be explained by the fact that public Austrian universities grant access to higher education with no tuition fees during the prescribed duration of study and several exemptions from paying tuition fees thereafter.

The study program of the department reflects the diversity of CS. The bachelor's, master's and PhD programs are based on research-oriented teaching (as opposed to having a purely practical orientation). They were implemented in 2012 based on curricula of the Association for Computing Machinery (ACM), the Association for Information Systems (AIS), and the Institute of Electrical and Electronics Engineers (IEEE), as well as of comparable foreign universities. Both bachelor's and master's degree programs have specialization branches called "study programs". Upon enrollment, students must decide which study program they would like to follow. The bachelor's and master's study programs offered in 2016 are listed in Table 3.1.

In January 2016, there were a total of 53 professors (among them associate and full professors) and more than 300 researchers, of which approximately 211 were doctoral researchers employed at the university. There are 7 research institutes, each of them

[1]Since the term "faculty" has different meanings in North American English (academic staff) and in British English (division within a university), this dissertation employs the term "department" in order to refer to a division of a university devoted to a particular discipline.

Table 3.1: List of the bachelor's and master's study programs at the *Faculty of Informatics of the TU Wien*. The programs placed within one column are either bachelor's or master's programs, instead those placed between the two columns exist as both bachelor and master's programs.

Bachelor's Programs	**Master's Programs**
Business informatics	Business informatics
Computer engineering	Computer engineering
Media informatics and visual computing	Media informatics Visual computing
Medical informatics	Medical informatics
Software & information engineering	Software engineering & Internet computing
	Computational logic

consisting of several research groups, which are normally staffed with one or more professors, associate professors and other research and academic staff. The average size of each group is 15-20 people. In total, there are 20 research groups in the department, which conduct research on five major areas: (i) business informatics, (ii) computer engineering, (iii) distributed and parallel systems, (iv) logic and computation, and (v) media informatics and visual computing. A description of the research activity of the different major areas can be found in Appendix 8.3.2.

Although strategies to encourage academic staff to conduct interdisciplinary research have not been implemented, it has seven doctoral programs with different approaches to manage the specialization. There is a traditional European doctorate and six different structured programs, which were established after the third cycle of the Bologna Process and follow an Anglo-American doctoral model. All doctoral programs operate concurrently. Doctoral researchers of all the programs participate in research groups, share the same work environment and are supervised by the same group of professors. Moreover, they are all expected to achieve the same standards of quality and to publish their results in peer-reviewed international journals and conferences during their doctoral studies.

3.1 Traditional European Doctoral Program

The traditional European program (a master-apprentice model) awarded its first doctoral degree in 1902 and in 2014 it enrolled 463 doctoral researchers. The majority of doctoral researchers in the department are enrolled in this program. It is typically conceived as a single-supervised approach with individual professors independently selecting prospective doctoral researchers to work with them. The program of study is loosely regulated without compulsory courses, milestones, or a limited time frame in which to complete the degree. Doctoral researchers are free to choose their courses and when to take them, in order to earn a minimum of 18 ECTS credits to graduate. In 2015 the program was modified in order to introduce two new features inspired by the structured programs: fundamental courses and proficiency evaluations. Up until then, the program of studies had no compulsory courses, but doctoral researchers who enrolled after 2015 are now required to pass two fundamental courses equaling six course credits. The latter aim to provide a fundamental understanding of the theories and methods that underpin scientific activities and careers (e.g., philosophy of science and methodologies, career planning, research methods). The remaining courses are chosen by the doctoral researcher with the expectation that they be related to the his/her research area. The second modification was the introduction of a proficiency evaluation, which is an assessment of the doctoral candidates and their research plan after the first year of their PhD studies. Typically, doctoral researchers in this program are university assistants, project assistants (funded by a third-party partner), and other are scholarship recipients or are self-funded.

3.2 Structured Doctoral Programs

The structured programs follow an Anglo-American doctoral model. There are published rules for application, selection and admission. They have structured curricula with both general and subject related courses and milestones, such as a qualifying exam which is to be taken at the beginning of the second year and has the form of a PhD proposal. There are two types of structured doctoral programs: doctoral school and doctoral colleges. While a doctoral school is a multiple-cohort program that covers the different areas within the discipline, doctoral colleges are single-cohort programs that focus on a specific research area, topic, or research milieu. At the department there is one doctoral school and five doctoral colleges. Our focus is on the two structured programs that have been running for longer time periods: the *Vienna PhD School of Informatics* (Faculty of Informatics, TU Wien, 2016c)—the only doctoral school covering all topics of the department—and the doctoral college *Mathematical Logic in Computer Science* (Faculty of Informatics, TU Wien, 2016a)—which focuses on a single topic—, both of which were implemented in 2009.

3.2.1 The Vienna PhD School of Informatics

This doctoral school is a multiple-cohort program established in 2009. In 2014 it enrolled 33 doctoral researchers. It is multidisciplinary covering the main CS research areas of the department. The program requires doctoral researchers to take a minimum of 21 ECTS course credits which corresponds to 7 courses. They need to take 4 courses in a primary and a secondary area, following the department's major research areas; and 3 fundamental courses. Once a year, a call for applications is made with explicit guidelines and a group of applicants is selected for admission. Each doctoral researcher is awarded a three-year scholarship and may choose any topic in CS that a professor agrees to supervise.

3.2.2 Doctoral College Mathematical Logic in Computer Science

This college is a single-cohort program established in 2009. In 2014 eight doctoral researchers were enrolled. It is coordinated by academic staff from CS, mathematics, and physics in order to have an interdisciplinary focus on a single area of CS: computational logic. The curriculum contains courses in computational logic and its mathematical foundation along with multidisciplinary and soft-skill courses and milestones. Doctoral researchers receive a regular university employment contract and work on a pre-existing research project.

3.2.3 Other Structured Programs

The remaining doctoral programs of the department are five doctoral colleges that focus on specific areas in CS or in the intersection of other disciplines with CS. Each of these programs implement structural strategies to promote interdisciplinarity, such as co-organization by different faculties, collaboration with experts from different fields, courses in different disciplines and co-supervision of doctoral researchers. They are funded as research projects. Therefore, they are active for a limited time. They each have 10 to 30 doctoral researchers who are offered a 3-year part-time employment as project assistants. In January 2016 there were 40 doctoral researchers enrolled in these five programs, which were at different stages: a couple of programs were about to finish, others had been running for two to three years and one had been recently implemented.

CHAPTER 4

Methodology

This section begins describing the methodological approach used in the course of this research effort, and how multiple methods of data collection and analysis have been orchestrated. Furthermore, it discusses the factors that influence the reliability of this study and explains the ethical issues involved.

4.1 Methodological Approach

The term "research methodology" refers to the inquiry strategy or design of a research project. According to Denzin and Lincoln (2000):

> "A strategy of inquiry comprises a bundle of skills, assumptions, and practices that the researcher employs as he or she moves from paradigm to the empirical world. Strategies of inquiry put paradigms of interpretation into motion. At the same time, strategies of inquiry connect the researcher to specific methods of collecting and analyzing empirical materials [...] Research strategies implement and anchor paradigms in specific empirical sites, or in specific methodological practices, such as making a case an object of study."

Two major methodological paradigms can be distinguished. The quantitative paradigm is based on positivism; the phenomena are reduced to empirical indicators which represent the truth. Epistemologically, the researcher and the concept investigated are independent entities. Therefore, the investigator is capable of studying a phenomenon without influencing it or being influenced by it. Techniques to ensure this include repeated measurements with minimal human intervention, randomization, blinding, highly structured protocols or questionnaires with a limited range of predetermined responses. Sample sizes are larger than those used in qualitative research, so that statistical methods can be conducted with representative samples (J. W. Carey, 1993). In contrast, the qualitative paradigm is based on interpretivism and constructivism (Y. S. Lincoln and E. G. Guba, 2000a; Schwandt, 2000). From an ontological perspective, there are multiple realities which are socially constructed, and on an epistemological level, there is no access to reality independent of our minds (P. L. Berger and Luckmann, 1966). The investigator and the object of study are interactively linked and the findings are created with the context that shapes the reality (Denzin and Y. S. Lincoln, 2000). Interviews, focus groups, or participant observations are some of the techniques employed in qualitative studies. Small and purposeful samples of respondents are selected since they can provide important information, rather than because they are representative of a larger group (Crouch and McKenzie, 2006).

In spite of the differences between the quantitative and qualitative paradigms, the two can be combined for complementary purposes. Steckler et al. (1992) argue that the combination of the two paradigms is useful for the analysis of complex phenomena as they require data from different sources and the application of multiple methodologies for a proper interpretation. Supporting the arguments for integrating qualitative and quantitative approaches are the benefits that result from this methodology. The literature underlines two main benefits: firstly, the cross-validation by combining two or more sources of data to analyze the same phenomenon (Denzin, 1970), and secondly, an attainment of complementary results yielded by the strengths of one method enhancing the other (Morgan, 1998).

Since education and research are highly complicated systems, the practice of educational research benefits from both methodological approaches and can be enhanced if qualitative and quantitative methods are taken as complementary ways of studying educational phenomena and not as mutually exclusive paradigms (Niglas, 2007; Steckler et al., 1992). Therefore, in our study we combine both paradigms in order to analyze interdisciplinarity at a doctoral level, where complexity extends over many dimensions. It not only integrates distinct disciplines, but also involves different types of stakeholders, takes place at various sites, on multiple levels (e.g., theoretical, methodological), and in diverse forms (e.g., multidisciplinarity, interdisciplinarity, transdisciplinarity). We sequentially use methods of both paradigms in order to use the strengths of each method to bolster the weaknesses of the others, at the same time that we capture various aspects of the same phenomena.

4.2 Research Design

This study is composed of four phases of analysis that combine both qualitative and quantitative methods in order to analyze doctoral interdisciplinarity (see Figure 4.1). In the following we present the aims and methodologies of the four phases. More detailed descriptions on the methodology of the three main phases are given in Chapters 5, 6, and 7.

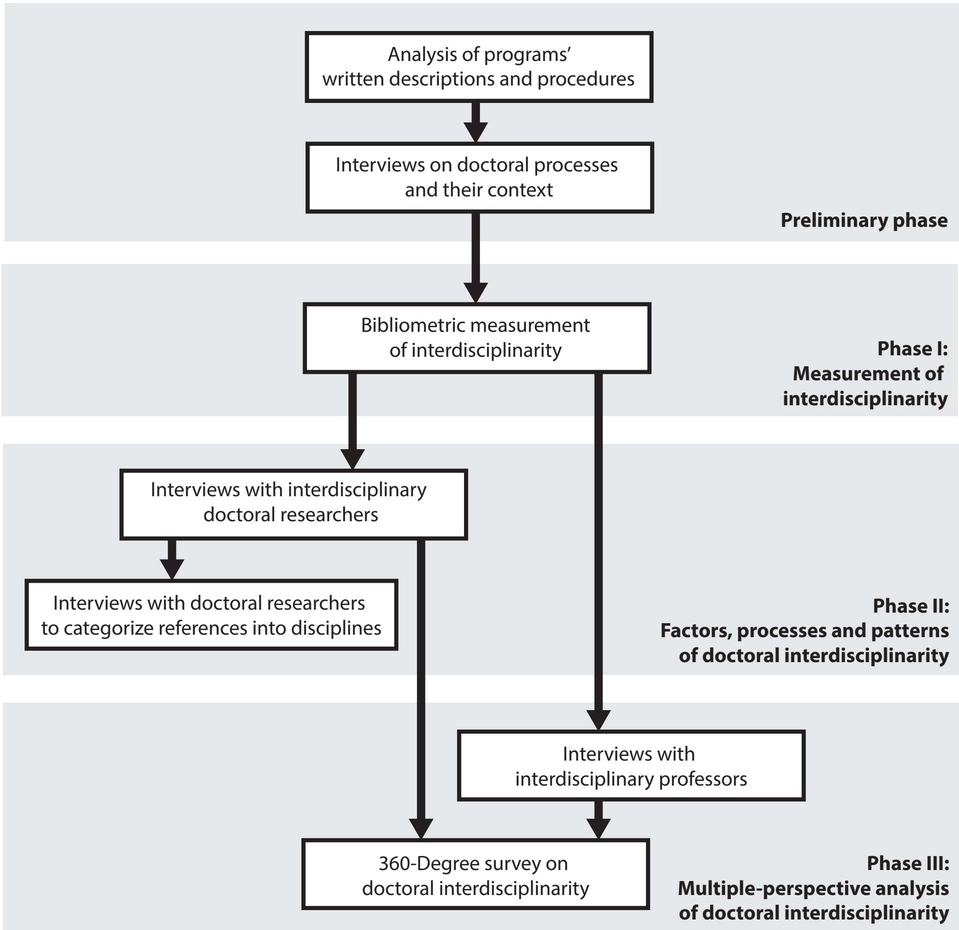

Figure 4.1: Research design.

4.2.1 Preliminary Phase: Doctoral Processes and their Context

The aim of this phase was to gain a better understanding of the context of the study—the *Faculty of Informatics of the TU Wien*—, such as its norms, procedures and culture, as well as rich insights into the processes of the doctorate—in particular of doctoral researchers of the programs that have been running for longer time periods: the traditional European doctorate, the Vienna PhD School of Informatics and the doctoral college "Mathematical Logic in Computer Science". Descriptions of these programs can be found in Chapter 3.

As a first step, descriptions of procedures and structures of the programs were collected from their web pages. Then doctoral researchers of the three doctoral programs were invited via email to participate in semi-structured interviews, which purpose, as communicated in the email, was to better understand the processes, contents and outcomes of different program models of doctoral education in Computer Science (CS). A total of 33 doctoral researchers volunteered to participate, of which 7 were in the traditional program, 20 in the PhD school, and 6 in the doctoral college. They were in different research groups of the department and phases in their doctoral studies. The participants also represented both genders and various nationalities. The interviews, which were 50-90 minutes long, covered several aspects of the experiences of doctoral researchers (see interview protocol in Appendix 8.3.2).

4.2.2 Phase I: Measurement of Interdisciplinarity

The aim of this phase (see Chapter 5) was to obtain empirical data about the scientific activity and interdisciplinarity of the doctoral researchers' publications and their coauthors. Following the National Academies (2005) report, we defined InterDisciplinary Research (IDR) as requiring an integration of concepts, techniques and/or data from different established research fields, without presuming the presence of teaming. Using this definition, we analyzed the interdisciplinarity of a published paper according to its integration of different knowledge sources or the extent to which different disciplines are cited.

Publication data from the doctoral researchers of the department and their coauthors (including their academic supervisor), as well as the references of the publications of both groups were gathered from several online sources. The Rao-Stirling diversity index (Porter and Rafols, 2009) was used to measure interdisciplinarity by capturing the number of disciplines cited in a publication, their degree of concentration and the similarity between them. We extended this index by implementing a new method in order to provide a more robust measurement of interdisciplinarity in the presence of missing bibliometric data. Subsequently, the extended index was used to measure the interdisciplinarity of doctoral researchers and professors within the department. The results of this measurement were used to identify participants for the next phases of this study.

4.2.3 Phase II: Factors, Processes and Patterns of Doctoral Interdisciplinarity

The aim of this phase of the study (see Chapter 6) was to understand which factors and processes contributed to interdisciplinary doctoral research, as well as the dispositions and experiences associated with doctoral researchers becoming interdisciplinary early career scientists. Fifteen doctoral researchers who had been identified in the previous phase as having produced IDR were invited to participate in in-depth interviews; all 15 researchers accepted. The interviews lasted between 50 and 80 minutes and focused on their experiences, their publications, the influence of the program, the department, and its academic staff, as well as the management of opportunities and tensions from multiple disciplines. These topics were selected from the literature on interdisciplinarity at the doctoral level and were used as guides for discussions instead of preconceived concepts around which to organize the data (see interview protocol in Appendix 8.3.2).

Through the analysis of the interviews, three patterns of doctoral interdisciplinarity emerged. These were validated with an additional analysis that was designed to compare the integration of disciplines cited in the publications of the doctoral researchers of the three patterns. For this purpose, the fifteen researchers were invited to a second round of interviews (see protocol in Appendix 8.3.2) in which they were asked to categorize the references of two of their publications into disciplines of knowledge (see full list of disciplines in Appendix 8.3.2). The distribution of the references to the different disciplines in the sections of the doctoral researchers' publications was statistically analyzed.

4.2.4 Phase III: Multiple-Perspective Analysis of Doctoral Interdisciplinarity

During the final phase (see Chapter 7), we analyzed the opinions of different academic stakeholders on interdisciplinary criteria—research processes and factors that take place in the context of the department. The criteria were identified based on: (i) a literature review, (ii) the analysis of the interviews with doctoral researchers conducted in the previous phase, and (iii) the analysis of additional semi-structured interviews with professors of the department who conduct integrate different disciplines in their publications. The last group consisted of 6 professors who were identified, using the Rao-Stirling diversity index and our extension to account for missing data, as the most interdisciplinary. The six professors agreed to participate in interviews that lasted between 45 and 60 minutes and focused on the interdisciplinarity of their doctoral researchers in relation with factors and processes that facilitate or impede it (see interview protocol in Appendix 8.3.2).

Once the criteria were identified, they were assessed by academic stakeholders following the 360-degree feedback methodology (Ward, 1997). This solicits the opinion of the different stakeholders around the concept under assessment. In this case feedback was gathered from doctoral and post-doctoral researchers, professors, doctoral program and department directors, visiting professors, and research funding agencies.

All individuals were invited to participate regardless of the interdisciplinarity of their research, education program or activity. Therefore, this phase allows for the comparison of the opinions of the less interdisciplinary individuals and the most interdisciplinary ones, while at the same time, it allows for the triangulation of the results produced from previous phases of this study

4.3 Researcher Reflexivity: Trustworthiness and Ethics

4.3.1 Researcher Perspective

This study comprises the analysis of processes in which doctoral researchers are involved. The author of this thesis has, therefore, a dual perspective: (i) as one of the doctoral researchers of the department, and (ii) as the investigator of this study.

Suzuki et al. (2007) argue that the success of the qualitative researcher is dependent partly on his/her understanding of the participants and context in which the data is gathered. Since the main researcher of this study is a doctoral researcher at the same institution where the research is conducted, she is acquainted with both the participants and the context. On the one hand, having the perspective of a doctoral researcher might introduce bias from the researcher's own experience—the strategies employed to minimized such bias are discussed in Section 4.3.3. On the other hand, having the perspective of a doctoral researcher allows for an intimate knowledge of some of the doctoral dimensions and experiences, as well as with the context of the study, where both participants and researcher pursue their PhD degrees. This perspective provided easy access to the group of participants through shared meanings of vocabularies, customs and procedures of the doctoral programs in the department (Fontana and Fey, 2000, p. 660). Moreover, sharing the same position suppresses no hierarchical power differential. This facilitated the confidence of the participants providing frank answers to questions, and allowed to effectively probe information.

As regards the perspective of a researcher, it provided detailed insights into doctoral processes that other rarely access during their doctorate. Reading much of the research on the doctorate, collecting first-hand accounts of doctoral researchers and professors, as well as attending conferences and discussions on the topic are examples of activities that provided a richer insight into the doctorate.

4.3.2 Trustworthiness in Quantitative Analysis

Internal validity

It is the extent to which a causal relationship is true (Trochim and Donnelly, 2006). The quantitative analyses conducted in this study do not aim to determine causality, instead they provide descriptive insights on the interdisciplinarity of publications and the distribution of references to different disciplines in the publications of the doctoral researchers.

External Validity

It refers to the extent to which the results of the study can be generalized to different settings, procedures and populations (Gravetter and Forzano, 2011).

Each university has its own specific characteristics that might affect IDR, such as location (J. Katz, 1994), industrial collaborations (Qin et al., 1997) or cultures and policies (Sá, 2008; Välimaa, 1998). Therefore, the findings are not necessarily transferable to other universities or disciplines.

Reliability

It relates to the quality of the measurement procedure used to collect data. In other words, it could be considered as the proportion of "truth" in the measurement (Trochim and Donnelly, 2006).

The accuracy of measurements of interdisciplinarity strongly depends on the quality of the bibliographic data, which is affected by missing data, wrong categorization of publications into disciplinary fields, precise taxonomies of disciplines, etc. In order to increase the reliability of our measurement, we have proposed a method to estimate the effect of missing bibliographic data in the measurement of interdisciplinarity (see Chapter 5). Nevertheless, the reliability of such measurement could still be improved as further avenues of research towards more precise indicators remain open.

Regarding the questionnaires used in the third phase of the study, special attention was given to the conceptualization of the content and its transformation into questions in order to minimize measurement error. Moreover, in order to assess the reliability of the questions, these were pilot-tested by 10 individuals who were asked to explain the meaning of each question. Questions were revised several times according to the feedback gathered in the pilot tests.

4.3.3 Trustworthiness in Qualitative Analysis

Trustworthiness in qualitative research remains a highly debated topic; no single method can lead to an ultimate truth on any matter (Atkinson et al., 2003; Y. S. Lincoln and E. G. Guba, 2000b). Establishing trustworthiness aims to determine if findings are sufficiently authentic and credible for researchers to trust in the results, conclusions and implications.

Lincoln and Guba (1986) established four general criteria to establish rigor in qualitative research. These criteria are adequate for studies with the aim of understanding rather than truth seeking. Rigor was addressed in this research by attending to the trustworthiness in the form of credibility, transferability, dependability, and confirmability.

Credibility

It aims to "establish the match between the constructed realities of respondents (or stakeholders) and those realities as represented by the evaluator and attributed to various stakeholders." (E. Guba and Y. Lincoln, 1989, p. 237).

Credibility in this research was established through prolonged engagement with the participants—the doctoral trajectory of the participants has been followed from 1 up to 3 years. Moreover, participants who have attended presentations and talks on the findings of this study have expressed that the findings of the qualitative study reflect their doctoral experience.

Transferability

It refers to the extent to which research findings may be applied to a different context (Y. S. Lincoln and E. G. Guba, 1986). As mentioned in Section 4.3.2, the results of this study are not necessarily generalizable to other educational context. Nevertheless, governments and universities across the globe are attempting to stimulate interdisciplinarity and they face similar challenges (Bruce et al., 2004; Geiger and Sá, 2008; Sá, 2008). This study provides rich descriptions of its context that might be relevant when considering other contexts. Thus, this study is valuable for generating both hypotheses and methods for subsequent research and to raise similar or related questions about other research environments.

Dependability

It refers to the quality of the integrated processes of data collection, data analysis, and theory generation. According to Lincoln and Guba (1986) this is determined by the ability of the researcher to follow the evolution of the research process and to ensure the coherence of methods, and the documentation of the progression of the research.

In order to address this concern, methodological changes and new research questions were recorded and reflected in field notes, together with concept maps that ensured that the changes in the methodology and research question would be coherent. Peer debriefing, not only with academic supervisors but also with other academics through research stays and visits, was also helpful in promoting dependability.

Confirmability

This measure of rigor requires assuring that interpretations and outcomes are rooted in data and are not figments of the researcher's imagination (E. Guba and Y. Lincoln, 1989).

Readers of this study are provided with excerpts from transcripts and publications of the participants. Together with the detailed description of the context of the study, the excerpts provide an empirical context to the readers and make it possible for them to scrutinize the empirical data emerging from this study.

4.3.4 Construct Validity

Construct validity refers to the degree to which inferences can legitimately be made from the operationalization of the study to the theoretical constructs on which those operationalizations are based (Trochim and Donnelly, 2006).

This study is a triangulation of analyses. It examines substantial amount of information from various sources (i.e., bibliometric data, interview data and survey data), and methods. The examination of the pieces of study by comparing them with other kinds of evidence on the same points provides strong evidence of the findings of this study.

4.3.5 Ethical Considerations

During this study four ethical issues have been addressed: (i) participants' informed consent, (ii) participants' anonymity, (iii) conflict of interest, and (iv) benefit for participants and academic institutions.

The process of informed consent was initiated with the invitation emails that informed participants of the objective of the interviews. Before each interview, participants were again informed of the objectives of this study and the confidentiality policies were explained. Stress was placed on the voluntary nature of the participation, and that participants were not obliged to answer all the interview questions. Additionally, they are permitted to withdraw at any time.

In order to ensure the participants' anonymity during the whole study, the data was kept in a safe repository and the accounts of the participants was safeguarded at all times. Only the main investigator had access to data that could identify the participants of the study. The particular details of the individuals have not been included in the publication of the findings of this study, therefore ensuring the anonymity of the participants. With the same objective in mind, some important pieces of information, such as their field of study within CS and the other disciplines, have been omitted as this would immediately reveal the identification of the participants.

Conflicts of interest may arise when activities or situations place an individual or institution in a real, potential or perceived conflict between the duties or responsibilities related to research, and personal, institutional or other interests. The main researcher of this study has coordinated one of the doctoral programs analyzed in this study, and her doctoral research was guided by the initiator and former director of the same program. Since these positions could not be avoided, they have been disclosed to the appropriate people and steps have been taken to minimize the potential conflict of interest. Before participation in this research, individuals were duly informed of the involvement of the institutional obligations of the main researcher and the main academic supervisor. They were also informed that in order to preserve their anonymity, the main investigator, who conducted all interviews, was the only person able to identify the participants. The qualitative data was not shared with any other person within the department, including the academic supervisor of this study. The latter repeatedly expressed his desire to minimize the potential conflict of interest, and manifested the responsibility to remain unbiased throughout the whole study. This includes the honest communication of research findings in order to avoid jeopardizing the integrity of the research.

Finally, the benefit of the participants and academic institutions with interdisciplinary programs has also been considered. The participants of this study have received the findings of this research. Through reading the accounts of other participants described in the publications and the quantitative results, they could reflect on their own experience and academic paths. Additionally, academic institutions could make use of the R implementation of the computation of the Rao-Stirling diversity index and uncertainty of interval, which we have provided as open source. This R package and its documentation

(Calatrava Moreno and Auzinger, 2016) have been contributed to the Comprehensive R Archive Network (CRAN).

CHAPTER 5

Measurement of Interdisciplinarity with Missing Bibliographic Data

Most quantitative measures of the output of InterDisciplinary Research (IDR) rely on bibliometric methods. Since such methods are commonly used to inform policy in science and technology, they require reliable indicators and results. While analytical indicators and tools have been refined over time, their results are in most cases not precise. The accuracy of such indicators depends on the quality of the bibliographic data, which should be correct and complete. Unfortunately, the gathering of a correct and complete bibliographic dataset is a complicated task due to the fact that not all scientific publications are indexed by digital libraries. Current bibliographic databases, such as the Web of Science (WoS) or Scopus, do not cover books, book chapters and many regional non-English journals in which some fields mainly publish. Even conference proceedings, which constitute the main publication venues in many applied fast-changing fields, are often not indexed. The gathering and comparison of records gathered from different bibliographic sources mitigates this problem to some extent. However, an additional problem affects top-down approaches to measure IDR such as the Rao-Stirling diversity index: the need for a predefined taxonomy of disciplines that classifies all publications in the dataset. This problem cannot be solved with the comparison of data gathered from different sources because not all libraries classify their publications into a taxonomy of disciplines nor use the same taxonomy, and even those that use a taxonomy might not classify all their indexed publications with it—as is the case of WoS. Manual classification of publications into disciplinary fields is also not viable for a large number of uncategorized publications. In consequence, top-down measurements of IDR usually deliver proxy results.

In this chapter we acknowledge the problem of dealing with incomplete data gathered from several libraries. We focus on the problem of uncategorized publications for the measurement of IDR with the Rao-Stirling index. We choose this index because it is a well-established bibliometric indicator that requires a complete categorization of all references into disciplinary fields; however, this problem has not received adequate attention in the literature. We propose a theoretical extension of the Rao-Stirling index to account for the uncertainty resulting from references that remain uncategorized. This work has been peer-reviewed and published in the journal *Scientometrics* (Calatrava Moreno, Auzinger, and Werthner, 2016).

5.1 Background

IDR measurements heavily rely on bibliometric methods and data due to the widely-held view that scientific research is disseminated via publications. Different types of approaches exist for measuring IDR, which have been accordingly endorsed for differing needs of analysis. For an extensive review of approaches, we refer to the work of Wagner et al. (2011). Among them, the most common method for measuring IDR is citation analysis, in which an exchange or integration among fields is captured via discipline-specific citations pointing to other fields. Two distinguishable strategies for measuring IDR are bottom-up and top-down. The first approach is based on clusters of articles without a predefined taxonomy of disciplines. The clustering is based on the structural relationships of a network of publications (Boyack and Klavans, 2010; C. Chen et al., 2010; Leydesdorff, 2007; Leydesdorff, Rafols, et al., 2013). In contrast, top-down approaches rely on a predefined taxonomy of disciplines that is used to classify publications into disciplinary fields (Leydesdorff, Carley, et al., 2013; Porter and Rafols, 2009; Rafols et al., 2012). While bottom-up approaches are suited for capturing emerging developments that do not fit into existing categories, the classification-based approach is useful for large-scale explorations, such as comparisons of areas of science using an extensive amount of data or the disciplinary breadth of research institutions. The latter approach is the focus of this chapter.

The results of citation analyses are subject to the quality of bibliographic data in terms of completeness and accuracy. Well-established top-down methods used to analyze the number of disciplines cited by a publication or their degree of concentration such as Shannon entropy (Shannon, 1948) and Herfindhal index (Rhoades, 1993) are designed to be used with datasets with complete information, since they cannot acknowledge the degree of missing data. This is also the case of the Rao-Stirling diversity index, a more complete top-down index proposed by Porter et al. (2007), and Porter and Rafols (2009). Precise IDR measurement using these methods requires a bibliographic dataset with: (i) complete records of references, (ii) a correct list of references for each publication, (iii) accurate categorization of publications into disciplinary fields, and (iv) the categorization of each reference into at least one discipline. The combination of such quality characteristics results in ground-truth bibliographic data, which is rarely attainable since no publication database provides adequate correctness and completeness in respect to both references and categorization into disciplinary fields.

Concerning references, verification mechanisms as discussed by van Raan (1996) are crucial to detect incomplete records of references and remove incorrect references in bibliographic sources, such as those encountered by Moed et al. (1995) and Chen et al. (2012). In regard to taxonomies of disciplines, their accuracy have been widely discussed in the literature without reaching consensus on an adequate one (National Research Council, 2010; Rafols and Leydesdorff, 2009). In spite of its weaknesses, the list of categories provided by WoS is the most widely used (Bensman and Leydesdorff, 2009; Pudovkin and Garfield, 2002). The exhaustive categorization of all references within a dataset into disciplinary fields remains an open issue under-discussed in the literature. Although the important consequences of missing data in bibliographic datasets have been acknowledged in the literature (Moed et al., 1985), to our knowledge the problem of uncategorized records in top-down IDR measurement has not been properly addressed. Some bibliometric studies minimize this problem by excluding uncategorized publications from the dataset. The use of the categories of WoS implies the exclusion of all publications other than journals indexed by WoS (i.e., proceedings papers, books, technical reports) (Bjurström and Polk, 2011; Carley and Porter, 2011; C. Chen et al., 2012). Other studies account for the percentage of uncategorized publications and compute the index on the categorized references (Porter and Rafols, 2009; Rafols et al., 2012). These approaches do not take into account the potential diversity of the excluded or missing data; hence interdisciplinarity is underestimated.

A method that automatizes the assignment of disciplines was implemented by Ponomarev et al. (2013) in order to categorize authors into one out of a small set of major research fields. It is based on aggregated information on the categories of the publications of the author and their references, for which disciplines are grouped into broad categories that relate to the research activity of the group of individuals. Disciplines unrelated to the research activity of the group of individuals are categorized as "others". Therefore, it does not allow for the automatic assignment of specific categories loosely related to the selected major fields, which is needed to compute the Rao-Stirling index.

In the following we propose a method which acknowledges missing data and determines the associated uncertainties, as well as its evaluation and its application for the measurement of IDR in a real scenario.

5.2 The Rao-Stirling Index

In this chapter we briefly introduce the Rao-Stirling index and present as our main theoretical contribution an extension of it that encodes the uncertainty caused by missing bibliographic data as an uncertainty interval. The Rao-Stirling index is a distance-based indicator, inspired by the Stirling index (Stirling, 2007), which not only captures the variety and balance of the disciplines cited by a paper, but also their disparity using a measure of similarity between disciplines. A hypothetical document $\mathcal{D}$ and a set $\mathcal{T}$ of $N_{\mathcal{T}}$

disciplines will serve as an example for the following explanations. The index can be expressed as:

$$I = 1 - \sum_{i,j} s_{ij}\ p_i\ p_j$$

where p_i is the proportion of references of the discipline i in a given paper. s_{ij} is a cosine measure of similarity between the disciplines i and j. It is a matrix of similarities where disciplines that are co-cited more often by the same paper are "closer" than disciplines that are less frequently co-cited (Porter and Rafols, 2009). It ensures low integration scores for publications citing very similar disciplines and high integration scores for publications citing very diverse disciplines. The integration score ranges from 0 to 1 (the metric can asymptotically approach this upper limit) as variety, balance, and disparity increase.

The information on the disciplines of the categorized references of $\mathcal{D}$ can be aggregated into a vector $\boldsymbol{c} = (c_1, c_2, \ldots, c_{N_\mathcal{T}})$ of reference counts per discipline. Each count c_i gives the number of references of $\mathcal{D}$ that belong to the i-th discipline of $\mathcal{T}$. Note that a reference can already be interdisciplinary and belong to several disciplines. By denoting the number of references that are cited by $\mathcal{D}$ with N_ref, we have for the 1-norm of $\boldsymbol{c}$ that

$$\sum_{i=1}^{N_\mathcal{T}} c_i = \|\boldsymbol{c}\|_1 \geq N_\mathrm{ref},$$

if complete bibliographical data is assumed. Each count c_i corresponds to a proportion p_i by the relation $p_i = \frac{c_i}{\|\boldsymbol{c}\|_1}$. The Rao-Stirling diversity I is then given as

$$I = 1 - \sum_{\substack{i=1\\j=1}}^{N_\mathcal{T}} s_{ij}\ p_i\ p_j = 1 - \frac{1}{\|\boldsymbol{c}\|_1^2} \sum_{\substack{i=1\\j=1}}^{N_\mathcal{T}} s_{ij}\ c_i\ c_j = 1 - \frac{\boldsymbol{c}\,\mathbf{S}\,\boldsymbol{c}^\intercal}{\|\boldsymbol{c}\|_1^2} \tag{5.1}$$

where the similarity matrix $\mathbf{S} = (s_{ij})$ encodes the distance between the different disciplines (Stirling, 2007).

5.3 Missing Data

Problems arise when the disciplines of one or more references are unknown. As a consequence, $\boldsymbol{c}$ cannot be determined and I is not well defined. The common approach is to simply omit these references and compute the index on the references categorized with disciplines (Bjurström and Polk, 2011; Carley and Porter, 2011; C. Chen et al., 2012; Porter and Rafols, 2009; Rafols et al., 2012). Depending on the counts $\boldsymbol{c}$ obtained from the categorized references, as well as the number of uncategorized references, the uncertainty can widely vary. For a single uncategorized reference among dozens categorized, the effect would be minor, whereas in the converse case, the uncertainty spans nearly the whole range of the index, rendering the initial estimate meaningless.

To capture the effects of missing data, we will compute the range in which the Rao-Stirling diversity I can vary when the uncategorized references are assigned to (sensible) arbitrary disciplines. While this range could be determined by enumerating all possible assignments and computing I for each, such an approach is computationally infeasible as it suffers from combinatorial explosion, i.e., an uncategorized reference can be assigned to $N_{\mathcal{T}}$ disciplines in $2^{N_{\mathcal{T}}}$ ways. Instead, we will formulate the search for an upper and lower bound on I as an optimization problem. In the following, we present its basic formulation and several subsequent refinements.

5.4 Uncertainty Estimation

Given a document $\mathcal{D}$, let us denote with $\boldsymbol{c}$ the reference counts per discipline for all references *categorized* into disciplinary fields. Furthermore, $\mathcal{D}$ is referencing u *uncategorized* documents, i.e., documents for which we have no information on their respective disciplines. We now aim to compute new sets $\boldsymbol{n}_-$ and $\boldsymbol{n}_+$ of reference counts per discipline such that all uncategorized references are assigned to one or more disciplines. Our goal is to obtain the smallest (resp. largest) possible diversity index I_- (resp. I_+) when computed with these new counts. Formally, we can state this requirement as

$$\begin{gathered}\boldsymbol{n}_- = \operatorname*{arg\,min}_{\boldsymbol{n}\in\mathbb{R}^{N_{\mathcal{T}}}} \left(1 - \frac{\boldsymbol{n}\,\mathbf{S}\,\boldsymbol{n}^\intercal}{\|\boldsymbol{n}\|_1^2}\right) \qquad \text{and} \qquad \boldsymbol{n}_+ = \operatorname*{arg\,max}_{\boldsymbol{n}\in\mathbb{R}^{N_{\mathcal{T}}}} \left(1 - \frac{\boldsymbol{n}\,\mathbf{S}\,\boldsymbol{n}^\intercal}{\|\boldsymbol{n}\|_1^2}\right) \\ \text{subject to } \begin{cases} c_i \le n_i \le c_i + u \quad (i = 1, 2, \ldots, N_{\mathcal{T}}) \\ \|\boldsymbol{c}\|_1 + u \le \|\boldsymbol{n}\|_1 \le \|\boldsymbol{c}\|_1 + N_{\mathcal{T}}\, u. \end{cases}\end{gathered} \tag{5.2}$$

In this formulation, $\boldsymbol{n}_-$ and $\boldsymbol{n}_+$ are given as those new counts $\boldsymbol{n}$ that minimize and maximize the Rao-Stirling diversity defined in Equation 5.1. These operations are subject to two constraints that ensure that the information obtained from the categorized references—in the form of the counts $\boldsymbol{c}$—is respected. The first constraint requires that the new count n_i for each discipline cannot decrease below c_i and that each discipline may acquire up to u reassigned references. The last constraint indicates that we expect each uncategorized reference to be assigned to at least one discipline and at most $N_{\mathcal{T}}$ disciplines. The optimization problem can also be stated in terms of proportions $\boldsymbol{p} = \boldsymbol{n}/\|\boldsymbol{n}\|_1$ (see Equation 5.1), which removes the normalization in the quadratic term:

$$\begin{gathered}\boldsymbol{p}_- = \operatorname*{arg\,min}_{\boldsymbol{p}\in\mathbb{R}^{N_{\mathcal{T}}}} (1 - \boldsymbol{p}\,\mathbf{S}\,\boldsymbol{p}^\intercal) \qquad \text{and} \qquad \boldsymbol{p}_+ = \operatorname*{arg\,max}_{\boldsymbol{p}\in\mathbb{R}^{N_{\mathcal{T}}}} (1 - \boldsymbol{p}\,\mathbf{S}\,\boldsymbol{p}^\intercal) \\ \text{subject to } \begin{cases} 0 \le p_i \le \dfrac{c_i + u}{c_j} p_j \quad (i, j = 1, 2, \ldots, N_{\mathcal{T}}) \\ \|\boldsymbol{p}\|_1 = 1, \end{cases}.\end{gathered} \tag{5.3}$$

A derivation of the transformation from (5.2) to (5.3) can be found in Appendix 8.3.2. While the formulation of the optimization problem in terms of counts $\boldsymbol{n}$ allows a more intuitive description of the various constraints, the formulation in terms of proportions $\boldsymbol{p}$ allows a more efficient computation of the solution as we show in Section 5.7.

5.5 Constraint Refinement

The full range of uncertainty in the Rao-Stirling diversity index regarding missing data is given as solutions to the optimization problems stated in Equations 5.2 and 5.3. We found, however, that such a general form considers situations that are highly unlikely to occur in real-world scenarios. In the above formulation it is possible that each uncategorized reference increases the per-discipline count of each discipline by one. This would indicate that such a reassigned reference is maximally interdisciplinary in the sense that it covers *all* disciplines. Since this is not a realistic scenario, we limit the number of disciplines that each uncategorized reference could belong to. If we assume that each uncategorized reference cannot cover more than k disciplines, we can represent this as an additional constraint in optimization problem (5.2):

$$\|\boldsymbol{n}\|_1 \leq \|\boldsymbol{c}\|_1 + k\,u. \tag{5.4}$$

In proportion space, the equivalent constraint for (5.3) is given as

$$p_i \geq \frac{c_i}{\|\boldsymbol{c}\|_1 + k\,u} \quad (i = 1, \ldots, N_{\mathcal{T}}). \tag{5.5}$$

Details on this derivation can be found in Appendix 8.3.2. In Section 5.8.3 we derive a value of $k = 4$ as suitable for uncertainty computations in our context. The impact of this choice on the actual calculations is discussed in Section 5.7.

5.6 Discipline Pruning

A reassignment of an uncategorized reference to an arbitrary subset of disciplines can lead to highly improbable results even when the cardinality of the subset is bounded as described in Section 5.5. This arises naturally due to the maximization of the Rao-Stirling diversity index in the aforementioned optimization problems. A concrete example could be a document in the field of Computer Science (CS) that exclusively cites previous works from its own discipline but has two uncategorized references. A possible reassignment that would significantly increase its diversity can be realized by assigning them to the unrelated disciplines of, for example, *zoology* and *Slavic literature*. While such an assignment is not invalid per-se, it is nevertheless prohibitively unlikely and in this section we present a method to exclude such improbable disciplines.

Our primary goal is to choose for each document a subset $\mathcal{T}_{\text{prune}}$ from the set $\mathcal{T}$ of all disciplines that includes such exceedingly unlikely candidates. Since we do not possess any knowledge on the disciplines of uncategorized references, we will infer this information from the disciplines of the categorized references. In the end, these deductions will lead to additional constraints for the optimization problems (5.2) and (5.3) of the form

$$n_i = 0 \quad \text{respective} \quad p_i = 0 \quad (i \in \mathcal{I}_{\text{prune}}) \tag{5.6}$$

where $\mathcal{I}_{\text{prune}}$ denotes the indices that correspond to the pruned disciplines that are contained in $\mathcal{T}_{\text{prune}}$.

A simple straightforward solution would be to just eliminate all disciplines that are not already observed from the categorized references, i.e., to set the constraint $n_i = 0$ (resp. $p_i = 0$), if $c_i = 0$. The problem with this approach is that it does not allow for the introduction of new disciplines through the reassignment of uncategorized references, which would underestimate the achievable diversity significantly.

In contrast, we take the mutual similarities of different disciplines into account for which we utilize the similarity matrix $\mathbf{S}$ as given in Equation 5.1. If the categorized references are from closely related disciplines, we only permit very similar disciplines to participate in the reassignment procedure, whereas we allow a larger set of disciplines for categorized references belonging to a diverse set of disciplines.

Our method is based on the concept of a *discipline neighborhood* $\mathcal{H}_i$ of a discipline $\tau_i \in \mathcal{T}$ with index i given by all those disciplines that have a similarity higher than a given value Δ, i.e.,

$$\mathcal{H}_i = \{\tau_j \in \mathcal{T} : \mathbf{S}_{ij} \geq \Delta\} \tag{5.7}$$

where Δ effectively controls the size of $\mathcal{H}_i$. The set of permissible disciplines $\mathcal{T}_{\text{valid}}$ is then given as a union of such neighborhoods—one for each discipline that is observed from the categorized references. Note that the set of removed disciplines $\mathcal{T}_{\text{prune}}$ is given as the complement of this set, i.e., $\mathcal{T}_{\text{prune}} = \mathcal{T} \setminus \mathcal{T}_{\text{valid}}$. For the actual computation of this set of neighborhoods, we propose the following objectives:

Completeness: Each neighborhood should contain at least two observed disciplines. This ensures that each neighborhood includes at least all disciplines that are more similar than the next most similar known discipline.

Cohesion: The neighborhoods should form a single connected component to avoid having multiple disjoint discipline clusters. For documents with references in, for example, two dissimilar disciplines, an omission of this objective could lead to a set of permissible disciplines that are very similar to either of these two known disciplines without considering the disciplines in between them.

Conciseness: The neighborhoods should be chosen in such a way as to yield the smallest possible set of permissible disciplines that fulfills the previous objective. The actual meaningfulness of the upper bound of the uncertainty interval is ensured in this way.

As we show in Appendix 8.3.2, we can obtain a set of permissible disciplines $\mathcal{T}_{\text{valid}}$ that obeys these objectives with the help of maximal spanning trees on the complete graph of disciplines when regarding the similarity matrix $\mathbf{S}$ as its adjacency matrix. Furthermore, our approach provides a user-chosen *tolerance* parameter—modulating the similarity values Δ of Equation 5.7—with which the strictness of the pruning can be controlled. A tolerance of 0 would allow all disciplines to participate in the redistribution process (i.e., $\mathcal{T}_{\text{prune}} = \emptyset$) while a value of 1 does not introduce any additional tolerance. Note that the corresponding constraints (see Equation 5.6) effectively reduce the dimensionality of the optimization problem and it is possible to compute (5.2) or (5.3) only on those discipline counts or proportions that are not members of $\mathcal{T}_{\text{valid}}$. Details on the employed algorithms for these methods can be found in Section 5.7 and our choice of the tolerance value is motivated in Section 5.8.3.

5.7 Computational Methods

In this section, we describe the computational methods used to compute the solutions of the optimization problems (5.2) or (5.3) while taking the constraints (5.4)-(5.6) into account. We choose different solution strategies for finding the reassignments with lowest possible diversity index I_- and highest possible diversity index I_+. The need for different strategies lies in the nature of the similarity measure between different disciplines, given by the similarity matrix $\mathbf{S}$; it has to be *positive semidefinite* to yield a non-negative diversity index for arbitrary discipline counts. The associated quadratic form $\boldsymbol{c}\,\mathbf{S}\,\boldsymbol{c}^\intercal$ is thus a *convex* function in $\boldsymbol{c}$, while $-\boldsymbol{c}\,\mathbf{S}\,\boldsymbol{c}^\intercal$ is *concave*. Thus, the Rao-Stirling diversity (5.1) is a concave function and its maximization (to obtain I_+) can be computed with the help of quadratic programming (Nocedal and Wright, 2006). Note that the constraints (5.2)-(5.5) constitute linear functions, which can be incorporated into the computation as linear equality and inequality constraints and do not impact its polynomial runtime complexity (Kozlov et al., 1980).

The minimization of a concave function has significantly worse complexity and the computation of I_- lies in the class NP-hard (Pardalos and Vavasis, 1991; Sahni, 1974). However, we exploit the fact that the Rao-Stirling diversity is purely concave in the sense that all the eigenvalues of the similarity matrix $\mathbf{S}$ are non-positive. From this follows that all local minima lie on the vertices of the polytope that is bounded by the constraints of the optimization problems (Floudas and Visweswaran, 1995). A search over all possible vertices yields the global minimum in exponential time, since the polytope for optimization problem (5.2) has $2^{N_\mathcal{T}}$ vertices, where $N_\mathcal{T}$ denotes the number of disciplines with $N_\mathcal{T} = 249$ in our case. Our constraint refinement of Section 5.5 reduces the search space significantly and, apart from a more realistic uncertainty estimation, ensures the efficient computability of I_-. Limiting the discipline reassignment to at most four disciplines (i.e., $k = 4$) limits the search space to only $\sum_{i=1}^{k=4} \binom{N_\mathcal{T}}{i} = 1.6 \times 10^8$ vertices, which can be explored exhaustively on commodity hardware. See Section 5.8.3 for a discussion of the choice of $k = 4$.

The discipline pruning and the corresponding maximal spanning tree have negligible computational overhead but reduce the dimensionality of the aforementioned minimization or maximization problem even further. The computation of I_- especially benefits from this approach. For the minimum spanning tree computation, Prim's algorithm is used (Prim, 1957).

5.8 Evaluation of the Method

The evaluation of the proposed method was conducted empirically. Following the framework for knowledge integration and diffusion suggested by Liu et al. (2012), the uncertainty intervals of the interdisciplinarity of the publications of a set of individuals were calculated. Ground-truth bibliographic data provided by the authors in personal interviews was used to evaluate the method. The results of our method computed with incomplete data from digital libraries were compared with the results of the Rao-Stirling index calculated with ground-truth data.

5.8.1 Sample Frame

The sample frame of this study consists of the publications of doctoral researchers at the *Faculty of Informatics of the TU Wien* between 2009 and 2014. Doctoral researchers are usually the main authors of their publications and have a thorough knowledge of the literature they reference. CS is an ideal field to use in evaluating our method because gathering publication data with a high percentage of categorized references is especially challenging. While in other fields conferences serve as venues for community building and maintenance, in CS they focus on selectivity, quality and fast dissemination—needed in such a fast-evolving field—which drives down conference acceptance rates (Grudin, 2011). Therefore, CS researchers target their publications at conferences, which are regarded as the primary means of publication in the field. Since conference publications are not associated to the taxonomy of disciplines of WoS, which we use in this analysis, a high number of uncategorized references is obtained.

5.8.2 Data Collection

In order to gather the most complete and accurate record of publications and their references, data was gathered from different sources. First, the publication database of the university was used to collect all the publications of doctoral researchers of the CS department published between 2009 and 2014. This database contains a very exhaustive list of publications authored by those affiliated to the university, as its records are used to compute the financial assignments to the different research groups. Because the publication database of the university does not keep records of references, in the next step we gathered more data from online bibliographic databases: (i) Scopus from Elsevier, which offers high coverage of articles; and (ii) WoS from Thomson Reuters, which provides a comprehensive citation search and encompasses publications of multiple online databases, resulting in multidisciplinary coverage.

The association of publications to disciplinary fields was possible using the taxonomy of disciplines of WoS (see Appendix 8.3.2). In this list, disciplines are called Category Terms (CTs). It contains 249 CTs and is elaborated based on a combination of subject matter expert judgments and inter-journal citation patterns that together serve to cluster journals into topical groupings. Since there is no consensus on a perfect taxonomy of disciplines, the one of WoS was selected because its extensive use in the bibliometric analyses of previous related work, but other taxonomies could also be used. As a measure of similarity between CTs, we used the co-citation similarity matrix provided by Porter and Rafols (2009). The combination of several databases increases the completeness of the record of references at the same time that it decreases the percentage of publications categorized with CTs—only journal publications indexed by WoS are categorized.

The dataset was gathered in March 2014. It contains 1,746 publications authored by the 225 doctoral researchers affiliated to the university who published between 2009 and 2014. The extraction of references was possible for 1,068 publications indexed by WoS or Scopus. The association of CTs to references was possible for 979 of the publications that had references indexed by WoS. A total of 12,243 references were extracted, of which 5,310 are categorized with CTs.

5.8.3 Computation of the Rao-Stirling Index and its Uncertainty Interval

We calculated the Rao-Stirling index and the uncertainty interval of the 1,068 publications for which the extraction of references was possible. The limit of discipline reassignment for the uncertainty interval was set to $k = 4$. This score is at the 99th percentile of the number of CTs used by WoS to categorize the journals of our dataset. The tolerance was also set to the 99th percentile of similarity between CTs ($t = 0.233$) in order to incorporate a slight diversity into the pool of similar CTs to be used in the reassignment procedure.

The results can be observed in Figure 5.1. It is very typical for publications to have only some of their references categorized, while the rest remain uncategorized (publication IDs 81-979). When every single reference of a publication is categorized with the same single CT both endpoints of the uncertainty interval are 0, as no CTs need to be redistributed (IDs 1-6). In case where a publication that references a single CT has uncategorized references (IDs 7-80), the lower bound of the interval would be 0 (all uncategorized references could be assigned to the same single CT), while the upper bound would be greater than 0 (the uncategorized references could be assigned to different CTs). If all references of a publication are uncategorized, the Rao-Stirling cannot be computed and the size of the uncertainty interval is at maximum (IDs 980-1068).

The size of the uncertainty interval indicates the level of accuracy of the Rao-Stirling index. The interval is large when publications contain a large proportion of uncategorized references, while it converges to a single value when all references are categorized (see

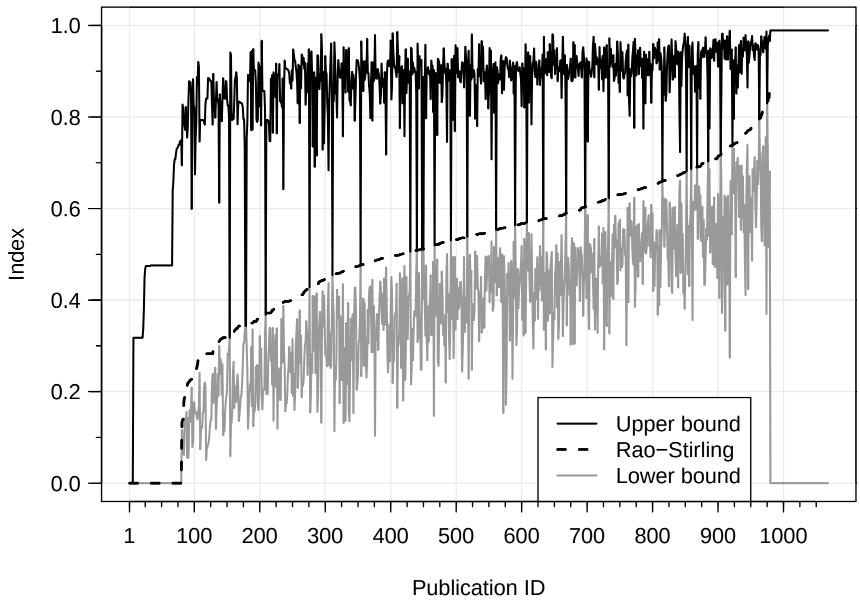

Figure 5.1: Rao-Stirling indices calculated with incomplete data (dashed line) and upper and lower endpoints of our uncertainty intervals (black and gray solid lines) for the 1,068 doctoral publications from which references could be extracted. While the Rao-Stirling index ignores the missing data, the lower and upper bounds of our uncertainty intervals take into account the uncategorized references, performing sensible reassignments of CTs that deliver the lowest and highest diversity index respectively. The publications are ordered along the x-axis according to their Rao-Stirling index.

Figure 5.2). The significance of this relationship is confirmed through linear regression analysis with p-value $< 2.2 \cdot 10^{-16}$.

5.8.4 Collection of Ground-truth Data

We refer to ground-truth data as complete and correct publication records with complete and correct categorization of references. The manual gathering of such data is very time-consuming. Therefore, a sample of publications was selected from the whole publication dataset. We applied stratified sampling with samples of equal size in each stratum, in order to obtain a sample of publications with different degrees of completeness and interdisciplinarity. Publications were divided into mutually exclusive sub-groups depending on two variables: (i) the proportion of categorized references among all references of a paper; and (ii) the degree of interdisciplinarity of a publication, calculated using the Rao-Stirling index with the incomplete publication dataset that was previously gathered from the digital libraries WoS and Scopus (see Section 5.8.2). Both variables were divided into 4 intervals, creating 16 sub-groups of publications. From each sub-group 3 publications were randomly selected, yielding a sample of 48 publications. First authors

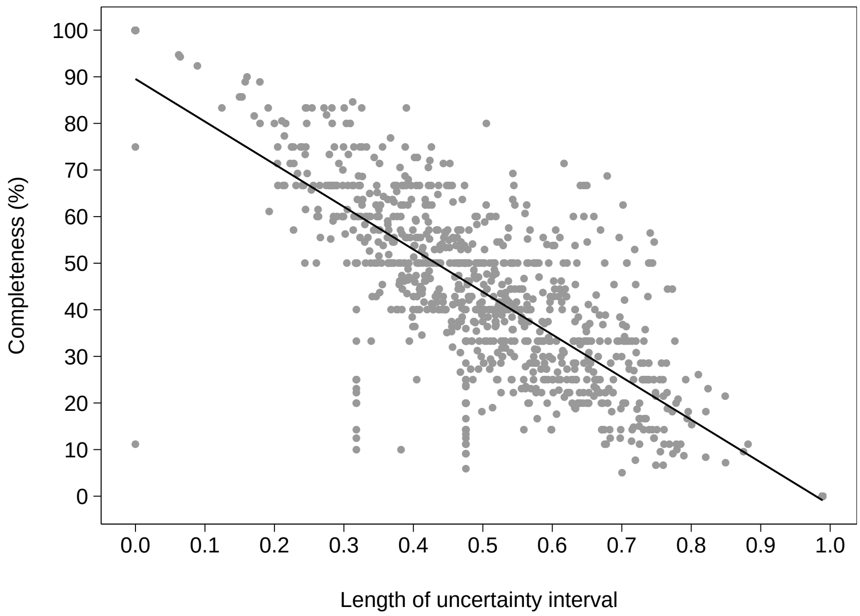

Figure 5.2: Relationship of the length of our uncertainty interval and the data completeness of the 1,068 doctoral publications for which references could be extracted. The completeness of a publication is defined as the ratio of categorized references in relation to its total number of references. The linear regression is represented with a black line. It can be seen that our approach captures the uncertainty associated with varying completeness.

were invited to participate in our study. In a few cases a coauthor was invited due to reasons such as expertise or availability. In personal interviews, the participants categorized the references of their publications using one to four CTs from the taxonomy of WoS. For each interview we provided the following material:

- Digital copies of the author's publication and all its references which were gathered manually from digital libraries.
- A print-out of the taxonomy of CTs of WoS. In order to make the search of CTs easier for the participants, CTs were grouped into macro-disciplines.

Data collection via personal interviews was chosen over a questionnaire in order to ensure the gathering of higher quality data, which allowed us to:

- Explain the importance of providing objective data. Since IDR has a good connotation, it was important to make our participants understand that they were not going to be evaluated in terms of interdisciplinarity. We asked them to provide us with the most objective data without exaggerating interdisciplinarity or single-disciplinarity.

- Make sure that participants became acquainted with the taxonomy of CTs, as none of the participants were familiar with it.
- Confirm that participants understood their task. Participants were asked to think out loud and explain their choice of CTs for verification purposes.
- Make sure that each participant followed the same criteria to categorize publications into disciplines.

The interview protocol can be found in Appendix 8.3.2.

5.8.5 Comparative Analysis

In order to evaluate the performance of our method, its results were compared with the measurement of IDR based on completed data. The ground-truth data provided by the interview participants was used to complete the missing categorization of references from their publications. We computed the Rao-Stirling index of these publications again, this time using the completed data. The results of the Rao-Stirling index with completed data are compared with the results of the Rao-Stirling index with incomplete data in Figure 5.3. On average the results of the Rao-Stirling index calculated with completed data are higher and less variable (see Table 5.1).

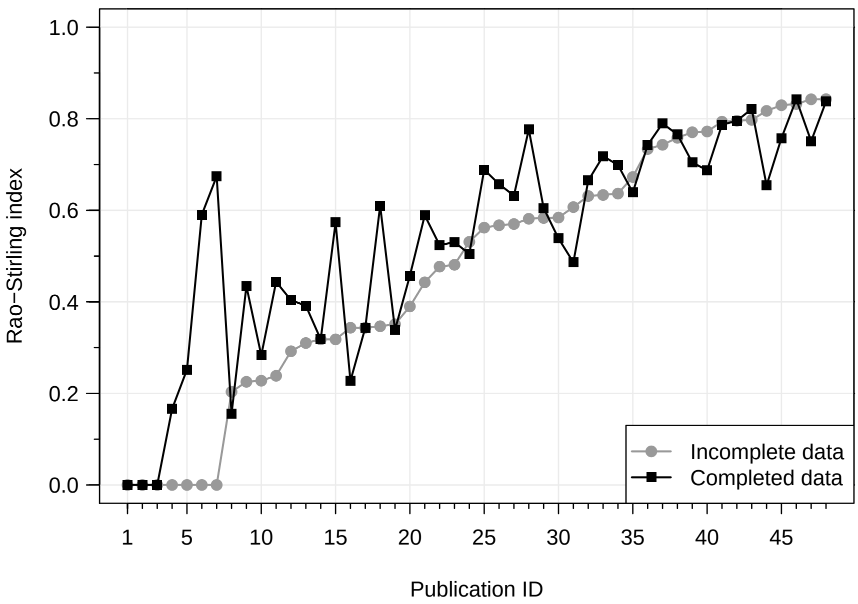

Figure 5.3: Rao-Stirling indices of the 48 publications of the sample with incomplete (gray line) and completed (black line) data. The publications are ordered according to their Rao-Stirling index with incomplete data. Depending on the degree of incompleteness, large deviations of the diversity index can be observed.

Table 5.1: Estimated mean and Standard Deviation (SD) of the Rao-Stirling index of the 48 publications of the sample calculated with incomplete and completed data. These estimated values were calculated with a bootstrapped sample of 50,000 elements with replacement.

Rao-Stirling index	**Estimated mean**	**SD**
Incomplete data	0.47495	0.03929
Completed data	0.53862	0.03307

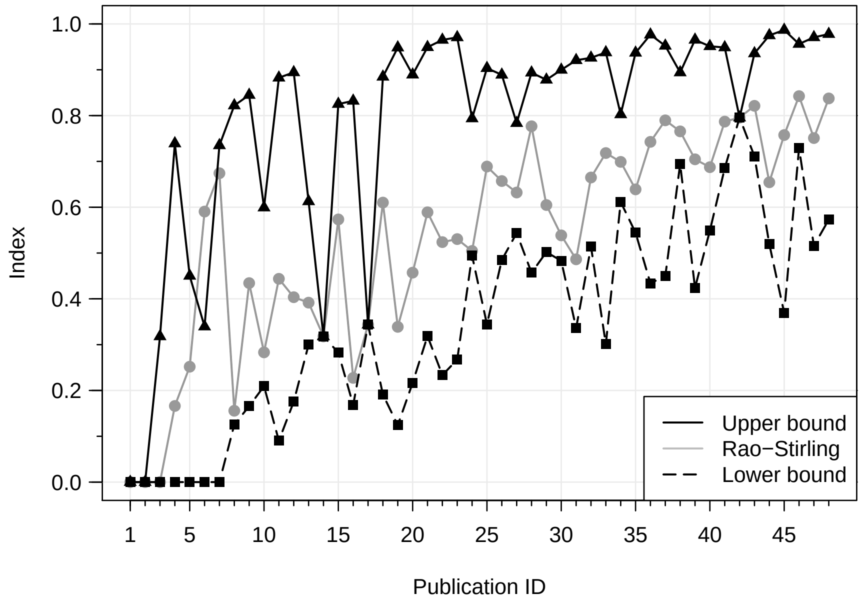

Figure 5.4: Indices of the 48 publications of the sample: Rao-Stirling calculated with completed data (gray solid line), upper (black solid line) and lower (black dashed line) bounds of the uncertainty interval calculated with incomplete data and parameters $k = 4$ and $t = 0.233$. The uncertainty interval includes in its range the results of the Rao-Stirling index with completed data in almost all cases, which indicates its good performance.

Since the bounds of the uncertainty interval are an estimation of the possible highest and lowest Rao-Stirling index of a publication with incomplete data, its result is correct when the interval includes the Rao-Stirling index with completed data (see Figure 5.4). The accuracy of the uncertainty interval is affected by the degree of categorized reference completeness of the publications.

In order to assess the performance of both our method and the Rao-Stirling index, where both use incomplete data, we compare the average of their results to the ones of the Rao-Stirling index with completed data (see Table 5.2). Since our method provides a measure of uncertainty, we also assess its performance by weighting the results of

Table 5.2: Estimated mean, bias and standard deviation of the indices of the 48 publications of the sample: Rao-Stirling index with completed data (first row), Rao-Stirling with incomplete data (second row), the center of the uncertainty interval (third row), and the center of the uncertainty interval weighted according to its size (fourth row). These estimated values were calculated with a bootstrapped sample of 50,000 elements with replacement. A visual representation of these values can be observed in Figure 5.5.

Diversity index	**Estimated mean**	**Bias**	SD
Rao-Stirling with completed data	0.539	$-9.646{\cdot}10^{-6}$	$3.308{\cdot}10^{-2}$
Rao-Stirling with incomplete data	0.475	$1.390{\cdot}10^{-4}$	$3.929{\cdot}10^{-2}$
Center uncertainty interval	0.569	$2.869{\cdot}10^{-5}$	$2.964{\cdot}10^{-2}$
Weighted center uncertainty interval	0.558	$1.342{\cdot}10^{-2}$	$3.266{\cdot}10^{-2}$

the uncertainty interval according to the size of the intervals, where smaller intervals have more weight than larger ones. Thus, more accurate intervals (publications with more complete data) have more weight than inaccurate intervals (publications with more incomplete data).

The results of our method are closer to the ones of the Rao-Stirling index with completed data. Both the center and the weighted center of the interval are provide more accurate IDR measurements than the Rao-Stirling index with incomplete data. The most accurate results are those of the weighted center of the uncertainty interval, whose standard deviation even includes the actual mean of the Rao-Stirling index with completed data (see Figure 5.5).

5.9 Measurement of Interdisciplinarity across Doctoral Programs

5.9.1 Sample Frame

From the 225 doctoral researchers affiliated to the department identified in March 2014 for the evaluation of the interval of uncertainty (see Section 5.8.1), a total of 195 studied in the three doctoral programs on we focus in this study—164 doctoral researchers were in the traditional program, 23 in the doctoral school and 8 in the doctoral college.

5.9.2 Analysis and Results

The interdisciplinarity of all publications was calculated using the Rao-Stirling index and its uncertainty interval. The interdisciplinarity of each doctoral researcher was computed by averaging the interdisciplinarity of his/her publications. The results of the measurement of the interdisciplinarity of the doctoral researchers can be observed in Figures 5.6 and 5.7.

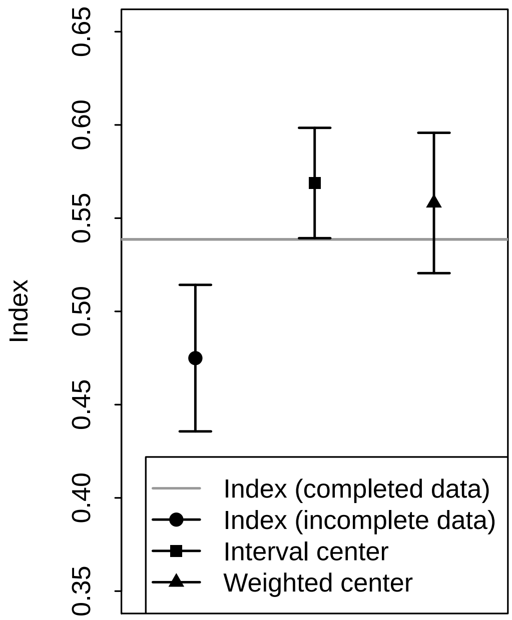

Figure 5.5: Comparison of the estimated mean of the Rao-Stirling index with completed data (gray horizontal line) with the estimated means and standard deviations of the Rao-Stirling index with incomplete data (circle), the center of the uncertainty interval (square) and the weighted center of the uncertainty interval (triangle). These estimated values were calculated with a bootstrapped sample of 50,000 elements with replacement (see Table 5.2). Our uncertainty interval shows a better performance than the Rao-Stirling index with incomplete data. The aggregated results of our uncertainty interval are closer to the results of the Rao-Stirling index with completed data.

The vertical axis of Figure 5.6 represents the Rao-Stirling index varying from 0 = no interdisciplinarity to 1 = the highest possible interdisciplinarity. The three horizontal lines in the chart represent the mean interdisciplinarity of the doctoral researchers of each program. Therefore, it can be observed that the three programs have similar average interdisciplinarity. Moreover, the three programs also yield similar distributions. This is confirmed by generating empirical distribution functions from these data and evaluating the hypothesis that they stem from the same underlying continuous distribution function (see Figure 5.7). Using the two-sample Anderson-Darling test, the hypothesis is not rejected at a p-value 0.05, and in fact, the goodness-of-fit values are high (i.e., 0.67, 0.92 and 0.67) for the pairings (Doctoral College – Doctoral School, Doctoral School – Traditional Program and Traditional Program – Doctoral College) of the empirical distribution function. This strongly indicates that the difference in the distribution of interdisciplinary exhibited by doctoral researchers in all three programs is minor.

5.10 Conclusion

The accuracy of citation-based IDR measurements heavily depends on the quality of the bibliographic data. The combination of data from several sources might help to enhance the quality of data but it certainly does not assure ground-truth bibliographic data. The dataset gathered for the evaluation of our methods is an example of an incomplete one, even though data from three different digital libraries was extracted and combined. Not all publications of our dataset have a complete record of references, and not all references are categorized with CTs. The Rao-Stirling index is incapable of taking both problems into account as it is not designed to handle missing data.

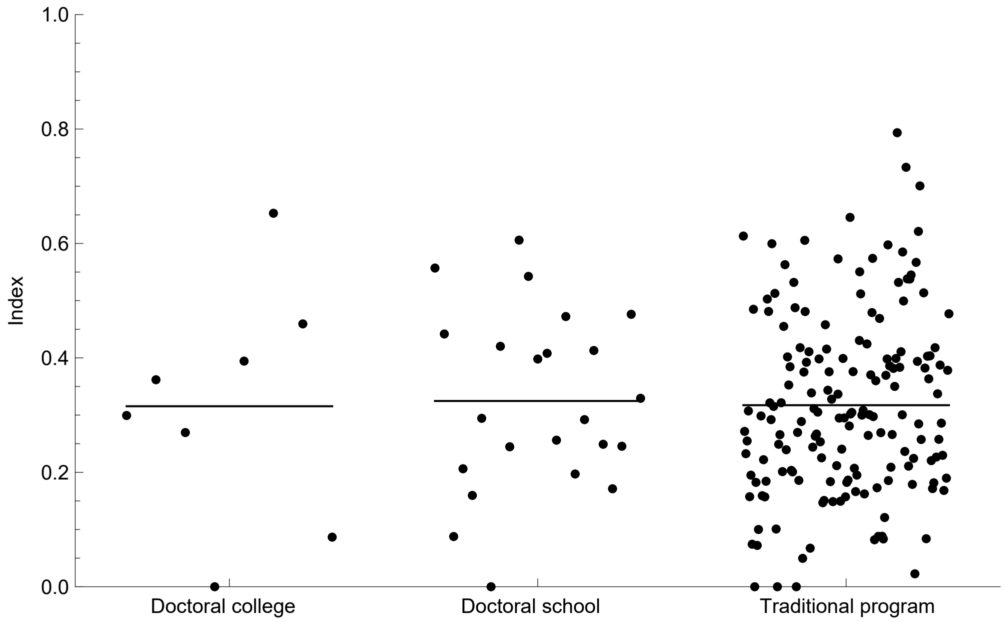

Figure 5.6: Interdisciplinarity of the doctoral researchers of the three doctoral programs measured with the Rao-Stirling diversity index and its interval of uncertainty.

Our method tackles the problem of uncategorized references, extending the Rao-Stirling index to encode the uncertainty caused by missing data as an interval. A high degree of incompleteness in publications particularly interdisciplinary in nature may also result in underestimating the upper bound of the uncertainty interval. This is especially problematic when a publication only has one reference categorized by a single CTs. Such a degree of incompleteness affects the rational redistribution of CTs needed to compute the upper endpoint of the uncertainty interval (see publication ID=6 in Figure 5.3 and 5.4). The main benefit of the uncertainty interval is that it acts as a confidence indicator of the results delivered by the Rao-Stirling index. On the one hand, publications with a low proportion of uncategorized references have correspondingly small uncertainty intervals, implying a more reliable measurement of the Rao-Stirling index. On the other hand, publications with a high proportion of uncategorized references have correspondingly large uncertainty intervals, indicating an unreliable measurement of the Rao-Stirling index. This finding proves the importance of selecting publications with a proportion of categorized references above a threshold value when computing an index of interdisciplinarity, as in the analysis of Rafols et al. (2012).

The empirical evaluation of our method confirms that the acknowledgment of missing data delivers a more accurate aggregated IDR measurement than the Rao-Stirling index. Our contribution constitutes a first approach to measure IDR taking into account the inaccuracy of the bibliographic data, but other problems still affect the results of the

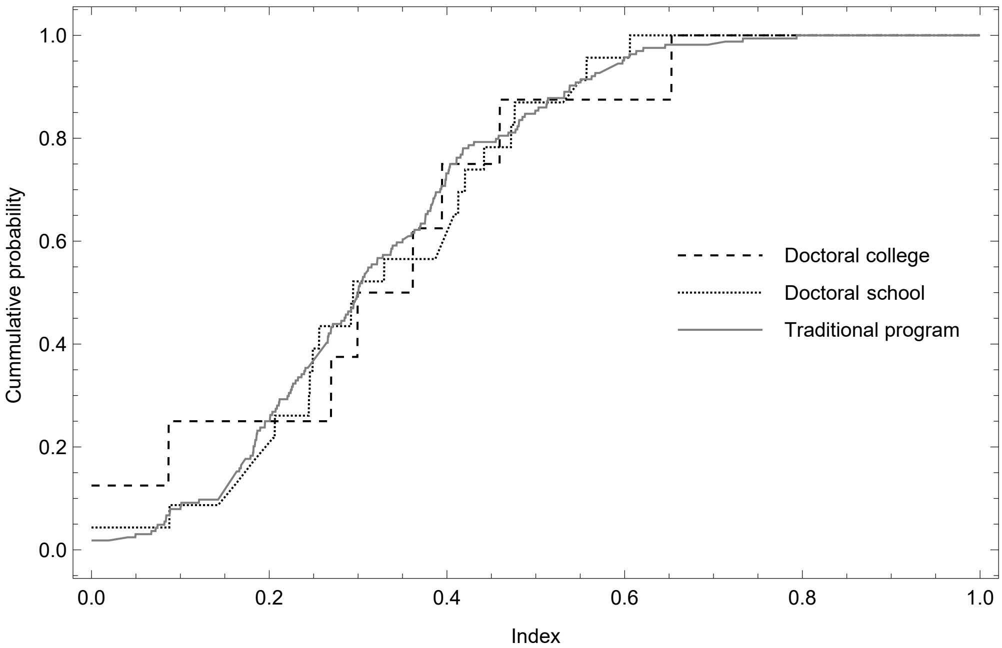

Figure 5.7: Distribution of the interdisciplinarity of the doctoral researchers of the three programs measured with the Rao-Stirling diversity index and its interval of uncertainty.

Rao-Stirling and other IDR indices. Future analysis to evaluate this method should be conducted using other taxonomies of disciplines. Further work would be needed in order to tackle the problem of incomplete and incorrect records of references, as well as incorrect categorization of publications into disciplinary fields. Additional issues to consider are the use of a precise taxonomy of disciplines and similarity matrix. Therefore, further avenues of research towards more precise IDR indicators remain open. To aid these efforts, we are providing the source code for our implementation of the uncertainty computation to the community, which can be found at `https://gitlab.com/mc.calatrava.moreno/robustrao.git`. Moreover, the source code and its documentation have been contributed as an R package to the CRAN.

The results of the measurement of interdisciplinary of the doctoral researchers of the three programs suggest, first, that although the three programs manage specialization and interdisciplinarity differently, there are no significant differences among the three programs regarding the production of interdisciplinary publications. Second, although some doctoral researchers are publishing interdisciplinary research, these are exceptional cases. The following phases of this study take these results as a starting point to understand the process of becoming an interdisciplinary early-career researcher when the different doctoral structures yield comparable levels of interdisciplinarity according to the quantitative measurement.

CHAPTER 6

Factors, Processes and Patterns of Doctoral Interdisciplinarity

The measurement of the interdisciplinarity of the doctoral researchers of the department of Computer Science (CS) conducted in the previous phase (see Chapter 5) allowed for a comparison of interdisciplinarity across doctoral programs. Although no significant differences in the interdisciplinarity of the researchers of the different doctoral programs could be observed, some doctoral researchers of each program did present a high degree of interdisciplinarity. These are exceptional cases because they take place in a context where the interdisciplinarity policies of the doctoral programs do not appear to yield differences in doctoral researchers' interdisciplinarity. Moreover, most of the doctoral researchers of the three programs conduct rather single-disciplinary research.

In this phase, those interdisciplinary doctoral researchers were invited to participate in interviews which were aimed to understand what factors, processes, dispositions, and experiences contribute to the interdisciplinarity of early career researchers. Moreover, the analysis of their accounts led us to identify three patterns of doctoral interdisciplinarity in CS. This work has resulted in two peer-reviewed journal publications: one in the *Journal of Higher Education Policy and Management* (Calatrava Moreno and Danowitz, 2016a), and the second in *ACM Transactions on Computing Education* (Calatrava Moreno and Danowitz, 2016b) (conditionally accepted).

6.1 Conceptual Framework

Borrego and Newswander (2010) reported on the complexity of interdisciplinary teaching and learning from the perspectives of engineering, science, and humanities. The humanities perspective was based on the literature on interdisciplinary studies, while the engineering and science perspectives were analyzed using empirical data in the form of successful proposals to the U.S. National Science Foundation's Integrative Graduate Education and Research Traineeship (IGERT) due to the sparse literature about interdisciplinary learning in these fields. They identified and proposed the following outcomes of interdisciplinary doctoral experiences: (i) the disciplinary grounding as the degree to which the doctoral researcher selects and adequately employs the disciplinary perspectives, theories, methods, validation, and forms of communication; (ii) integration as the ability of the disciplinary synthesis or the identification of a common ground among the disciplinary perspectives; (iii) teamwork as the collaboration with other experts with distinct complementary skills and knowledge; (iv) communication as the translation across the disciplines in order to manage differences and find connecting points; and (v) critical awareness as the ability to assess the benefits, challenges, and limitations of the research, valuing outside perspectives and other horizons of knowledge.

According to the literature on training scientists for interdisciplinary or transdisciplinary work, the above-mentioned outcomes are influenced by curricula, experiential learning and internships, which contribute to cultivate an interdisciplinary orientation: attitudes, beliefs, values, conceptual skills, knowledge, and behaviors that underpin a scientist's interdisciplinary approach (Holley, 2009). Previous work focuses on the structures and processes of preparing people to work with team members from different disciplines and does not consider the antecedent experiences or values a doctoral researcher may bring to his or her doctoral program. This is a curious omission because an individual's cross-disciplinary orientation emerges over one's lifespan. As Stokols (2014) explains, an individual's transdisciplinary orientation is a constellation of personal attributes that emerges developmentally over the course of the scholar's career, initiating from exposure to multiple learning environments, mentors, and research settings. Each stage of an individual's development (from kindergarten through high school, college, graduate school, and continuing education) contributes to his or her overall intellectual orientation.

In order to study the relationship between the doctoral researcher and their study program, we drew on concepts from sociocultural perspectives, a multifocal approach in which the individual and the context are viewed as mutually constitutive. Sociocultural theories hold that the social experience represents what individuals encounter when they engage in interactions with other people. Furthermore, individual development is also influenced when interacting in activities that involve societal values, intellectual tools, and cultural institutions. Lattuca's (2002) research—in which she applies a sociocultural perspective to how academic staff create interdisciplinarity approaches to teaching and research—strongly underlines the interpersonal, departmental, institutional, and disciplinary conditions that influence what individuals can or may do in a given place at a given time. Furthermore, she argues that studies must situate academic staff in multiple contexts in order to provide a more complete understanding of their learning and productivity. This same argument is applicable to doctoral experiences since doctoral researchers are being socialized into the same organizations as other academic staff. Subsequent research by Hopwood (2010) of how and what doctoral researchers learn through teaching, journal editing, and mentoring showed that these factors actively shape doctoral researchers' experiences and outcomes. In interpreting the findings of the study, he notes:

> "It points to social interaction and mediation in understanding how this learning took place, offering a view of individuals as intentional and resourceful. This replaces deficit views of students with notions of agentic, purposeful learners, swapping top-down conceptions focused on institutional provisions with individual, contextualized accounts of learning." (p. 830)

Although Lattuca's (2002) and Hopwood's (2010) studies vividly illustrate the importance of the interrelationship between individual experiences and sociocultural milieu, both fail to consider the wider contexts and interaction that individuals have prior to their doctoral program or departmental experience. To address this gap, we consider a specific dimension of the sociocultural perspective: relational interdependence. In particular, we draw upon Billett's (2006) research in work and working life in order to bridge researchers' predoctoral dispositions and their program experiences, and to explain how and why they do InterDisciplinary Research (IDR). Billett proposes that "individuals are subject to the social world, in its immediate and premediate forms, through a relational interdependence" (p. 65). Extrapolating research findings from the workplace (Billett, 1998) to a doctoral program would suggest that an individual's experiences prior to and during participation in a doctoral program would shape his or her program in different ways and influence how they work and learn.

6.2 Method

Since the aim of this phase was the understanding of the factors and processes that contribute to IDR, the first task was to identify the interdisciplinary doctoral researchers of the department. Figure 6.1 represents the methodology we followed for such purpose, which starts with the measurement of interdisciplinarity conducted in the previous phase of the study (see Chapter 5). This measurement allowed for the identification of interdisciplinary doctoral researchers based on a rather objective measure—references to other disciplines—, rather than on teamwork or communication (Rafols and Meyer, 2007).

Fifteen of the most interdisciplinary researchers were selected for their high Rao-Stirling index. These are marked with rings in Figure 6.2. A few doctoral researchers with high Rao-Stirling index were not selected because they were not the first author of interdisciplinary publications. Their interdisciplinarity index was the result of their collaboration with other interdisciplinary researchers within the sample who were the first authors of interdisciplinary publications and were selected for interview. This criterion allowed us to focus on doctoral researchers whose main line of research is interdisciplinary.

The doctoral researchers were invited via email to participate in interviews. The email explained how they had been selected to participate in the study, and the researcher's

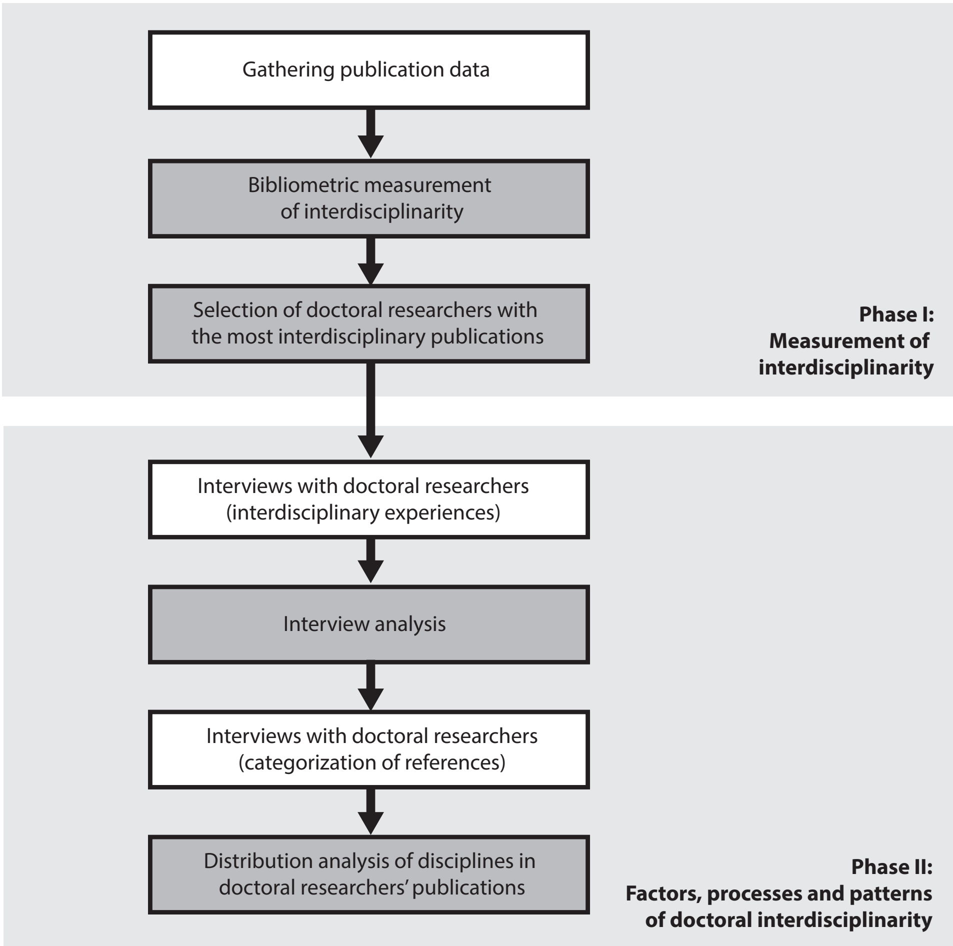

Figure 6.1: Methodology employed in phases I and II. The data collection is represented with white boxes and the gray ones refer to the analysis of the data.

interest in understanding what factors contributed to the integration of disciplines in their publications. Each of the fifteen researchers agreed to participate. All participants had been doctoral candidates for at least 1.5 years. One researcher had recently graduated and two were in the process of writing their theses.

The data was collected using in-depth interviews (H. J. Rubin and I. S. Rubin, 1995), which lasted between 50 and 80 minutes and focused on their experiences, their publications, the influence of the program, the department and its academic staff; the management of opportunities and tensions from working in multiple disciplines were also discussed These topics were selected from the literature on interdisciplinarity at the doctoral level and were used as guides for discussions instead of as preconceived concepts around which to organize the data. Although the questions were prespecified and listed in an interview

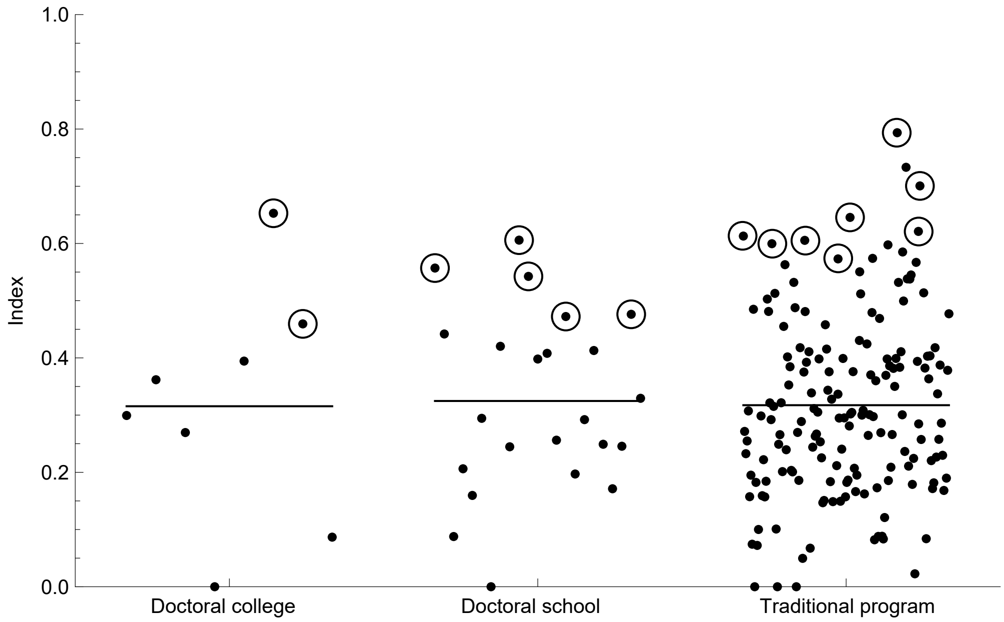

Figure 6.2: Identification of the most interdisciplinary doctoral researchers (marked with rings) according to the Rao-Stirling diversity index and its interval of uncertainty.

protocol (see Appendix 8.3.2), they were reworded and reordered as needed, so as to maintain a "natural" conversation with the participants. Additionally, each researcher could report on issues especially relevant for him or her. The interview guide was basically used as a conversation guide. It was a tool for ensuring that important topics were addressed, and for maintaining consistency across individual interviews.

The interviews were recorded and transcribed. After having read the interviews several times to obtain an overview of the data, the information was then separated, sorted and synthesized through qualitative coding following the steps and practices specific to grounded theory. We selected incident-to-incident coding (Charmaz, 2006) for our initial analysis of the interviews. The comparison of incidents allowed for the identification of important topics that could be treated analytically. This was an emerging process in which information was compared at different levels: data to codes, code to code, participant to participant. By making and coding numerous comparisons, our coding system was further refined. Coded data was also synthesized and organized establishing subcodes that specified the properties and dimensions of a code. Therefore, the data that had been previously fractured during the initial coding was later reassembled to provide coherence to the emerging analysis results.

This research process facilitated the interpretation and understanding of the processes of becoming an interdisciplinary early-career research in the respective doctoral programs. Moreover, it also led to the development of further ideas and questions which dealt with: (i) the understanding of how doctoral researchers link knowledge from other disciplines into their CS research, and (ii) the relationship of the processes of becoming interdisciplinary with different forms of interdisciplinarity.

With the above in view, we interviewed the fifteen doctoral researchers again. This time we asked them to categorize the references of two of their publications into disciplinary fields using one to four disciplines of the same taxonomy that was used in the previous study (see Appendix 8.3.2). Data of the 30 publications were collected in personal interviews (see interview protocol in Appendix 8.3.2), instead of via a questionnaire, in order to ensure high quality data. The procedure was the following:

1. Prior to the interview all the references of the participants' publications were gathered and then downloaded in digital format and saved on a computer that we used in each of the individual interviews.
2. At the beginning of each interview we explained the purpose of the meeting and the importance of the participant providing objective data without exaggerating interdisciplinarity or single-disciplinarity. Since interdisciplinarity is receiving increased attention from the scientific community, policymakers, and funders (Holland, 2014), we emphasized that they (our participants) would not be evaluated in terms of interdisciplinarity.
3. The participants became acquainted with the taxonomy of disciplines before they were asked to categorize their disciplines. Time was given to each researcher to read through the list of disciplines and ask for clarification if needed.
4. Participants could use computers to open the references one at a time. They were given as much time as needed to recognize the reference, and read it if necessary.
5. To categorize each reference, participants were then asked to which discipline/s the reference was contributing. It was explained that contribution refers to an advancement of a field. The example given was that the mere use of the statistical test ANOVA in a publication does not constitute a contribution to statistics since it is not an advancement of the statistics field.
6. To confirm that the request and the task was understood, each participant was asked to think out loud and explain their choice of disciplines for each reference.
7. Once the participant had finished the categorization of each reference, they were asked whether the reference contributes to any other discipline. The participant was reminded that the categorization into only one discipline is as correct as the categorization into multiple disciplines.

The categorization of references into disciplinary fields could have been obtained from the Web of Science, as it was done in the first phase of this study; however, the categorization

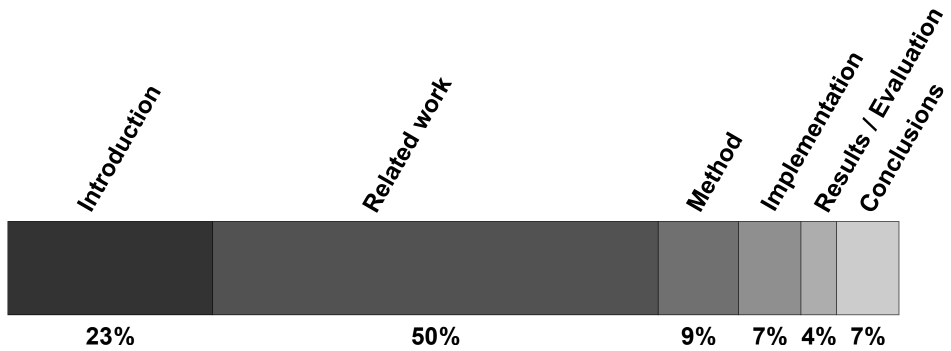

Figure 6.3: Distribution of the 1,042 references among the sections of the doctoral researchers' publications.

process described above provided us not only with a very reliable categorization by the first author of the publication, but also with information on the distribution of referenced disciplines into the sections of the researchers' publications. The latter is important because references to other disciplines in scientific publications have different functions depending on the section in which they are placed. For instance, a reference in a section that describes the state of the art is likely to illustrate the latest advances related to the topic of the publication. Instead, a reference in a section that describes the methodology will probably support the methodological approach.

A total of 1,042 references were categorized into disciplines. In order to facilitate the comparison of sections across the 30 researchers' publications, the latter were mapped to a common structure of sections. A typical structure of CS publications was selected, which also correspond to the most frequent structure in our dataset: introduction, related work, methods, implementation, results/evaluation, and conclusion. Since references are not equally distributed among the sections of the publications, we calculated the percentage of references in the different sections and based our analysis on the sections with the highest proportions of references. These are "introduction" and "related work", containing 23% and 50% of the references respectively (see Figure 6.3). By focusing on these sections a more robust comparison across publications can be conducted.

In the following sections, the results of the analyses are presented. Quotes taken from the interview material are labeled indicating the researcher's doctoral program and source of funding.

6.3 Factors and Processes Influencing Doctoral Interdisciplinarity

The analysis of the interviews revealed two different kind of aspects that influence doctoral interdisciplinarity: the first included the disposition of the individual and their experiences prior to doctoral studies; the second contained process and factors related to the context in which they conduct their research, such as the doctoral program and the department, as well as their interaction with other individuals.

6.3.1 Antecedents and Attributes of the Individual

We define "antecedents" as a constellation of personal attributes that emerge gradually and shape the intellectual orientation of the individual prior to the beginning of doctoral studies. It is important to realize that the following antecedents are not disjointed. They interrelate in theory and practice, in complex and important ways.

Values

Personal values generate behavior providing an internal reference of what is good, important, useful, desirable and constructive (Rokeach, 1973). We refer to interdisciplinary values as described by Stokols (2014)—the principles that predispose the individual towards acquiring a broad understanding of complex research and societal problems and translating integrative insights about them into practical solutions. The early attraction to IDR often appeals to social consciousness and connects with the public good (Pfirman and P. Martin, 2010). In this sense, five of the interviewed researchers see their PhD as a part of something bigger to which they are contributing. The synthesis of areas is a key aspect of their research that elevates the significance of the application area to a level where it is not just one of many possible areas where technology can be applied. As one researcher notes:

> "For me it is not so important that I have a big technological invention, but that I solve [a real-world problem]. It is not just a topic that I would easily exchange for some other problem. The fit between the two areas is important."
>
> Quote 6.3.1: Researcher in the doctoral school with scholarship.

These doctoral researchers reported that peers who conduct fundamental CS research do not necessarily share their values, and view research initiatives with holistic approaches as less rigorous. Yet values play an important role here because doctoral researchers may appeal to the value of their IDR to justify and assure themselves of the relevance and complexity of their study. However, the majority of researchers with high IDR did not share this opinion. Ten of the interviewed researchers have a more discipline-centric view and consider the other disciplines as application examples for CS methods. They understand the value of their research as an advancement of CS, which they regard as valuable because it could eventually serve the public good and affect the development of other disciplines when experts in other fields build upon it.

The interdisciplinary intellectual orientations highlighted in this section reflect the intellectual identity of the individuals. Doctoral researchers with high interdisciplinary values are proud of their interdisciplinarity and define themselves not as computer scientists, but as “inter-a-couple-of-areas” researchers, whereas researchers with a discipline-centric view define themselves as computer scientists even if their publications are highly interdisciplinary.

Motivations

In order to illustrate the kinds of motivations that drive doctoral researchers to conduct IDR, we draw upon the self-determination theory (Gagné and Deci, 2005). In this case, motivation for interdisciplinarity can be seen as a continuum between amotivation and intrinsic motivation, where the former involves having no intention to conduct IDR and the latter describes an individual purely motivated by enjoyment or interest in the interdisciplinary topic itself. In between, there are several types of extrinsic motivations that vary in their degree of self-determination.

Interdisciplinary values in combination with intellectual interests beyond the boundaries of a single discipline resulted in a powerful intrinsic motivation for four of the interviewed researchers. On the one hand, working in two areas was seen as providing greater intellectual enrichment and was regarded by these researchers as more interesting and satisfying than single-discipline research, even though connecting different disciplines involves difficulties. An intrinsic reward, on the other hand, was reported to come from working on a solvable problem with a direct application that does not have the characteristic uncertainty of basic research, of not knowing how the outcome is going to be used in practice. As one researcher explained, this justified the added effort required to carry out interdisciplinary work:

> “Although understanding other fields takes additional effort, it is also rewarding because you are not focusing on a problem that is the size of an ant. You can have a broad perspective and actually have an impact with your work.” Quote 6.3.2: Researcher in the doctoral school with scholarship.

Ten out of the remaining eleven doctoral researchers also reported to be intrinsically motivated by their research, but with their main interest in the field of CS. The choice on their interdisciplinary topic was mainly motivated by external factors such as the availability of funding or their own beliefs of what constitutes a good research topic in CS. The interest that the CS community has in a topic, its scalability, and its applicability to different scenarios are some of the attributes that describe a good topic in CS. Such researchers are primarily concerned with consolidating a career in the field of CS, rather than in the intersection of disciplines.

Previous Skills and Knowledge

A scholar’s intellectual orientation emerges gradually over the course of her or his career and is shaped through exposure to multiple learning environments, mentors, and research settings (Stokols, 2014). Undergraduate and graduate studies, as well as work experiences, are formative stages during which intellectual orientation emerges more clearly (Bammer, 2005; Golde and Gallagher, 1999; Misra et al., 2009).

Although in the last years new undergraduate and graduate interdisciplinary curricular strategies have been implemented in some European universities, none of the researchers in the sample graduated from an interdisciplinary undergraduate or graduate program. Instead, they graduated from a program that had either a broad coverage of CS or a focus on specific areas within the discipline. Some researchers had experience with other disciplines prior to the start of their doctoral work. In two cases, motivational factors led researchers to receive training in other disciplines, while another two came into contact with other disciplines through work and research initiatives. Such experiences not only provided them with an overview of the research possibilities that disciplinary intersectionality offers, but also developed their ability to synthesize disparate disciplinary and philosophical perspectives, foster the skills needed to conceptualize and work with constructs and theories. This situation manifested itself in a researcher's experience in bridging two fields.

> "I have a background in CS and a lot of training in [other discipline]. I bring the two fields together. There are computer scientists in this field who don't have the skills in [the other discipline] but they contribute to this area. On the other hand, there are the experts in [the other discipline] that do not need to have any technical knowledge about using a software application, and even they contribute to this field. Then, there is me, I consider myself to be in the middle. I have training in both areas and I try to combine them, which is sometimes difficult."
>
> Quote 6.3.3: Researcher in the traditional program and self-funded.

Other researchers without previous experience in other disciplines had either a broad education in CS (seven researchers) or were specialized in a subfield of CS (four researchers). Those with a broad education developed the ability to identify, learn, and combine the necessary CS methods to solve a problem independently of the field of application, whereas those specialized in a subfield of CS had slight acquaintance with another discipline to which the CS methods are applied.

6.3.2 Processes during Doctoral Studies

Although all researchers that we interviewed have published high interdisciplinary work according to the quantitative measurement, the substantial differences in their antecedent experiences influence the subsequent doctoral experiences.

Policy and Structural Factors

The demand for ubiquitous computing in society has resulted in an increase of collaborations between faculties of CS and other disciplines. Moreover, joint projects with industrial partners have become an important income stream for CS faculties. Applied CS research aims to provide technological solutions for existing problems in a real-world context and/or a different field of expertise. Thus, the research of such projects generally involves some form of interdisciplinarity.

Many research projects in the department fit this description. All the interviewed researchers that receive funding from these kinds of projects (six researchers) understand the importance of responding to the needs and requirements of research patrons in order to fund their research. The availability of funding constitutes an extrinsic motivational factor that leads researchers to adapt their research plans to the research objectives of their funded project. Accepting a project assistantship necessitates focusing on the project's research field and topic, which reduces the research autonomy of project members. The application scenario (the other discipline) is usually regarded only as a case study or evaluation scenario for a new technology or methodology in the field of CS, where the main contribution lies. This is motivated by the uncertainty of future funding for the specific intersection between disciplines where the previous research was done. As a result, members of project teams focus on CS with the goal of deepening their expertise in CS through consecutive projects applied to different disciplines. This drive to demonstrate expertise in CS was observed in the participants with less interdisciplinary antecedent experiences. One researcher described how it discourages researchers from emphasizing the connection between CS and another field:

> "One should try to write publications that are not application driven. For instance, the term [application scenario] should not be in the title [...] It is good to include a wide variability of [other applications], so that nobody could say that it is biased to [application scenario] [...] I had enough of [that application scenario]. Now I would like to adapt the methods that I developed and make them better for general applications."
> Quote 6.3.4: Researcher in the traditional program with project assistantship.

University assistants (three in the sample) have more research autonomy than project assistants. Their research questions are mainly influenced by their doctoral group's line of research, their supervisor and the researcher's interdisciplinary antecedents. The doctoral college with academic staff from several departments (one doctoral researcher represented in the sample), had the most interdisciplinary organization. This integrative approach, nevertheless, was compromised by the source of researchers' financial support: a project assistantship where the research does not necessarily involve other disciplines or departments nor does it require IDR.

The five financially independent researchers (e.g., self-funded, scholarship recipients) including three in the doctoral school and two in the traditional program, had the highest level of research autonomy. Their autonomy allowed them to be free to choose and change their dissertation topic, provided they could find a supervisor for their research. Although all interdisciplinary researchers in this situation would prefer to have an employment in the department, only the four who had highly interdisciplinary antecedent experiences valued the freedom that financial independence granted them because it allowed them to fulfill their interdisciplinary aspirations and realize their values. A researcher explained:

> "I think the scholarship gave me the possibility to discover my topic. I doubt I would have been able to do that if I would have had a specific customer for my research, like the research institute, or a project with a more defined problem." Quote 6.3.5: Researcher in the doctoral school with scholarship.

Financial independence allows doctoral researchers and supervisors to experiment with new research questions and unconventional paths. This is especially the case when the research questions, although promising, are too unconventional and at high risk to be financed by their research group or other entities, as was the case of three researchers. They recognized this situation, as one indicated:

> "The methods employed in my research although very useful, are unusual and very difficult to frame because they are in between everyone's. In addition, due to the novelty of the research question that I tackle, I need to sell the problem and the solution at the same time, which is an additional difficulty. However, I am very well shielded from that by the fellowship that I receive. I brought my own money and the department accepted my topic."
> Quote 6.3.6: Researcher in the traditional program with scholarship.

Scientific Networks: Collaboration and Supervision

Project assistantships, especially those supported by industrial partners or external funders, determine who the doctoral researchers' supervisor and project leader will be, as well as their academic network. Dissertation supervisors are often project leaders and influence the degree to which different disciplines are integrated in the project. As one researcher described, this had a direct influence on his research and dissertation:

> "My supervisor is concerned that my Ph.D. is maybe too applied. He means that the contribution to the field [CS] is very limited if you are very applied. In my PhD thesis I have to state how I can use these methods with other data of other fields."
> Quote 6.3.7: Researcher in the traditional program with project assistantship.

Because applied projects usually involve some form of interdisciplinarity, they usually require the participation of research or industry partners from different fields. The most common approach of collaboration in these projects is multidisciplinary. Although such collaborations might produce excellent research, the exchange of knowledge is limited, and each researcher continues on an independent trajectory with low interdisciplinary enrichment (Borrego and Newswander, 2008). Cross-collaborations were especially hindered when partners assume the role of a client who is not involved in the research activity, and just provides a problem description and feedback on the resulting product or software. This situation was reported by five out of the six interviewed researchers that are involved in projects requiring collaboration with different fields. One researcher commented on the lack of knowledge exchange with the industrial partner:

> "I am given the description of their problem, data and the expected result. From that point on I do not receive any more input from them."
> Quote 6.3.8: Researcher in the traditional program with project assistantship.

The four doctoral researchers with a higher degree of autonomy than project assistants but low interdisciplinary antecedents chose to conduct IDR due to external motivational factors. All of them became participants in the supervisor's research agenda and networked with the supervisor's collaborators. Their cross-disciplinary collaborations are, therefore, heavily influenced by the research interests of the supervisor. In contrast, the four researchers with a high degree of autonomy and high interdisciplinary antecedents selected highly interdisciplinary lines of research even before finding a supervisor. They were determined to find a supervisor interested in their interdisciplinary aspirations and took an active role in presenting their topic to prospective supervisors, rather than simply accepting an available topic. For three out of the four researchers with high autonomy and high interdisciplinary antecedents, finding a willing supervisor of IDR was challenging, as one researcher reported:

> "I contacted people in different universities and presented to them what I wanted to do. I think I talked with at least 10 professors. I described the idea of what I wanted to do but most of them told me that they didn't have time. It was difficult to get in. My supervisor said 'well, that is interesting. Have a look at this material and come back with a written proposal'. We refined the proposal in two or three meetings and I started to do my work."
> Quote 6.3.9: Researcher in the traditional program and self-funded.

Because research in CS is highly collaborative, single-authored publications are uncommon. Doctoral researchers in CS normally collaborate with other doctoral and postdoctoral researchers in their research group. However, interdisciplinary doctoral researchers with an unconventional topic often find themselves working solo as their colleagues do not have experience in the topic. This was the case of three researchers in the sample. For all of them, a supervisor who shares their IDR perspective and values was reported to be especially important:

> "My Ph.D. is supposed to be in [a CS area], but some parts belong to other disciplines. I think my supervisor would be very angry and would defend my

research against someone who is trying to say that it is not the right topic in CS." Quote 6.3.10: Researcher in the traditional program with scholarship.

In order to gain specific knowledge and feedback that is not available in their research group, these three doctoral researchers with unconventional topics also network more with academics of other disciplines, compared to the rest of the interviewed researchers. Moreover, truly interdisciplinary collaborations (i.e., different disciplines working closely together combining their knowledge in an integrated way) were common among these doctoral researchers. For all of them, such networking efforts resulted in adding a secondary supervision from another research field, which could be considered an indicator of truly IDR.

6.4 Patterns of Doctoral Interdisciplinarity in Computer Science

According to the Rao-Stirling index, each of the fifteen researchers who participated in this study had referenced different disciplines in their research. While this is true, there are differences on how and to what extent these different disciplines are actually integrated into the research of the doctoral researchers. It is the analysis of their interviews that revealed this additional information about their interdisciplinarity.

6.4.1 Patterns of Interdisciplinarity

Three distinct patterns of interdisciplinarity researcher emerged, which are also related to different higher education structures and processes. The *integrative pattern* refers to the incorporation of knowledge from different fields with holistic understanding that goes beyond a single discipline. The *disciplinary pattern* refers to a juxtaposition of disciplines in which the disciplinary elements retain their original identity; this juxtaposition also occurs in the *specialist pattern*. The difference between the last two patterns is associated with the educational structures that the doctoral researchers followed during their undergraduate and graduate studies (see Figure 6.4).

Integrative Pattern

The integrative pattern describes individuals who truly conduct IDR, synthesizing different disciplines and establishing a new level of discourse that goes beyond the boundaries of a single field. Their research emphasizes holistic thinking by tackling the research question from different knowledge perspectives that aid the understanding of a bigger picture.

Four doctoral researchers with this pattern were identified. All of them had received a broad education in CS—covering the general principles and overarching concepts of CS—and they also had contact and experiences with other disciplines prior to the start of their doctoral studies. Two of them received training in other disciplines informally or by enrolling in related university studies. The other two had participated in research

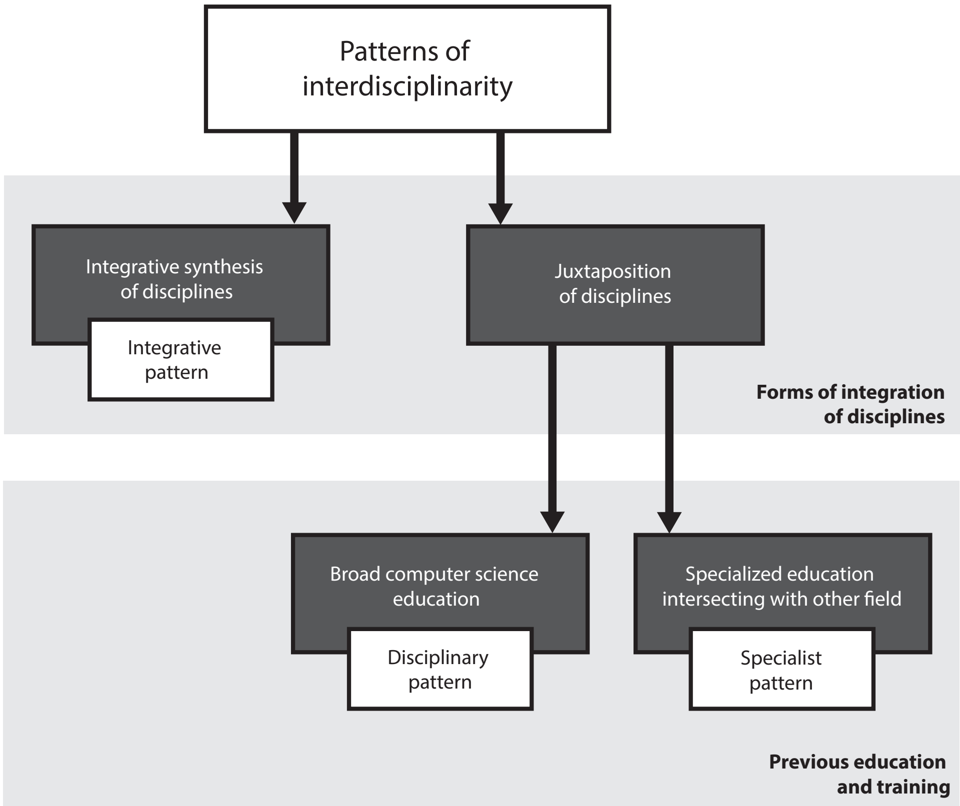

Figure 6.4: Patterns of interdisciplinarity in computer science.

initiatives that related CS to other disciplines. Three of the four integrative researchers reported that such experiences gave them an overview of the research possibilities at the intersection of disciplines, which later became the line of research during their doctoral studies:

> "I have always been interested in [other discipline]. I worked in [other discipline] for my master's thesis and in a job. I also read a lot about the area, and got to know that [other discipline combined with CS] was something that was developing as an interesting topic."
> Quote 6.4.1: Integrative researcher in the doctoral school with scholarship.

All four integrative researchers commented that IDR requires more effort than traditional CS, and perceived that IDR might bring them future career challenges in traditional departments organized by separation between the fields. However, their intrinsic motivation to conduct IDR, and the added intellectual enrichment of working in multiple fields was regarded as more interesting and satisfying than single-disciplinary research.

> "I had no idea that CS could be applied to [a specific discipline] which is my hobby. Only when I decided to study for a PhD and did some literature research did I find out that there is a lot of [other discipline] in computing research. When I saw this, I suddenly identified the field for me because it is computation, which is my profession, and it is [other discipline], which is my passion [...] However, it is hard because I am in the middle. The worst thing of it is when you are not accepted by computer scientists and also not by [experts in the other field]."
> Quote 6.4.2: Integrative researcher in the traditional program and self-funded.

Integrative doctoral researchers derived intrinsic satisfaction from working on a problem that directly applies to society. This contrast with basic research, which is often conducted in the absence of knowing its possible consequence for application. In this sense, three of the four integrative researchers reported that it was important to have a positive impact in the real world, rather than having a major technological invention. The influence of interdisciplinary values on integrative doctoral researchers is clear. IDR appeals to their social conscience and desire to contribute to the public good. In this sense, our participants see their PhD as contributing to a larger cause meaning the public good. Thus, the synthesis of multiple disciplines is critical in order to have a significant impact. The application area is viewed as an essential part of the topic where the doctoral researcher can contribute and network, even if this involves diverging from the discipline of the CS department and not reaching the high level of expertise of scientists who specialize:

> "I like working on a real-world problem, that is important for me... something that might be applied in order to make the world a bit better in the end [...] That is what motivates me, but of course sometimes you feel you are not really an expert. I am an expert in this intersection, but I will never know as much about the technology as somebody who is focusing only on this part."
> Quote 6.4.3: Integrative researcher in the doctoral school with scholarship.

As discussed in Section 6.3.1, such values are important for reinforcing the motivation of the doctoral researcher to conduct research with positive repercussion in society, at the same time, vindicating the complexity of their research when its scientific value is perceived by single-disciplinary researchers.

The interdisciplinary goals and motivation of integrative doctoral researchers were supported by financial independence (scholarships of self-funding) which freed them from working on a narrowly defined CS project and afforded them the option to choose PhD topic and supervisor; it gave them the opportunity to conduct truly interdisciplinary research (see Quote 6.3.5 from an integrative researcher with scholarship). Financial independence led to scientific independence so researchers could focus on their fields of interest and explore unconventional lines of research without having to adhere to the single-disciplinary expectations of research patrons.

The support of academic staff to conduct truly interdisciplinary research was also crucial to facilitate doctoral researchers' true interdisciplinarity, as well as the contact with a network of researchers of other disciplines to gain knowledge and feedback outside CS. Three of the four researchers classified in this pattern actively sought out a suitable supervisor for their interdisciplinary PhD. Quote 6.3.9 et seq. provide examples of the agentive actions that these interdisciplinarity researchers took in order to receive supervision for their research topics.

> "I applied to be a student volunteer at a conference. The person who became my supervisor was there. I liked what s/he talked about. Later I sent an email to that person saying that I wanted to work on a couple of ideas that are related to what is now my PhD topic. [...] We always choose people that are similar-minded to us. I chose that one."
> Quote 6.4.4: Integrative researcher in the doctoral school with scholarship.

It could also be observed that they are rather agentive initiating collaborations with experts of other disciplines, and work closer with them, as compared with researchers that fall within the disciplinary and specialist patterns.

> "Especially when you are at a technical university but you work in [the other field], you need collaborations to survive. [...] One needs many years to establish contacts in other fields. [...] I decided to become an intern in a research group in [the other field]. That's how I got to know my second supervisor [...] I have also tried to spread the message that I am looking for people in [the other field]." Quote 6.4.5: Integrative researcher in the traditional program with a scholarship.

Disciplinary and Specialist Patterns

The disciplinary and specialist patterns describe doctoral researchers who conduct basic research in multidisciplinary projects. Within their research project, disciplines are placed side by side with each making a separate contribution to the project without real integration. Six participants were identified as disciplinary researchers and five as specialist researchers. Their research is not of inferior quality nor less necessary to solve real-world problems, than the research of integrative researchers. The difference is that researchers in the disciplinary and specialist patterns had a discipline-centric perspective of their research—investigation aimed to contribute to a single field and exclusively targeting its venues and audience. These researchers view the primary purpose and value of their work as advancing CS. Nevertheless, they reported that their work had the potential to be useful to other disciplines if experts in other fields apply their contributions to solve problems in other fields:

> "I developed a technique that is purely CS but it is useful when it is applied to [other field]. Eventually, this technique will be used by professionals in [other field]. This is motivating me to improve my work because I know that if it's really good they might use it."
> Quote 6.4.6: Specialist researcher in traditional program with project assistantship.

> "I wouldn't say that I have contributed to another field. I may have contributed in the sense that my tool might be useful for [experts in other discipline], but not in a scientific way."
> Quote 6.4.7: Disciplinary researcher in the doctoral school with scholarship.

Although disciplinary and specialist doctoral researchers find their research motivating, their incentive to involve other disciplines in their research is not intrinsic. Instead, it is driven by extrinsic factors such as project funding, supervising, and the interest of the CS community in the topic. This is a major differentiator for this pattern. The seven researchers in the disciplinary and specialist patterns responding to the expectations of research funders had limited freedom in what they would study and how they would go about it. One researcher explained how the choice of the topic was influenced by PhD funding:

> "When I started to think about doing a PhD, I was planning to do something in [a CS area], but at the end it turned out that there was not going to be another project in that area. When the project in which I am currently employed was accepted, I knew that I was going to do my PhD in this other topic [related to the project] because I would have funding for three and a half years, and that would be enough to finish the PhD."
> Quote 6.4.8: Disciplinary researcher in the traditional program with project assistantship.

When interdisciplinarity occurred, it was due to the project requirements rather than the doctoral researcher's intrinsic motivation. The project typically defines the topic, determines the academic supervisor and shapes collaboration with other fields.

> "In our first meeting my supervisor presented what s/he was doing and recommended his/her topics. [...] I then had to select subfields and discuss them with my supervisor. Depending on his/her feedback, I thought about the direction I should take. Without him/her, my topic wouldn't be my topic. Definitely."
> Quote 6.4.9: Disciplinary researcher in the doctoral school with scholarship.

In contrast, the four researchers who had more autonomy to choose their topic made their decision on what they thought constitutes a good research topic in order to build a strong foundation for a career in CS.

> "This topic is getting more and more interesting, and more and more people are working on it. Since I started my PhD, this topic has attracted the attention of top US American and European universities. [...] If you do not hit it [a topic] when it is hot, later it is going to be more difficult. [...] I was motivated to work on a hot topic, although I did not know what the outcome would be."
> Quote 6.4.10: Disciplinary researcher in the doctoral school with scholarship.

The skills and experiences doctoral researchers acquired prior to their PhD studies constitute important factors that differentiate the disciplinary and specialist patterns:

Disciplinary Pattern All researchers in the disciplinary pattern had had a broad CS education. They had studied the theories and methods of CS sub-fields extensively. This enabled them to combine different CS methods to solve problems in various other disciplines. This is common in some CS areas, such as information science which can be applied in many other disciplines as different as genetic research, finance, etc.

> "It is good to learn to have knowledge of different areas of CS because you can then adapt to new tasks and new jobs. Since CS is prone to changes, you must always be in touch with the new technologies and be able to follow them in order to address new problems."
> Quote 6.4.11: Disciplinary researcher in the doctoral school with scholarship.

These researchers regard other fields involved in their research as application areas that can be easily exchanged with other fields while still applying similar CS methods. Their research focus in CS is seen as their main contribution.

> "Instead of writing a whole bunch of code for each particular field of application, one has to find a way to describe your problem abstractly, and then focus on the modeling and programing."
> Quote 6.4.12: Disciplinary researcher in the doctoral school with scholarship.

Because a doctoral researcher's subsequent funded research project might involve a totally different application area from a different discipline, the researcher considers the effort and resources required to holistically integrate CS and other disciplines to be too high.

> "The key point is that I have limited possibilities to dedicate myself to the other field. [...] In the future I plan to do further CS research with new interesting use cases and scenarios."
> Quote 6.4.13: Disciplinary researcher in the doctoral school with scholarship.

Specialist Pattern Five of the six researchers of this pattern had a highly specialized master's education in the intersection of CS and one more discipline, such as medical informatics, computational biology, or computational economics. In most cases their studies included introductory courses to the field of application. The course curricula aligned with the scientific interests of the research groups of the department. Therefore, most researchers of this pattern had worked on a related research topic during their master's studies, some of them under the supervision of a professor who later became their doctoral supervisor.

> "My master's program offered two courses on [a specific application of CS to another field]. I took both and the professor offered me four topics related to those courses for my master's thesis. I made a random choice and I became interested in the topic, so I continued with the same topic for my PhD again under his supervision." Quote 6.4.14:
> Specialist researcher in the traditional program with project assistantship.

Doctoral researchers in the disciplinary pattern, unlike those in the specialist pattern, do not think that the areas of application can be easily exchanged as they have invested more time and effort to develop knowledge of the other discipline. Instead of considering themselves interdisciplinary researchers, they see themselves as computer scientists that improve CS methods and tools that serve a particular field. The purpose of their work is to contribute to the field of CS and its community.

> "I figured out my PhD research question as I was talking with experts in the other field and reading related literature for my master's thesis. [...] I would not say that I am an expert in [the other field] or I need to be one. However, one should have sufficient knowledge about [the other field] because I am not just developing a technique. I am developing something that will have some application." Quote 6.4.15:
> Specialist researcher in the traditional program with project assistantship.

The policies and structures seem to influence the placement of researchers of each pattern in the doctoral programs. Figure 6.5 shows the researcher classification into the three patterns. Although the doctoral college is an interdisciplinary program that integrates three different departments, the researchers of this program were classified into the specialist pattern. They are employed in projects with strong CS projects, therefore, counteracting the interdisciplinary design of their program. In contrast, specialist pattern researchers are not enrolled in the doctoral school because it mostly recruited doctoral researchers with broad knowledge of CS. The traditional program includes doctoral researchers of the three patterns due to the overall flexibility of its academic program which is largely determined by the doctoral researcher, the doctoral supervisor and the source of funding.

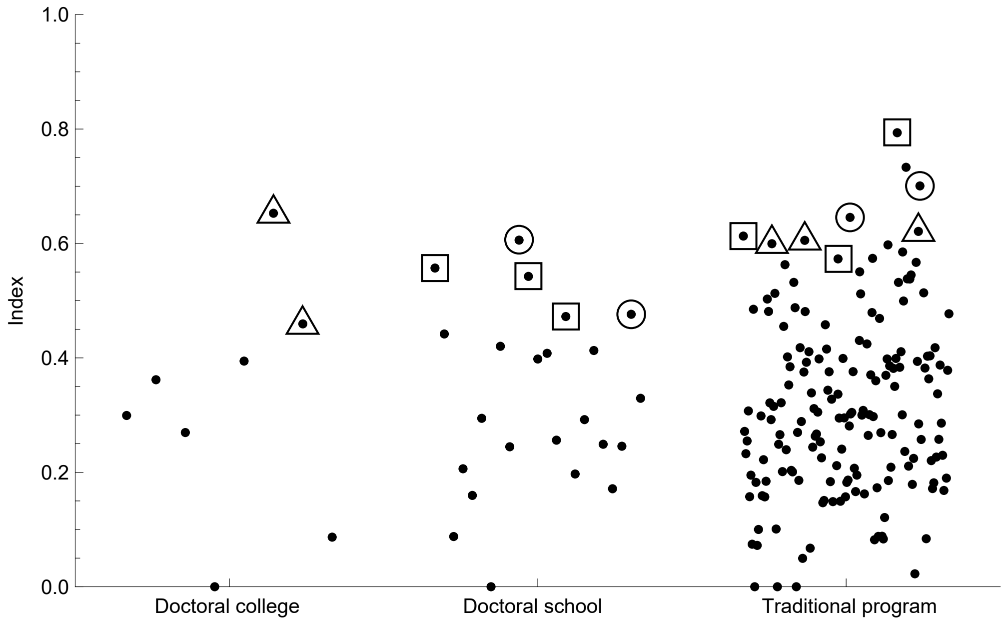

Figure 6.5: Researchers' interdisciplinarity per program. Each point represents a doctoral researcher. Integrative researchers are marked with a circle, disciplinary researchers with a square, and specialist researchers with a triangle. The vertical axis represents the results of Rao-Stirling diversity index, which varies from 0 (no interdisciplinarity), to 1 (the highest possible interdisciplinarity).

The three patterns reflect different intellectual orientations that are associated with variations in researchers' intellectual identity. While researchers who comply with the disciplinary and specialist patterns define themselves as computer scientists, those described by the integrative pattern are proud of their interdisciplinarity and define themselves not as computer scientists, but as researchers across disciplines while making the case for their interdisciplinarity.

6.4.2 Integration of Other Disciplines in their Publications

When doctoral researchers were asked how they integrate different disciplines into their publications the responses differed between researchers in the integrative pattern and those in the disciplinary and specialist patterns.

Integrative researchers report that other disciplines have the potential to play a major role in their publications. As one researcher explained, more or less emphasis could be given either to CS or to other disciplines depending on how one wants to shape the publication:

> "I could give three different perspectives to my work: either from CS, [other discipline] or [other discipline]. The same work could be published in all those communities. That is why, at the beginning, I told my supervisor that I could publish in any of them because they talk about the same thing."
> Quote 6.4.16: Integrative researcher in the doctoral school with scholarship.

Although their papers typically focus on CS, references to other disciplines are used for various purposes: to provide insights into the application area; to produce conceptual frames for a methodology; or for building upon previous work. As one researcher noted, contributions of other disciplines are not confined to specific sections of the paper:

> "If one is discussing his or her work in a specific setting, it is better if one talks from the perspective of [the other field] because the insights are deeper. Regarding previous work, one has a lot of CS papers in which to build upon, but one also brings concepts from other fields. They [contributions from other disciplines] just naturally appear and one introduces them where they are needed to provide a more complete picture of the research."
> Quote 6.4.17: Integrative researcher in the doctoral school with scholarship.

Doctoral researchers who conform to the disciplinary and specialist patterns also use references from other fields. However, their references are less integrated or have a lesser contribution to their publications. One researcher described how s/he keeps a clear separation between the different fields referenced in his/her publications:

> "From time to time I certainly also reference papers from [other disciplines], but I clearly present them in the light of CS. I say 'this is a CS paper and these are my ideas and they are originally from [other disciplines], but we will use them now in this context.' Other sections of my papers, such as the motivation, methods or results focus exclusively on CS." Quote 6.4.18: Specialist researcher in the doctoral college with project assistantship.

The following text from an introduction to one of this researcher's publications demonstrates how the methods and main contribution belong to the field of CS, although there is relevant work from other disciplines:

> "A [non-CS method] has many applications in very broad settings ranging from [list of other disciplines] to several areas of CS (see [references to CS publications]). The computational properties of [such method] are worth studying, particularly in the presence of huge volumes of data. [...] In this paper we consider [CS methods] and introduce [new CS methods]."
> Quote 6.4.19: Excerpt of the section "introduction" of a publication of a specialist researcher in the doctoral college with project assistantship.

References to other fields are not necessarily used as a base upon which to build research. The references are often used as a narrative resource to captivate the reader. As one researcher explains, references can be used to facilitate the readers' understanding of abstract concepts that are difficult to comprehend:

> "Referencing works from other fields is useful to help your reader or reviewer to understand your paper. They will understand that you are not working with imaginary things, but with concepts that are easily understandable because they resemble things that are familiar to them. Then, they could think 'yes, this could work in the real world. It is not conclusive, but it is a proof of concept that could work'."
> Quote 6.4.20: Disciplinary researcher in the doctoral school with scholarship.

Another use of references to other fields is to explain the relevance and possible application of the CS work. Such references add value to the research conducted by the researcher even if its usefulness for a given application has not been established. Most are used to introduce and provide motivation and justification for the research. Occasionally, references are used to describe the state of the art of the other field or its methods.

> "The introduction is where I try to give some justification for its usefulness for [the other field]. The related work is CS. I just cite publications of [the other field] in case they support my technique. This only happened once... actually, I only learned about this study because I talked to [expert in other field] who referred me to the paper I referenced. The rest of the paper should just be CS." Quote 6.4.21: Specialist researcher in the traditional program with project assistantship.

Doctoral researchers whose publications reference other disciplines to which they do not contribute, try to maintain separation between the disciplines. This limits the scope and implications of the research to their area of expertise. If the separation of disciplines is not clear, readers might misinterpret the purpose of the publication. They might, for example, expect more interdisciplinary results or the integration of more complex concepts from the other discipline. One researcher explained his/her experience, which is followed by an excerpt from one of his/her publications where this separation is made clear:

> "Sometimes it is difficult to make reviewers understand that I focus on the programing part and that the use of examples from other fields is not part of my contribution."
> Quote 6.4.22: Disciplinary researcher in the doctoral school with scholarship.

> "The aim of this evaluation is to demonstrate the good performance of these techniques at modeling the functional capabilities of some typical real-world examples. [...] It is important to clarify that our intention is not to invent novel [concepts of other discipline] nor to improve existing ones."
>
> Quote 6.4.23: Excerpt from the section "evaluation" of a publication of a disciplinary researcher in the doctoral school with scholarship.

Doctoral researchers' accounts of how integration of different disciplines was carried out are supported by a quantitative analysis of the integration of references with different disciplines in 30 publications authored by the participants. This analysis is based on the researchers' categorization of their references explained in Section 6.2. Doctoral researchers categorized 650 references into one to four disciplines, resulting in 1120 categorizations. On average each publication had 1.72 categories. We calculated the proportions of references categorized into fields other than CS in the introduction and related work sections of the publications, which contain the highest number of references in the researchers' publications, as reported in Figure 6.3. The results are presented in Table 6.1.

Table 6.1: Proportion of references to disciplines other than CS, in the sections "introduction" and "related work" of the publications of researchers in the integrative, disciplinary, and specialist patterns. These estimated values were calculated with a bootstrapped sample of 50,000 elements with replacement.

Pattern	Proportion	
	Introduction	Related work
Integrative	63.37%	52.68%
Disciplinary	20.94%	35.57%
Specialist	18.92%	19.59%

Table 6.2: Results of the chi-square test for equality of two proportions to check whether the proportion of references to disciplines different from CS is equal for each pattern in the sections "introduction" and "related work". P-values lower than 0.05 are marked in bold.

Pattern	P-value	
	Introduction	Related work
Integrative – Disciplinary	**0.291e-8**	**0.439e-5**
Integrative – Specialist	**0.558e-10**	**0.451e-14**
Disciplinary – Specialist	1.4×10^{-1}	**0.900e-3**

We compared these proportions pairwise with the chi-square test for equality of two proportions with a 95% confidence level. The tested null hypothesis assumed that the proportions of the two patterns for a given section are equal, while the alternative hypothesis supposed that the proportion of the first one is greater than the proportion of the second one. According to the results of Table 6.2, the null hypothesis is rejected for all cases except for the comparison of the proportions in the introduction section of researchers in the disciplinary and specialist patterns. Therefore, we assume that integrative researchers integrate more references from other fields in the sections analyzed than researchers who fall within the disciplinary and specialist patterns. This constitutes an empirical indication of their more holistic integration of disciplines. In contrast researchers in the disciplinary and specialist patterns reference a higher proportion of works in the field of CS, which corresponds to their main interest. However, researchers in the disciplinary pattern are more likely to integrate more references in their related work than researchers in the specialist pattern.

Table 6.3: Summary of the characteristics of the patterns of interdisciplinarity.

	Integrative	**Disciplinary**	**Specialist**
Type of interdisciplinarity	Truly interdisciplinary	Multidisciplinary	Multidisciplinary
Values	High	Medium-Low	Medium-Low
Motivation	High	Medium-Low	Medium-Low
Previous skills and knowledge	CS and other discipline	Broad CS knowledge	Specialized CS knowledge applied to other discipline
Funding	Self-funded and scholarship recipients	University and project assistantships	University and project assistantships
Supervision	Co-supervision	Single-supervision	Single-supervision
Collaboration	High agency networking with other discipline	Supervisor's networks. Different disciplines with new projects	Supervisor's networks. Same discipline with with new projects
Disciplines other than CS in publications	As important as CS	Less important than CS	Less important than CS

The patterns of interdisciplinarity identified in this study indicate that not only diverse kinds of interdisciplinarity exist, but there are also different kinds of interdisciplinary doctoral researchers. Table 6.3 summarizes the characteristics of each pattern of interdisciplinarity.

6.5 Discussion and Implications

A variety of issues are conflated with the pursuit of interdisciplinary scholarship among young researchers. Institutions with a long, single disciplinary tradition, such as the context of our study, add a layer of complexity to the implementation of structural and curricular strategies that aim to promote interdisciplinarity (Golde and Gallagher, 1999). Common strategies for interdisciplinarity are grounded on the notion that it brings together ideas and people from different disciplines in order to jointly frame a problem. As a result, most of those strategies are based on curricular structures that involve different departments, members from different departments and courses from different fields; as it is the case of the university where this study is conducted. Our findings support Boden, Borrego, and Newswander's (2011) observation that because higher education institutions have evolved to support single-discipline research, they may be ill-equipped to facilitate IDR and such curricular initiatives alone are insufficient.

Our study shows that interdisciplinary doctoral research depends upon far more than the presence of such structures. As Boden et al. (2011) have suggested, it takes a unique type of individual to flourish as a truly interdisciplinary doctoral researcher. Truly interdisciplinary prospective doctoral researchers, who saw themselves between intellectual communities, broke the mold of the traditional doctoral applicant in terms of high interdisciplinary values, motivations, as well as skills and knowledge. Those with low interdisciplinary antecedent experiences did not pursue a truly integrated research agenda and work within cohesive research communities in CS. Their experiences are actually more similar to the experiences of doctoral researchers with discipline-specific topics. Our findings suggest that actual predoctoral work in a field other than CS is far more important than Nash's (2008) and Stokol's (2014) frameworks, and descriptions of predisposing variables and principles would suggest for a doctoral researcher to engage in IDR. Therefore, from the perspective of policy and practice, recruitment of doctoral researchers to engage in IDR should consider antecedent experiences in addition to exceptional academic records.

Funding, independence and freedom are factors associated with creativity and interdisciplinarity (Amabile, 2006). However, interdisciplinary expectations often do not match available research positions which, if accepted, result in unfulfilled values and suppress the intrinsic motivation of the doctoral researchers with high interdisciplinary antecedents. Financial autonomy gives researchers the necessary independence to fulfill their interdisciplinary ambitions. It is remarkable that all the truly interdisciplinary researchers interviewed were financially independent, enrolled either in the traditional program (self-funded or as recipients of external scholarships) or in the doctoral school (recipients of departmental scholarships), even though neither of these programs implemented these funding schemes in order to facilitate interdisciplinarity. Given that the funding scheme of the doctoral college is based on existing research projects to which doctoral researchers are assigned, research autonomy is constrained and the degree of research integration depends on project objectives.

Academic staff also serve as gatekeepers of interdisciplinarity. Single disciplinary membership and the lack of institutional incentives towards IDR discourage academic staff from an interdisciplinary career. This results in a low number of truly integrated research projects and fewer opportunities to be supervised, even if the doctoral researchers are financially independent. Supervising IDR involves additional effort on the supervisor's part, s/he has to supervise in a different way (and ignore the departmental and disciplinary ties that discourage IDR) therefore shielding the doctoral researcher from unsupportive academic staff. As interdisciplinary supervision often involves double supervision, the supervisor of a truly interdisciplinary doctoral researcher should value the scientific contribution made not only to her or his own research fields but also to other fields. Although double supervision was uncommon in this study, all the truly interdisciplinary researchers interviewed sought additional supervision in order to complement the expertise of their main supervisor. Their connection to a second supervisor was only possible because they also invested more effort into the development of their own network compared with the researchers who focused exclusively on CS (and mostly rely on the networks of their supervisors). In this respect, truly interdisciplinary doctoral researchers resemble the innovative researchers described by van Rijnsoever, Hessels, and Vandeberg (2008) as researchers who engage more in research collaborations. Therefore, social and community skills should also be taken into account during the process of recruiting a different kind of doctoral researcher (D. Boden et al., 2011).

Collaborations with other disciplines, however, do not necessarily constitute a multidisciplinary or interdisciplinary team, as defined by Rosenfield (1992) or Young (1998). We observed that project members from different disciplines do not research as a team. Moreover, in a few cases, external project partners did not participate in research activities. The research outcome is, therefore, advancing solely one field, while team members from other fields only act as advisors and do not integrate the research outcome into their own field. As stated by Pfirman and Martin (2010), the difficult task of managing teams becomes even more challenging when the team is interdisciplinary. Without institutional support, resources, and recognition—factors which help overcome the personal and professional challenges associated with interdisciplinary collaborations—both academic staff and doctoral researchers are discouraged from pursuing IDR.

The sociocultural perspective that suggests that individuals are subject to the social world, in its immediate and premediate forms, through a relational interdependence (Billett, 2006), strongly elucidates the importance of considering both researchers' predoctoral experiences and dispositions with their doctoral settings and interactions to explain their involvement in IDR. The factors identified in this study are closely interrelated, and should not be considered independently, but rather as a linked set of determinants. They play a crucial role in interdisciplinarity at the doctoral level, giving rise to IDR in programs without an interdisciplinary focus or compromising the interdisciplinary goals of an interdisciplinary program. Moreover, these factors are involved in the definition of the three empirically derived patterns of interdisciplinarity in the field of CS.

According to Holley (2006) there are two models of interdisciplinary education. One model assumes that individuals are trained as interdisciplinary researchers and approach knowledge production as a process that takes place outside disciplinary boundaries. In the second model, individuals receive training in a specific discipline, and over the course of their professional career, they engage with problems that cannot be solved by a single-disciplinary approach. In Holley's account, the definition of interdisciplinarity is grounded in the disciplines, and has been characterized as "disciplined interdisciplinarity" (Klein, 1990; Messmer, 1978). Holley's first model describes the individuals that conform to our integrative pattern, whose early education experiences influenced their intellectual identity in a way that individuals describe themselves as being naturally interdisciplinary and perceiving knowledge in an interdisciplinary manner (Lattuca, 2001). Doctoral researchers described by the disciplinary pattern follow Holley's second model since they received a single-disciplinary education and had contact with other disciplines only as an application of their CS research. As a result, their interdisciplinary understanding is deeply informed by their CS disciplinary expertise. However, our study indicates that interdisciplinary education at the doctoral level in CS is more complex than has been described. For instance, researchers in the specialist pattern do not conform to any of Holley's models. On the one hand, such doctoral researchers received prior education in other field—as characterized by Holley's first model—although they were trained and socialized mainly in a single discipline. On the other hand, they identify themselves as computer scientists and conceptualize interdisciplinarity as an extension of their disciplinary knowledge, which equates to Holley's second model. In order to ascertain the patterns of interdisciplinarity identified in this study, we not only consider researchers' previous education, but also their values and motivation, as well as their actual use of diverse fields of knowledge.

The results of the quantitative analysis derived from the integration of disciplines into sections of doctoral researchers' publications provide a further description of the three patterns identified in this study. Our quantitative analysis shows that although all participating researchers link knowledge from other disciplines with CS, information is integrated in different ways. While researchers that conform to integrative pattern utilize references from other fields as a base on which their research is conducted, those in the disciplinary and specialist patterns juxtapose their main discipline with other disciplines. Empirical analysis of citations in doctoral researchers' publications revealed that researchers in the integrative pattern incorporate more references from other disciplines into their publications, in comparison with researchers described by the disciplinary and specialist patterns. Therefore, this analysis supports our pattern taxonomy.

These above findings pave the way for furthering research and policy initiatives, for nurturing early career scientists' interdisciplinary development and for maximizing their IDR productivity; this in turn, provides insights for a greater support system for doctoral researchers to develop their careers as interdisciplinary scholars.

CHAPTER 7

Multiple-Perspective Analysis of Doctoral Interdisciplinarity

In this third and latest part of the study, presents the assessment of how the fulfillment and importance of doctoral interdisciplinarity is perceived not only by doctoral researchers, but also by other academic stakeholders (i.e., post-doctoral researchers, professors, program directors, department directors, visiting professors, and research funding agencies). The 360-degree feedback methodology (Ward, 1997) is employed to integrate their opinions on the fulfillment and importance of interdisciplinary doctoral processes and factors that take place at a higher education institution. To the best of our knowledge this is the first time that this kind of comparative analysis is utilized at an institutional level in the literature of assessment of interdisciplinarity. In this chapter we explain the methodological modifications to 360-degree feedback methodology for its utilization in our study, as well as its implementation. Then, we present the results and discuss the implications for education and research policies. This work has been peer-reviewed and published in the proceedings of the *IEEE International Conference on Information Technology Based Higher Education and Training (ITHET)* (Calatrava Moreno, 2013; Calatrava Moreno, Kynčlová, et al., 2016) and the *IEEE Global Engineering Education Conference* (Calatrava Moreno, 2014).

7.1 Method and Implementation

We base our analysis on the 360-degree feedback methodology (Ward, 1997), also known as the 360-degree performance appraisal. In human resources or industrial psychology, this method is utilized by organizations to collect information about the practice and performance of an individual from different viewpoints. Its name stems from the fact that it solicits feedback from the *stakeholders* “around” the individual such as subordinates, peers, supervisors, customers, etc. Main advantages of this methodology include: (i) a multiple-perspective judgment that delivers a rounded portrait of the assessment; and (ii) increased validity due to the inclusion of the complementary opinions of stakeholders with different expertise.

Conceptual modifications of the 360-degree feedback methodology were made in order to adapt it to our context. Rather than evaluating individuals, we aim at assessing doctoral interdisciplinarity; thus, feedback is gathered from the following academic stakeholders: doctoral researchers, post-doctoral researchers, professors, doctoral program directors (i.e., dean and deans of studies), department directors, visiting professors and research funding agencies. We also introduced a methodological alteration to the 360-degree feedback by utilizing a double scale that not only assesses fulfillment of criteria but also their importance. Each criterion was evaluated with two questions, one evaluating its fulfillment (e.g., *To what extent... ?*) and the other assessing its importance (e.g., *How important is it... ?*).

This double scale has a dual purpose. On the one hand, it allows for a double analysis of the alignment of opinions of the different stakeholders. An example of a problematic misalignment can be observed in Figure 7.1 where both doctoral researchers and professors assess the fulfillment of a criterion as low, but they have disparate opinions on its importance. After the identification of such misalignments, the stakeholders could share and discuss their perspectives with each other with the aim of understanding and achieving common goals. On the other hand, it aims to provide information for effective resource allocation and adequate prioritization of actions for improvement. For instance, a criterion which fulfillment is assessed as low, would only be listed in the agenda of priorities if its importance is high.

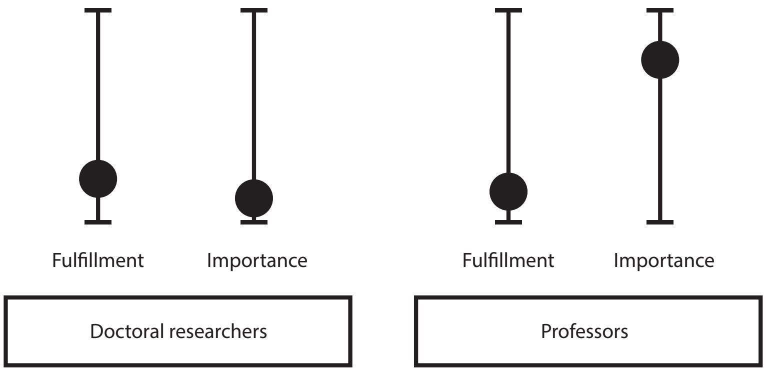

Figure 7.1: Example of misaligned opinions of stakeholder groups.

Since the aim of this study is to assess doctoral interdisciplinarity, important factors and processes that contribute to the interdisciplinary development of doctoral researchers constituted the set of criteria to be assessed by the stakeholders. In the literature addressing interdisciplinary education, some works have listed qualities of interdisciplinary work (Boix Mansilla, 2006b) or the skills it requires and so, by implication, have outlined criteria for assessment, which range from goals of interdisciplinary education (Kavaloski, 1979; Newell and Green, 1982) over cognitive skills (Newell, 1990), to processes and outcomes facilitating InterDisciplinary Research (IDR) (Lattuca et al., 2004).

Our assessment is based on factors and processes involved in IDR at the doctoral level. The criteria were selected based on the analysis of (i) a literature review, (ii) the semi-structured interviews conducted in the second part of this study (see Chapter 6) with interdisciplinary doctoral researchers who were identified using the Rao-Stirling diversity index and its interval of uncertainty (see Chapter 5), (iii) additional interviews with interdisciplinary professors also identified with the Rao-Stirling diversity index and its interval of uncertainty.

The following criteria were selected:

1. Overall interdisciplinarity: An assessment of the overall interdisciplinarity of the doctoral researchers' research.
2. Work environment: An interdisciplinary work environment is suggested by Huutoniemi (2010) as a quality criterion to emphasize integration and synergy of disciplines, as it allows for interactions between disciplines (Newswander and Borrego, 2009). Moreover, it has also been described as both a quality outcome and goal for interdisciplinary programs (Borrego and Cutler, 2010).
3. Courses: Coursework distributed across disciplines and departments is a common strategy to promote interdisciplinarity among doctoral researchers (Newswander and Borrego, 2009). It has been widely implemented both in the form of courses that integrate different disciplines (Mitrany and Stokols, 2005; Richter and Paretti, 2009) and as an assemblage of several disciplinary courses (Graybill and Shandas, 2010).
4. Methodologies: The diversity of research methods in doctoral dissertations appears to be closely associated with its integration of disciplines (Mitrany and Stokols, 2005). Since single-disciplinarity is often tied to the use of certain methodologies (Bruun, Hukkinen, et al., 2005), training in different methodologies has been suggested as one of the measures institutions should take in order to support the interdisciplinarity of their doctoral researchers (Graybill and Shandas, 2010).
5. Collaboration: Since complex real-world problems often require expertise across disciplines, collaboration with other disciplines is regarded as essential for IDR. It has been described as a key factor in facilitating the exposure of doctoral researchers to multiple disciplinary perspectives as well as to encourage a broader approach integrating those perspectives within the dissertation study (Mitrany and Stokols, 2005), and as a learning outcome of interdisciplinarity (Borrego and Cutler, 2010). Efforts to spur collaborative research across traditional departmental and disciplinary boundaries both within and outside academia (Institute of Medicine and National Academy of Sciences and National Academy of Engineering, 2005; *Report of*

the Interdisciplinary Task Force 2005; Sá, 2008) are strategies for interdisciplinarity. In the interviews conducted in the previous phase of this study, doctoral researchers also emphasized the necessity for collaboration with experts in other disciplines as part of an important process for conducting their IDR (see Section 6.3.2).

6. Contribution: Interdisciplinary contributions have been defined as enterprises in which some of the concepts and insights of one discipline contribute to the problems and theories of another (M. A. Boden, 1997). These constitute the natural outcome of IDR. However, as the amount of knowledge in any field continues to increase dramatically, it is increasingly difficult for doctoral researchers to make significant research contributions in more than one field (Golde and Gallagher, 1999).

7. Conceptualization: The degree to which doctoral researchers integrate previous literature in bridging theories and methods of two or more fields. Researchers achieve varying levels of integration in their work, from single disciplinary research where no integration occurs, through a moderate degree of integration, to a full integration of disciplines (Huutoniemi et al., 2010).

8. Funding: Many authors highlight the influence of funding structures on the prospects for IDR (Carayol and Nguyen-Thi, 2005; Knight and Pettigrew, 2007; Welsh et al., 2006). Its influence at the doctoral level was confirmed in our previous qualitative analysis (see Section 6.3.2), in which the characteristics of different sources of funding exerted a strong influence on the researchers' IDR.

9. Supervision: Members of the department exercise enormous influence over researchers' doctoral studies. It is common for doctoral researchers to work for and with their supervisor, their most important mentor, who not only advises doctoral researchers' course of study but also directs their research. The supervisor's earlier research and current research interests provide the intellectual foundation for the doctoral dissertation (Golde and Gallagher, 1999). In the interviews conducted in the second phase of this study, both doctoral researchers and professors discussed the important role of supervision in facilitating IDR (see Section 6.3.2).

10. Co-supervision: IDR programs often encourage co-supervision from experts in different fields (Maglaughlin and Sonnenwald, 2005; Manathunga et al., 2006). Mitrany and Stokols (Mitrany and Stokols, 2005) found striking differences in an analysis of the integration of disciplines that compared doctoral researchers receiving supervision in a single-field with doctoral researchers receiving supervision from professors in different departments. Moreover, in our prior qualitative study, we observed that truly interdisciplinary researchers often sought dual supervision in order to complement the expertise of their main supervisor (see Section 6.3.2).

These criteria were transformed into questions and their reliability was pilot tested by 10 stakeholders who were asked to explain the meaning of each question in an interview. After the questions were revised according to the feedback gathered in the pilot test, they were uploaded to an online survey platform to be answered by the all stakeholders. All stakeholders evaluated all criteria in terms of importance. However, not all stakeholders had the knowledge to assess the fulfillment of the criteria. For example, external stakeholders (e.g., research funding agencies or visiting professors) might not have enough knowledge to assess the fulfillment of the criteria. Therefore, each group of stakeholders evaluated a set of criteria on which they could provide feedback as shown in Figure 7.2.

According to our prior qualitative analysis of interviews with doctoral researchers, IDR depends upon far more than the presence of interdisciplinary higher education structures and strategies (see Section 6.3.1). Therefore, doctoral researchers also assessed their single- or inter-disciplinary intellectual orientation prior to the beginning of their doctoral studies: their antecedents. The following antecedents were identified and only doctoral researchers assessed them in the survey:

- Values: We refer to interdisciplinary values as described by Stokols (2014): "The principles that predispose the individual towards acquiring a broad understanding of complex research and societal problems and translating integrative insights about them into practical solutions".
- Motivation: We draw upon the self-determination theory to describe it as a continuum between amotivation and intrinsic motivation, where the former involves having no intention to conduct IDR and the latter describes an individual motivated by interest in the interdisciplinary topic itself (Gagné and Deci, 2005).
- Previous skills and knowledge: Exposure to multiple learning environments, mentors and research settings that shape the intellectual orientation of a scholar (Stokols, 2014).

At the beginning of 2016, stakeholders were invited via email to answer the online survey (see Appendix 8.3.2). The introduction to the survey included indications that aimed to obtain a higher quality of participants' responses. First, since there is an extensive theology around the differences between inter- , trans- and multi- disciplinary research, each with its own shade of meaning, we provided our respondents with a simplified definition of IDR. We used this term to describe research where two or more disciplines work together and quoted a definition provided by The National Academies (2005). Second, respondents were asked to provide their most objective answers. We explicitly stated that this study makes no assumption that IDR is better or more valuable than other types of research.

The first part of the survey consisted of demographic questions that allowed us to categorize respondents into stakeholder groups, areas of expertise in Computer Science (CS), and doctoral programs in the case of doctoral respondents. The following questions regarding the set of criteria were formulated slightly different for each stakeholder group. For instance, regarding the criterion Overall interdisciplinarity doctoral researchers

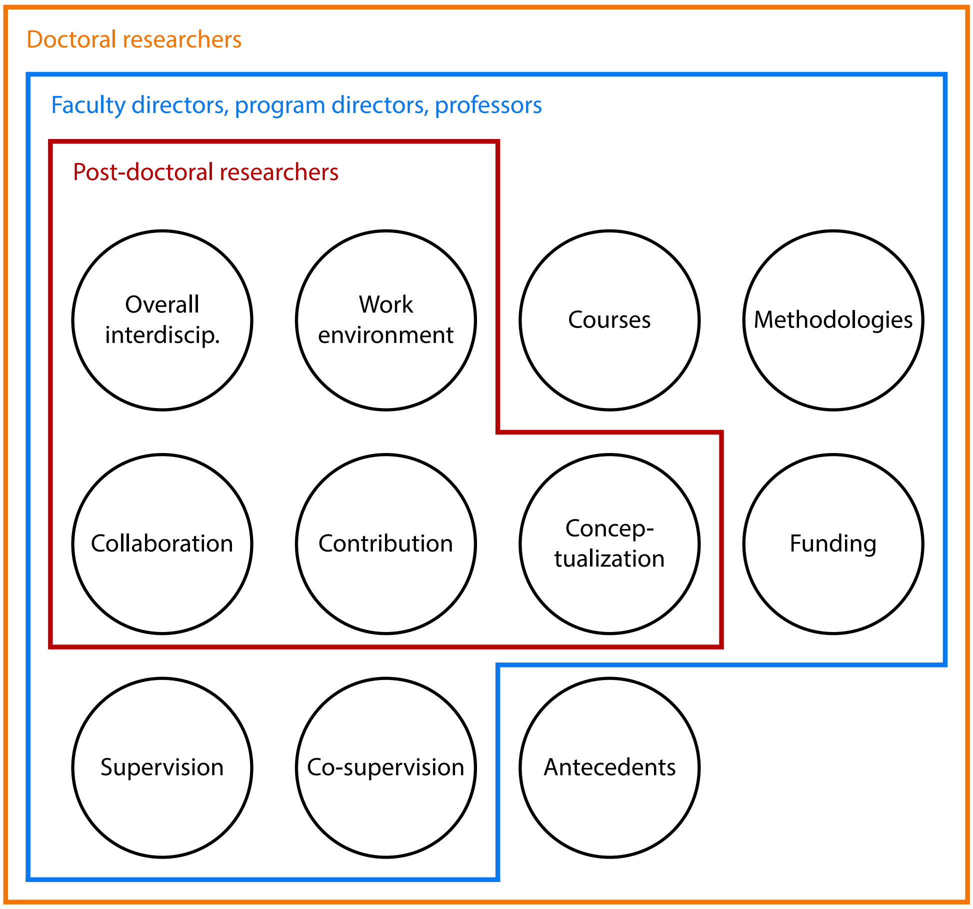

Figure 7.2: Interdisciplinary criteria. Different stakeholder groups assess the fulfillment of the criteria comprised in squares.

were asked to assess the interdisciplinarity of their doctoral research, post-doctoral researchers assessed the interdisciplinarity of the doctoral researchers in their research group, professors assessed the interdisciplinarity of the research conducted by doctoral researchers they supervise, and department directors assessed the interdisciplinarity of the doctoral researchers of the department as a whole. Each question was rated using a 4-point Likert scale in order to avoid neutral answers (Krosnick and Presser, 2010), with one point indicating the lowest interdisciplinarity rating, and four points indicating the highest. All tests were performed with a 95% confidence level. Additionally, whenever possible all the assumptions of the corresponding tests were verified.

7.2 Results

The 360-degree methodology allows for the analysis of the data from different perspectives (i.e., per criteria, doctoral program, research area and stakeholder group). We focus on the analysis of stakeholder groups and discuss the results of the assessment of those groups with a higher response rate (i.e., doctoral researchers, professors, department directors and external individuals). Additionally, we briefly discuss the results of the analysis of criteria and doctoral programs.

A total of 107 individuals responded (see Table 7.1 and 7.2) and their responses were analyzed using statistical methods. All results presented in this section have been transformed to the interval [0,1].

Table 7.1: Number of participants and population per stakeholder group.

Stakeholder group	**Respondents (Population)**
Doctoral researchers	44 (211)
Post-docs	11 (99)
Professors	25 (53)
Program directors	1 (5)
Department directors	3 (3)
Visiting professors	12 (28)
Funding agencies	11 (58)

Table 7.2: Number of participants and population per doctorate program.

Doctorate program	**Respondents (Population)**
Traditional	23 (138)
Doctoral school	12 (27)
Doctoral college	1 (1)
Other new doctorate programs	8 (45)

7.2.1 Interdisciplinary criteria

In general, the fulfillment and importance of Overall interdisciplinarity as well as the rest of the interdisciplinary criteria are very moderate (see Table 7.3). Methodologies is the most fulfilled and most important criterion, not only on average for all respondents but also for each stakeholder group. The least fulfilled is Co-supervision and the criterion considered least important is Courses.

The influence of doctoral policies and departmental structures can be observed in the data, as in the case of the low fulfillment of Co-supervision, which could be explained by the fact that none of the doctoral programs enforce double-supervision from experts in different fields. Nevertheless, this would not be a priority for improvement in the context of this department as it is considered one of the least important criteria for both stakeholders within the department as well as external stakeholders. The low fulfillment of Work environment might relate to the fact that the university where this study was conducted is not a campus university but a multi-site where the different faculties are situated in designated buildings located at various locations around the city.

Table 7.3: Estimated normalized mean and standard error of the aggregated assessment of all stakeholders on the fulfillment and importance of each criterion. These estimated values are calculated with a bootstrapped sample of 50,000 elements with replacement.

Criteria	Estimated mean		Std. error	
	Fulfillment	Importance	Fulfillment	Importance
Overall interdisciplinarity	0.435	0.466	0.035	0.030
Work environment	0.310	0.485	0.029	0.033
Courses	0.414	0.392	0.036	0.027
Methodologies	0.581	0.633	0.028	0.033
Collaboration	0.467	0.497	0.033	0.032
Contribution	0.392	0.370	0.033	0.027
Conceptualization	0.482	0.386	0.035	0.029
Funding	0.423	0.515	0.038	0.034
Supervision	0.545	0.463	0.041	0.032
Co-supervision	0.270	0.404	0.035	0.029

7.2.2 Stakeholder groups

We conducted a comparative analysis of responses from individuals in different stakeholder groups.

In general, doctoral training within the department seems to facilitate interdisciplinarity for those stakeholders who consider it important. Stakeholders (i.e., doctoral researchers, post-doctoral researchers, professors) for whom interdisciplinary doctoral research is of a high priority are more likely to see it realized. This can be observed from the survey results for fulfillment and importance of the criterion Overall interdisciplinarity, which shows a very significant positive correlation coefficient of 0.63 (see Figure 7.3). It is important to note that similar correlations exist between fulfillment and importance for Overall interdisciplinarity as assessed by doctoral researchers, post-docs and professors.

Table 7.4 contains the aggregated assessment of all criteria for each stakeholder group. All stakeholder groups have a rather moderate opinion on the fulfillment and importance of the interdisciplinary criteria. Professors believe interdisciplinary criteria to be more fulfilled and important. Their opinion contrasts with the immediately higher and

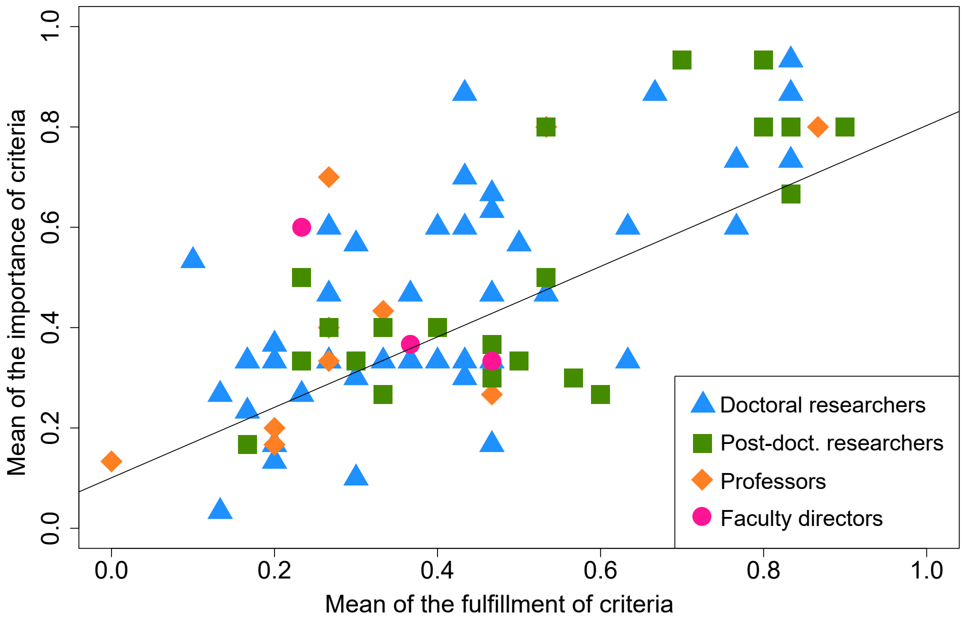

Figure 7.3: Normalized mean of fulfillment and importance of the criteria. Each point represents the assessment of a respondent.

lower hierarchical groups in the department—department directors and post-doctoral researchers—whose assessment of both fulfillment and importance of all criteria is lower on average. Interestingly, professors are also the only stakeholder group who assessed the fulfillment of the criteria higher than their importance, which contrasts again with department directors and post-doctoral researchers whose assessment presents the largest difference between average fulfillment and importance.

In the following, we provide an insight on results that stand out for each of the stakeholder groups with the highest response rate.

Doctoral Researchers

Doctoral researchers' assessment of fulfillment and importance of the criterion Overall interdisciplinarity are comparable (0.40 and 0.42). Moreover, these two variables show a very significant positive correlation (0.61).

One of the results of our previous qualitative study based on interviews with doctoral researchers is that funding for interdisciplinarity constitutes a very influential factor that plays an important role in facilitating interdisciplinarity at the doctoral level. According to the results of this survey, doctoral researchers consider appropriate funding for IDR to be the second most important requirement for conducting research of this kind. A

Table 7.4: Normalized estimated mean and standard error of fulfillment and importance of all criteria per stakeholder group. These estimated values are calculated with a bootstrapped sample of 50,000 elements with replacement.

Stakeholder groups	Mean		Std. error	
	Fulfillment	Importance	Fulfillment	Importance
Doctoral researchers	0.397	0.449	0.01539	0.01503
Post-docs	0.327	0.400	0.03487	0.03378
Professors	0.524	0.512	0.01981	0.02098
Department directors	0.356	0.433	0.03115	0.04749
Visiting professors	–	0.461	–	0.02919
Funding agencies	–	0.470	–	0.03283

striking observation from the data is that the fulfillment of appropriate funding does not correlate with any other fulfillment and importance criteria (see Figure 7.4). This indicates that the appropriateness of the funding provided to doctoral researchers for conducting IDR does not seem to have any relation with the fulfillment and importance of other criteria. The missing correlations with the fulfillment and importance of Overall interdisciplinarity illustrate this discrepancy, which is also present in the assessment of professors. Another disconnection with the appropriateness of funding is also indicated by the missing correlation with the importance of the same criterion. Again, this lack of correlation could also be found in responses obtained from professors. Further explanatory research would be necessary to explain this issue. For instance, it would be important to investigate whether doctoral researchers are funded with means not tailored to the level of interdisciplinarity that their research necessitates, or whether research funding is not sufficiently controllable by the applicants to match the interdisciplinarity or single-interdisciplinarity of their research.

Another interesting result from doctoral researchers' responses is the relation of the fulfillment and the importance of taking courses in different disciplines. The criterion Courses shows a very significant positive correlation (0.69) between fulfillment and importance. This would indicate that, to a large extent, doctoral researchers take courses that fit the interdisciplinarity or single-interdisciplinarity of their research. This result does not only apply to doctoral researchers in the traditional program who have greater freedom to choose any course, but also to those in the structured programs who follow a specific course curriculum.

Moreover, we analyzed whether single-disciplinary and interdisciplinary doctoral researchers assessed the fulfillment and importance of criteria in a different way from each other. We used the fulfillment assessment of Overall interdisciplinarity to separate doctoral researchers into two groups: single-disciplinary (1-2 points on the Likert scale) and interdisciplinary (3-4 points). The number of doctoral researchers in the single-disciplinary group was 37, with 8 in the interdisciplinary group.

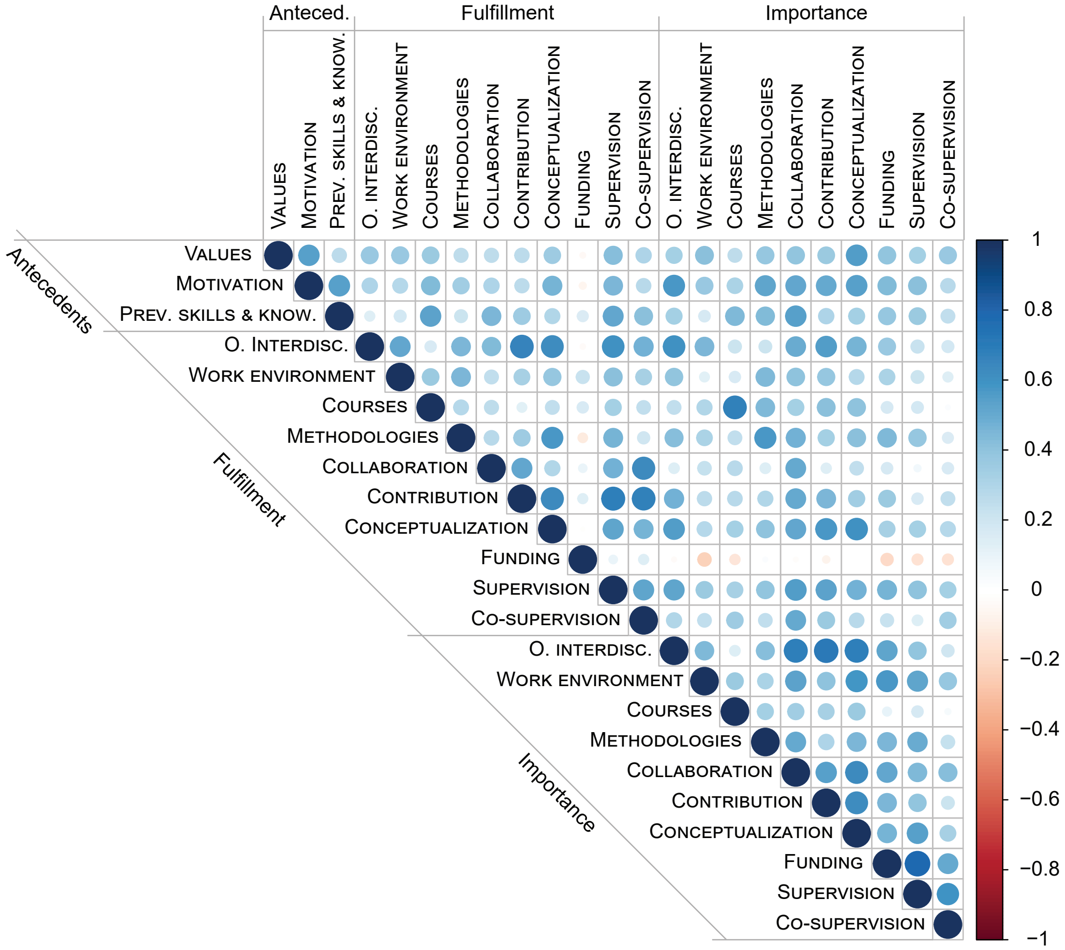

Figure 7.4: Matrix of Spearman correlations of doctoral researchers' assessment of their antecedents, as well as fulfillment and importance of the rest of criteria.

We used the one-sample Wilcoxon signed-ranked test (Wilcoxon, 1945) to test differences between the two groups. The tested null hypothesis assumed that the median fulfillment of the criteria assessed by interdisciplinary doctoral researchers is equal to the median fulfillment assessed by all doctoral researchers. The alternative hypothesis supposed that the fulfillment assessed by interdisciplinary doctoral researchers is greater than the median fulfillment of all doctoral researchers. Based on the results of this test (see Table 7.5) the null hypothesis is rejected for the criteria Collaboration, Conceptualization, Supervision and Co-supervision. Thus these criteria represent the potential criteria where the fulfillment of interdisciplinary doctoral researchers is considered to be higher than for all doctoral researchers.

Table 7.5: Results of the Wilcoxon test to check whether the fulfillment of the criteria assessed by the interdisciplinary doctoral researchers is greater than the median fulfillment assessed by all doctoral researchers.

Criteria (fulfillment)	P-value
Work Environment	0.17
Courses	0.10
Methodologies	0.07
Collaboration	**0.02**
Contribution	**0.01**
Conceptualization	**0.01**
Funding	0.12
Supervision	**0.02**
Co-supervision	**0.02**

Interesting findings can be observed in Table 7.6, which contains the results of the Wilcoxon test to check whether the median assessment of the importance of criteria is equal for both groups. The alternative hypothesis assumes that the median assessment of importance of single-disciplinary doctoral researchers is lower than the median assessment of all doctoral researchers. The null hypothesis is rejected only in the case of the criterion Contribution. This indicates that this criterion is the only one that is considered less important by single-disciplinary doctoral researchers. Therefore, we assume that single-disciplinary doctoral researchers do not consider the rest of the criteria less important.

Professors

Their assessment of the fulfillment of Overall interdisciplinarity is the highest of all stakeholder groups (0.56) and, in general, they also give more importance to the set of criteria than the rest of the stakeholder groups give. Professors who consider doctoral interdisciplinarity important are likely to have doctoral researchers also conducting IDR. This is indicated by a very significant high correlation coefficient between their assessment

Table 7.6: Results of the Wilcoxon test to check whether the importance of the criteria assessed by single-disciplinary doctoral researchers is lower than the median of the importance assessed by all doctoral researchers.

Criteria (importance)	P-value
Overall interdisciplinarity	0.71
Work environment	0.76
Courses	0.96
Methodologies	1.00
Collaboration	0.98
Contribution	**0.01**
Conceptualization	0.60
Funding	1.00
Supervision	0.98
Co-supervision	0.96

of the fulfillment and the importance of Overall interdisciplinarity (0.74). In other words, there is a strong positive relation between the interdisciplinarity of their doctoral researchers and their opinion on the importance of interdisciplinarity at the doctoral level. A similar correlation between the fulfillment and the importance of Overall interdisciplinarity could also be observed in the assessment of doctoral researchers. In their case, the correlation coefficient is only a bit lower (0.61). A possible interpretation of this result could be that doctoral researchers have fewer opportunities to conduct IDR than professors so when they consider it important. However, further explanatory research should be conducted in order to confirm this theory.

The data also suggest that professors who find additional supervision from other disciplines important are more likely to co-supervise their doctoral researchers together with experts from other fields. However, doctoral researchers are not as likely to have additional supervision from other disciplines even when they consider it important. This fact is indicated by the correlations of the fulfillment and importance of Co-supervision of professors and doctoral researchers. While professors present a very significant correlation of 0.74, for doctoral researchers it is just 0.34. Further explanatory research could investigate if this dissonance could be mitigated with discussions between supervisors and doctoral researchers about the need for additional supervision from another field. Since professors seem to have a better possibility of achieving co-supervision when they deem it important, doctoral researchers could benefit from communicating their need for feedback from other disciplines to their supervisors.

Another interesting finding is that professors on average, in contrast to other stakeholder groups, consider Collaboration rather important (0.61). It is their second most important criterion after Methodologies. Since supervision from an expert in a different field could be regarded as one of the most intense forms of collaboration for a doctoral researcher, it is interesting to observe that professors' assessment of the importance of Co-supervision (0.44) is comparably lower than their opinion on the importance of Collaboration. A similar difference between the importance of these two criteria could also be observed in the assessment of post-doctoral researchers.

Further analysis of the importance of Collaboration for professors indicates discrepancies with the department directors, who regard this criterion considerably less important (0.33) than professors do. Moreover, the correlation between the fulfillment and the importance of such a criterion for professors is just 0.52. This indicates that professors who think that collaboration with experts in other disciplines is important at the doctoral level do not necessarily see it fulfilled in the investigations of their doctoral researchers. As mentioned above, Collaboration is one of the most important criterion for professors. Therefore, such a discrepancy would merit further communication between professors and department directors in order to plan strategies to facilitate collaboration with other fields.

Department Directors

Although each of the three department directors is critical of the fulfillment of Overall interdisciplinarity (0.33), they do consider it important (0.78). However, the level of its importance contrasts with the level of importance they give to the rest of the criteria, which is considerably lower. Department directors show remarkable consensus in their assessment. While the standard deviation of the assessment of other stakeholders ranges between 0.26 and 0.31 in the assessment of fulfillment, and between 0.31 and 0.33 in the assessment of importance, the standard deviation of the department directors is just 0.14 in the assessment of fulfillment and 0.17 in importance.

In their opinion, only Work Environment and Co-supervision are moderately important (0.56), while the rest of the criteria have low importance (0.33) for each of the three members. A qualitative study on the opinions of department directors would be necessary to explain their low assessment on the importance of the interdisciplinary criteria and to determine if there are any other important criteria that should be included in future assessments.

As mentioned in Section 3.1, last year the course curricula of the traditional program was changed to provide more comprehensive doctoral training on research methodologies. In spite of this, the fulfillment of Methodologies is, in their opinion, still rather low (0.33) in comparison with the assessment of doctoral researchers and professors (0.58 and 0.61, respectively). This discordance is especially important because this criterion is the most important in the opinion of all stakeholder groups on average. Therefore, future policy changes regarding doctoral training in methodologies should be analyzed and evaluated prior to their implementation, as more emphasis on training in research methodologies could be considered superfluous by other stakeholder groups in the department who already see it being somewhat fulfilled.

Table 7.7: Number of doctoral researchers with low and high interdisciplinary antecedents.

Antecedents	Number of doctoral researchers	
	Low (1-2 points)	High (3-4 points)
Values	22	23
Motivation	27	18
Previous skills and knowledge	26	19

External Stakeholders

Visiting professors and research funding agencies share similar opinions on the importance of criteria. Their assessment on the importance of Overall interdisciplinarity is very similar (visiting professors: 0.44; funding agencies: 0.42). Both groups identified Methodologies as the most important criterion (0.67 and 0.73, respectively), followed by Work environment (0.56 and 0.67, resp.). Moreover, they also assessed Conceptualization (0.36 and 0.33, resp.) and Courses (0.36 and 0.36, resp.) as the least important criteria.

7.2.3 Doctoral Researchers' Antecedents

In order to quantitatively evaluate the influence of the antecedents identified in the qualitative phase of our study (see Section 6.3.1), we tested whether the fulfillment and importance of Overall interdisciplinarity is greater for doctoral researchers with higher interdisciplinary antecedents. For each antecedent, we divided doctoral researchers into two groups according to their assessment: low (1-2 points on the Likert scale) or high (3-4 points). The number of participants assigned to each group can be observed in Table 7.7. The one-sample Wilcoxon signed-ranked test (Wilcoxon, 1945) was used again to test hypotheses on the fulfillment and importance of the different criteria.

The null hypothesis assumed that the median fulfillment assessment of doctoral researchers with high interdisciplinary antecedents is equal to the median fulfillment assessment of all doctoral researchers. The alternative assumed that the assessment of doctoral researchers with interdisciplinary antecedents is greater than the median assessment of all doctoral researchers. According to the results of Table 7.8, the null hypothesis is rejected for the criteria Overall interdisciplinarity, Courses, Conceptualization and Co-supervision. This indicates that doctoral researchers with a higher number of interdisciplinary antecedents are likely to have a higher fulfillment of these criteria.

We also tested whether the median importance assessment of doctoral researchers with high interdisciplinary antecedents is equal to the median importance assessment of all doctoral researchers. This time the alternative hypothesis assumed that median importance assessment of doctoral researchers with high interdisciplinary antecedents is

Table 7.8: Results of the Wilcoxon test to check whether the fulfillment of the doctoral researchers with higher interdisciplinary *Values*, *Motivation* and *Previous skills and knowledge* is greater than the median of all doctoral researchers.

Criteria (fulfillment)	P-value		
	Values	Motivation	Previous skills and knowledge
Overall interdiscip.	**0.02**	**0.03**	0.05
Work environment	0.60	0.60	0.87
Courses	**0.01**	**0.00**	**0.00**
Methodologies	0.62	0.66	0.81
Collaboration	0.06	**0.01**	**0.00**
Contribution	0.11	0.13	**0.04**
Conceptualization	**0.00**	**0.00**	**0.00**
Funding	0.13	0.32	0.06
Supervision	0.79	0.45	0.35
Co-supervision	**0.00**	**0.00**	**0.00**

Table 7.9: Results of the Wilcoxon test to check whether the importance of the doctoral researchers with higher interdisciplinary *Values*, *Motivation* and *Previous skills and knowledge* is greater than the median of all doctoral researchers.

Criteria (importance)	P-value		
	Values	Motivation	Previous skills and knowledge
Overall interdiscip.	**0.01**	**0.01**	**0.01**
Work environment	**0.01**	**0.02**	0.10
Courses	**0.02**	**0.01**	**0.01**
Methodologies	**0.00**	**0.00**	**0.00**
Collaboration	**0.00**	**0.00**	**0.00**
Contribution	**0.03**	**0.02**	**0.05**
Conceptualization	**0.00**	**0.01**	**0.02**
Funding	**0.00**	**0.00**	**0.00**
Supervision	**0.00**	**0.01**	**0.01**
Co-supervision	**0.01**	**0.04**	**0.02**

greater than the median assessment of all doctoral researchers. The results are displayed in Table 7.9. We rejected the hypotheses in almost all cases, and therefore we assume that most interdisciplinary criteria are more important for doctoral researchers who have interdisciplinary antecedents.

We also compared the antecedents of doctoral researchers from different types of programs (i.e., the traditional program, doctoral school and doctoral colleges) using Kruskal-Wallis one way analysis of variance (Kruskal and Wallis, 1952), which tests whether their criteria assessment originates from the same distribution. For each of the interdisciplinary antecedents, we tested the hypothesis for whether the medians of all doctoral programs are equal against the alternative that at least one of them is different.

The p-values of Values, Motivation and Previous skills and knowledge result in 0.38, 0.28 and 0.35. Since these p-values are higher than 0.050, the null hypothesis about equality of the medians cannot be rejected for each of the interdisciplinary antecedents. We could conclude that no statistical difference is observed in the interdisciplinary antecedents of doctoral researchers in these three kinds of programs.

7.2.4 Doctorate Programs

We were also interested in the interdisciplinarity of doctoral researchers participating in different programs. For this reason, we grouped doctoral researchers according to the kind of doctoral program they are enrolled in, i.e., the traditional program, doctoral school, doctoral colleges. We used again the Kruskal-Wallis one way analysis of variance (Kruskal and Wallis, 1952) in order to analyze the distribution of the assessment of these three groups of doctoral researchers on the fulfillment and the importance of Overall Interdisciplinarity. The tested null hypothesis assumed that the medians are equal for all the groups of doctoral researchers.

The resulting p-values are 0.37 for fulfillment and 0.50 for importance. Since the p-values are higher than 0.050, the null hypotheses cannot be rejected in both cases. This means there is no statistical difference between the fulfillment and the importance of Overall Interdisciplinarity across the programs.

7.3 Conclusion

In this chapter we propose a multiple-perspective assessment of the interdisciplinarity of doctoral education based on the 360-degree feedback methodology in order to gather information on the opinions of different academic stakeholders of an institution. With this methodology we integrate the views of different academic stakeholders in order to obtain not only a global assessment but also intermediate evaluations of each valuation criterion, doctoral program and group of stakeholders. Its design allows for a comparison of stakeholders' opinions not only on the accomplishment of interdisciplinary criteria (fulfillment) but also on their relevance (importance). The utility of such a comparison lies in its informative potential. Achieving an alignment of around organizational objectives and stakeholders' expectations constitutes a significant step towards improving the performance and significance of the strategies in place as well as the development of new ones.

Concerning the context in which this study was conducted, this method provided evidence of a strong alignment of opinions of all stakeholder groups on the importance of training in interdisciplinary methodologies, as well as a discrepancy between professors and department directors on its fulfillment. The opinions of both stakeholder groups also differed in the importance that collaboration with experts in other disciplines has in the training of the doctoral researchers of the department. Discordances were also observed in the answers of department directors, who assessed IDR as being quite important but consistently assessed the rest of the criteria as being of low importance. The analysis of such discrepancies between and within groups could serve as a base for developing a communication plan to gain both understanding and alignment of the different perspectives, which could eventually lead to a re-design of the assessment tool with new criteria.

The correlation analyses and statistical tests conducted on the criteria provide an indication of their relation to the interdisciplinarity of the research conducted by the doctoral researchers. The results of this analysis provide useful information as the criteria assessed in this study can be influenced with education and research policies. For instance, we found evidence that doctoral researchers who are co-supervised by experts in other disciplines or whose main supervisors encourage interdisciplinarity, conduct more IDR. This is also the case for doctoral researchers with interdisciplinary dispositions and experiences prior to the start of their doctoral studies. Therefore, if the department decides to promote IDR, the results of this analysis could guide policy changes regarding doctoral supervision, undergraduate and graduate education, as well as doctoral admission.

The results also revealed the existence of undesired situations such as the missing correlations between the fulfillment and importance of adequate funding for IDR. This serves as a motivation for further analysis to explain the role that funding has on the production of IDR at the given institution. The absence of significant differences between the interdisciplinarity of doctoral researchers of the different types of programs would also require the attention of the department to purposefully develop strategies to improve their relevance and value to IDR.

While the proposed method allows for the analysis of an alignment of opinions, the planning of actions for improvement, and the identification of problematic issues, it has a limited explanatory and descriptive power and it does not measure interdisciplinarity per se. Such limitations have been addressed with the previous phases of this study (i.e., the qualitative analysis of interviews, and the bibliometric measurement of interdisciplinarity). This latest multi-perspective phase has served to validate findings of the previous phases, as well as to provide additional insights that motivate further research with both qualitative and quantitative methods.

CHAPTER 8

Conclusion

The purpose of this thesis was to increase understanding of doctoral interdisciplinarity in three Computer Science (CS) programs with different approaches to manage specialization: a traditional European doctorate program, a doctoral school that covers different areas within CS, and an interdisciplinary doctoral college organized by three distinct departments. This study contributes to understanding interdisciplinarity by combining multiple analytical approaches to various aspects of the doctoral experience that are typically examined independently.

The previous three chapters present a variety of analyses of different aspects of interdisciplinarity. Firstly, a bibliometric method was improved to provide a more accurate measure of interdisciplinarity in the presence of missing data. This method was later utilized to measure the interdisciplinarity of the publications of doctoral researchers and their co-authors, as well as the three doctoral programs by aggregating measurements of interdisciplinarity of their respective doctoral researchers. Using the results of the bibliometric analysis, interdisciplinary doctoral researchers were selected to participate in the subsequent phase of the study. The second approach relied on the analysis of interview data with doctoral researchers who were identified as interdisciplinary through the results of the bibliometric method. This provided a greater insight into the experiences of interdisciplinary doctoral researchers, identifying how and why they conducted InterDisciplinary Research (IDR). Finally, the third approach employed a 360-degree survey in order to gather, analyze and compare the opinions of a more comprehensive group of stakeholders: not only interdisciplinary individuals, but those who focus on a single discipline; not only doctoral researchers but also other academic stakeholders (i.e., post-PhD researchers, professors, department directors, funding agencies and visiting professors). They assessed the extent of fulfillment as well as importance of interdisciplinary processes and factors for the doctoral researchers in the department where this study has been conducted.

This final chapter provides an overview of the main findings and reflects on the strengths and limitations of the investigation, discusses the implications of its findings, and proposes future examinations of IDR.

8.1 Summary of Results

This thesis was guided by four research questions that are addressed in Chapters 5, 6 and 7:

1. *How to efficiently and effectively measure interdisciplinarity in a research institution?*
2. *What dispositions and experiences are associated with doctoral researchers becoming interdisciplinary early career scientists?*
3. *What are the factors and facilitators of interdisciplinary doctoral research that stem from traditional and structured doctoral programs?*
4. *How do perspectives on doctoral IDR of different university stakeholders coincide?*

Chapter 5 presents a bibliometric method in order to respond to the first question. Efficiency refers to the accomplishment of the task with minimal waste of time and effort. One of the most laborious and time-demanding exercises for bibliometric analysis is the gathering of bibliographic data. In order to minimize the expense of this task, our proposed approach relies on data that is already available at the institution (i.e., the publication database) as well as further data which can be gathered automatically from digital libraries (i.e., references and their categorization into disciplines). This approach facilitates periodical monitoring, which requires the output of clear and conclusive results. Furthermore, in order to ensure a consistent analysis of the results over time, bias can be minimized by repeating the same data collection and analysis procedures as those previously used. Among the existing bibliometric methods, top-down citation-based methods satisfy these requirements, and interdisciplinary indices, in particular, deliver clear-cut results that can be interpreted in a straightforward and objective manner. The Rao-Stirling diversity index was selected for this purpose because it not only captures the variety and balance of the disciplines cited by a paper, but also their disparity, using a measure of similarity between disciplines. Regarding effectiveness—the degree to which objectives are achieved and problems solved—missing bibliographic data appeared to be problematic because bibliometric measurements are not capable of reflecting the inaccuracies introduced by incomplete records. This particularly occurs in CS, where the high proportion of publications that are not categorized into disciplines constitutes a serious obstacle for the analysis of interdisciplinarity with top-down bibliometric methods. This problem was addressed by developing an extension of the Rao-Stirling diversity index that acknowledges uncategorized publications by calculating an interval of uncertainty using computational optimization. Its evaluation confirmed that the uncertainty interval is not only useful for estimating the inaccuracy of interdisciplinary measurements, but it also delivers slightly more accurate aggregate interdisciplinary measurements than the Rao-Stirling index. In order to facilitate its utilization, its code has been publicly made available.

Chapter 6 addresses the second and third research questions. The second question focuses on the individuals. The analysis of the accounts of interdisciplinary doctoral researchers revealed that their inclination to conduct truly interdisciplinary research was shaped before their doctoral studies. The three following kinds of antecedents could be distinguished: *values*, *motivations* and *previous skills and knowledge*. Instead, the third question referred to the doctoral structures and processes. Rather than explicit strategies implemented to facilitate IDR—such as courses related to distinct disciplines and doctoral programs that bring different departments together—interdisciplinarity of doctoral researchers was influenced by their form of funding, autonomy, supervision and scientific networks. The aspects related to each research question are interdependent: antecedents are interrelated with doctoral processes and structures. The analysis of such links led to the identification of three distinct patterns of interdisciplinarity: *integrative*, *disciplinary* and *specialist*. A summarized characterization of a doctoral researcher described by the integrative pattern would be "the truly interdisciplinary doctoral researcher". Integrative doctoral researchers have interdisciplinary aspirations which they continue to fulfill during their doctoral studies because they have: (i) the necessary means (i.e., research funding), (ii) the liberty to decide on the focus of their research (i.e., research autonomy), and (iii) supervisors who encourage and support their IDR. They are agentive in developing their own networks with experts in other disciplines, resulting in additional supervision. These integrative doctoral researchers were found in the PhD school and the traditional program. Conversely, the disciplinary and specialist patterns describe doctoral researchers who conduct multidisciplinary research. Although they reference other disciplines in their publications, their research focuses on CS and there is barely any knowledge exchange with the other disciplines. The difference between the disciplinary and specialist patterns lays on one of the antecedents: previous skills and knowledge. Researchers described by the disciplinary pattern received a broad education in CS which enabled them to combine different CS methods that can be applied to a wide range of other disciplines (e.g., information science applied to the analysis data of other disciplines). The choice of the application discipline was influenced by the availability of data and funding. Since each of the future research projects of these researchers might involve completely different disciplines, the required effort for achieving a comprehensive understanding of the other disciplines is considered significant. In contrast, researchers who conform to the specialist pattern received a highly specialized graduate education in CS at the boundary of another field (e.g., medical informatics, computational biology). Doctoral researchers of the disciplinary and specialist patterns were supervised by professors who encouraged a strong focus on CS, and mainly found collaborators within the networks of their supervisors. Researchers of both patterns were found in the doctoral college and the traditional program. The true interdisciplinarity or multidisciplinarity of these groups was validated with an analysis of the distribution of references to other disciplines in the sections of doctoral researchers' publications. The identification of the different patterns of interdisciplinarity constitutes a theoretical contribution to the field of interdisciplinary higher education: the patterns indicate that interdisciplinary education depends on more complex settings than has been described in the previous literature (Holley, 2006).

Finally, chapter 7 presents the assessment of the opinions of different academic stakeholders. The 360-degree survey method was utilized in order to answer the fourth research question. Each of the stakeholders assessed the fulfillment and importance of a set of interdisciplinary criteria. These included factors and processes that have been identified as facilitators of IDR in the literature and the interviews conducted in this study. In general, all stakeholder groups had moderate opinions on the fulfillment and importance of interdisciplinarity as well as interdisciplinary factors and processes. In brief, with reference to the similarities and differences between the different group opinions, it should be noted that the alignment of their views was strong regarding the importance of doctoral training in interdisciplinary methodologies—a factor which was considered the most important by all groups of stakeholders. Its fulfillment, however, was assessed as high by professors but as low by the directors of the department. Interestingly, the latter group believed it is important that doctoral researchers conduct IDR, although they assessed the importance of each of the criteria as low. The responses to the survey were also analyzed utilizing statistical correlations which revealed that, unlike the rest of criteria, adequate funding for interdisciplinarity does not have any relationship with the fulfillment and importance of any other criteria. In other words, doctoral interdisciplinarity appeared not be related with adequate funding to support IDR. In addition, statistical tests were utilized to analyze differences in the assessment of interdisciplinary and single-disciplinary doctoral researchers. The first group showed a more interdisciplinary antecedents (i.e., values, motivations, previous skills and knowledge), as well as a higher fulfillment of some processes and factors that facilitate interdisciplinarity. However, there was no significant difference between both groups as to how important these factors and processes are for their doctoral research. In other words, single-disciplinary doctoral researchers believe that the factors and processes that facilitate interdisciplinarity are also important for doctoral research in general.

A summary of the research questions, methods and findings of this thesis is presented in Table 8.1. Each of the approaches used in this study has its own focus and taken together they offer important insights about doctoral IDR.

8.2 Strengths and Limitations of the Study

Each single method utilized in this thesis to examine interdisciplinarity has its own strengths and limitations. The advantage of bibliometric methods is that they are based on large samples of scholarly work that can be efficiently processed using computer-based methods. Such analyses rely on non-ambiguous measures of disciplines and interdisciplinarity, and therefore, are well-suited to provide quantitative measures of interdisciplinarity. The extension of the Rao-Stirling diversity index presented in Chapter 5, contributes

Table 8.1: Summary of the research questions, methods and results of this thesis.

Research question	**Method**	**Findings**
1	Bibliometrics	Interval of uncertainty of the Rao-Stirling diversity index
2	Semi-structured interviews	Values, motivations, previous skills and knowledge
3	Semi-structured interviews	Funding, autonomy, supervision, scientific networks
4	360-Degree survey	Differences of opinions, relationships between criteria

to the development of more robust indicators when bibliographic data is incomplete. In addition to the slight increase on the accuracy of its measurements, this extension is useful to quantify the degree of uncertainty of a measurement of interdisciplinarity: the more bibliographical information missing, the higher the uncertainty of the measurement. This information is essential for identifying inaccurate measurements and therefore, for increasing the reliability of the analysis. However, bibliometric methods in general—including the extension of the Rao-Stirling index presented here—have limitations. They do not provide great insight into or explanation of the form and processes of discipline integration. Additionally, the quality of the results of bibliometric analyses is heavily influenced by the quality of the data. Although the extension of the Rao-Stirling index mitigates this problem by tackling the problem of uncategorized references, other bibliographical problems persist. Examples include incomplete records of references and incorrect categorizations of publications into disciplines, both of which still affect bibliometric methods including our extension.

Conversely, the qualitative analysis allows a detailed and in-depth examination, which is not restricted to specific questions and can be guided and redirected by the researchers in real time. It appreciates the subtleties and complexities about the research subjects and topics, such as the social context of individuals' experiences, which are often missed in quantitative analyses. Important limitations of qualitative analysis include the expensive and time-consuming nature of data collection and analysis, as well as often the reliance on a relatively small number of participants. Such limitations can restrict the scope of such an investigation. Since our analysis aimed to identify aspects that contribute to the interdisciplinarity of doctoral researchers, only those candidates identified as integrating different disciplines in their publications participated in this part of the study. Therefore, the accounts of doctoral researchers who do not integrate other disciplines in their research, and the perspectives of other academic stakeholders have not been analyzed qualitatively. However, they have been addressed with the subsequent quantitative analysis.

The utilization of surveys allowed the collection of data from a wide range and high number of individuals. Since this method has the capability of involving a larger and more diverse population in the study, statistical techniques can be employed to analyze multiple variables and their statistical significance. The use of a 360-degree survey provides additional advantages to the conventional survey method: a broader perspective of the subject of analysis since feedback comes from different stakeholders, and the possibility to analyze the alignment of the stakeholders' opinions. Moreover, the introduction of a double scale to assess both fulfillment and importance is useful in determining whether the realization of certain interdisciplinary factors and processes are regarded as essential or unneeded. Regarding the survey questions and answers, these are pre-defined and standardized. This has both advantages and disadvantages. On the one hand participants are provided with identical questions and means to answer them—which reduces bias. Whereas on the other hand, participants are obliged to provide simple feedback; thus, the analysis of complex aspects is not viable. The flexibility of design is also reduced because it cannot be adapted during data gathering, and therefore, the research is hampered from exploring aspects that manifest as interesting or intriguing.

With regard to the entire study, the following strengths and limitations should be noted. The literature on the analysis and evaluation of IDR argues for the need for multifaceted and multi-method analyses in order to address its complexity from different perspectives (Huutoniemi, 2010; Schilling et al., 2001; Wagner et al., 2011). This is however, a very uncommon practice because it involves the burden of expense and expertise. Therefore, the combination of three different approaches for analyzing doctoral interdisciplinarity represents an important contribution of this study, not only to examine different aspects of interdisciplinarity, but also to reinforce the design and validity of this research. Moreover, the limitations of one approach are addressed by the other approaches, and the findings are corroborated by the results provided by the different methods. In addition, the use of CS methods—rarely used in combination with empirical methods in studies of interdisciplinarity—facilitated the analysis of large amounts of information that could not have been scrutinized otherwise. However, this study is limited to a specific field within a specific higher education institution. Therefore, as discussed in Section 4.3.3, the findings of this study are not necessarily transferable to other institutions. Despite this limitation, governments and universities across the globe are attempting to stimulate interdisciplinarity and they face similar challenges (Bruce et al., 2004; Geiger and Sá, 2008; Sá, 2008). Therefore, this investigation is well suited to generate both hypotheses and methods for subsequent research and to raise questions about program design and funding practices.

8.3 Implications

The importance of the findings from this study is twofold. Firstly, with reference to education policy and practice, it is necessary to understand the influences of the department, its professors and doctoral structures on doctoral interdisciplinarity. Secondly, the study offers novel contributions to the state-of-the-art scientometrics, and theories in interdisciplinary studies.

8.3.1 Implications for Education Policy and Practice

The research contained in this dissertation is relevant for developing strategies for interdisciplinarity at institutions of higher education. The study is also useful for research funding agencies that encourage IDR. Implications for designing strategies that nurture doctoral researchers' engagement in interdisciplinary inquire are discussed below.

Measuring Interdisciplinarity

Scientometrics are increasingly used to inform science and technology policy (Rafols et al., 2013). Although policy should not rely exclusively on quantitative metrics, they are useful indicators for the appraisal of educational initiatives with relatively low researcher bias. The benefits of the use of bibliometric indicators of interdisciplinarity in higher education institutions are twofold: Firstly, when carried out periodically, the interdisciplinarity development can be tracked over time. Secondly, the results constitute preliminary information that helps to inform debates, uncover problems, and formulate hypotheses for further examinations. The latter case applied to this study, as the bibliometric measurement provided the first indication that the interdisciplinary structure of the doctoral college does not yield a higher integration of disciplines compared with the other programs.

Differentiating Interdisciplinarity from True Interdisciplinarity

Understanding the two connotations of the term "interdisciplinarity" and the different forms of interdisciplinarity is essential to precisely determine interdisciplinary goals of research programs and projects. The term "interdisciplinary" is often used in an undifferentiated manner neglecting the subtleties of the different kinds of IDR. Therefore, projects and programs are often called interdisciplinary when different disciplines participate, although their research output might be far from truly interdisciplinary. A typical example is doctoral programs co-organized by different departments that contribute their single-disciplinary courses to the curriculum of the program. Doctoral researchers take a number of courses from each department before they commit themselves to single-disciplinary research supervised by one professor. Another example is the case of CS projects where data of other disciplines are employed for the sole purpose of developing and testing state-of-the-art CS methods.

Initiatives that aim for interdisciplinary outcomes should consider the different forms of IDR and reflect on: (i) the kind of interdisciplinarity they are aiming for; (ii) the plan of action to accomplish it; (iii) the conceptualization of interdisciplinary outcomes (i.e., the contributions to each discipline); and (iv) the definition of the initiative's success. Professors, peers, departments and funding agencies should differentiate between the various forms of interdisciplinarity and critically scrutinize the answers to these matters.

Different Doctoral Researchers for Different Doctoral Programs

A further reason, related to the previous argument, as to why doctoral programs and projects should reflect on the kind of interdisciplinarity to be conducted, is that the doctoral researchers to be recruited should match the description of the program.

Before the start of their doctorate, individuals have been exposed to multiple learning environments, mentors and experiences that contribute to shape their intellectual orientation (Stokols, 2014). As observed during this investigation, the interdisciplinary skills and knowledge that individuals gain prior to their doctoral studies, as well as the development of interdisciplinary values and motivations, predispose individuals to conduct IDR. Such predisposition is important to sustain their interest in interdisciplinary work, in spite of the additional time and effort required in developing an understanding of more than one discipline. Therefore, an important factor for the success of an interdisciplinary program is to recruit a doctoral candidate with a different profile: not necessarily one with the best transcripts of records. The recruitment should be considered as an optimization problem where the combination of the three following characteristics should be at a maximum: (i) the transcript of records, (ii) the interdisciplinary antecedents, and (iii) the social and collaborative skills of the individual. A doctoral candidate that does not fulfill the two latter characteristics would be a better fit for a single-disciplinary program since the possible lack of engagement with IDR potentially compromises the network and the community that an interdisciplinary program aims to build.

Funding for Truly Interdisciplinary Research

Several studies agree on the importance of funding to facilitate and promote IDR (Jahn et al., 2012; Pohl et al., 2008). This investigation not only confirms this observation, but also discusses how the characteristics of funding are crucial factors in facilitating or constraining interdisciplinarity, particularly in the case of doctoral researchers. Those described by the integrative pattern were either self-funded or recipients of a scholarship. Such forms of funding provided them the necessary autonomy for conducting IDR. University and funding institutions should consider granting research funds to doctoral candidates with truly interdisciplinary research plans in a way that their research autonomy is maintained. Such funding should permit doctoral researchers to choose the disciplines that they plan to integrate into their research, as well as to select their supervisors and their contributions to the different disciplines. Additionally, in order to bring interdisciplinary doctoral researchers to the same professional level as single-disciplinary ones (who are typically employed as project and university assistants), such funding should not be granted in the form of a scholarship. Ideally, these researchers should have the status of scientific personnel with the same healthcare and social benefits. It is paradoxical that doctoral researchers who confront the additional challenges of IDR also need to face precarious working conditions. Still waiting to be investigated is whether professors are more likely to supervise truly interdisciplinary research when the work is not financed with the group budget (i.e., university or projects assistantships).

Collaboration Opportunities for Interdisciplinary Researchers

While the doctoral researchers described by the disciplinary and specialist patterns come into contact with experts of other disciplines through the networks of their supervisor and pre-established project partners, researchers described by the integrative pattern show greater agency in the development of their own networks with other disciplines. The latter group described this as a long and difficult process, but also a necessary one in order to receive advice and feedback that members of their department cannot provide. The means of engagement with experts in other disciplines were via conferences, research stays and internships. Since integrative researchers are self-funded or recipients of a scholarship, they have to cover part of, if not all the expenses of their scientific activity themselves. Instead, those disciplinary and specialist researchers employed as university or project assistants have most of these expenses covered by their research group or project. Although this inequality also affects self-funded and scholarship recipients that conduct single-disciplinary research, it is especially unfortunate for truly interdisciplinary doctoral researchers because collaboration with other disciplines is essential for their research. Therefore, initiatives to finance the network development of truly interdisciplinary researchers should be implemented in order to support the soundness of their research from the perspectives of all the disciplines involved.

Supervision and Mentoring

Truly interdisciplinary doctoral researchers require a special kind of supervision. Supervising IDR requires being open about the cultures and disciplinary norms of other disciplines. It also requires understanding and valuing integrated knowledge production, and at times ignoring departmental and disciplinary ties that discourage research contributions to other fields. This is important in order to avoid pragmatic interdisciplinary projects (Lengwiller, 2006), which are common among doctoral researchers described by the disciplinary pattern. Such projects aim to fulfill the interdisciplinary requirements of funding institutions with very low interest in the integration of knowledge from other disciplines.

Since truly interdisciplinary doctoral research often requires joint supervision—as is the case of the researchers described by the integrative pattern—academic supervisors should be able to share their academic authority on the doctoral research with other scholars. Communication between supervisors is also important for furthering their understanding of the requirements, complexity of another research discipline and ensuring that the research project is relevant for both disciplines, but not overly-ambitious.

In addition to academic supervision, often a task-oriented activity (e.g., completion of a project), interdisciplinary doctoral researchers would benefit from receiving advice on their long-term development. Since truly interdisciplinary doctoral researchers may be weakly integrated into their department, career mentoring could help them to strategically plan a professional and scientific career.

Continuity of Interdisciplinary Research Topics

One of the reasons for CS doctoral researchers described by the disciplinary pattern to invest less effort into the integration of other disciplines in their research is the uncertainty of whether a particular combination of disciplines will continue to be funded. Since each of the future research projects might combine CS with a different discipline, CS researchers focus on their field of expertise rather than on the integration and exchange of knowledge of both disciplines. Although the outcome of such projects may be relevant and substantial, it is not truly interdisciplinary. If support for furthering established collaborations cannot be maintained over time, true interdisciplinary is unlikely to take place. The responsibility for the implementation of strategies that support initiatives which integrate certain combinations of disciplines over time would fall on the departments, universities and funding agencies.

Opening the Gates to Interdisciplinarity

The choice of the PhD topic of most doctoral researchers described by the disciplinary and specialist patterns was heavily influenced by their supervisors. In some cases, their PhD topic was a continuation of the research conducted for their master thesis, which was supervised by the same professor. In other cases, doctoral supervisors suggested their own current interests as possible lines of research. Consequently, doctoral supervisors act as gatekeepers of IDR. Encouraging professors to conduct IDR, is therefore crucial to promoting doctoral interdisciplinarity. The university and department should examine and implement procedures that encourage and foster such interdisciplinary endeavors and to remove disincentives for professors (and also post-doctoral researchers).

Communication between Academic Stakeholders

The analysis of the responses of academic stakeholders in the 360-degree survey, revealed discordances in their assessment of the fulfillment and importance of interdisciplinary factors and processes. Once discordances have been identified, they should be discussed in order to clarify what each group of stakeholders is trying to achieve. Communication between stakeholders should aim to build an understanding of each other's goals, invite feedback, and build positive relationships so as to ensure progress towards common strategic objectives.

The results illustrate that these organizations must recognize the diversity of the definitions of interdisciplinarity held by researchers, and suggest that this diversity may be an obstacle in providing effective support for those conducting IDR.

8.3.2 Implications for Future Research

This dissertation lays important groundwork for the development of improved interdisciplinary measures and the future examination of the circumstances and processes of becoming an interdisciplinary early career scientist. Subsequent research should address the limitations of this investigation discussed in Section 8.2. In addition to these, four additional lines of future work are discussed in this section.

The first relates to one of the limitations previously discussed: the exclusive focus of the qualitative analysis on doctoral researchers who conduct IDR. Further analyses of the accounts of other individuals would be necessary to answer other related open questions. For instance, obstacles for IDR could be analyzed via interviews with doctoral researchers who do not integrate different disciplines in their research although they have interdisciplinary antecedents or aspirations. An important perspective, which should be further examined, as mentioned at the beginning of this paragraph, is that of professors who supervise IDR. In this investigation they were interviewed in order to identify the set of assessment criteria for the 360-degree survey. A preliminary analysis of their accounts revealed inconsistencies in their opinion of IDR. Most of them emphasized their interest in IDR and provided examples of interdisciplinary activities in which they are involved, such as: (i) participation in interdisciplinary projects, (ii) implementation of interdisciplinary programs, (iii) networking with experts in other disciplines, and (iv) encouraging doctoral researchers to conduct IDR. However, as the interviews proceeded and the obstacles of an interdisciplinary career were discussed, the same individuals emphasized the importance of doctoral researchers focusing on CS rather than on the other discipline: the publications, research contributions, attendance at conferences and research visits of doctoral researchers should all converge towards CS. The investigation into their conflicting opinions lay beyond the scope of this study, however an examination of these views would be helpful in determining how this affects the supervision of doctoral researchers' and their own interdisciplinarity.

A second line of future research would involve replicating the study in other institutions and doctoral programs. This would allow for the identification of contextual and extraneous variables influencing the analysis. Replication studies could either focus on the clarification of issues raised by the original study or extend its generalizability. The latter would be particularly helpful to determine to what extent the findings can be generalized to different contexts, disciplines, cultures and individuals.

Further research should also expand on the current study by using a longitudinal design. Repeated observations conducted over long periods of time with the same participants are useful to establish sequences of events during and after doctoral studies. Therefore, it would be possible to detect developments or changes in the characteristics of interdisciplinary early career researchers beyond a single moment in time.

The fourth line of future work relates to the notion of continuous assessment. The analyses conducted in this investigation should not be considered as single events, but rather as forming part of a continuous cycle of planning and identifying goals, collecting and evaluating evidence, as well as implementing changes to planning based on that evidence (Crisp and Muir, 2012; Maki, 2012; R. Miller, 2007). Eventually, a software tool could be developed to assist with the tasks of data collection, cleaning, analysis and storage.

Lastly, this research illustrates that there is much more to understand about IDR in order to provide support for the next generation of interdisciplinary academics. At the same time, the examination of established interdisciplinary initiatives is the first step of their refinement, leading ultimately to IDR excellence.

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Acronyms

ACM Association for Computing Machinery. 33

AIS Association for Information Systems. 33

CRAN Comprehensive R Archive Network. 46, 64

CS Computer Science. 3–6, 9, 11, 12, 23–25, 33, 35, 36, 40, 45, 52, 55, 65, 70–92, 97, 111–113, 116, 117, 120, 121, 125, 167, 168, 170–176, 178

CT Category Term. 56–59, 62, 63, 157

HHI Herfindahl-Hirschman Index. 23

ID Interdisciplinarity. 11–16

IDR InterDisciplinary Research. 1–4, 10, 13–18, 25, 28–32, 40, 42, 47–49, 58, 59, 61–64, 67, 72, 73, 75, 77–80, 90–92, 95–97, 101, 102, 104, 105, 110–122, 125, 171, 172, 175–177

IEEE Institute of Electrical and Electronics Engineers. 33

IGERT Integrative Graduate Education and Research Traineeship. 31

NSF National Science Foundation. 31

OECD Organization for Economic Co-operation and Development. 10, 11, 123

WoS Web of Science. 22, 47, 49, 55–58, 157

Bibliography

Abernethy, K. and Treu, K. (2015). "Evolving the information technology major by embracing interdisciplinarity". In: *Journal of Computing Sciences in Colleges* 31.2, pp. 208–216.

Aboelela, S. W., Larson, E., Bakken, S., Carrasquillo, O., Formicola, A., Glied, S. A., Hass, J., and Gebbie, K. M. (2007). "Defining interdisciplinary research: Conclusions from a critical review of the literature". In: *Health Services Research* 42.1 Pt 1, pp. 329–346. DOI: 10.1111/j.1475-6773.2006.00621.x.

Amabile, T. M. (2006). *Creativity in context: Update to 'the social psychology of creativity'*. Oxford, UK: Westview.

Amir, S. (1985). "On the degree of interdisciplinarity of research programs: A quantitative assessment". In: *Scientometrics* 8.1-2, pp. 117–136.

Aparac-Jelušić, T., Ibekwe-SanJuan, F., Huvila, I., Ma, L., Ortiz-Repiso Jimenez, V., and Warner, J. (2013). "Crossing the boundaries in information science: Perspectives on interdisciplinarity". In: *Proceedings of the American Society for Information Science and Technology* 50.1, pp. 1–3. DOI: 10.1002/meet.14505001009.

Astin, A. W. (1985). *Achieving educational excellence: A critical assessment of priorities and practices in higher education.* San Francisco, USA: Jossey-Bass.

Atkinson, P., Coffey, A., and Delamont, S. (2003). *Key themes in qualitative research: Continues and changes.* New York, USA: Altamira Press.

Atkinson, P. and Parry, O. (2000). *The Doctoral Experience: Success and Failure in Graduate School.* London, UK: Taylor & Francis.

Bammer, G. (2005). "Integration and implementation sciences: Building a new specialization". In: *Ecology & Society* 10.2, pp. 95–107.

Barry, A., Born, G., and Weszkalnys, G. (2008). "Logics of interdisciplinarity". In: *Economy and Society* 37.1, pp. 20–49. DOI: 10.1080/03085140701760841.

Bensman, S. J. and Leydesdorff, L. (2009). "Definition and identification of journals as bibliographic and subject entities: Librarianship versus ISI Journal Citation Reports methods and their effect on citation measures". In: *Journal of the American Society for Information Science and Technology* 60.6, pp. 1097–1117. DOI: 10.1002/asi.21020.

Berger, P. L. and Luckmann, T. (1966). *The Social Construction of Reality: A Treatise in the Sociology of Knowledge.* Garden City, USA: Doubleday.

Berger, W. H. and Parker, F. L. (1970). "Diversity of planktonic foraminifera in deep-sea sediments". In: *Science* 168.3937, pp. 1345–1347. DOI: 10.1126/science.168.3937.1345.

Billett, S. (1998). "Understanding workplace learning: Cognitive and sociocultural perspectives". In: *Current issues and new agendas in workplace learning.* Ed. by D. Boud. Adelaide, Australia: NCVER, pp. 47–68.

— (2006). "Relational interdependence between social and individual agency in work and working life". In: *Studies in Higher Education* 13.1, pp. 53–69. DOI: 10.1207/s15327884mca1301_5.

Bjurström, A. and Polk, M. (2011). "Climate change and interdisciplinarity: A co-citation analysis of IPCC Third Assessment Report". In: *Scientometrics* 87.3, pp. 525–550. DOI: 10.1007/s11192-011-0356-3.

Blackwell, A. F. (2015). "HCI as an inter-discipline". In: *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems.* CHI EA '15. Seoul, Republic of Korea: ACM, pp. 503–516. ISBN: 978-1-4503-3146-3. DOI: 10.1145/2702613.2732505.

Boden, D., Borrego, M., and Newswander, L. K. (2011). "Student socialization in interdisciplinary doctoral education". In: *Higher Education* 62.6, pp. 741–755. DOI: 10.1007/s10734-011-9415-1.

Boden, M. A. (1997). "What is interdisciplinarity?" In: *Interdisciplinarity and the organization of knowledge in Europe. A conference organized by the Academia Europaea.* Ed. by R. Cunningham. Cambridge, UK: Office for official publications of the European Communities.

Boix Mansilla, V. (2006a). "Interdisciplinary work at the frontier: An empirical examination of expert interdisciplinary epistemologies". In: *Issues in Integrative Studies* 24, pp. 1–31.

Boix Mansilla, V. (2006b). "Assessing expert interdisciplinary work at the frontier: An empirical exploration of "symptoms of quality"". In: *Research Evaluation* 15.1, pp. 17–29.

Boix Mansilla, V. and Duraisingh, E. D. (2007). "Targeted assessment of students' interdisciplinary work: An empirically grounded framework proposed". In: *The Journal of Higher Education* 78.2, pp. 215–237.

Borrego, M. and Newswander, L. K. (2008). "Characteristics of successful cross-disciplinary engineering education collaborations". In: *Journal of Engineering Education* 97.2, pp. 123–134. DOI: 10.1002/jee.2008.97.issue-2.

— (2010). "Definitions of interdisciplinary research: Toward graduate-level interdisciplinary learning outcomes". In: *The Review of Higher Education* 34.1, pp. 61–84. DOI: 10.1353/rhe.2010.0006.

Borrego, M. and Cutler, S. (2010). "Constructive alignment of interdisciplinary graduate curriculum in engineering and science: An analysis of successful IGERT proposals". In: *Journal of Engineering Education* 99.4, pp. 355–369.

Boyack, K. W. and Klavans, R. (2010). "Co-citation analysis, bibliographic coupling, and direct citation: Which citation approach represents the research front most accurately?" In: *Journal of the American Society for Information Science and Technology* 61.12, pp. 2389–2404. DOI: 10.1002/asi.21419.

Brandt, P., Ernst, A., Gralla, F., Luederitz, C., Lang, D. J., Newig, J., Reinert, F., Abson, D. J., and Wehrden, H. VON (2013). "A review of transdisciplinary research in sustainability science". In: *Ecological Economics* 92, pp. 1–15.

Brint, S. (2005). "Creating the future: 'New directions' in American research universities". In: *Minerva* 43.1, pp. 23–50.

Bruce, A., Lyall, C., Tait, J., and Williams, R. (2004). "Interdisciplinary integration in Europe: The case of the Fifth Framework programme". In: *Futures* 36.4, pp. 457–470.

Bruun, H., Hukkinen, J., Huutoniemi, K., and Klein, J. T. (2005). *Promoting interdisciplinary research: The case of the Academy of Finland.* Publications of the Academy of Finland 8/05. Helsinki, Finland: The Academy of Finland.

Bruun, H., Langlais, R., and Janasik, N. (2005). "Knowledge networking: A conceptual framework and typology". In: *VEST* 18.3-4, pp. 73–104.

Calatrava Moreno, M. C. (2013). "Towards a flexible assessment of higher education with 360-degree feedback". In: *IEEE International Conference on Information Technology based Higher Education and Training (ITHET).* IEEE. Antalya, Turkey. DOI: 10.1109/ITHET.2013.6671041.

— (2014). "A 360-degree evaluation framework for doctoral programs". In: *IEEE Global Engineering Education Conference (EDUCON).* IEEE, pp. 850–853. DOI: 10.1109/EDUCON.2014.6826195.

Calatrava Moreno, M. C. and Auzinger, T. (2016). *robustrao: An Extended Rao-Stirling Diversity Index to Handle Missing Data.* https://cran.rstudio.com/web/packages/robustrao/index.html. Accessed: 15-09-2016.

Calatrava Moreno, M. C., Auzinger, T., and Werthner, H. (2016). "On the uncertainty of interdisciplinarity measurements due to incomplete bibliographic data". In: *Scientometrics* 107.1, pp. 213–232. DOI: 10.1007/s11192-016-1842-4.

Calatrava Moreno, M. C. and Danowitz, M. A. (2016a). "Becoming an interdisciplinary scientist: An analysis of students' experiences in three computer science doctoral programmes". In: *Journal of Higher Education Policy and Management* 38.4, pp. 448–464. DOI: 10.1080/1360080X.2016.1182670.

— (2016b). "Interdisciplinarity in computer science: Emergent patterns from doctoral experiences". In: *ACM Transactions on Computing Education.* Conditionally accepted.

Calatrava Moreno, M. C., Kynčlová, P., and Werthner, H. (2016). "A Multiple-Perspective Analysis of Doctoral Interdisciplinarity". In: *IEEE International Conference on Information Technology based Higher Education and Training (ITHET).* IEEE. Istanbul, Turkey.

Cambrosio, A., Limoges, C., Courtial, J. P., and Laville, F. (1993). "Historical scientometrics? Mapping over 70 years of biological safety research with coword analysis". In: *Scientometrics* 27.2, pp. 119–143.

Carayol, N. and Nguyen-Thi, T. U. (2005). "Why do academic scientists engage in interdisciplinary research?" In: *Research Evaluation* 14.1, pp. 70–79.

Carey, G. E. and Smith, J. A. (2007). "Jack-of-all-trades, master of none: Postgraduate perspectives on interdisciplinary health research in Australia". In: *BMC health services research* 7.1. DOI: 10.1186/1472-6963-7-48.

Carey, J. W. (1993). "Linking qualitative and quantitative methods: Integrating cultural factors into public health". In: *Qualitative Health Research* 3.3, pp. 298–318. DOI: 10.1177/104973239300300303.

Carley, S. and Porter, A. L. (2011). "A forward diversity index". In: *Scientometrics* 90.2, pp. 407–427. DOI: 10.1007/s11192-011-0528-1.

Cassi, L., Mescheba, W., and De Turckheim, E. (2014). "How to evaluate the degree of interdisciplinarity of an institution?" In: *Scientometrics* 101.3, pp. 1871–1895.

Charmaz, K. (2006). *Constructing Grounded Theory.* London, UK: Sage Publications.

Chen, C., Hu, Z., Liu, S., and Tseng, H. (2012). "Emerging trends in regenerative medicine: A scientometric analysis in CiteSpace". In: *Expert Opinion on Biological Therapy* 12.5, pp. 593–608. DOI: 10.1517/14712598.2012.674507.

Chen, C., Ibekwe-SanJuan, F., and Hou, J. (2010). "The structure and dynamics of cocitation clusters: A multiple-perspective cocitation analysis". In: *Journal of the American Society for Information Science and Technology* 61.7, pp. 1386–1409. DOI: 10.1002/asi.21309.

Chi-Chih Yao, A. (2015). "Interdisciplinarity: A view from theory of computation". In: *Federated Computing Research Conference.* FCRC '15. Portland, Oregon, USA: ACM. ISBN: 978-1-4503-3966-7. DOI: 10.1145/2820468.2820472.

Cole, J. R., Cole, S., et al. (1974). "Social stratification in science". In: *American Journal of Physics* 42.10, pp. 923–924.

Crisp, K. M. and Muir, G. M. (2012). "Assessing development of an interdisciplinary perspective in an undergraduate neuroscience course". In: *Journal of Undergraduate Neuroscience Education* 10.2, pp. 88–95.

Crouch, M. and McKenzie, H. (2006). "The logic of small samples in interview-based qualitative research". In: *Social Science Information* 45.Dec, pp. 483–499. DOI: 10.1177/0539018406069584.

Denzin, N. K. (1970). *The research act in sociology.* London, UK: Butterworth.

Denzin, N. K. and Lincoln, Y. S. (2000). "Introduction: The Discipline and Practice of Qualitative Research". In: *Handbook of Qualitative Research.* Ed. by N. K. Denzin and Y. S. Lincoln. 2nd. Sage Publications.

desJardins, M. (2013). "Computation, complexity, and emergence: An interdisciplinary honors seminar". In: *Proceeding of the 44th ACM Technical Symposium on Computer Science Education.* SIGCSE '13. Denver, USA: ACM, pp. 83–88. ISBN: 978-1-4503-1868-6. DOI: 10.1145/2445196.2445224.

Domik, G. and Fischer, G. (2010). "Coping with complex real-world problems: Strategies for developing the competency of transdisciplinary collaboration". In: *Key Competencies in the Knowledge Society.* Ed. by N. Reynolds and M. Turcsányi-Szabó. Springer, pp. 90–101.

Eckstein, H.-H., Niedermeier, H.-P., Noppeney, T., Umscheid, T., Wenk, H., and Imig, H. (2006). "Certification of vascular centers–a project of the German Society for Vascular Surgery". In: *European Journal of Vascular and Endovascular Surgery* 32.3, pp. 279–285.

European Union Research Advisory Board (2004). *Interdisciplinarity in research.*

European University Association (2007). *Doctoral programmes in Europe's universities: achievements and challenges; report prepared for European universities and ministers of higher education.* Brussels, Belgium.

— (2010). *Salzburg II Recommendations. European universities' achievements since 2005 in implementing the Salzburg Principles. Report prepared for European Universities and Ministers of Higher Education.* Brussels, Belgium.

Ewell, P. T. (1984). *The self-regarding institution: Information for excellence. NCHEMS executive overview.* Boulder, USA: National Center for Higher Education Management Systems.

Ewell, P. T. (1991). "To capture the ineffable: New forms of assessment in higher education". In: *Review of Research in Education* 17.1, pp. 75–125.

Faculty of Informatics, TU Wien (2016a). *Doctoral program 'Mathematical Logic in Computer Science'*. URL: http://www.dbai.tuwien.ac.at/drkolleg/.

— (2016b). *Faculty of Informatics. Main research areas.* URL: http://www.informatik.tuwien.ac.at/research.

— (2016c). *The Vienna PhD School of Informatics.* URL: http://www.informatik.tuwien.ac.at/teaching/phdschool.

Floudas, C. A. and Visweswaran, V. (1995). "Quadratic Optimization". In: *Handbook of Global Optimization*. Ed. by R. Horst and P. M. Pardalos. Nonconvex Optimization and Its Applications. Springer, pp. 217–269. ISBN: 978-1-4613-5838-1.

Fontana, A. and Fey, J. H. (2000). "The interview: From structured questions to negotiated text". In: *Handbook of Qualitative Research*. Ed. by N. K. Denzin and Y. S. Lincoln. 2nd. Sage Publications.

Friedman, K. (2013). "The challenge of interdisciplinary research". In: *Proceedings of the 9th ACM Conference on Creativity & Cognition*. C&C '13. Sydney, Australia: ACM, pp. 11–11. ISBN: 978-1-4503-2150-1. DOI: 10.1145/2466627.2485920.

Gagné, M. and Deci, E. L. (2005). "Self-determination theory and work motivation". In: *Journal of Organizational Behavior* 26.4, pp. 331–362.

Gardner, S. K., Jansujwicz, J. S., Hutchins, K., Cline, B., and Levesque, V. (2014). "Socialization to interdisciplinarity: Faculty and student perspectives". In: *Higher Education* 67.3, pp. 255–271. DOI: 10.1007/s10734-013-9648-2.

Garfield, E., Malin, M. V., and Small, H. (1978). "Citation data as science indicators". In: *Toward a metric of Science: The Advent of Science Indicators*. Ed. by Y. Elkana, J. Lederberg, R. K. Merton, A. Thackaray, and H. Zuckerman. New York, USA: John Wiley & Sons, pp. 179–208.

Geiger, R. L. and Sá, C. M. (2008). *Tapping the riches of science: Universities and the promise of economic growth*. Cambridge, USA: Harvard University Press.

Gipp, B. and Beel, J. (2009). "Citation Proximity Analysis (CPA)-A new approach for identifying related work based on Co-Citation Analysis". In: *Proceedings of the 12th International Conference on Scientometrics and Informetrics (ISSI'09)*. Vol. 2. International Society for Scientometrics and Informetrics, pp. 571–575.

Golde, C. M. and Walker, G. E. (2006). *Envisioning the future of doctoral education: Preparing stewards of the discipline. Carnegie essays on the doctorate.* San Francisco, USA: Jossey-Bass Publishers.

Golde, C. M. (1998). "Beginning Graduate School: Explaining First-Year Doctoral Attrition". In: *New Directions for Higher Education* 1998.101, pp. 55–64. ISSN: 1536-0741. DOI: 10.1002/he.10105.

Golde, C. M. and Gallagher, H. A. (1999). "The challenges of conducting interdisciplinary research in traditional doctoral programs". In: *Ecosystems* 2.4, pp. 281–285.

Gravetter, F. J. and Forzano, L. B. (2011). *Research methods for the Behavioral Sciences*. 4th ed. Belmont, USA: Wadsworth Cengage Learning.

Graybill, J. K., Dooling, S., Shandas, V., Withey, J., Greve, A., and Simon, G. L. (2006). "A rough guide to interdisciplinarity: Graduate student perspectives". In: *BioScience* 56.9, pp. 757–763.

Graybill, J. K. and Shandas, V. (2010). "Doctoral student and early career academic perspectives". In: *The Oxford handbook of interdisciplinarity*. Ed. by R. Frodeman, J. T. Klein, and C. Micham. Oxford, UK: Oxford University Press, pp. 404–418.

Grudin, J. (2011). “Technology, Conferences, and Community”. In: *Communications of the ACM* 54.2, pp. 41–43. ISSN: 0001-0782. DOI: 10.1145/1897816.1897834.

Guba, E. and Lincoln, Y. (1989). “Judging the quality of fourth generation evaluation”. In: *Fourth generation evaluation*. Ed. by E. Guba and Y. Lincoln. Newbury Park, USA: Sage.

Haines, V. A., Godley, J., and Hawe, P. (2011). “Understanding Interdisciplinary Collaborations as Social Networks”. In: *American Journal of Community Psychology* 47.1-2, pp. 1–11. DOI: 10.1007/s10464-010-9374-1.

Hartley, R. V. L. (1928). “Transmission of Information1”. In: *Bell System Technical Journal* 7.3, pp. 535–563. DOI: 10.1002/j.1538-7305.1928.tb01236.x.

He, Q. (1999). “Knowledge discovery through co-word analysis”. In: *Library trends* 48.1, pp. 133–133.

Heckhausen, H. (1972). “Discipline and interdisciplinarity”. In: *Interdisciplinarity. Problems of teaching and research in universities*. Ed. by R. Cunningham. Paris, France: OECD, pp. 83–89.

Herfindahl, O. C. (1950). “Concentration in the US steel industry”. PhD thesis. Columbia University, USA.

Hill, M. O. (1973). “Diversity and evenness: a unifying notation and its consequences”. In: *Ecology* 54.2, pp. 427–432. DOI: 10.2307/1934352.

Hirschman, A. O. (1945). *National power and the structure of foreign trade*. Berkeley, USA: University of California Press.

Holland, D. (2014). *Integrating knowledge through interdisciplinary research*. Abingdon, UK: Routledge Publishing.

Holley, K. A. (2006). “The cultural construction of interdisciplinarity: Doctoral student socialization in an interdisciplinary neuroscience program”. PhD thesis. Los Angeles, USA: University of Southern California.

— (2009). “The challenge of an interdisciplinary curriculum: A cultural analysis of a doctoral-degree program in neuroscience”. In: *Higher Education* 58.2, pp. 241–255. DOI: 10.1007/s10734-008-9193-6.

Holley, K. A. (2015). “Doctoral education and the development of an interdisciplinary identity”. In: *Innovations in Education and Teaching International* 52.6, pp. 642–652. DOI: 10.1080/14703297.2013.847796.

Hopwood, N. (2010). “Doctoral experience and learning from a sociocultural perspective”. In: *Studies in Higher Education* 35.7, pp. 829–843. DOI: 10.1080/03075070903348412.

Huutoniemi, K., Klein, J. T., Bruun, H., and Hukkinen, J. (2010). “Analyzing interdisciplinarity: Typology and indicators”. In: *Research Policy* 39.1, pp. 79–80. DOI: 10.1016/j.respol.2009.09.011.

Huutoniemi, K. (2010). “Evaluating interdisciplinary research”. In: *The Oxford handbook of interdisciplinarity*. Ed. by R. Frodeman, J. T. Klein, and C. Micham. Oxford, UK: Oxford University Press.

Institute of Medicine and National Academy of Sciences and National Academy of Engineering (2005). *Facilitating Interdisciplinary Research*. Washington, USA: The National Academies Press. ISBN: 978-0-309-09435-1. DOI: 10.17226/11153.

Ivanitskaya, L., Clark, D., Montgomery, G., and Primeau, R. (2002). “Interdisciplinary learning: Process and outcomes”. In: *Innovative Higher Education* 27.2, pp. 95–111. DOI: 10.1023/A:1021105309984.

Jacobs, J. A. and Frickel, S. (2009). “Interdisciplinarity: A critical assessment”. In: *Annual review of Sociology* 35.1, pp. 43–65. DOI: 10.1146/annurev-soc-070308-115954.

Jahn, T., Bergmann, M., and Keil, F. (2012). “Transdisciplinarity: Between mainstreaming and marginalization”. In: *Ecological Economics* 79, pp. 1–10. DOI: 10.1016/j.ecolecon.2012.04.017.

Jost, L. (2006). “Entropy and diversity”. In: *Oikos* 113.2, pp. 363–375. DOI: 10.1111/j.2006.0030-1299.14714.x.

Karlovčec, M. and Mladenić, D. (2015). “Interdisciplinarity of scientific fields and its evolution based on graph of project collaboration and co-authoring”. In: *Scientometrics* 102.1, pp. 433–454. DOI: 10.1007/s11192-014-1355-y.

Karlqvist, A. (1999). “Going beyond disciplines”. In: *Policy Sciences* 32.4, pp. 379–383. DOI: 10.1023/A:1004736204322.

Katz, J. S. and Martin, B. R. (1997). “What is research collaboration?” In: *Research Policy* 26.1, pp. 1–18. DOI: http://dx.doi.org/10.1016/S0048-7333(96)00917-1.

Katz, J. (1994). “Geographical proximity and scientific collaboration”. In: *Scientometrics* 31.1, pp. 31–43. DOI: 10.1007/BF02018100.

Kavaloski, V. C. (1979). “Interdisciplinary education and humanistic aspiration: A critical reflection”. In: *Interdisciplinarity and higher education*. Ed. by J. J. Kockelmans. University Park, USA: Pennsylvania State University Press, pp. 224–243.

Kehm, B. (2006). “Doctoral education in Germany within the European framework”. In: *Europeanising doctoral studies: The Russian Federation and Germany on the way to Bologna*. Ed. by G. Gorzka and U. Lanzendorf. Munich, Germany: Unidruckerei, Kassel University Press, pp. 51–70.

Kessler, M. M. (1963). “Bibliographic coupling between scientific papers”. In: *American Documentation* 14.1, pp. 10–25.

Klein, J. T. (1990). *Interdisciplinarity: History, theory, and practice*. Detroit, USA: Wayne State University Press.

— (2010). “A taxonomy of interdisciplinarity”. In: *The Oxford handbook of interdisciplinarity*. Ed. by R. Frodeman, J. T. Klein, and C. Micham. Oxford, UK: Oxford University Press, pp. 51–70.

Klein, J. T. (1985). “The interdisciplinary concept: Past, present and future”. In: *Interdisciplinarity revisited: Re-assessing the concept in the light of institutional experience*. Ed. by L. Levin and I. Lind. Stockholm, Sweden: OECD/CERI, Swedish National Board of Universities and Colleges, Linköping University, pp. 104–136.

— (1996). *Crossing boundaries: Knowledge, disciplinarities, and interdisciplinarities*. Charlottesville, USA: University Presss of Virginia.

— (2001). “The Discourse of Transdisciplinarity: An Expanding Global Field”. In: *Transdisciplinarity: Joint Problem Solving among Science, Technology, and Society: An Effective Way for Managing Complexity*. Ed. by J. T. Klein, R. Häberli, R. W. Scholz, W. Grossenbacher-Mansuy, A. Bill, and M. Welti. Basel, Switzerland: Birkhäuser Verlag, pp. 35–44. ISBN: 978-3-0348-8419-8. DOI: 10.1007/978-3-0348-8419-8_4.

Knight, L. and Pettigrew, A. (2007). “Explaining process and performance in the co-production of knowledge: A comparative analysis of collaborative research projects”. In: *Proceedings of Organization Studies as Applied Science: The Generation and Use of Academic Knowledge about Organizations*.

Kozlov, M., Tarasov, S., and Khachiyan, L. (1980). “The polynomial solvability of convex quadratic programming”. In: *USSR Computational Mathematics and Mathematical Physics* 20.5, pp. 223–228. ISSN: 0041-5553. DOI: 10.1016/0041-5553(80)90098-1.

Krosnick, J. A. and Presser, S. (2010). “Question and questionnaire design”. In: *Handbook of survey research*. Ed. by J. D. Wright and P. V. Marsen. 2nd. Bingley, UK: Emerald Group Publishing.

Kruskal, W. H. and Wallis, W. A. (1952). “Use of ranks in one-criterion variance analysis”. In: *Journal of the American Statistical Association* 47.260, pp. 583–621.

Lattuca, L. R. (2001). *Creating interdisciplinarity: Interdisciplinary research and teaching among college and university faculty*. Nashville, USA: Vanderbilt University Press.

— (2002). “Learning interdisciplinarity: Sociocultural perspectives on academic work”. In: *The Journal of Higher Education* 73.6, pp. 711–739. DOI: 10.1353/jhe.2002.0054.

— (2003). “Creating interdisciplinarity: Grounded definitions from college and university faculty”. In: *History of Intellectual Culture* 3.1.

Lattuca, L. R., Voigt, L. J., and Fath, K. Q. (2004). “Does interdisciplinarity promote learning? Theoretical support and researchable questions”. In: *The Review of Higher Education* 28.1, pp. 23–48.

Lengwiller, M. (2006). “Between charisma and heuristics: Four styles of interdisciplinarity”. In: *Science and Public Policy* 33.6, pp. 423–434. DOI: 10.3152/147154306781778821.

Lenoir, Y. L., Larose, F., and Geoffroy, Y. (2000). “Interdisciplinary practices in primary education in Quebec: Results from ten years of research”. In: *Issues in Integrative Studies* 18, pp. 89–114.

Leydesdorff, L. (2007). “Betweenness centrality as an indicator of the interdisciplinarity of scientific journals”. In: *Journal of the American Society for Information Science and Technology* 58.9, pp. 1303–1319. DOI: 10.1002/asi.20614.

Leydesdorff, L., Carley, S., and Rafols, I. (2013). “Global maps of science based on the new Web-of-Science categories”. In: *Scientometrics* 94.2, pp. 589–593. DOI: 10.1007/s11192-012-0784-8.

Leydesdorff, L., Rafols, I., and Chen, C. (2013). “Interactive overlays of journals and the measurement of interdisciplinarity on the basis of aggregated journal–journal citations”. In: *Journal of the American Society for Information Science and Technology* 64.12, pp. 2573–2586. DOI: 10.1002/asi.22946.

Lincoln, Y. S. and Guba, E. G. (2000a). “Paradigmatic controversies, contradictions and emerging confluences”. In: *Handbook of Qualitative Research*. Ed. by N. K. Denzin and Y. S. Lincoln. 2nd. Sage Publications.

Lincoln, Y. S. and Guba, E. G. (1986). “But is it rigorous? Trustworthiness and authenticity in naturalistic evaluation”. In: *New Directions for Program Evaluation* 1986.30, pp. 73–84. ISSN: 1551-2371. DOI: 10.1002/ev.1427.

— (2000b). “When research is not enough: Community, care, and love”. In: *The Review of Higher Education* 23.3, pp. 241–256.

Lindner, A. B. and Taddei, F. (2007). "Forming the next generation of European interdisciplinary scientists". In: *Science Education: Models and Networking of Student Research Training Under 21, NATO Security through Science Series - E: Human and Societal Dynamics* 16, pp. 172–182.

Liu, Y., Rafols, I., and Rousseau, R. (2012). "A framework for knowledge integration and diffusion". In: *Journal of Documentation* 68.1, pp. 31–44. DOI: 10.1108/00220411211200310.

Lundberg, J., Tomson, G., Lundkvist, I., Skår, J., and Brommels, M. (2006). "Collaboration uncovered: Exploring the adequacy of measuring university-industry collaboration through co-authorship and funding". In: *Scientometrics* 69.3, pp. 575–589. DOI: 10.1007/s11192-006-0170-5.

Lyall, C. and Meagher, L. (2012). "A masterclass in interdisciplinarity: Research into practice in training the next generation of interdisciplinary researchers". In: *Futures* 44.6, pp. 608–617.

Maglaughlin, K. L. and Sonnenwald, D. H. (2005). "Factors that impact interdisciplinary natural science research collaboration in academia". In: *Proceedings of the 10th International Conference of the International Society for Scientometrics and Informetrics (ISSI).* Vol. 2. ISSI, pp. 499–508.

Maki, P. L. (2012). *Assessing for learning: Building a sustainable commitment across the institution.* Sterling, USA: Stylus Publishing.

Manathunga, C., Lant, P., and Mellick, G. (2006). "Imagining an interdisciplinary doctoral pedagogy". In: *Teaching in Higher Education* 11.3, pp. 365–379.

Marshakova-Shaikevich, I. (1973). "System of Document Connections Based on References". In: *Scientific and Technical Information Serial of VINITI* 6.2, pp. 3–8.

Martyn, J. (1964). "Bibliographic coupling". In: *Journal of Documentation* 20.4, pp. 236–236.

Mâsse, L. C., Moser, R. P., Stokols, D., Taylor, B., Marcus, S. E., Morgan, G. D., Hall, K. L., Croyle, R. T., and Trochim, W. M. (2008). "Measuring Collaboration and Transdisciplinary Integration in Team Science". In: *American Journal of Preventive Medicine* 35.2, s151–160. DOI: 10.1016/j.amepre.2008.05.020.

Messmer, M. W. (1978). "The vogue of the interdisciplinary". In: *The Centennial Review* 22.4, pp. 467–478.

Mielke, R. R., Scerbo, M. W., Gaubatz, K. T., and Watson, G. S. (2008). "A multidisciplinary model for M&S graduate education". In: *Proceedings of the 2008 Spring Simulation Multi-conference.* SpringSim '08. Ottawa, Canada: Society for Computer Simulation International, pp. 763–769. ISBN: 1-56555-319-5.

Miles, M. and Rainbird, S. (2015). "Evaluating interdisciplinary collaborative learning and assessment in the creative arts and humanities". In: *Arts and Humanities in Higher Education* 14.4, pp. 409–425.

Millar, M. M. (2013). "Interdisciplinary research and the early career: The effect of interdisciplinary dissertation research on career placement and publication productivity of doctoral graduates in the sciences". In: *Research Policy* 42.5, pp. 1152–1164.

Miller, R. C. (1982). "Varieties of interdisciplinary approaches in the social sciences: A 1981 overview". In: *Issues in Integrative Studies* 1, pp. 1–37.

Miller, R. (2007). *Assessment in cycles of improvement: Faculty designs for essential learning outcomes.* Association of American Colleges and Universities.

Misra, S., Harvey, R. H., Stokols, D., Pine, K. H., Fuqua, J., Shokair, S. M., and Whiteley, J. M. (2009). "Evaluating an interdisciplinary undergraduate training program in health promotion research". In: *American Journal of Preventive Medicine* 36.4, pp. 358–365.

Mitrany, M. and Stokols, D. (2005). "Gauging the transdisciplinary qualities and outcomes of doctoral training programs". In: *Journal of Planning Education and Research* 24.4, pp. 437–449.

Moed, H., Burger, W., Frankfort, J., and Raan, A. F. van (1985). "The application of bibliometric indicators: Important field-and time-dependent factors to be considered". In: *Scientometrics* 8.3-4, pp. 177–203. doi: 10.1007/BF02016935.

Moed, H., De Bruin, R., and Leeuwen, T. van (1995). "New bibliometric tools for the assessment of national research performance: Database description, overview of indicators and first applications". In: *Scientometrics* 33.3, pp. 381–422. doi: 10.1007/BF02017338.

Morgan, D. L. (1998). "Practical strategies for combining qualitative and quantitative methods: Applications to health research". In: *Qualitative health research* 8.3, pp. 362–376. doi: 10.1177/104973239800800307.

Muterspaw, K., Urner, T., Lewis, R., Babic, I., Srinath, D., Peck, C., Cerda-Granados, D., Lemiszki, P., Sánchez-Miranda, M., Mayorga-Méndez, M., Petursson, O., and Smith, B. (2015). "Multidisciplinary research and education with open tools: Metagenomic analysis of 16S rRNA using Arduino, Android, Mothur and XSEDE". In: *Proceedings of the 2015 XSEDE Conference: Scientific Advancements Enabled by Enhanced Cyberinfrastructure*. XSEDE '15. St. Louis, Missouri: ACM. isbn: 978-1-4503-3720-5. doi: 10.1145/2792745.2792767.

Mutz, R., Bornmann, L., and Daniel, H.-D. (2015). "Cross-disciplinary research: What configurations of fields of science are found in grant proposals today?" In: *Research Evaluation* 24.1, pp. 30–36. doi: 10.1093/reseval/rvu023.

Nash, J. M. (2008). "Transdisciplinary training: Key components and prerequisites for success". In: *American Journal of Preventive Medicine* 35.2, S133–S140. doi: 10.1016/j.amepre.2008.05.004.

National Research Council (2010). *Data on federal research and development Investments: A pathway to modernization.* Washington, USA: The National Academies Press.

Nerad, M. (2012). "Conceptual approaches to doctoral education: A community of practice". In: *Alternation* 19.2, pp. 57–72.

Newell, W. H. (1990). "Interdisciplinary curriculum development". In: *Issues in Integrative Studies* 8.1, pp. 69–86.

Newell, W. H. and Green, W. J. (1982). "Defining and teaching interdisciplinary studies". In: *Improving College and University Teaching* 30.1, pp. 23–30.

Newswander, L. K. and Borrego, M. (2009). "Engagement in two interdisciplinary graduate programs". In: *Higher Education* 58.4, pp. 551–562.

Niglas, K. (2007). "Introducing the quantitative-qualitative continuum: An alternative view on teaching research methods courses". In: *Learning and teaching of research methods at university. Research in Educational Sciences.* Ed. by M. Muronen, J. Rautopuro, and P. Väisänen. Finnish Educational Research Association.

Nocedal, J. and Wright, S. J. (2006). *Numerical Optimization.* 2nd. Springer Series in Operations Research and Financial Engineering. Springer. isbn: 9780387400655. doi: 10.1007/978-0-387-40065-5.

Nyhagen, G. M. and Baschung, L. (2013). "New organisational structures and the transformation of academic work". In: *Higher Education* 66.4, pp. 409–423. DOI: 10.1007/s10734-013-9612-1.

OECD (1982). *The University and the community: The problems of changing relationships.* Paris, France: OECD.

Palmer, C. L. (2001). *Work at the boundaries of science: Information and the interdisciplinary research process.* Springer Science & Business Media.

Pardalos, P. M. and Vavasis, S. A. (1991). "Quadratic programming with one negative eigenvalue is NP-hard". In: *Journal of Global Optimization* 1.1, pp. 15–22. ISSN: 0925-5001. DOI: 10.1007/BF00120662.

Pechar, H. and Thomas, J. (2004). "Austria". In: *Doctoral studies and qualifications in Europe and the United States: Status and prospects.* Ed. by J. Sadlak. Studies on Higher Education. Bucharest, Romania: UNESCO, pp. 51–70.

Pecher, H. and Thomas, J. (2004). "Austria". In: *Doctoral studies and qualifications in Europe and the United States: Status and prospects.* Ed. by J. Sadlak. Bucharest, Romania: UNESCO, pp. 13–35.

Pfirman, S. and Martin, P. (2010). "Facilitating interdisciplinary scholars". In: *The Oxford handbook of interdisciplinarity.* Ed. by R. Frodeman, J. T. Klein, and C. Micham. Oxford, UK: Oxford University Press, pp. 387–403.

Pisapia, J., Townsend, T., and Razzaq, J. (2013). *University efforts to support interdisciplinary research: Leadership and unintended consequences.* Glasgow, UK.

Pohl, C., Kerkhoff, L. VAN, Hirsch Hadorn, G., and Bammer, G. (2008). "Integration". In: *Handbook of transdisciplinary research.* Ed. by G. Hirsch Hadorn, H. Hoffmann-Riem, S. Biber-Klemm, W. Grossenbacher-Mansuy, D. Joye, C. Pohl, U. Wiesmann, and E. Zemp. Springer, pp. 411–424.

Ponomarev, I., Sulima, P., Basner, J., Jensen, U., Schnell, J., Jo, K., Nagahara, L. A., Lee, J. S., and Moore, N. M. (2013). "A new approach for automated author discipline categorization and evaluation of cross-disciplinary collaborations for grant programs". In: *Proceedings 14th International Society of Scientometrics and Informetrics Conference.* Vol. 2.

Porter, A. L. and Chubin, D. E. (1985). "An indicator of cross-disciplinary research". In: *Scientometrics* 8.3, pp. 161–176. DOI: 10.1007/BF02016934.

Porter, A. L. and Rafols, I. (2009). "Is science becoming more interdisciplinary? Measuring and mapping six research fields over time". In: *Scientometrics* 81.3, pp. 719–745. DOI: 10.1007/s11192-008-2197-2.

Porter, A. L., Cohen, A. S., Roessner, J. D., and Perreault, M. (2007). "Measuring researcher interdisciplinarity". In: *Scientometrics* 72.1, pp. 117–147. DOI: 10.1007/s11192-007-1700-5.

Prim, R. (1957). "Shortest connection networks and some generalizations". In: *The Bell System Technical Journal* 36.6, pp. 1389–1401. ISSN: 0005-8580. DOI: 10.1002/j.1538-7305.1957.tb01515.x.

Pudovkin, A. I. and Garfield, E. (2002). "Algorithmic procedure for finding semantically related journals". In: *Journal of the American Society for Information Science and Technology* 53.13, pp. 1113–1119. DOI: 10.1002/asi.10153.

Qin, J., Lancaster, F. W., and Allen, B. (1997). "Types and levels of collaboration in interdisciplinary research in the sciences". In: *Journal of the American Society for Information Science* 48.10, pp. 893–916. DOI: 10.1002/(ISSN)1097-4571.

Raan, A. VAN (1996). "Advanced bibliometric methods as quantitative core of peer review based evaluation and foresight exercises". In: *Scientometrics* 36.3, pp. 397–420. DOI: 10.1007/BF02129602.

Rafols, I. and Meyer, M. (2007). "How cross-disciplinary is bionanotechnology? Explorations in the specialty of molecular motors". In: *Scientometrics* 70.3, pp. 633–650. DOI: 10.1007/s11192-007-0305-3.

Rafols, I., Ciarli, T., Zwanenberg, P. VAN, and Stirling, A. (2013). "Towards indicators for 'opening up' science and technology policy". In: *Atlanta Conference on Science, Technology and Innovation Policy.*

Rafols, I. and Leydesdorff, L. (2009). "Content-based and algorithmic classifications of journals: Perspectives on the dynamics of scientific communication and indexer effects". In: *Journal of the American Society for Information Science and Technology* 60.9, pp. 1823–1835. DOI: 10.1002/asi.21086.

Rafols, I., Leydesdorff, L., O'Hare, A., Nightingale, P., and Stirling, A. (2012). "How journal rankings can suppress interdisciplinary research: A comparison between innovation studies and business & management". In: *Research Policy* 41.7, pp. 1262–1282. DOI: 10.1016/j.respol.2012.03.015.

Rafols, I. and Meyer, M. (2010). "Diversity and network coherence as indicators of interdisciplinarity: case studies in bionanoscience". In: *Scientometrics* 82.2, pp. 263–287. DOI: 10.1007/s11192-009-0041-y.

Reichert, S., Tauch, C., Geddie, K., and Crosier, D. (2005). *Trends IV: European universities implementing Bologna.* Brussels, Belgium: European University Association.

Report of the Interdisciplinary Task Force (2005). Tech. rep. Association of American Universities.

Rhoades, S. A. (1993). "The Herfindahl-Hirschman Index". In: *Federal Reserve Bulletin* 79.Mar, pp. 188–189.

Richter, D. M. and Paretti, M. C. (2009). "Identifying barriers to and outcomes of interdisciplinarity in the engineering classroom". In: *European Journal of Engineering Education* 34.1, pp. 29–45. DOI: 10.1080/03043790802710185.

Rijnsoever, F. J. VAN, Hessels, L. K., and Vandeberg, R. L. (2008). "A resource-based view on the interactions of university researchers". In: *Research Policy* 37.8, pp. 1255–1266. DOI: 10.1016/j.respol.2008.04.020.

Rinia, E. J., Leeuwen, T. N. VAN, Bruins, E. E. W., Vuren, H. G. VAN, and Raan, A. F. J. VAN (2002). "Measuring knowledge transfer between fields of science". In: *Scientometrics* 54.3, pp. 347–362. DOI: 10.1023/A:1016078331752.

Rokeach, M. (1973). *The nature of human values.* Vol. 438. Free press.

Rosenfield, P. L. (1992). "The potential of transdisciplinary research for sustaining and extending linkages between the health and social sciences". In: *Social Science & Medicine* 35.11, pp. 1343–1357. DOI: 10.1016/0277-9536(92)90038-R.

Rossini, F. A. and Porter, A. L. (1979). "Frameworks for integrating interdisciplinary research". In: *Research Policy* 8.1, pp. 70–79.

Rrnyi, A. (1961). "On measures of entropy and information". In: *Proceedings of the Fourth Berkeley Symposium on Mathematical Statistics and Probability.* Vol. 1, pp. 547–561.

Rubin, H. J. and Rubin, I. S. (1995). *Qualitative interviewing: The art of hearing data.* London, UK: Sage Publications.

Sá, C. M. (2008). "'Interdisciplinary strategies' in US research universities". In: *Higher Education* 55.5, pp. 537–552.

Sahni, S. (1974). "Computationally Related Problems". In: *SIAM Journal on Computing* 3.4, pp. 262–279. DOI: 10.1137/0203021.

Schilling, K. L., Smith, B., and McCann, J. (2001). "Interdisciplinary assessment for interdisciplinary programs". In: *Reinventing ourselves: Interdisciplinary education, collaborative learning and experimentation in higher education.* Ed. by B. L. Smith and J. McCann. Boston, USA: Anker Publishing, pp. 344–354.

Schummer, J. (2004). "Multidisciplinarity, interdisciplinarity, and patterns of research collaboration in nanoscience and nanotechnology". In: *Scientometrics* 59.3, pp. 425–465. DOI: 10.1023/B:SCIE.0000018542.71314.38.

Schwandt, T. A. (2000). "Three epistemological stances for qualitative inquiry: Interpretivism, hermeneutics, and social constructionism". In: *Handbook of Qualitative Research.* Ed. by N. K. Denzin and Y. S. Lincoln. 2nd. Sage Publications.

Shannon, C. E. (1948). "A mathematical theory of communication". In: *The Bell System Technical Journal* 27.3, pp. 379–423. DOI: 10.1002/j.1538-7305.1948.tb01338.x.

Simpson, E. H. (1949). "Measurement of diversity." In: *Nature* 163, pp. 688–688. DOI: 10.1038/163688a0.

Small, H. (1973). "Co-citation in the scientific literature: A new measure of the relationship between two documents". In: *Journal of the American Society for information Science* 24.4, pp. 265–269.

Smarkusky, D. L. and Toman, S. A. (2009). "An interdisciplinary approach in applying fundamental concepts". In: *Proceedings of the 10th ACM Conference on SIG-information Technology Education.* SIGITE '09. Fairfax, Virginia, USA: ACM, pp. 224–228. ISBN: 978-1-60558-765-3. DOI: 10.1145/1631728.1631800.

Sobiesk, E. J., Blair, J. R. S., Cook, J. D., Giordano, J. C., Goda, B. S., and Reynolds, C. W. (2006). "Designing an interdisciplinary information technology program". In: *Proceedings of the 7th Conference on Information Technology Education.* SIGITE '06. Minneapolis, MN: ACM, pp. 71–76. ISBN: 1-59593-521-5. DOI: 10.1145/1168812.1168831.

Steckler, A., McLeroy, K. R., Goodman, R. M., Bird, S. T., and McCormick, L. (1992). "Toward integrating qualitative and quantitative methods: An introduction". In: *Health education quarterly* 19.1, pp. 1–8.

Stember, M. (1991). "Advancing the social sciences through the interdisciplinary enterprise". In: *The Social Science Journal* 28.1, pp. 1–14.

Stewart, R. A. and Chen, L. (2009). "Developing a framework for work integrated research higher degree studies in an Australian engineering context". In: *European Journal of Engineering Education* 34.2, pp. 155–169. DOI: 10.1080/03043790902833325.

Stirling, A. (2007). "A general framework for analysing diversity in science, technology and society". In: *Journal of The Royal Society Interface* 4, pp. 707–719. DOI: 10.1098/rsif.2007.0213.

Stokols, D. (2014). "Training the next generation of transdisciplinarians". In: *Enhancing interdisciplinary communication & collaboration in interdisciplinary research.* Ed. by M. O'Rourke, S. Crowley, S. D. Eigenbrode, and J. D. Wulfhorst. Los Angeles, USA: SAGE Publications, pp. 56–81.

Suzuki, L. A., Ahuluwalia, M. K., Arora, A. K., and Mattis, J. S. (2007). "The pond you fish in determines the fish you catch: Exploring strategies for qualitative data collection". In: *The Counselling Psychologist* 35.2, pp. 295–327. DOI: 10.1177/0011000006290983.

Taşkın, Z. and Aydinoglu, A. U. (2015). "Collaborative interdisciplinary astrobiology research: A bibliometric study of the NASA Astrobiology Institute". In: *Scientometrics* 103.3, pp. 1003–1022.

Tedre, M. (2014). *The science of computing: Shaping a discipline.* New York, USA: CRC Press.

Tinto, V. (1997). "Toward a Theory of Doctoral Persistence". In: *Graduate Education in the United States. Contemporary Higher Education.* Ed. by M. Nerad, R. June, D. Sands Miller, and P. Altbach. New York, USA: Garland Publication.

Trochim, W. M. K. and Donnelly, J. P. (2006). *Research Methods Knowledge Base.* 3rd. Cincinnati, USA: Atomic Dog Publishing.

Välimaa, J. (1998). "Culture and identity in higher education research". In: *Higher Education* 36.2, pp. 119–138.

Vladutz, G. and Cook, J. (1984). "Bibliographic coupling and subject relatedness". In: *Proceedings of the American Society for Information Science* 21, pp. 204–207.

Wagner, C. S. (2005). "Six case studies of international collaboration in science". In: *Scientometrics* 62.1, pp. 3–26. DOI: 10.1007/s11192-005-0001-0.

Wagner, C. S., Roessner, J. D., Bobb, K., Klein, J. T., Boyack, K. W., Keyton, J., Rafols, I., and Börner, K. (2011). "Approaches to understanding and measuring interdisciplinary scientific research (IDR): A review of the literature". In: *Journal of Informetrics* 5.1, pp. 14–26. DOI: 10.1016/j.joi.2010.06.004.

Ward, P. (1997). *The Social Construction of Reality: A Treatise in the Sociology of Knowledge.* London, UK: Chartered Institute of Personnel and Development.

Weidman, J. C. and Stein, E. L. (2003). "Socialization of doctoral students to academic norms". In: *Research in Higher Education* 44.6, pp. 641–656.

Weingart, P. (2010). "A short history of knowledge formations". In: *The Oxford handbook of interdisciplinarity.* Ed. by R. Frodeman, J. T. Klein, and C. Micham. Oxford, UK: Oxford University Press, pp. 3–14.

Welsh, E., Jirotka, M., and Gavaghan, D. (2006). "Post-genomic science: Cross-disciplinary and large-scale collaborative research and its organizational and technological challenges for the scientific research process". In: *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* 364.1843, pp. 1533–1549.

White, H. D. and Griffith, B. C. (1981). "Author cocitation: A literature measure of intellectual structure". In: *Journal of the American Society for information Science* 32.3, pp. 163–171.

Wilcoxon, F. (1945). "Individual comparisons by ranking methods". In: *Biometrics Bulletin* 1.6, pp. 80–83.

Winskel, M., Ketsopoulou, I., and Churchouse, T. (2014). *UKERC interdisciplinary review. Synthesis report.* Working paper. UK Energy Research Centre.

Wolz, U. and Cassel, L. (2012). “The role of interdisciplinary computing in higher education, research and industry”. In: *Proceedings of the 43rd ACM Technical Symposium on Computer Science Education*. SIGCSE ‘12. Raleigh, North Carolina, USA: ACM, pp. 7–8. ISBN: 978-1-4503-1098-7. DOI: 10.1145/2157136.2157144.

Young, C. A. (1998). “Building a care and research team”. In: *Journal of the Neurological Sciences* 160.2, pp. 137–140. DOI: 10.1016/S0022-510X(98)00213-5.

Zhao, D. and Strotmann, A. (2008). “Evolution of research activities and intellectual influences in information science 1996–2005: Introducing author bibliographic-coupling analysis”. In: *Journal of the American Society for Information Science and Technology* 59.13, pp. 2070–2086.

Major Research Areas at the Faculty of Informatics

This appendix provides a short description of each of the major research areas carried out at the Faculty of Informatics. The information has been gathered from the website of the Faculty of Informatics (Sept. 2016).

Business Informatics

This area focuses on the methodological approaches that describe, explain, predict, and design models of information, communication, and architectures, as well as the systems to support these designs. Business informatics research is based on the profound transformation that information technologies have brought to organizations and the society. This area has a strong engineering and technical focus, while at the same time adopts a comprehensive approach to modeling that not only addresses technical aspects, but also economic and social issues as well.

The main fields of research and development are:

- Model engineering and software engineering
- Process engineering
- Inter-organizational systems, e-commerce and e-government
- Advanced manufacturing
- Web science and semantic web
- Network analysis
- Business intelligence
- Secure business
- Digital preservation and information management

Computer Engineering

This area deals primarily with scientific and technological research within dependable embedded and cyber-physical systems. The focal areas include: the integration of microelectronics, micro-systems technology, communications technology, and informatics. The low-level aspects of this area are closely related with electrical engineering, while higher-level implementation involves protocols and software.

Its research and development mainly focus on:

- Dependable and resilient hybrid systems
- Quantitative analysis and optimal control
- Autonomous systems
- Dependable distributed embedded real-time systems
- Dependable digital circuits and hardware architectures
- Automation systems integration
- Robust decision theory

Distributed and Parallel Systems

This area comprises all aspects of distributed, parallel, and heterogeneous systems, including their communication services and standards, as well as their integration in global interaction and information networks. The main focus lies in creating and analyzing systems that should or can use multiple computers or computer systems, jointly.

The core research and development topics are:

- Cloud, elastic and services computing
- Internet of things and Internet engineering
- Adaptive computing
- Design paradigms for distributed and parallel systems
- Parallel algorithms and data structures
- Interfaces, languages and libraries for high performance and parallel computing
- Run-time systems and scheduling
- Performance measurement and benchmarking

Logic and Computation

This area researches the methods and technologies to construct, analyze, model and utilize a wide range of "intelligent" software. The application areas are databases, semantic systems, knowledge representation, constraint solving, and formal methods for both hardware and software.

Its main fields of research and development are:

- Foundations of databases and information systems
- Knowledge representation and semantic systems
- Formal methods and verification for system safety and security
- Constraints and satisfiability
- Computational logic and deduction
- Algorithms, complexity, and cryptography
- Problem solving and optimization
- Natural computing

Media Informatics and Visual Computing

Research in this area combines the development of key technologies and technical procedures in the areas of computer vision, computer graphics as well as augmented, mixed and virtual reality with the design of innovative interfaces. The aim is to create new possibilities of interaction for the users of these technologies, and their implementation in diverse areas of application. Computational visual methods (i.e., computer graphics and computer vision) are central topics and include: modeling, image synthesis, scientific visualization and visualization of information from large masses of data, the processing of sensor data, and recognition of structures contained within that data. Areas of application include, for example: visual surveillance, 3D reconstruction, bioinformatics, and content-based multi-modal retrieval.

The main research and development topics of this area are:

- Computer graphics
- Computer vision
- Visualization and visual analytics
- Virtual, augmented and mixed reality

- Media analysis and retrieval
- Human-computer interaction and socially embedded computing
- Assistive technologies and ubiquitous computing
- Additive fabrication and manufacturing

Transformation of the Optimization Problem

In this appendix, we show how to transform the optimization problems between count space and proportion space. Starting with the optimization problem given in Equation 5.2, we transform the per-discipline counts $\boldsymbol{n}$ into per-discipline proportions $\boldsymbol{p}$ by applying $\boldsymbol{p} = \boldsymbol{n}/\|\boldsymbol{n}\|_1$. The quadratic form $\frac{\boldsymbol{n}\,\mathbf{S}\,\boldsymbol{n}^\intercal}{\|\boldsymbol{n}\|_1^2}$ becomes $\boldsymbol{p}\,\mathbf{S}\,\boldsymbol{p}^\intercal$ due to linearity. The normalization of $\boldsymbol{p}$ is captured by the constraint $\|\boldsymbol{p}\|_1 = 1$. The transformation of the other constraints requires more effort and after proving a general transformation lemma in Section 8.3.2, we will apply it to convert the various constraints on $\boldsymbol{n}$ from count space to proportion space (see Sections 8.3.2 and 8.3.2).

Constraint Transformation Lemma

To transform the constraints given in count space to their corresponding form in proportion space, we will develop a lemma that treats the general case of arbitrary constraints. In Sections 8.3.2 and 8.3.2 we employ it to transform the concrete constraints that arise from the formulation of the discipline assignment as an optimization problem. Here and below, we represent the per-discipline count $\boldsymbol{n}$ as a sum of the initial count $\boldsymbol{c}$ and the additional count $u\boldsymbol{\lambda}$ that arises from the assignment of disciplines to the uncategorized references, i.e., $\boldsymbol{n} = \boldsymbol{c} + u\boldsymbol{\lambda}$.

Lemma 1 (Transformation Lemma)**.** *Let* $\boldsymbol{q}(\boldsymbol{\lambda}) = \frac{\boldsymbol{c}+u\boldsymbol{\lambda}}{\|\boldsymbol{c}+u\boldsymbol{\lambda}\|_1} \in \mathbb{R}^n$ *where* $\boldsymbol{\lambda} \in \mathbb{R}^n$ *is contained in the intersection of the non-identical* $(n-1)$*-dimensional hyperplanes* $\boldsymbol{a}\cdot\boldsymbol{\lambda} = \alpha$ *and* $\boldsymbol{b}\cdot\boldsymbol{\lambda} = \beta$*. Thus,* $\boldsymbol{q}(\lambda)$ *constitutes a hyperplane in the space* $\|\cdot\|_1 = 1$ *and the sign of the expression*

$$((u\,\beta + \boldsymbol{b}\cdot\boldsymbol{c})\,\boldsymbol{a} - (u\,\alpha + \boldsymbol{a}\cdot\boldsymbol{c})\,\boldsymbol{b})\cdot\boldsymbol{p} \tag{1}$$

determines on which side of this hyperplane a point $\boldsymbol{p}$ *lies.*

Proof. Since the hyperplanes intersect, we can assume—apart from $\boldsymbol{a} \neq \mathbf{0}$ and $\boldsymbol{b} \neq \mathbf{0}$—that $\boldsymbol{a}$ and $\boldsymbol{b}$ are linear independent. As a consequence, there exist $i, j \in \{1, \ldots, n\}$ with $i \neq j$ such that the elements $a_i \in \boldsymbol{a}$ and $b_j \in \boldsymbol{b}$ are nonzero. The linear system given by the hyperspace equations $\boldsymbol{a} \cdot \boldsymbol{\lambda} = \alpha$ and $\boldsymbol{b} \cdot \boldsymbol{\lambda} = \beta$ allows us to express two components of $\boldsymbol{\lambda}$ as

$$\lambda_i = \frac{a_j(\beta - \underline{\boldsymbol{b}} \cdot \underline{\boldsymbol{\lambda}}) - b_j(\alpha - \underline{\boldsymbol{a}} \cdot \underline{\boldsymbol{\lambda}})}{a_j b_i - a_i b_j} \quad \text{and} \quad \lambda_j = \frac{a_i(\beta - \underline{\boldsymbol{b}} \cdot \underline{\boldsymbol{\lambda}}) - b_i(\alpha - \underline{\boldsymbol{a}} \cdot \underline{\boldsymbol{\lambda}})}{a_i b_j - a_j b_i}$$

where $\underline{\boldsymbol{v}} \in \mathbb{R}^{n-2}$ denotes a vector $\boldsymbol{v} \in \mathbb{R}^n$ with the i-th and j-th component removed. The components q_m of $\boldsymbol{q}$ can be written as

$$q_m(\underline{\boldsymbol{\lambda}}) = \frac{1}{N(\underline{\boldsymbol{\lambda}})} \begin{cases} -a_j(b_i c_i + u(\beta - \underline{\boldsymbol{b}} \cdot \underline{\boldsymbol{\lambda}})) + b_j(a_i c_i + u(\alpha - \underline{\boldsymbol{a}} \cdot \underline{\boldsymbol{\lambda}})) & m = i \\ -a_i(b_j c_j + u(\beta - \underline{\boldsymbol{b}} \cdot \underline{\boldsymbol{\lambda}})) + b_i(a_j c_j + u(\alpha - \underline{\boldsymbol{a}} \cdot \underline{\boldsymbol{\lambda}})) & m = j \\ (a_j b_i - a_i b_j)(c_k + u\lambda_k) & m \neq i, j \end{cases}$$

with

$$N(\underline{\boldsymbol{\lambda}}) = u(a_j - a_i)(\beta - \underline{\boldsymbol{b}} \cdot \underline{\boldsymbol{\lambda}}) + u(b_i - b_j)(\alpha - \underline{\boldsymbol{a}} \cdot \underline{\boldsymbol{\lambda}}) + (b_i + b_j)(\|\boldsymbol{c}\|_1 + u\|\underline{\boldsymbol{\lambda}}\|_1).$$

To compute the $n-2$ vectors that span the $(n-2)$-dimensional space of $\boldsymbol{q}(\underline{\boldsymbol{\lambda}})$, we compute its derivative with respect to all components λ_k of $\underline{\boldsymbol{\lambda}}$ with $k \in \{1, \ldots, n\}$ and $k \neq i, j$. As only the sign of the final expression is of interest, uniform scaling of these vectors is permitted and we omit the $N(\underline{\boldsymbol{\lambda}})^{-2}$ term that arises with the differentiation. We get

$$\frac{\partial q_m}{\partial \lambda_k} = \begin{cases} u(\alpha(b_j - b_k) + \beta(a_k - a_j)) + (a_k b_j - a_j b_k)\|\boldsymbol{c}\|_1 + Dc_i & m = i \\ u(\alpha(b_k - b_i) + \beta(a_i - a_k)) + (a_i b_k - a_k b_i)\|\boldsymbol{c}\|_1 + Dc_j & m = j \\ u(\alpha(b_i - b_j) + \beta(a_j - a_i)) + (a_j b_i - a_i b_j)\|\boldsymbol{c}\|_1 + Dc_k & m = k \\ Dc_m & m \neq i, j, k \end{cases}, D = \begin{vmatrix} a_i & a_j & a_k \\ b_i & b_j & b_k \\ 1 & 1 & 1 \end{vmatrix}.$$

Together with the normal vector $\mathbf{1} = (1, \ldots, 1)$ of the $\|\cdot\|_1 = 1$ hyperplane, of which $\boldsymbol{q}(\underline{\boldsymbol{\lambda}})$ is a subset, we can compute the "binormal" vector $\boldsymbol{r}$ as the $(n-1)$-ary product

$$\boldsymbol{r} = \left| \begin{array}{c:c:c} \dfrac{\partial \boldsymbol{q}}{\partial \underline{\boldsymbol{\lambda}}} & \mathbf{1} & \begin{matrix} \boldsymbol{e}_1 \\ \vdots \\ \boldsymbol{e}_n \end{matrix} \end{array} \right|$$

of the $(n-2)$ derivatives, the normal vector $\mathbf{1}$ and the set of standard basis vectors $\boldsymbol{e}_1, \ldots, \boldsymbol{e}_n$ and we obtain

$$\boldsymbol{r} = (\boldsymbol{a} \cdot \boldsymbol{c} + u\,\alpha)(\|\boldsymbol{b}\|_1 \mathbf{1} - n\,\boldsymbol{b}) - (\boldsymbol{b} \cdot \boldsymbol{c} + u\,\beta)(\|\boldsymbol{a}\|_1 \mathbf{1} - n\,\boldsymbol{a}).$$

The scaled signed distance between an arbitrary point $\boldsymbol{p}$ and the hyperplane defined by its normal vector $\boldsymbol{r}$ yields the desired expression

$$(\boldsymbol{p} - \boldsymbol{q}(\mathbf{0})) \cdot \boldsymbol{r} = \big((u\,\beta + \boldsymbol{b} \cdot \boldsymbol{c})\,\boldsymbol{a} - (u\,\alpha + \boldsymbol{a} \cdot \boldsymbol{c})\,\boldsymbol{b}\big) \cdot \boldsymbol{p}.$$

□

Hypercube Constraints

In this section, we transform the constraints $c_i \leq n_i \leq c_i + u$ of (5.2), which describe a hypercube in $N_{\mathcal{T}}$ dimensions, to proportion space. We will abbreviate $N_{\mathcal{T}}$ with N and see that due to the normalization by the 1-norm, the hypercube is projected onto a $(N-1)$-dimensional hyperplane along the radial directions. First, we observe that after the projection, the hypercube vertex $\boldsymbol{c}_{\min} = (c_1, \dots, c_N)$ that lies closest to the origin is a convex combination of its neighboring vertices, i.e., for $\boldsymbol{\mu} = (\mu, \dots, \mu_N)$ with $\|\boldsymbol{\mu}\|_1 = 1$ we have that

$$\frac{\boldsymbol{c}_{\min}}{\|\boldsymbol{c}_{\min}\|_1} = \frac{\boldsymbol{c}}{\|\boldsymbol{c}\|_1} = \sum_{i=1}^{N} \mu_i \frac{\boldsymbol{c} + \hat{\boldsymbol{u}}_i}{\|\boldsymbol{c}\|_1 + u} = \frac{\boldsymbol{c} + u\,\boldsymbol{\mu}}{\|\boldsymbol{c}\|_1 + u} \implies \boldsymbol{\mu} = \frac{\boldsymbol{c}}{\|\boldsymbol{c}\|_1},$$

which confirms the convexity of the combination since $0 \leq c_i/\|\boldsymbol{c}\|_1 \leq 1$. $\hat{\boldsymbol{u}}_i$ denotes a vector of zeros with u as the i-th component and we will use $\check{\boldsymbol{u}}_i$ for a vector of u entries with zero at the i-th component. The vertex $\boldsymbol{c}_{\max} = (c_1 + u, \dots, c_N + u)$ that lies farthest from the origin can also be represented by a convex combination of its neighbors, since

$$\frac{\boldsymbol{c}_{\max}}{\|\boldsymbol{c}_{\max}\|_1} = \frac{\boldsymbol{c} + \boldsymbol{u}}{\|\boldsymbol{c}\|_1 + Nu} = \sum_{i=1}^{N} \mu_i \frac{\boldsymbol{c} + \check{\boldsymbol{u}}_i}{\|\boldsymbol{c}\|_1 + (N-1)u} = \frac{\boldsymbol{c} + \boldsymbol{u} - u\,\boldsymbol{\mu}}{\|\boldsymbol{c}\|_1 + (N-1)u}$$

$$\implies \boldsymbol{\mu} = \frac{\boldsymbol{c} + \boldsymbol{u}}{\|\boldsymbol{c}\|_1 + Nu}.$$

This leads us to the conclusion that all $(n-1)$-dimensional facets that contain either $\boldsymbol{c}_{\min}$ or $\boldsymbol{c}_{\max}$ lie completely in the interior of the hypercube's projection and, consequently, their $(n-2)$-facets that contain those vertices do not contribute to the boundary of the projected hypercube. Note that is not the case for any other facet. This also indicates that the constraints $\|\boldsymbol{c}\|_1 + u \leq \|\boldsymbol{n}\|_1 \leq \|\boldsymbol{c}\|_1 + (N-1)\,u$ and $\|\boldsymbol{c}\|_1 \leq \|\boldsymbol{n}\|_1 \leq \|\boldsymbol{c}\|_1 + Nu$ are effectively equivalent after projection onto $\|\cdot\|_1 = 1$.

To determine the form of the constraints $c_i \leq n_i \leq c_i + u$ in proportion space, we project the $(n-2)$-dimensional ridges of the associated hypercube onto the $(n-1)$-dimensional hyperplane defined by $\|\cdot\|_1 = 1$. Each ridge is given as an intersection of two of the hyperplanes that contain the facets of the hypercube. For $\boldsymbol{n} = \boldsymbol{c} + u\,\boldsymbol{\lambda}$, they are given as $\lambda_i = 1$ and $\lambda_j = 0$. All ridges can be obtained by varying $i, j \in \{1, \dots, n\}$ with $i \neq j$. Note that $\boldsymbol{\lambda} = \boldsymbol{0}$ or $\boldsymbol{\lambda} = \boldsymbol{1}$ are omitted due to the convexity argument given above.

In the context of Lemma 1, the hyperplane equations are $\boldsymbol{a} = \hat{\boldsymbol{1}}_i$ and $\alpha = 1$ as well as $\boldsymbol{b} = \hat{\boldsymbol{1}}_j$ and $\beta = 0$. An application of Equation 1 gives the expression $(u+c_i)p_j - c_j p_i \geq 0$ as criterion that $\boldsymbol{p}$ lies inside the projection of the hypercube. This gives the hypercube constraints of the optimization problem (5.2) in proportion space (see Equation 5.3) as

$$p_i \leq \frac{c_i + u}{c_j} p_j, \quad i, j \in \{1, \dots, N\}.$$

Note that these constraints trivially hold for the diagonal elements $i = j$ as well, since $u \geq 0$. In the case of vanishing reference count c_j for a given discipline j, we simply set $p_i \leq \infty$ and effectively omit the constraint.

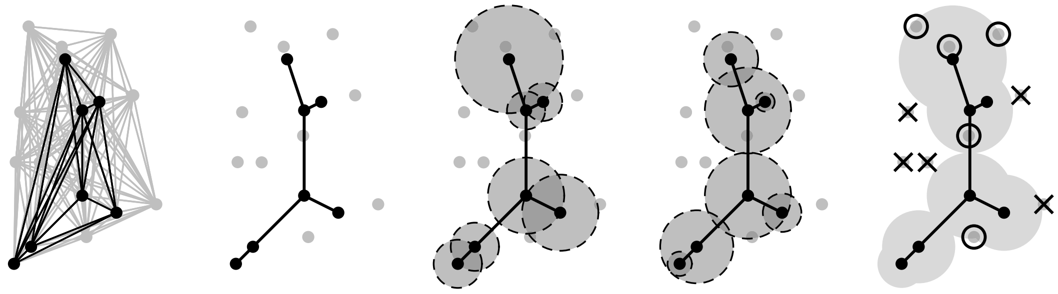

Figure 1: Illustration of our discipline pruning method. (Left) Using the similarity matrix $\mathbf{S}$ as the adjacency matrix of a complete graph, the disciplines that are known from the categorized references are represented as the vertices of the black subgraph. Other disciplines of $\mathcal{T}$ are given in gray and the similarity between two disciplines is visualized by the length of the corresponding edge, with low similarity corresponding to an increased length. (Center left) A spanning tree is constructed between the known disciplines, thus maximizing the mutual similarity. (Center) Condition II (see Eq. 2) ensured that each neighborhood—depicted as a ball—includes at least two disciplines. (Center right) Condition I (see Eq. 2) connects adjacent neighborhoods and guarantees the connectedness of the set of neighborhoods. (Right) The union of both conditions determines the final neighborhoods and all disciplines that are contained in them (black rings) participate in the discipline assignment. All remaining disciplines (black cross marks) are pruned away. Note that the actual computation takes place in a high-dimensional space and this 2D figure serves only as an illustration.

Constraint Refinement

By limiting the number of disciplines that each uncategorized reference can be assigned to by k, we arrive at the additional count-space constraint $\|\boldsymbol{n}\|_1 \leq \|\boldsymbol{c}\|_1 + k\,u$ (see Equation 5.4). With the hypercube constraints of the previous section and after writing $\boldsymbol{n} = \boldsymbol{c} + u\,\boldsymbol{\lambda}$, it can be stated as $\|\boldsymbol{\lambda}\|_1 = k$ and $\lambda_i \geq 0, i \in \{1, \ldots, N\}$. In terms of Lemma 1, we have that $\boldsymbol{a} = \mathbf{1}$ and $\alpha = k$ as well as $\boldsymbol{b} = \hat{\mathbf{1}}_i$ and $\beta = 0$. Applying (1) gives $-c_i\|\boldsymbol{p}\|_1 + (u\,k + \|\boldsymbol{c}\|_1)p_i \geq 0$ and we obtain the proportion-space equivalent of constraint (5.4) as

$$p_i \geq \frac{c_i}{\|\boldsymbol{c}\|_1 + k\,u}, \quad i \in \{1, \ldots, N\}.$$

Discipline Pruning

In this section, we present a method to compute the set $\mathcal{T}_{\text{valid}}$ of disciplines that fulfills the requirements laid out in Section 5.6 with an accompanying illustration given in Figure 1. For this, we exploit the properties of the similarity matrix $\mathbf{S}$ that encodes the closeness between different scientific disciplines. Since it is symmetric (i.e., discipline τ_i has the same similarity with τ_j as τ_j with τ_i) and its entries are non-negative, it can be seen as the adjacency matrix of a *complete* undirected graph $\mathcal{G}$ with positive (or vanishing) edge weights. Note that while the conventional similarity matrix has ones along its diagonal, we assume that graph to be loop-free without invalidating our argument. We will denote the set of vertices of a graph g with $V(g)$ and its edges with $E(g)$, where the latter is a subset of $V(g) \times V(g)$.

Each vertex in $V(\mathcal{G})$ corresponds to a discipline, whereas an edge in $E(\mathcal{G})$ with non-zero weights indicates a certain similarity between its respective disciplines. We now construct the set $\mathcal{T}_{\text{valid}}$ of vertices and later validate it against the required properties of Section 5.6. In the first step, we take the subgraph $\mathcal{G}_{\text{known}}$ of $\mathcal{G}$ that contains as vertices only those disciplines that are found in the categorized references of the document at hand, which yields again a complete graph. Next, a *maximum spanning tree* $\mathcal{G}_{\text{span}}$ is computed from $\mathcal{G}_{\text{known}}$ and for each of its vertices $v_i \in V(\mathcal{G}_{\text{span}})$, we compute a *local similarity threshold* Δ_i by

$$\Delta_i = t \min\Bigg(\underbrace{\min\left\{2w(e) : e \in E(\mathcal{G}_{\text{span}}) \text{ and } v_i \in e\right\}}_{I}, \underbrace{\max\left\{w(e) : e \in E(\mathcal{G}_{\text{span}}) \text{ and } v_i \in e\right\}}_{II}\Bigg) \quad (2)$$

where the weight of an edge e is denoted by $w(e)$ and t is a user-given tolerance value in the interval $[0, 1]$. In the final step, we construct around each vertex v_i of the spanning tree $\mathcal{G}_{\text{span}}$ a discipline neighborhood $\mathcal{H}_i$ given by

$$\mathcal{H}_i = \{v_j \in V(\mathcal{G}) : w(e_{ij}) \geq \Delta_i \text{ and } \{v_i, v_j\} \in e_{ij}\}$$

where e_{ij} is an edge of the initial complete graph $\mathcal{G}$ that contains both vertices v_i and v_j. The set $\mathcal{T}_{\text{valid}}$ of disciplines that participate in the reassignment process are obtained by the union of all neighborhoods, i.e.,

$$\mathcal{T}_{\text{valid}} = \bigcup_{v_i \in V(\mathcal{G}_{\text{span}})} \mathcal{H}_i.$$

This definition of $\mathcal{T}_{\text{valid}}$ fulfills all objectives stated in Section 5.6 for a tolerance of $t = 1$:

Completeness Due to condition II in the computation of Δ_i, each neighborhood $\mathcal{H}_i$ contains at least one edge of $E(\mathcal{G})$ and, consequently, its two endpoints.

Cohesion Due to condition I in the computation of Δ_i and the fact that a spanning tree of a complete graph is connected, the neighborhoods form a single connected set.

Conciseness The maximal spanning tree $\mathcal{G}_{\text{span}}$ is the subgraph with the highest internal similarity that still provides a connected subgraph. In this sense, it produces the smallest neighborhoods that are still connected due to the fact that condition I ensures that the neighborhoods only "touch" along the edge with the least similarity.

Note that higher tolerances ($t < 1$) violate these objectives only in their original sense but would respect them for appropriately scaled similarity values.

NP-Hardness of Reference Redistribution

As shown in Section 5.7, the positive semidefinite similarity matrix $\mathbf{S}$ leads to a concave bilinear form $-\boldsymbol{c}\,\mathbf{S}\,\boldsymbol{c}^\intercal$ when trying to minimize the Rao-Stirling diversity index. Thus, the associated optimization problem is NP-hard. In this section, we give an example to showcase that simple heuristics already fail for trivial toy example and should illustrate the problem without the intricacies of complexity classes. For this, we choose the arguably most obvious heuristic, namely, to redistribute uncategorized references to the discipline that already has the highest number of categorized references associated with it.

Setting

As mentioned above, the similarity matrix $\mathbf{S}$ that is used in the Rao-Stirling diversity index is positive semidefinite and the index, given by

$$I = 1 - \frac{\boldsymbol{c}\,\mathbf{S}\,\boldsymbol{c}^\intercal}{\|\boldsymbol{c}\|_1^2}$$

is a concave function in $\boldsymbol{c}$. As described in Chapter 5, the minimization of this function is used to compute the lower bound of the uncertainty interval. Due to the purely concaveness, the minima lie on the vertices of the polytope that is spanned by the constraints on $\boldsymbol{c}$ (Floudas and Visweswaran, 1995).

Example Setting

We provide a simplified setting to show the complexity of the minimization problem. If we assume only the existence of three different disciplines, the similarity matrix can be given as

$$\mathbf{S}(\alpha) = \begin{pmatrix} 1 & \alpha & 0 \\ \alpha & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

where α describes the similarity between the first and the second disciplines. We assume that the third discipline is completely dissimilar to the first and second discipline. A hypothetic document with both categorized and uncategorized references serves as the basis for this example. We assume the following categorized references in the three disciplines

$$\boldsymbol{c}(c_3) = \begin{pmatrix} 2 & 2 & c_3 \end{pmatrix}$$

where the first two disciplines are cited by two references each. The number of references that cite the third discipline is given by c_3. Finally, the number of uncategorized references is given by u. In total $2 + 2 + c_3 + u$ references are present in this example of which u references are uncategorized.

Example Minimization

The diversity index $I(\alpha, c_3, u)$ of our setting is thus given as

$$\begin{aligned} I(\alpha, c_3, \boldsymbol{u}) &= 1 - \frac{(\boldsymbol{c}(c_3) + \boldsymbol{u})\, \mathbf{S}(\alpha)\, (\boldsymbol{c}(c_3) + \boldsymbol{u})^\intercal}{\|(\boldsymbol{c}(c_3) + \boldsymbol{u})\|_1^2} \\ &= 2\,(4 + c_3 + u)^{-2} \Big(4(1-\alpha) - 2u((1+\alpha)(\lambda+\mu) - 2) \\ &\qquad - u^2\Big((\lambda+\mu)((\lambda+\mu) - 1) - (1-\alpha)\lambda\mu\Big) \\ &\qquad + c_3(4 + u(\lambda+\mu))\Big) \end{aligned}$$

with $\boldsymbol{u} = u\begin{pmatrix}\lambda & \mu & 1-\lambda-\mu\end{pmatrix}$ where $0 \le \lambda \le 1$ (resp. $0 \le \mu \le 1-\lambda$) determine the extent at which the uncategorized references are redistributed to the first (resp. second) discipline. The remainder is redistributed to the third discipline. Since the minimum of the index is attained at the vertices of the constraint polytope, it can only be located at one of three extremal reference redistributions I_1, I_2, and I_3. For these, all the uncategorized references are redistributed to the either the first, second, or third discipline. The diversity index of these three extremal cases is given as

$$\begin{aligned} I_1(\alpha, c_3, u) &= I\left(\alpha, c_3, \begin{pmatrix}u & 0 & 0\end{pmatrix}\right) = (4 + c_3 + u)^{-2}\,(2c_3(4+u) + 4(2+u)(1-\alpha)) \\ I_2(\alpha, c_3, u) &= I\left(\alpha, c_3, \begin{pmatrix}0 & u & 0\end{pmatrix}\right) = I_1(\alpha, c_3, u) \\ I_3(\alpha, c_3, u) &= I\left(\alpha, c_3, \begin{pmatrix}0 & 0 & u\end{pmatrix}\right) = (4 + c_3 + u)^{-2}\,(8(c_3 + u + 1 - \alpha)). \end{aligned}$$

For a fixed similarity between the first and second discipline of $\alpha = 0.6$, these quantities can be plotted as surfaces over the number of uncategorized references u and the number of references c_3 that cite the third discipline (see Figure 2).

To further clarify the exposition, we chose a fixed $u = 2$ for the following discussion (see Figure 3). Note that the same conclusion is valid for any $u > 1$.

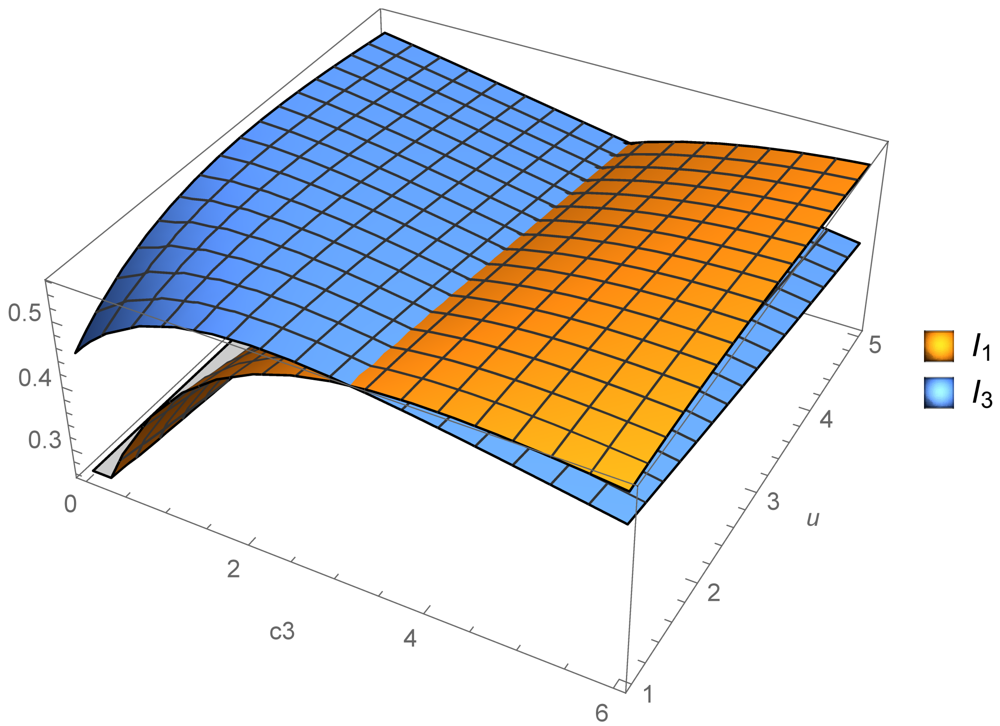

Figure 2: Rao-Stirling diversity index after redistributing u uncategorized references to the first (resp. third) discipline denoted as I_1 (resp. I_3). Depending on the initial number of references that are categorized into the third discipline c_3, either I_1 or I_3 realized the minimal achievable index.

Depending on the value of c_3, the minimum can be attained by redistributing all references to either the first or third discipline. In the case of $c3 = 3$, the minimum can be achieved by redistributing the uncategorized references to the first discipline (i.e., $I_1 < I_3$ for $c3 = 3$). For $c3 = 4$, a redistribution to the third discipline yields the minimal index (i.e., $I_3 < I_1$ for $c3 = 4$). Thus, it cannot be assumed that simply adding all uncategorized references to the discipline with the highest number of categorized references would yield the minimal index. In both aforementioned cases, the third discipline has the highest number of categorized references (i.e., $c3 = 3$ or 4 both > 2).

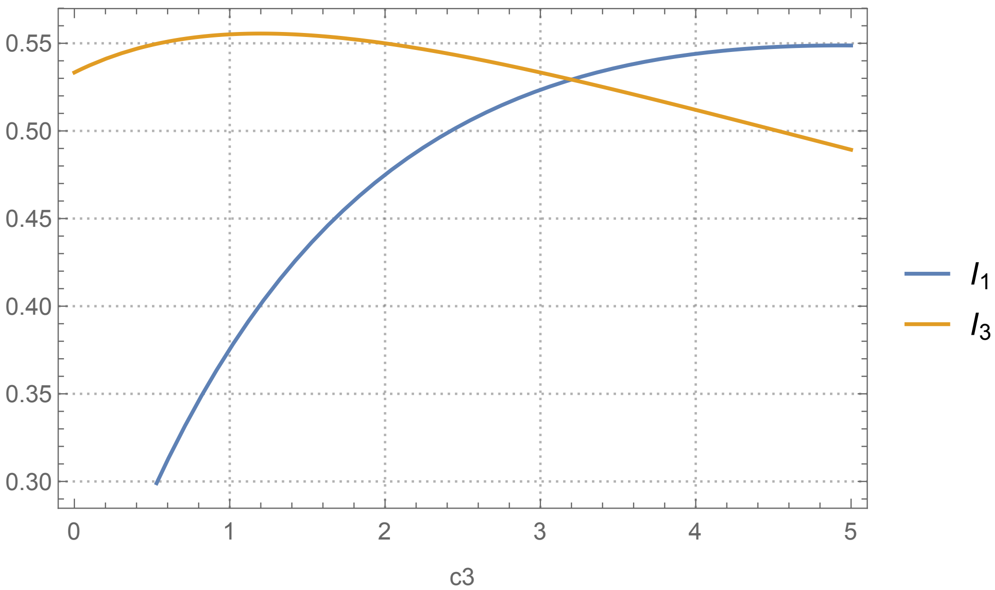

Figure 3: A slice of Figure 2 for two uncategorized disciplines. If four references are already categorized into discipline three (i.e., $c_3 = 4$), a redistribution of all uncategorized references to it yields the minimal index (i.e., $I_3 < I_1$). However, this strategy is not generally applicable since for $c_3 = 3$, a redistribution to the first discipline yields the minimal index. This example shows that a simple redistribution to the discipline with the highest number already assigned references (i.e., third discipline in both cases) does not yield the minimal index in all cases.

Taxonomy of Disciplines

The taxonomy of disciplines of the Web of Science (WoS) is the most widely used in bibliometric studies (Bensman and Leydesdorff, 2009; Pudovkin and Garfield, 2002). It contains 249 disciplinary fields, called CTs, which are derived from a combination of subject matter expert judgments and inter-journal citation patterns that together, serve to cluster journals into topical groupings. We used this taxonomy in phases I and II (see Chapters 5 and 6) of this study. It allowed for the mapping of publications to disciplinary fields and to determine which disciplines were integrated in each publication through its references, which are also mapped to disciplinary fields.

The 249 CTs grouped into macro-disciplines, following the methodology of Porter and Rafols (2009). The groupings are derived from observed relationships between the CTs based on the similarity matrix (i.e., their co-citation in articles). Using a type of factor analysis—Principal Component Analysis (PCA)—, each CT was located on a single factor, upon which the CT loaded the highest. These groupings aimed to enhance the visualization of of CTs in order to facilitate a faster categorization of publications into disciplinary fields to the participants of the second phase of this study (see Chapter 6).

The following tables show the list of CTs grouped into macro-disciplines. The participants of the second phase of this study used the list to categorize the references of their publications into disciplinary fields. The space on the right of the name of each CT, was used to indicate which references are categorized with a given CT. The number in parenthesis next to each CT is the identifier that was used in the database which stored the data of the publication database created for this study.

Biomedical sciences
Allergy (7)
Biochemistry & molecular biology (21)
Biotechnology & applied microbiology (25)
Cell & tissue engineering (29)
Cell biology (30)
Dermatology (56)
Gastroenterology & hepatology (94)
Genetics & heredity (95)
Immunology (113)
Infectious diseases (115)
Medical laboratory technology (15)
Medicine, research & experimental (153)
Microbiology (157)
Multidisciplinary sciences (161)
Oncology (172)
Parasitology (180)
Pathology (181)
Pharmacology & pharmacy (184)
Rheumatology (221)
Transplantation (239)
Tropical medicine (242)
Urology & nephrology (244)
Veterinary sciences (245)
Virology (246)

Reproductive sciences
Anatomy & morphology (8)
Andrology (9)
Developmental biology (57)
Endocrinology & metabolism (65)
Microscopy (158)
Obstetrics & gynecology (170)
Ophthalmology (174)
Reproductive biology (219)

Clinical medicine
Anesthesiology (10)
Cardiac & cardiovascular systems (28)
Critical care medicine (50)
Dentistry, oral surgery & medicine (55)
Emergency medicine (64)
Engineering, biomedical (68)
Hematology (105)
Materials science, biomaterials (135)
Orthopedics (177)
Peripheral vascular disease (183)
Physiology (194)
Primary health care (200)
Radiology, nuclear medicine & medical imaging (215)
Rehabilitation (216)
Respiratory system (220)
Sport sciences (231)
Surgery (234)

Health sciences
Education, scientific disciplines (61)
Geriatrics & gerontology (101)
Gerontology (102)
Health care sciences & services (103)
Health policy & services (104)
Integrative & complementary medicine (118)
Medicine, general & internal (151)
Nursing (168)
Nutrition & dietetics (169)
Pediatrics (182)
Public, environmental & occupational health (214)
Substance abuse (233)

Ecology sciences
Anthropology (11)
Biodiversity conservation (22)
Biology (23)
Ecology (58)
Entomology (81)
Evolutionary biology (87)
Ornithology (176)
Zoology (249)

Environmental science and technology
Agricultural engineering (3)
Engineering, environmental (72)
Engineering, ocean (79)
Environmental sciences (82)
Fisheries (90)
Limnology (122)
Marine & freshwater biology (134)
Meteorology & atmospheric sciences (156)
Oceanography (171)
Toxicology (238)
Water resources (247)

Agricultural sciences
Agriculture, dairy & animal science (4)
Agriculture, multidisciplinary (5)
Agronomy (6)
Chemistry, applied (32)
Food sciences & technology (33)
Forestry (93)
Horticulture (109)
Materials science, paper & wood (141)
Materials science, textiles (142)
Mycology (163)
Plant sciences (196)
Soil science (229)

Geosciences
Archeology (12)
Engineering, petroleum (80)
Geochemistry & geophysics (96)
Geography, physical (98)
Geology (99)
Geosciences, multidisciplinary (100)
Imaging science & photographic technology (112)
Mineralogy (159)
Paleontology (179)
Remote sensing (218)

Chemistry
Biochemical research methods (20)
Biophysics (24)
Chemistry medicinal (34)
Chemistry, analytical (31)
Chemistry, inorganic & nuclear (33)
Chemistry, multidisciplinary (35)
Chemistry, organic (36)
Crystallography (51)
Physics, atomic, molecular & chemical (187)

Physics
Astronomy & astrophysics (17)
Instruments & instrumentation (117)
Mining & mineral processing (160)
Nuclear science & technology (167)
Optics (175)
Physics, fluids & plasmas (189)
Physics, mathematical (190)
Physics, multidisciplinary (191)
Physics, nuclear (192)
Physics, particles & fields (193)
Spectroscopy (230)

Materials sciences
Chemistry, physical (37)
Electrochemistry (63)
Materials science, ceramics (136)
Materials science, coatings & films (138)
Materials science, multidisciplinary (14)
Metallurgy & metallurgical engineering (155)
Nanoscience & nanotechnology (164)
Physics, applied (186)
Physics, condensed matter (188)
Polymer science (199)

Engineering sciences
Acoustics (1)
Energy & fuels (66)
Engineering, aerospace (67)
Engineering, chemical (69)
Engineering, marine (76)
Engineering, mechanical (77)
Engineering, multidisciplinary (78)
Materials science, characterization & testing (137)
Mathematics, applied (145)
Mechanics (147)
Thermodynamics (237)

Civil engineering
Construction & building technology (48)
Engineering, civil (70)
Engineering, geological (73)
Ergonomics (84)
Materials science, composites (139)
Transportation (240)
Transportation science & technology (241)

Computer sciences
Automation & control systems (18)
Computer science, artificial intelligence (41)
Computer science, cybernetics (42)
Computer science, hardware & architecture (43)
Computer science, information systems (44)
Computer science, interdisciplinary applications (45)
Computer science, software engineering (46)
Computer science, theory & methods (47)
Engineering, electrical & electronic (71)
Information science & library science (116)
Robotics (22)
Telecommunications (235)

Mathematics, interdisciplinary
Mathematical & computational biology (143)
Mathematics, interdisciplinary applications (146)
Medical informatics (149)
Psychology, mathematical (209)
Social sciences, mathematical methods (226)
Statistics & probability (232)

Industrial engineering & management sciences
Business (26)
Engineering, industrial (74)
Engineering, manufacturing (75)
Industrial relations & labor (114)
Management (133)
Mathematics (144)
Operations research & management science (173)

Cognitive sciences
Behavioral sciences (19)
Clinical neurology (39)
Language & linguistics (120)
Linguistics (123)
Neuroimaging (165)
Neurosciences (166)
Psychiatry (201)
Psychology (202)
Psychology, biological (204)
Psychology, clinical (205)
Psychology, experimental (208)
Psychology, multidisciplinary (210)
Psychology, psychoanalysis (211)

Ethical & social issues
Ethics (85)
History & philosophy of science (107)
Medical ethics (148)
Medicine, legal (152)
Philosophy (185)
Social issues (223)
Social sciences, biomedical (224)

Social/psychology & related
Communication (40)
Criminology & penology (49)
Cultural studies (52)
Demography (54)
Education & educational research (60)
Education, special (62)
Ethnic studies (86)
Family studies (88)
Film, radio, television (89)
Hospitality, leisure, sport & tourism (110)
Law (121)
Psychology, applied (203)
Psychology, developmental (206)
Psychology, educational (207)
Psychology, social (212)
Religion (217)
Social sciences, interdisciplinary (225)
Social work (227)
Sociology (228)
Women's studies (248)

Policy sciences
Agricultural economics & policy (2)
Architecture (13)
Area studies (14)
Business, finance (27)
Economics (59)
Environmental studies (83)
Geography (97)
History (106)
History of social sciences (108)
International relations (119)
Planing & development (195)
Political science (198)
Public administration (213)
Urban studies (243)

Literature & arts
Art (15)
Asian studies (16)
Classics (38)
Dance (53)
Folklore (91)
Humanities, multidisciplinary (111)
Literary reviews (124)
Literary theory & criticism (125)
Literature (126)
Literature, African, Australian, Canadian (127)
Literature, American (128)
Literature, British Isles (129)
Literature, German, Dutch, Scandinavian (130)
Literature, romance (131)
Literature, Slavic (132)
Medieval & renaissance studies (154)
Music (162)
Poetry (197)
Theater (236)

Interview Protocols

This appendix presents the interview guides[1] that were used in this research study. Not only the interview questions are listed, but the introduction and information given to the participants prior to start of the interview is also provided.

The following protocols were used in different phases of this research study:

Protocol for Interview on Doctoral Processes at the Faculty of Informatics was used in the preliminary phase in order to gain a better understanding of the context of this study, its norms, procedures and culture as well as deep insights into its doctoral processes.

Interview Protocol for the Categorization of References into Disciplines guided the interviews in phase II for the evaluation of the uncertainty of interval of the Rao-Stirling diversity index. It was also used in phase III for the analysis of disciplines that cross-disciplinary doctoral researchers reference in the sections of their publications.

Protocol for Interview with Interdisciplinary Doctoral Researchers was utilized in phase III to understand which factors and processes contributed to the cross-disciplinarity of doctoral researchers.

Protocol for Interview with Interdisciplinary Professors was used in phase III to identify the important interdisciplinary criteria affecting interdisciplinarity in the department where this study was conducted.

Protocol for Interview on Doctoral Processes at the Faculty of Informatics

Introduction to the Interview

I am a doctoral researcher enrolled in the Faculty of Informatics. My research focuses on doctoral education in the field of CS. My main supervisor is Prof. Hannes Werthner. I

[1]The participants of this study normally use the word "faculty" with its British meaning (academic division) instead of with its North American meaning (academic staff). Therefore, in these interviews and questionnaires, this term refers to the *Faculty of Informatics*.

am also involved in the organization of the Vienna PhD School of Informatics.

The aim of this interview is to gain a better understanding of doctoral education in the Faculty of Informatics. I would like to know more about the procedures and background of this department, and about the processes and outcomes of the doctoral programs. With this interview, I want to better understand your experiences as a doctoral researcher. I thank you for taking the time to participate.

As I mentioned in the email, I would like to record this interview. Do I have your permission for audio recording? I remind you that all the information in this interview is confidential. I am the only person with access to the recording. Not even my academic supervisor will have access to it. During the interview, you do not need to mention people's names. You could refer to them as "a colleague of mine", "my supervisor", "a collaborator", etc. You are free to decide which questions you would like to answer, and you may also stop the interview at any time.

Background Questions

1. Tell me about yourself. (What is your age? What is your nationality? What are your interests? What is your family status?)
2. What is your field of interest in CS?
3. What did you study before starting your PhD?

Entry into the PhD Program

4. What influenced your decision to embark a PhD program?
5. How did you find out about your PhD program?
6. What was the procedure for admittance into your PhD program?
7. How did you choose your field of research?
8. How did you choose your PhD courses? What role did they play in your PhD research?
9. What are the requirements of your doctoral program that need to be met in order to attain a PhD? (e.g., courses, milestones, publications.)

Conceptions of Research

10. What does research mean for you?
11. What does becoming a successful doctoral researcher in your research group and in your field entail?

Supervision

12. How did you come to know your supervisor?
13. How (and why) did you choose your supervisor?
14. How often do you meet your supervisor?
15. Could you describe your meetings with your supervisor?
16. In which ways does your supervisor support you?
17. What does your supervisor expect from you, and how do you know?

Interdisciplinarity

18. Is your research related to other disciplines? If so, how?
19. What is the role that these disciplines play in your research?

Institute and Research Group

20. How does your research align with the research that is being conducted in your research group? And with that conducted at your institute?
21. Could you describe your relationship with other members of your research group? And with those of your institute?
22. Do you think that you fit in your research group? And in your institute?

Network Partners

23. Who has been influential in the progress of your PhD so far? (Positive or negative)
24. What kind of support has this individual provided? Please give a few examples.
25. How influential are the members of your research group in the progress of your PhD?
26. Which scientific collaborations (and co-authors) have you had? Please describe how they support/influence your work.

Future Career

27. What was your career goal when you began your PhD program? Has it changed?
28. How have your doctoral experiences prepared you for a scientific career (or the career of your choice)?

Additional Questions

29. Is there anything that we have not discussed that would help me understand your experiences as a doctoral researcher?

Interview Protocol for the Categorization of References into Disciplines

I am a doctoral researcher in the Faculty of Informatics. I analyze doctoral education in CS with a focus on interdisciplinarity. My main supervisor is Prof. Hannes Werthner. I am also involved in the organization of the Vienna PhD School of Informatics.

Explanation for the Evaluation of the Method of the Uncertainty of Interval
Part of my research involves measuring the interdisciplinarity of publications using bibliometric methods. I use an approach that calculates the interdisciplinarity of a paper based on the disciplines that are integrated in the publication through its references. A problem commonly encountered is that bibliographic data is often incomplete: sometimes references are not categorized into disciplines. This missing data introduce inaccuracies in the measurement. In order to tackle this problem, I have developed a method that enables calculating the associated uncertainties produced by missing data. This method needs to be evaluated empirically. The evaluation consists of a comparison of the results of measurements computed with incomplete bibliographic data gathered from digital libraries with the same measurements calculated with complete ground-truth data. Therefore, I would like to ask you to provide me ground-truth bibliographic data from one of your publications.

Explanation for the Validation of the Patterns of Doctoral Interdisciplinarity
As a part of my research I analyze how diverse disciplines are integrated in the different sections of doctoral publications. Therefore, today I would like to ask you to categorize the references of two of your publications into disciplinary fields.

I have downloaded digital copies of all the references cited in your publication/s to my computer. I will ask you to open them one by one and categorize each into 1 to 4 disciplines. I have printed the list of disciplines (see Appendix 8.3.2) that you should use to categorize the references of your publication/s. Note that you should not try to categorize the references into many disciplines. What I am asking you to do is to categorize the references into the disciplines that best describe them. It does not matter if it is only one or four (the maximum number).

For each of your references to be categorized I will ask you the following question: "To which discipline/s does this publication contribute". Contributions should be understood as an advancement for a field. For example, it might be that one publication is conducting a statistical data analysis using the statistical test ANOVA. In such a case, the use of the statistical test does not constitute an advancement of the field of statistics. Therefore, that publication would not be categorized into the field of statistics. Do you understand what I mean?

Before you start categorizing your references into disciplines, I would like you to read the list of disciplines. Take your time to become familiar with it.

I would also like to mention that this study makes no assumption that IDR is better or worse than single-disciplinary research. For me it is important that you categorize your references in an honest way.

Questions for the Categorization of References into Disciplines

Let's start with the first reference. Take the time you need to recognize it. You can read it if needed.

To which discipline/s does this publication contribute? Please think out loud and I will be taking note of your answer.

Why do you think that this publication contributes to [discipline/s]?

Does it contribute to any other discipline/s? It is perfectly alright if the publication only contributes to one discipline. I am just checking that we are not forgetting anything.

(Repeat process for each reference to be categorized)

Protocol for Interview with Interdisciplinary Doctoral Researchers

Introduction to the Interview

I am a doctoral researcher in the Faculty of Informatics. I analyze doctoral education in CS with a focus on interdisciplinarity. My main supervisor is Prof. Hannes Werthner. Apart of that, I am also involved in the organization of the Vienna PhD School of Informatics.

I have been measuring research interdisciplinarity of researchers in the Faculty of Informatics at the TU Wien. This measurement was based on the disciplines that doctoral researchers cite in their publications. This method delivers a measure of interdisciplinary according to the number of disciplines cited in a publication, the degree of concentration and the similarity between them.

According to the data, your publications cite works that relate to disciplines other than CS. This is why I decided to invite you to participate in this interview. I would like to thank you for taking the time to participate.

The aim of this interview is to know more about the factors and facilitators of doctoral interdisciplinarity in the Faculty of Informatics. Therefore, I would like to know more about your research and the role that these other disciplines play in your CS research.

As I mentioned in the email, I would like to record this interview. Do I have your permission for audio recording? I remind you that all the information in this interview is confidential. I am the only person with access to the recording. Not even my academic supervisor will have access to it. During the interview, you do not need to mention people's names. You could refer to them as “a colleague of mine”, “my supervisor”, “a collaborator”, etc. You are free to decide which questions you would like to answer, and you may also stop the interview at any time.

Before we start the interview, I would like to clarify the meaning of the term “interdisciplinarity”. There are different forms of interdisciplinarity, such as multidisciplinarity, transdisciplinarity, etc. However, during this interview I will use the term “interdisciplinarity” in a general way to describe the research where two or more disciplines work together.

I would also like to mention that this study makes no assumption that interdisciplinary research is better or worse than single-disciplinary research. For me it is important that you answer all questions in an honest manner, without exaggerating your interdisciplinarity or your focus on CS.

Background Questions

1. Which is your field of interest within CS?
2. What did you study before starting your PhD?
3. In which doctoral program are you enrolled in?
4. How are you funded?

Research Topic

5. Tell me about your PhD topic. What is it about?
6. How did you come to choose this topic?
7. Have you also worked on research not related to your PhD topic? If so, what was it?
8. In which field/s do you situate your scholarship? (within and outside CS)
9. How valuable is your research to other disciplines?

If the interviewee conducts IDR:

10. How would you describe the value of your single-disciplinary research to disciplinary scholars?
11. How would you describe the value of your research to interdisciplinary scholars?

Courses

1. What courses have you taken during your PhD?
2. Have you studied courses related to disciplines other than CS? What about before your PhD?
3. How have these courses influenced your PhD?
4. Are you teaching any courses? If so, on what subject? How do they relate to your PhD?

Research and Publications

I have here a list of your publications. Could you tell me if this list if correct? Let's have a look at the list together.

5. What disciplines are involved in the publications on this list?
6. What is the relationship between these disciplines?
7. What makes these areas compatible?
8. Do these areas present incompatibilities? If yes, which ones?
9. How do you manage the connection between these areas (method, theories, evaluation)?
10. How do you integrate these disciplines into one work?
11. How challenging is conducting research that involves different areas of study?
12. What opportunities does this fusion of disciplines provide for you? And for the field? And for other people?
13. What kind of knowledge do you need from each discipline?
14. In which scientific communities (venues) are you publishing your work?

If the participant is publishing in more than one discipline:

15. What does publishing in more than one discipline entail?
16. How do you maintain a rigorous standard in your work and make it acceptable for each community?

If the participant is publishing only in CS:

17. What is the reason for publishing your work only in CS?
18. What would publishing in other fields involve?

For all participants:

19. What are the general steps you take when conducting research and writing publications?
20. How are different disciplines integrated into the sections of your publications?

Network Partners

21. According to your list of publications, you have a number of co-authors. Could you tell me what their fields of expertise are?
22. How did you establish connection with them?
23. How do they contribute to your research?
24. How do they influence your work?
25. How do you plan the content and methods of your papers with your co-authors?

If the participant is a member of a research project:

26. What are the fields of expertise of the other members of the project?
27. What knowledge they contribute to the project?
28. What are their activities/tasks in the project? And in the writing of publications?

Doctoral Supervisor

29. How many supervisors do you have? What is the field of research of your supervisor/s?
30. How did you meet and choose your supervisor/s?
31. How has your supervisor influenced the extent of which the other disciplines are integrated in your research?
32. What is the expertise of your supervisor/s in other disciplines different to CS?

Academic Structures

Now, I would ask you to reflect on the influence that different academic structures in the Faculty of Informatics have on the single-disciplinarity or interdisciplinarity of your research.

33. How has your doctoral program influenced your decision in conducting the type of research that you conduct?
34. How does your group influence the kind of research that you conduct?
35. What about the influence of the Faculty of Informatics as a whole?
36. Is there any other academic structure influencing your research?

Additional Questions

If the participant considers that s/he is conducting IDR:

37. What aspects (academic or non-academic) have contributed to the fact that your research is interdisciplinary?

If the participant considers that s/he is conducting mainly CS research:

38. What aspects (academic or non-academic) have determined that your research focuses mainly on CS?

For all participants:

39. Is there anything we have not discussed that would help me understand your relation with other disciplines other than CS?

Protocol for Interview with Interdisciplinary Professors

I am a doctoral researcher enrolled in the Faculty of Informatics. I analyze doctoral education in CS with a focus on interdisciplinarity. My main supervisor is Prof. Hannes Werthner. I am also involved in the organization of the Vienna PhD School of Informatics.

I have been measuring the research interdisciplinarity of the doctoral researchers and professors in the Faculty of Informatics at the TU Wien. This measurement was based on the disciplines that doctoral researchers and their supervisors reference in their publications. This method delivers a measure of interdisciplinary according to the number of disciplines cited in a publication, their degree of concentration and the similarity between them.

According to the data, your publications cite works that relate to disciplines other than CS. This is why I decided to invite you to participate in this interview. I would like to thank you for taking the time to participate.

The aim of this interview is to identify important factors and processes that contribute to the interdisciplinarity of doctoral researchers.

As I told you in the email, I would like to record this interview. Do I have your permission for audio recording? I remind you that all the information in this interview is confidential. I am the only person with access to the recording. Not even my academic supervisor will have access to it. During the interview, you do not need to mention people's names. You could refer to them as "a researcher I supervise", "a member of my group", "a collaborator", etc. You are free to decide which questions you would like to answer, and you may also stop the interview at any time.

Before we start the interview, I would like to clarify the meaning of the term "interdisciplinarity". There are different forms of interdisciplinarity such as multidisciplinarity, transdisciplinarity, etc. However, during this interview I will use the term "interdisciplinarity" in a general way to describe the research where two or more disciplines work together.

I would also like to mention that this study makes no assumption that IDR is better or worse than single-disciplinary research. For me it is important that you answer all questions in an honest manner, without exaggerating interdisciplinary or single-disciplinary aspects of the research that you and your doctoral researchers conduct.

Background Questions

1. What is your research about?

2. In which discipline/s do you situate your scholarship? (within and outside CS)

3. In which discipline/s do you situate the research of your doctoral researchers from the last 4 years?

4. What kind of research do they conduct? (Fundamental, applied, experimental, interdisciplinary, etc.)

Interdisciplinary Research

5. In your opinion, what issues are necessary or important when conducting doctoral IDR in your field? Why? Could you elaborate on them?

6. What issues are not so important but still an advantage when conducting doctoral IDR in your field? Why? Could you elaborate on them?

Doctoral Researchers

7. How were your doctoral researchers that conduct IDR recruited? what were the selection criteria?

8. How did they get into their particular PhD topic?

9. What kind of previous experience did they have with the topic? and with the other discipline?

10. In your opinion, do doctoral researchers that conduct IDR in your field need additional training (e.g., courses) in the other disciplines?

11. What kind of characteristics and skills should doctoral researchers that conduct IDR in this area have?

Research and Publications

I have here a list of the publications of your doctoral researchers. Let's have a look at it together.

12. What disciplines are included in the publications of this list?

13. What kind of knowledge of each discipline is required?

14. What does conducting this kind of research entail? (people, expertise, tools, data, etc.) Could you elaborate on these issues?

15. Could you describe the process of designing and implementing such research projects?

16. What are the differences, if any, in the design and implementation of fundamental research projects?

Funding

17. What kind of funding typically supports the doctoral researchers who participated in that research?

18. How likely is it that the source of funding would repeatedly support new projects in that particular integration of fields? And in completely different fields?

19. How do different sources of funding (e.g., project, scholarship, university, self-funding) suit the different kinds of research (e.g., fundamental, applied, in cooperation with industry, interdisciplinary, etc.)?

Network Partners

20. Did you collaborate with other people other than your doctoral researchers for these projects? If so, could you tell me about their expertise (not only scientific expertise)?

If other people collaborated in the projects:

21. How did they become members of the projects?
22. What was their role in the project?
23. How did they contribute to the research activity?
24. What was their motivation for participating in the projects?
25. Are they collaborating in successive projects with your team?

For all participants:

26. Are there differences in the involvement of external partners of an interdisciplinary project and a CS project? If so, what are the differences?

Supervision

27. Would you say that doctoral researchers who co-authored these research publications need different supervision than those who conduct research exclusively in CS? If so, in which way?
28. Do the doctoral researchers who co-authored these publications receive additional supervision? If so, in which fields?

If doctoral researchers receive double supervision in fields other than CS:

29. Could you explain why are they receiving this additional supervision?
30. How was this double supervision agreed/suggested?

For all participants:

31. In your opinion, how does supervision influence the fact that doctoral researchers conduct fundamental, applied, or interdisciplinary research?

Academic Structures

Now I would ask you to reflect on the influence that different academic structures within the Faculty of Informatics have on the single-disciplinarity or interdisciplinarity of your doctoral researchers.

32. How does the PhD program (e.g., traditional European program, PhD school, doctoral college) influence the interdisciplinarity or single-disciplinarity of your doctoral researchers?
33. How does your research group influence your students' choice between interdisciplinarity or single-disciplinarity?
34. How does the *Faculty of Informatics* as a whole influence the interdisciplinarity or single-disciplinarity of your doctoral researchers?
35. Is there any other academic structure influencing their research?

Additional Questions

36. Is there anything that we have not discussed that would help me understand the interdisciplinarity or single-disciplinarity of your doctoral researchers?

360-Questionnaires

This appendix presents the questionnaires that were used in phase III of this study[2]. As explained in Section 7.1 each stakeholder group assessed a different set of criteria according their knowledge on the doctoral structures and processes of the context where the study was conducted. A total of five different questionnaires were prepared:

- Questionnaire for Doctoral Researchers
- Questionnaire for Post-Doctoral Researchers
- Questionnaire for Faculty Members
- Questionnaire for Members of the Directive Board
- Questionnaire for External Individuals

The different questionnaires were shown to the respondents based on their answer to two demographic questions that asked them whether they are members of the Faculty of Informatics in the TU Wien and their position in the Faculty.

[2]The participants of these questionnaires normally use the word "faculty" with its British meaning (academic division) instead of with its North American meaning (academic staff). Therefore, in these questionnaires, this term refers to the *Faculty of Informatics*.

Introduction to the Questionnaires

360° Opinions on Interdisciplinarity at Doctoral Level

Presence and Importance of Interdisciplinarity During PhD in Computer Science

The primary goal of this project is to compare the alignment of opinions on interdisciplinarity of different academic stakeholders (i.e., doctoral researchers, post-doctoral researchers, professors, department directors, external individuals). We focus on the field of Computer Science and the context of this analysis is the Faculty of Informatics of the Technische Universität Wien.

Participation is voluntary and responses will be *anonymous*. We will not identify who you are through the survey responses.

This survey is *very short*. It will not take you more than 5 minutes to complete it.

If you have any questions about this study, or want further information, please contact:
María del Carmen Calatrava Moreno
Vienna University of Technology
E-mail: calatrava@ec.tuwien.ac.at

Privacy

A note on privacy: This survey is anonymous. The record of your survey responses does not contain any identifying information about you, unless a specific survey question explicitly asked for it. If you used an identifying token to access this survey, please rest assured that this token will not be stored together with your responses. It is managed in a separate database and will only be updated to indicate whether you did (or did not) complete this survey. There is no way of matching identification tokens with survey responses.

Participants' Objectivity

This analysis makes no assumption that interdisciplinary research is better or more valuable than other types of research. Therefore, we ask participants to provide their most objective answers.

Definition of Interdisciplinarity

There is an extensive theology around the differences between inter- , trans- , multi-disciplinary research, each with its own shade of meaning. For the purpose of this survey we adopt the term 'interdisciplinary research' to describe research where two or more disciplines work together.

A more detailed definition is provided in a National Academies' report (2005): 'Interdisciplinary research is a mode of research by teams or individuals that integrates information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or bodies of specialized knowledge to advance fundamental understanding'.

Institute of Medicine, National Academy of Sciences, and National Academy of Engineering. *Facilitating Interdisciplinary Research.* Washington, DC: The National Academies Press, 2005. doi:10.17226/11153.

1. *** I have read and understood the introduction to this survey**
   Choose one of the following answers
   ☐ Yes

Questionnaire for Doctoral Researchers

Demographics

1. *** Are you a member of the Faculty of Informatics at TU Wien?**
   Choose one of the following answers
   - ☐ Yes
   - ☐ No, I am external to the Faculty of Informatics

2. *** How are you related to the Faculty of Informatics at TU Wien?**
   Choose one of the following answers
   - ☐ Professor / doctoral supervisor
   - ☐ Post-doc
   - ☐ Doctoral researcher
   - ☐ Other ____________________

3. *** What is your research field?**
   For info visit: `http://www.informatik.tuwien.ac.at/research`
   Check any that apply
   - ☐ Computational Intelligence
   - ☐ Media Informatics and Visual Computing
   - ☐ Computer Engineering
   - ☐ Distributed and Parallel Systems
   - ☐ Business Informatics
   - ☐ Other field different to Computer Science ____________________

4. *** In which doctoral program are you enrolled?**
   Please select one answer
   - ☐ Traditional doctoral program
   - ☐ Vienna PhD School of Informatics
   - ☐ Mathematical Logic in Computer Science
   - ☐ Adaptive Distributed Systems
   - ☐ Environmental Informatics
   - ☐ Logical Methods in Computer Science (LogiCS)
   - ☐ Cyber-Physical Production Systems
   - ☐ Computational Perception
   - ☐ Other ____________________

Antecedents

5. *** Did you have previous experiences with discipline/s other than Computer Science before starting your PhD?**
   (E.g., as a hobby, as part of your studies, as part as your work)
   Choose one of the following answers

   Not at all ☐—☐—☐—☐ To a large extent

6. *** Did you wish to conduct interdisciplinary research before deciding on your PhD topic?**
   Choose one of the following answers

   Not at all ☐—☐—☐—☐ To a large extent

7. *** Was the choice of your PhD topic motivated by its contribution to societal, human or environmental welfare?**
   Choose one of the following answers

   Not at all ☐—☐—☐—☐ To a large extent

Interdisciplinary Research at Doctoral Level

8. *** How interdisciplinary is the research that you conduct?**
   Choose one of the following answers

   Not interdisciplinary ☐—☐—☐—☐ Very interdisciplinary

9. *** How interdisciplinary is the environment where you conduct your research?**
   (Environment = research group for researchers at the Faculty, company for those in industry, etc.)
   Choose one of the following answers

   Not interdisciplinary ☐—☐—☐—☐ Very interdisciplinary

10. *** Have you taken a broad range of university courses related to disciplines other than Computer Science?**
    (E.g., courses on other disciplines, CS courses that integrate concepts or methods of other disciplines)
    Choose one of the following answers

    Not at all ☐—☐—☐—☐ To a large extent

11. *** Are you familiar with different research methodologies?**
    (E.g., qualitative, quantitative, formal, experimental, etc.)

Choose one of the following answers

Not at all ☐—☐—☐—☐ To a large extent

12. *** Do you collaborate with experts in disciplines other than Computer Science?**
Choose one of the following answers

Not at all ☐—☐—☐—☐ To a large extent

13. *** Are your publications also contributing to disciplines other than Computer Science?**
Choose one of the following answers

Not at all ☐—☐—☐—☐ To a large extent

14. *** Is your research based on previous work of disciplines other than Computer Science?**
Choose one of the following answers

Not at all ☐—☐—☐—☐ To a large extent

15. *** In your opinion, is the nature of the financial resources that fund your PhD adequate to support interdisciplinary research?**
(E.g., The project in which you are employed, your scholarship, your own funds.)
Choose one of the following answers

Not at all ☐—☐—☐—☐ To a large extent

16. *** Does your supervisor encourage that knowledge of more than one discipline is integrated into your research?**
Choose one of the following answers

Not at all ☐—☐—☐—☐ To a large extent

17. *** Do you receive additional academic supervision of an expert in a different discipline?**
Choose one of the following answers

Not at all ☐—☐—☐—☐ To a large extent

Importance Assessment

18. *** How important is it for you to conduct interdisciplinary research?**
Choose one of the following answers

Not at all important ☐—☐—☐—☐ Very important

19. *** How important is it for you to conduct research in an interdisciplinary environment?**
(Environment = research group for researchers at the Faculty, company for those in industry, etc.)
Choose one of the following answers

Not at all important ☐—☐—☐—☐ Very important

20. *** How important is it for you to take broad range of courses related to disciplines other than Computer Science?**
(E.g., courses on other disciplines, CS courses that integrate concepts or methods of other disciplines)
Choose one of the following answers

Not at all important ☐—☐—☐—☐ Very important

21. *** How important is it for you to be familiar with different research methodologies?**
(E.g., qualitative, quantitative, formal, experimental, etc.)
Choose one of the following answers

Not at all important ☐—☐—☐—☐ Very important

22. *** How important is it for you to collaborate with experts in disciplines other than Computer Science?**
Choose one of the following answers

Not at all important ☐—☐—☐—☐ Very important

23. *** How important is it for you to publish publications that also contribute to disciplines other than Computer Science?**
Choose one of the following answers

Not at all important ☐—☐—☐—☐ Very important

24. *** How important is it for you to base your research on previous work of disciplines other than Computer Science?**
Choose one of the following answers

Not at all important ☐—☐—☐—☐ Very important

25. *** How important is for you the availability of funds for interdisciplinary research?**
Choose one of the following answers

Not at all important ☐—☐—☐—☐ Very important

26. *** How important is it for you to receive encouragement to conduct research that involves knowledge of more than one discipline?**
    Choose one of the following answers

    Not at all important ☐—☐—☐—☐ Very important

27. *** How important is it for you to receive additional supervision of an expert in a different discipline?**
    Choose one of the following answers

    Not at all important ☐—☐—☐—☐ Very important

Questionnaire for Post-Doctoral Researchers

Demographics

1. *** Are you a member of the Faculty of Informatics at TU Wien?**
   Choose one of the following answers
   ☐ Yes
   ☐ No, I am external to the Faculty of Informatics

2. *** How are you related to the Faculty of Informatics at TU Wien?**
   Choose one of the following answers
   ☐ Professor / doctoral supervisor
   ☐ Post-doc
   ☐ Doctoral researcher
   ☐ Other ____________________

3. *** What is your research field?**
   For info visit: `http://www.informatik.tuwien.ac.at/research`
   Check any that apply
   ☐ Computational Intelligence
   ☐ Media Informatics and Visual Computing
   ☐ Computer Engineering
   ☐ Distributed and Parallel Systems
   ☐ Business Informatics
   ☐ Other field different to Computer Science ____________________

Interdisciplinary Research at Doctoral Level

4. *** How interdisciplinary is the research conducted by the doctoral researchers of your research group?**
   Choose one of the following answers

   Not interdisciplinary ☐—☐—☐—☐ Very interdisciplinary

5. *** How interdisciplinary is the environment where doctoral researchers of your group conduct their research?**
   (Environment = research group for researchers at the Faculty, company for those in industry, etc.)
   Choose one of the following answers

   Not interdisciplinary ☐—☐—☐—☐ Very interdisciplinary

6. *** To what extent do doctoral researchers of your group collaborate with experts in disciplines other than Computer Science?**
   Choose one of the following answers

   Not at all ☐—☐—☐—☐ To a large extent

7. *** To what extent do the publications of doctoral researchers of your group also contribute to disciplines other than Computer Science?**
   Choose one of the following answers

   Not at all ☐—☐—☐—☐ To a large extent

8. *** To what extent do doctoral researchers of your group base their research on previous work of disciplines other than Computer Science?**
   Choose one of the following answers

   Not at all ☐—☐—☐—☐ To a large extent

Importance Assessment

In your opinion, ...

9. *** ... how important is it that doctoral researchers of your group conduct interdisciplinary research?**
   Choose one of the following answers

   Not at all important ☐—☐—☐—☐ Very important

10. *** ... how important is it that the doctoral researchers of your group conduct their research in an interdisciplinary environment?**
    (Environment = research group for researchers at the Faculty, company for those in industry, etc.)
    Choose one of the following answers

    Not at all important ☐—☐—☐—☐ Very important

11. *** ... how important is it that doctoral researchers of your group take a broad range of courses related to disciplines other than Computer Science?**
    (E.g., courses on other disciplines, CS courses that integrate concepts or methods of other disciplines)
    Choose one of the following answers

    Not at all important ☐—☐—☐—☐ Very important

12. *** ... how important is it that doctoral researchers of your group are familiar with different research methodologies?**

(E.g., qualitative, quantitative, formal, experimental, etc.)
Choose one of the following answers

Not at all important ☐—☐—☐—☐ Very important

13. * ... how important is it that doctoral researchers of your group collaborate with experts in disciplines other than Computer Science?
Choose one of the following answers

Not at all important ☐—☐—☐—☐ Very important

14. * ... how important is it that the research of doctoral researchers of your group is also contributing to disciplines other than Computer Science?
Choose one of the following answers

Not at all important ☐—☐—☐—☐ Very important

15. * ... how important is it that doctoral researchers of your group base their research on previous work of disciplines other than Computer Science?
Choose one of the following answers

Not at all important ☐—☐—☐—☐ Very important

16. * ... how important are funds for interdisciplinary research for doctoral researchers of your group?
Choose one of the following answers

Not at all important ☐—☐—☐—☐ Very important

17. * ... how important is it that doctoral researchers of your group are encouraged by their supervisors to conduct research that involves knowledge of more than one discipline?
Choose one of the following answers

Not at all important ☐—☐—☐—☐ Very important

18. * ... how important is it that doctoral researchers of your group receive additional supervision of an expert in a different discipline?
Choose one of the following answers

Not at all important ☐—☐—☐—☐ Very important

Questionnaire for Faculty Members

Demographics

1. *** Are you a member of the Faculty of Informatics at TU Wien?**
   Choose one of the following answers
   - ☐ Yes
   - ☐ No, I am external to the Faculty of Informatics

2. *** How are you related to the Faculty of Informatics at TU Wien?**
   Choose one of the following answers
   - ☐ Professor / doctoral supervisor
   - ☐ Post-doc
   - ☐ Doctoral researcher
   - ☐ Other ____________________

3. *** Are you a member of the directive board of the Faculty of Informatics at the TU Wien?**
   Choose one of the following answers
   - ☐ Yes
   - ☐ No

4. *** Are you directing any of doctoral programs of the Faculty of Informatics at the TU Wien?**
   Choose one of the following answers
   - ☐ Yes
   - ☐ No

5. *** What is your research field?**
   For info visit: `http://www.informatik.tuwien.ac.at/research`
   Check any that apply
   - ☐ Computational Intelligence
   - ☐ Media Informatics and Visual Computing
   - ☐ Computer Engineering
   - ☐ Distributed and Parallel Systems
   - ☐ Business Informatics
   - ☐ Other field different to Computer Science ____________________

Interdisciplinary Research at Doctoral Level

6. *** How interdisciplinary is the research conducted by your doctoral researchers?**
   Choose one of the following answers

   Not interdisciplinary ☐—☐—☐—☐ Very interdisciplinary

7. *** How interdisciplinary is the environment where your doctoral researchers conduct their research?**
   (Environment = research group for researchers at the Faculty, company for those in industry, etc.)
   Choose one of the following answers

   Not interdisciplinary ☐—☐—☐—☐ Very interdisciplinary

8. *** To what extent do your doctoral researchers take a broad range of courses related to disciplines other than Computer Science?**
   (E.g., courses on other disciplines, CS courses that integrate concepts or methods of other disciplines)
   Choose one of the following answers

   Not at all ☐—☐—☐—☐ To a large extent

9. *** To what extent are your doctoral researchers familiar with different research methodologies?**
   (E.g., qualitative, quantitative, formal, experimental, etc.)
   Choose one of the following answers

   Not at all ☐—☐—☐—☐ To a large extent

10. *** To what extent do your doctoral researchers collaborate with experts in disciplines other than Computer Science?**
    Choose one of the following answers

    Not at all ☐—☐—☐—☐ To a large extent

11. *** To what extent are the publications of your doctoral researchers also contributing to disciplines other than Computer Science?**
    Choose one of the following answers

    Not at all ☐—☐—☐—☐ To a large extent

12. *** To what extent is the research of your doctoral researchers based on previous work of disciplines other than Computer Science?**
    Choose one of the following answers

    Not at all ☐—☐—☐—☐ To a large extent

13. *** To what extent is the nature of the funding of your doctoral researchers appropriate to support interdisciplinary research?**
Choose one of the following answers

Not at all ☐—☐—☐—☐ To a large extent

14. *** To what extent do you encourage your doctoral researchers to conduct research that involves knowledge of more than one discipline?**
Choose one of the following answers

Not at all ☐—☐—☐—☐ To a large extent

15. *** To what extent do your doctoral researchers receive additional academic supervision of an expert in a different discipline?**
Choose one of the following answers

Not at all ☐—☐—☐—☐ To a large extent

Importance Assessment

In your opinion, ...

16. *** ... how important is it that your doctoral researchers conduct interdisciplinary research?**
Choose one of the following answers

Not at all important ☐—☐—☐—☐ Very important

17. *** ... how important is it that your researchers conduct their research in an interdisciplinary environment?**
(Environment = research group for researchers at the Faculty, company for those in industry, etc.)
Choose one of the following answers

Not at all important ☐—☐—☐—☐ Very important

18. *** ... how important is it that your researchers take a broad range of courses related to disciplines other than Computer Science?**
(E.g., courses on other disciplines, CS courses that integrate concepts or methods of other disciplines)
Choose one of the following answers

Not at all important ☐—☐—☐—☐ Very important

19. *** ... how important is it that your researchers are familiar with different research methodologies?**
(E.g., qualitative, quantitative, formal, experimental, etc.)

Choose one of the following answers

Not at all important ☐—☐—☐—☐ Very important

20. * ... how important is it that your researchers collaborate with experts in disciplines other than Computer Science?
Choose one of the following answers

Not at all important ☐—☐—☐—☐ Very important

21. * ... how important is it that the publications of your doctoral researchers are also contributing to disciplines other than Computer Science?
Choose one of the following answers

Not at all important ☐—☐—☐—☐ Very important

22. * ... how important is it that the research of your doctoral researchers is based on previous research of disciplines other than Computer Science?
Choose one of the following answers

Not at all important ☐—☐—☐—☐ Very important

23. * ... how important are funds for interdisciplinary research for your researchers?
Choose one of the following answers

Not at all important ☐—☐—☐—☐ Very important

24. * ... how important is it that doctoral researchers are encouraged to conduct research that involves knowledge of more than one discipline?
Choose one of the following answers

Not at all important ☐—☐—☐—☐ Very important

25. * ... how important is it that your doctoral researchers receive additional supervision of an expert in a different discipline?
Choose one of the following answers

Not at all important ☐—☐—☐—☐ Very important

Questionnaire for Members of the Directive Board

Demographics

1. *** Are you a member of the Faculty of Informatics at TU Wien?**
   Choose one of the following answers
   - ☐ Yes
   - ☐ No, I am external to the Faculty of Informatics

2. *** How are you related to the Faculty of Informatics at TU Wien?**
   Choose one of the following answers
   - ☐ Professor / doctoral supervisor
   - ☐ Post-doc
   - ☐ Doctoral researcher
   - ☐ Other ____________________

3. *** Are you a member of the directive board of the Faculty of Informatics at the TU Wien?**
   Choose one of the following answers
   - ☐ Yes
   - ☐ No

4. *** Are you directing any of doctoral programs of the Faculty of Informatics at the TU Wien?**
   Choose one of the following answers
   - ☐ Yes
   - ☐ No

5. *** What is your research field?**
   For info visit: `http://www.informatik.tuwien.ac.at/research`
   Check any that apply
   - ☐ Computational Intelligence
   - ☐ Media Informatics and Visual Computing
   - ☐ Computer Engineering
   - ☐ Distributed and Parallel Systems
   - ☐ Business Informatics
   - ☐ Other field different to Computer Science ____________________

Interdisciplinary Research at Doctoral Level

6. *** How interdisciplinary is the research conducted by doctoral researchers of the Faculty?**
   Choose one of the following answers

   Not interdisciplinary ☐—☐—☐—☐ Very interdisciplinary

7. *** How interdisciplinary is the environment where doctoral researchers of the Faculty conduct their research?**
   (Environment = research group for doctoral researchers at the Faculty, company for those in industry, etc.)
   Choose one of the following answers

   Not interdisciplinary ☐—☐—☐—☐ Very interdisciplinary

8. *** To what extent do doctoral researchers of the Faculty take a broad range of courses related to disciplines other than Computer Science?**
   (E.g., courses on other disciplines, CS courses that integrate concepts or methods of other disciplines)
   Choose one of the following answers

   Not at all ☐—☐—☐—☐ To a large extent

9. *** To what extent are doctoral researchers of the Faculty familiar with different research methodologies?**
   (E.g., qualitative, quantitative, formal, experimental, etc.)
   Choose one of the following answers

   Not at all ☐—☐—☐—☐ To a large extent

10. *** To what extent do doctoral researchers of the Faculty collaborate with experts in disciplines other than Computer Science?**
    Choose one of the following answers

    Not at all ☐—☐—☐—☐ To a large extent

11. *** To what extent are the publications of doctoral researchers of the Faculty also contributing to disciplines other than Computer Science?**
    Choose one of the following answers

    Not at all ☐—☐—☐—☐ To a large extent

12. *** To what extent is the research of doctoral researchers of the Faculty based on previous work of disciplines other than Computer Science?**
    Choose one of the following answers

    Not at all ☐—☐—☐—☐ To a large extent

13. *** To what extent is the nature of the funding of doctoral researchers of the Faculty appropriate to support interdisciplinary research?**
Choose one of the following answers

Not at all ☐—☐—☐—☐ To a large extent

14. *** To what extent are doctoral researchers of the Faculty encouraged by their supervisors to conduct research that involves knowledge of more than one discipline?**
Choose one of the following answers

Not at all ☐—☐—☐—☐ To a large extent

15. *** To what extent do doctoral researchers of the Faculty receive additional academic supervision of an expert in a different discipline?**
Choose one of the following answers

Not at all ☐—☐—☐—☐ To a large extent

Importance Assessment

In your opinion, ...

16. *** ... how important is it that doctoral researchers of the Faculty conduct interdisciplinary research?**
Choose one of the following answers

Not at all important ☐—☐—☐—☐ Very important

17. *** ... how important is it that doctoral researchers of the Faculty conduct their research in an interdisciplinary environment?**
(Environment = research group for researchers at the Faculty, company for those in industry, etc.)
Choose one of the following answers

Not at all important ☐—☐—☐—☐ Very important

18. *** ... how important is it that doctoral researchers of the Faculty take a broad range of courses related to disciplines other than Computer Science?**
(E.g., courses on other disciplines, CS courses that integrate concepts or methods of other disciplines)
Choose one of the following answers

Not at all important ☐—☐—☐—☐ Very important

19. *** ... how important is it that doctoral researchers of the Faculty are familiar with different research methodologies?**

(E.g., qualitative, quantitative, formal, experimental, etc.)
Choose one of the following answers

Not at all important ☐—☐—☐—☐ Very important

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21. *** ... how important is it that the publications of doctoral researchers of the Faculty are also contributing to disciplines other than Computer Science?**
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Choose one of the following answers

Not at all important ☐—☐—☐—☐ Very important

23. *** ... how important are funds for interdisciplinary research for doctoral researchers of the Faculty?**
Choose one of the following answers

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24. *** ... how important is it that doctoral researchers of the Faculty are encouraged by their supervisors to conduct research that involves knowledge of more than one discipline?**
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Not at all important ☐—☐—☐—☐ Very important

25. *** ... how important is it that doctoral researchers of the Faculty receive additional supervision of an expert in a different discipline?**
Choose one of the following answers

Not at all important ☐—☐—☐—☐ Very important

Questionnaire for External Individuals

Demographics

1. *** Are you a member of the Faculty of Informatics at TU Wien?**
   Choose one of the following answers
   ☐ Yes
   ☐ No, I am external to the Faculty of Informatics

2. *** Select what best describes you.**
   Check any that apply
   ☐ Visiting professor at the Faculty of Informatics of the TU Wien.
   ☐ Member of a research funding agency.
   ☐ Member of the TU Wien (external to the Faculty of Informatics).
   ☐ Other ____________________

Note for Research Funding Agencies

3. *** Please answer the following questions having in mind the funding and research policies of your institution. Your answers should represent the perspective of your institution.**
   Choose one of the following answers
   ☐ Continue

Importance Assessment

In your opinion, ...

4. *** ... how important is it that doctoral researchers in the field of Computer Science conduct interdisciplinary research?**
   Choose one of the following answers

   Not at all important ☐—☐—☐—☐ Very important

5. *** ... how important is it that doctoral researchers in the field of Computer Science conduct their research in an interdisciplinary environment?**
   (Environment = research group for researchers at the Faculty, company for those in industry, etc.)
   Choose one of the following answers

   Not at all important ☐—☐—☐—☐ Very important

6. *** … how important is it that doctoral researchers in the field of Computer Science take a broad range of courses related to disciplines other than Computer Science?**
   (E.g., courses on other disciplines, CS courses that integrate concepts or methods of other disciplines)
   Choose one of the following answers

   Not at all important ☐—☐—☐—☐ Very important

7. *** … how important is it that doctoral researchers in the field of Computer Science are familiar with different research methodologies?**
   (E.g., qualitative, quantitative, formal, experimental, etc.)
   Choose one of the following answers

   Not at all important ☐—☐—☐—☐ Very important

8. *** … how important is it that doctoral researchers in the field of Computer Science collaborate with experts in disciplines other than Computer Science?**
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   Not at all important ☐—☐—☐—☐ Very important

9. *** … how important is it that the research of doctoral researchers in the field of Computer Science is also contributing to disciplines other than Computer Science?**
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10. *** … how important is it that doctoral researchers in the field of Computer Science base their research on previous work of disciplines other than Computer Science?**
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   Choose one of the following answers

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13. *** ... how important is it that doctoral researchers in the field of Computer Science receive additional supervision of an expert in a different discipline?**
Choose one of the following answers

Not at all important ☐—☐—☐—☐ Very important

Curriculum Vitae

María del Carmen Calatrava Moreno

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Experience

Jan 2016 - Dec 2016	Project assistant TU Wien, Institute of Software Technology and Interactive Systems
July 2011 - Dec 2015	University assistant TU Wien, Institute of Software Technology and Interactive Systems
Oct 2015 - Nov 2015	Visiting researcher University of Oxford, Department of Education
Apr 2015 - Oct 2015	Visiting researcher University of Tokyo, Department of Technology Management for Innovation
Oct 2014 - Nov 2014	Visiting researcher University of Oxford, Department of Education
Oct 2013 - Nov 2013	Visiting researcher University of Oxford, Department of Education
July 2010 - Oct 2010	Trainee TU Wien, Institute of Computer Graphics and Algorithms

Education

July 2011 - Present	Doctoral studies in Computer Science TU Wien
Feb 2012 - June 2013	Master's supplement degree, Innovation in Computer Science TU Wien
Oct 2008 - Jan 2011	Master's degree, Computer Software Engineering University of Jaén
Feb 2009 - June 2009	Exchange program: Master of Science, Computer Science Sapienza Università di Roma
Oct 2005 - Sept 2008	Bachelor's degree, Computer Software Engineering and Business University of Jaén

Languages

Spanish	Mother tongue
English	Full professional proficiency
German	Professional working proficiency
Italian	Professional working proficiency

For more information, please visit: `www.calatravamoreno.com`