novo nordisk fonden

The Danish **Bioinformatics** Landscape

Contents

Executive Summary

A wealth of advances in research and development can be gained from utilising 'big data' within the life sciences, but the ability to process and apply insights from these datasets is often rate limiting. With bioinformatics positioned between the traditionally separate disciplines of life science, computer science and mathematics, individuals with the required skillsets may not exist in sufficient numbers to fully capitalise on the potential of big data.

The Novo Nordisk Foundation (NNF) wishes to develop strategic initiatives in bioinformatics to help ensure that current and future needs for talented bioinformaticians in research and development are met across industry, academia and hospitals in Denmark. To assess the current situation and gain insight into the near-future situation in Denmark, the analysis presented herein was conducted by combining desk research with interviews and surveys with key stakeholders in these settings and represents the majority of those currently using bioinformatics in Denmark. The following report focuses on education and the workforce landscape of Danish bioinformatics and should be viewed as a directional guide to further discussion and exploration.

Life science research is strong in Denmark, with bioinformatics research activity largely focused to four geographical areas: the Copenhagen region, Aarhus, Aalborg and Odense. The Copenhagen and Aarhus areas account for over two-thirds of bioinformatics activity in Denmark, with their research environments typically organised as independent centres with an explicit focus on bioinformatics. The presence of big pharmaceutical companies and specialist consulting and software development companies in these geographical areas also contributes to this research activity.

The research herein revealed a range of skills that are needed in order to gain insight from large biological datasets and capitalise on these insights. These skills can be grouped into four key competency profiles:

- Core Bioinformatics profiles: experts in translating and interpreting large amounts of biological data into insights, typically holding Master's degrees in bioinformatics,
- Application profiles: those with a basic understanding of programming and algorithm design to support and solve problems relevant to their fields,
- Data Science & Software Design profiles: those with an educational background in computer science, and
- Profiles from Other Domains that possess skills applicable to bioinformatics research and development (such as physics, statistics or mathematics).

The number of such individuals involved in bioinformatics research in Denmark has grown significantly over the past five years across all three sectors (life science industry, academia and healthcare). This demand is expected to increase over the next five years with academia and industry anticipating an acceleration of growth that translates to 87% and 160% more profiles required in five years' time, respectively.

This increased demand is driven by the growing importance of bioinformatics and an expanding scope, particularly as more teams in academia work across disciplines, and industry becomes aware of the potential for bioinformatics to drive innovation and accelerate solution development.

Sufficient educational throughput in Denmark will be a key element in ensuring this growing demand is met. Across institutions, the number of students admitted to relevant identified Master's degree programmes each year has steadily increased over the 2012–2016 period and this increase is expected to continue over the next few years. In particular, the number of Core Bioinformatics profiles graduating each year is expected to increase by 60% within the next five years, again reflecting an increased awareness of the subject area and its growing importance and potential.

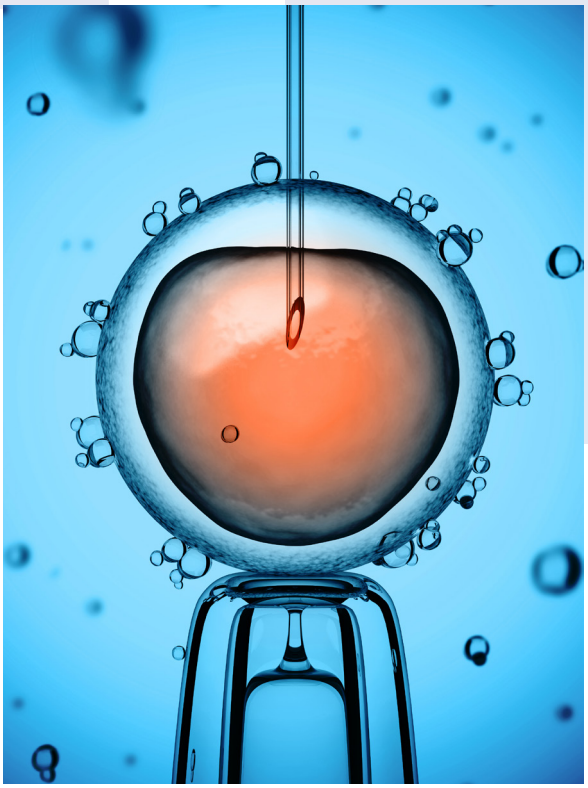
While more Master's and PhD students within the Core Bioinformatics profile will graduate each year over the next five years, the anticipated number of available profiles in five years' time is approximately in line with the expected demand for such individuals. However, many of the currently enrolled students may join workforces outside of Denmark if not offered employment opportunities quickly following completion of their courses. Moreover, given that this analysis represents a baseline anticipation of demand as new companies and research units are likely to be established, it is very likely the supply of Core Bioinformatics profiles will struggle to meet future demand.

For the three other profile types, there will be more than enough graduates to potentially satisfy demand; however, these profiles are integral to a wide range of educational programmes (for example, Application profiles include biochemistry and molecular biology graduates from the University of Copenhagen). Thus, while appropriate graduate profiles exist, competition for these among employers will continue to exist outside of bioinformatics. In the case of Data Science & Software Design profiles, competition is even larger as it extends beyond life science into business sectors such as banking, marketing and social media.

Based on this analysis, an adequate supply of appropriate future bioinformatic skillsets and profiles in Denmark will be dependent on addressing six key challenges:

Funding of bioinformatics research and education
The opinion among most key stakeholders in academia is that a strong foundation of talented Master's students exists, yet there is a need to boost the bioinformatics research environment. Study programme managers from the institutions supplying Core Bioinformatics profiles report that the key challenges to realising the needed increase in profiles are the lack of PhD grants and lack of supervisors for potential PhD students.
Successful integration of bioinformatics into other programmes
Interviews with study programme managers indicate that, in recent years, a closer collaboration between the bioinformatic research environments and other relevant research groups (molecular biology, biochemistry, bioengineering etc.) has been promoted. However, it is emphasised that these efforts should be expanded as much as possible.
Collaboration between the life sciences and data sciences
The supply of data scientists and software engineers exceeds current and future demand in life science, but these profiles are in high demand in banking, insurance and various branches of industry. Competition for the best graduates is high and there is little incentive to include further specialisation in bioinformatics and related subjects to the current curriculum. The interviewed stakeholders recommend developing initiatives that target both students and research environments to encourage interest in life science.
Provision of vocational training and education
The respondents of the survey from industry, academia and the healthcare sector articulate a growing need for vocational training and continuing education within bioinformatics and bioinformatics tools to ensure the current workforce, highly skilled in other domains, are able to work with bioinformatics and bioinformaticians. The current supply of such training in Denmark is limited and consists mainly of introductory courses on specific software tools that are provided by commercial businesses.
Retention and attraction of international talent
The labour markets for bioinformatics profiles are international. Survey respondents estimate that close to 25 percent of employees currently working with biodata and bioinformatics in Denmark have an international background. Similarly, the study managers from the programmes educating Core Bioinformatics profiles report that a large share of the Master's students in bioinformatics are from outside Denmark. Together, these findings present the challenge of ensuring that appropriate international talent is both attracted to and retained in the Danish workforce.
Continued and expanded access to state-of-the-art research infrastructure
Access to a fast, flexible and secure infrastructure and the ability to combine different types of sensitive data and perform analyses are key prerequisites for conducting bioinformatics research and participating in collaborative research with international scientists. Moreover, the availability of such infrastructure also increases the attractiveness of Denmark to international talent. Denmark already has a number of advanced data-handling facilities, such as Computerome, but continuous technological updating is required and collaborative efforts among stakeholders need to be encouraged.

In conclusion, life science research is strong in Denmark and individuals with bioinformatic competence profiles are already integral to this. This analysis indicates that the number of such individuals has grown significantly over the past five years across all sectors (industry, academia, healthcare) and that stakeholders expect this growth to continue through the coming five years, accelerating in industry and academia. Although the previously limited number of Core Bioinformatics graduates is anticipated to increase significantly, it is very likely that the supply of such profiles will struggle to meet future demand. Therefore, ensuring enough people are educated, including to PhD level, represents a key challenge. For the remaining three bioinformatics profiles (Application, Data Science & Software Design, and Other Domain) there will be more than enough graduates, but the challenge will be to ensure that a career in the life sciences is of interest to them. Similarly, Denmark needs to ensure it is positioned to attract and retain international talent, while ensuring talent within Denmark receives the best vocational training and has access to the necessary infrastructure.



The Importance of Bioinformatics

High-throughput sequencing technologies, digital imaging technologies and electronic patient data have created the possibility of making large quantitative analyses of biological phenomena. These 'big data' can provide new insights and approaches in several fields of biological and medical research. However, there is risk that the processing and utilisation of insights from large datasets – bioinformatics – can become a rate-limiting step.

Bioinformatics is an interdisciplinary field of science that combines research in molecular biology with the use of computer science, statistics, algorithm design and software engineering to extract value from different types of biological data. As it is an interdisciplinary field, individuals with the required skillsets may not exist in sufficient numbers to fully capitalise on the potential insights and advances possible with big data, limiting the success of the Danish life sciences sector.

To assess the current situation and gain initial insight into the near-future situation in Denmark, the analysis presented herein was conducted combining desk research with interviews and surveys with key stakeholders in industry, academia and hospitals across Denmark.

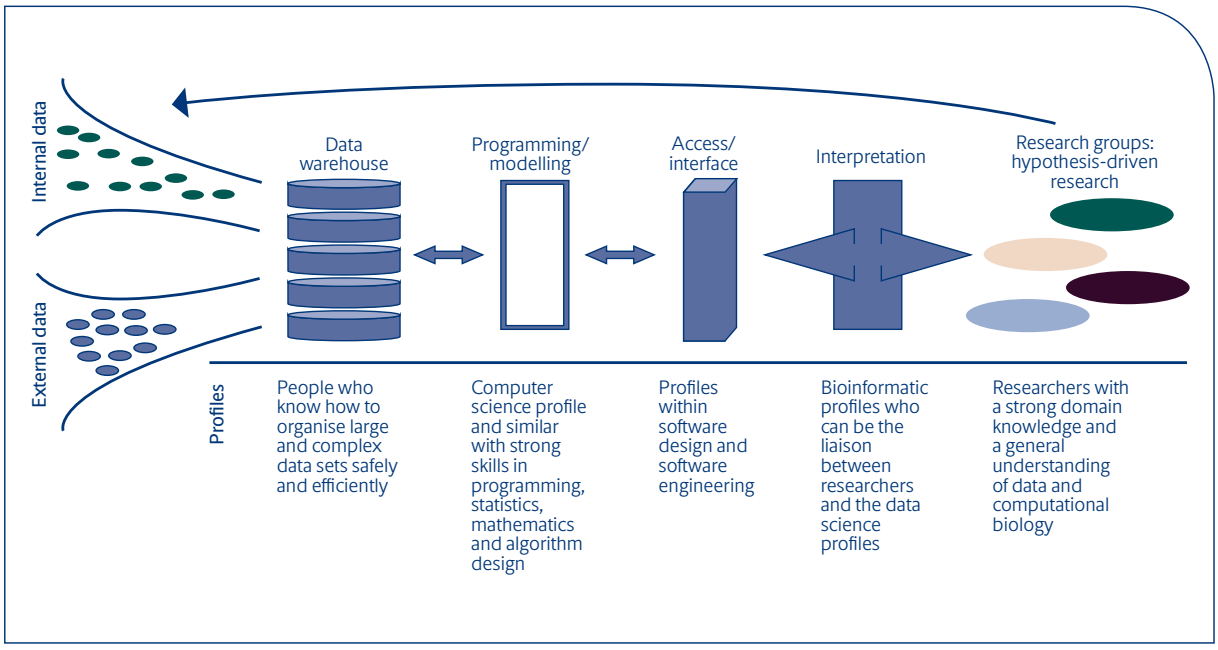
The Bioinformatics Value Chain

Deriving insights from big biological datasets is a complex task. Interviews with key stakeholders from the Danish bioinformatics communities have provided an overview of the process, outlined in Figure 1.

Typically, organisations working with biodata draw on large amounts of internal data (e.g. collected samples) and external data (e.g. official databases or registries). The data have to be organised, and programmes and software tools for data analysis have to be developed. Data handling is carried out by data scientists, while software engineers develop the required software tools for data analysis. Bioinformaticians are the link between the data scientists and research groups. They are responsible for analytical design and assist in interpretation of results. On the right-hand side of Figure 1 are research groups with in-depth knowledge of a specific domain (Application profiles). As indicated, the process can run in both directions: research groups develop hypotheses they want to test using available data, and data analyses give rise to new hypotheses and generate new research questions.

Some interviewed stakeholders also pointed out an advantage to having profiles within an organisation who understand how biodata can be transformed into new business models and who know how to organise support for the efficient use of biodata. Such individuals can be deployed in several places in the value chain; for instance, as team leaders of one or more research groups, or as part of an organisation's executive management team.

Figure 1. The bioinformatics value chain. Processes can run in both directions with research groups developing hypotheses to test using available data, and data analyses giving rise to new hypotheses and generating new research questions.



Source: IRIS Group based on interview with key stakeholders.*
*A special thanks to Evelyn Travnik, CIO at NNF Center for Biosustainability for inspiration.

Bioinformatics Competency Profiles

The different skills needed in the value chain can be grouped into four key competency profiles: Core Bioinformatics, Application, Data Science & Software Design, and profiles from Other Domains that possess skills applicable to bioinformatics research and development (Figure 2).

Figure 2. Overview of the four bioinformatics competency profiles.

CORE BIOINFORMATICS

- Bridge the gap between biology and computer science
- Typically have Master's degrees in bioinformatics
- Sound understanding of biology and biological data, and experts in translating and interpreting large amounts of biological data into valuable insights with help from advanced mathematical, statistical and computational techniques

APPLICATION

- Variety of educational backgrounds such as molecular biology, biochemistry or biotechnology
- Apply standard bioinformatics software tools to analyse and solve scientific problems relevant to their field
- Basic understanding of programming and algorithm design which supports their data analysis and interpretation

DATA SCIENCE & SOFTWARE DESIGN

- Educational background within computer science, but do not necessarily have any knowledge within biology
- Know how to organise, maintain and store large and complex data sets in a safe manner
- Can create sound and user-friendly software tools for data analysis

PROFILES FROM OTHER DOMAINS

- Profiles from other domains applicable to bioinformatics have an educational background within areas such as physics, statistics or mathematics
- Solid experience with how to find mathematical and statistical answers and solutions to highly complex research questions based on large datasets

Source: Developed by IRIS Group based on interviews with key stakeholders and desk research.

Analytical Approach and Landscape

The analysis presented herein sought to answer the following four questions:

1. What is the current and future demand for competences within the area of bioinformatics and biodata in both the public and private sector?
2. What is the current and projected supply of competences within the area of bioinformatics and biodata?
3. Where are the critical gaps in current and future competence demand and supply within bioinformatics and biodata?
4. Are existing research environments and the research infrastructure in Denmark sufficiently equipped to remedy critical gaps between supply and demand for competences within the area of bioinformatics and biodata?

To address these four questions, a five-stage research and analysis process was followed, as outlined in Figure 3.

Figure 3. Outline of the five stages of research and analysis.

1 Gaining field understanding	Desk and database research conducted to provide insight into bioinformatics in Denmark and identify appropriate stakeholders and universities for subsequent stages.
2 Developing analytical strategy	Interviews conducted to build a solid understanding of the bioinformatic value chain and inform the subsequent stakeholder surveys and interviews.
3 Mapping the demand	Survey on present and future demands for bioinformatic competences distributed to stakeholders in industry, academia and hospitals. Further interviews with key stakeholders on the demand side also conducted.
4 Mapping the supply	Official data (2012–2016) obtained from the Danish Ministry of Higher Education and Science. Study managers from a range of the identified programmes interviewed regarding present and future intake of students.
5 Analysing the gaps	Assessment of the potential future gaps of bioinformatic competences for all four profiles of the competency types.

In total, 300 surveys were distributed, of which 52 were completed; 25 key stakeholders in industry, academia and hospitals were interviewed regarding required competences; and 29 university study programme managers were interviewed regarding courses and student numbers. The respondents and interviewees provide representation of the majority of large industry players, academic sites and hospitals currently using bioinformatics. This analysis should be viewed as an indication of general trends and direction rather than a strictly quantified analysis.

Bioinformatics Landscape

Key regions that comprise bioinformatics activity in Denmark are outlined in Figure 4, indicating the approximate distribution of bioinformatics skills among the regions. For a full list of the identified centres, see Appendix 1.1.

The research environments in the Copenhagen region and in Aarhus are typically organised as independent centres with an explicit focus on bioinformatics. These environments are, in general, larger and have more senior researchers than the research environments in Aalborg and Odense.

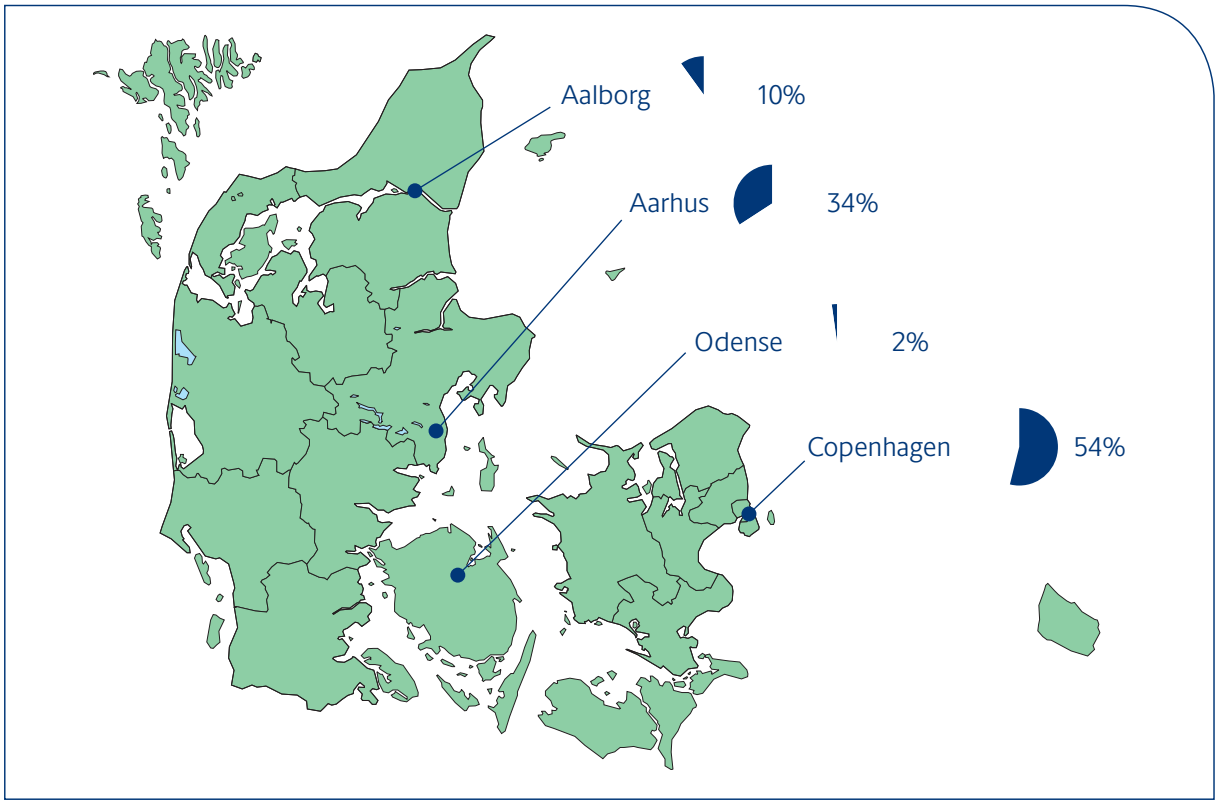
Many of the largest and most well-established research environments are located at the Technical University of Denmark, the University of Copenhagen and at Aarhus University. Furthermore, most big pharmaceutical companies are located in the Copenhagen region, while a number of companies specialising in consulting and software development in areas of bioinformatics (e.g. Qiagen) are located in Aarhus.

Bioinformatics, as a research area, is also gaining ground at other Danish universities. In Aalborg for instance, there are research groups both at the Department of Chemistry and Biosciences, and at the Cancer Data Science Lab at Aalborg University Hospital. Similarly, bioinformatics is an emerging field of research at the University of Southern Denmark. Over the last six–seven years, the university has focused on establishing a bioinformatics research environment that targets recruiting international talent.

A BRIEF HISTORY OF DANISH BIOINFORMATICS

In Denmark, bioinformatics has evolved as an interdisciplinary field of research over the last 25 years with anchoring at several Danish universities. The first Danish bioinformatics research environment took shape at the Technical University of Denmark in Copenhagen in 1993. It was based on a DKK 25 million grant from the Danish National Research Foundation to the Centre for Biological Sequence Analysis. Some years later, in 2001, the Bioinformatics Research Centre at Aarhus University was established as a collaboration between the Faculty of Science and the Faculty of Health. In 2002, the Bioinformatics Centre was founded at the University of Copenhagen, partly by a grant from the Novo Nordisk Foundation. The centre played a key role in kick-starting bioinformatics research and education at the university. Around the same time, research groups with a focus on specific areas of bioinformatics and computational biology were formed at the University of Southern Denmark and Aalborg University. In 2007, the Centre for Protein Research was established at the University of Copenhagen through a grant from the Novo Nordisk Foundation. The Centre has a strong focus on computational biology represented by the Translational Disease Systems Biology Group. More recently, other research environments have been established, often as a collaboration between the established centres at the universities and the hospital units. Examples include the Department of Molecular Medicine in Aarhus and the Unit for Genomic Medicine at Rigshospitalet in Copenhagen.

Figure 4. Regional distribution of bioinformatics skills profiles. Source: IRIS Group survey of industry, academia and hospitals (N=52)



Demand for Individuals with Bioinformatics Competences

The following results are based on the survey responses from key research, industry, academic and hospital environments, representing the majority of important players across these sectors in Denmark currently using bioinformatics. However, not every site is represented. Moreover, it is conceivable that the full expansion of big data enterprises requiring further bioinformatic expertise have not been fully appreciated. Therefore, it is likely that the following demand represents an absolute baseline position and anticipation.

Across life science industry, academia and the healthcare sector, the previous five-year period has been associated with an increased demand for individuals with bioinformatics and related skills (Figure 5). The greatest increase in demand has been within industry, with demand more than doubling (136%) during that period. Similarly, all sectors expect a further increase in demand over the next five-year period, with the increase accelerating in both industry and academia.

Reviewing the demand by bioinformatic profile type across all sectors, there has been, and will continue to be, an increased demand for all four bioinformatic profiles, with an overall doubling of demand for all profile types over the next five years (Figure 6). The steep upward trend in the demand for all profiles reflects that bioinformatics is considered a promising field of research with a broad range of applications. Thus, a wide range of stakeholders within industry, academia and hospitals expect to build up bioinformatic capacities in their organisations.

Figure 5. Increasing demand across industry, academic and healthcare sectors, separated by bioinformatic profile type seen during the previous five years and expected over the next five years.

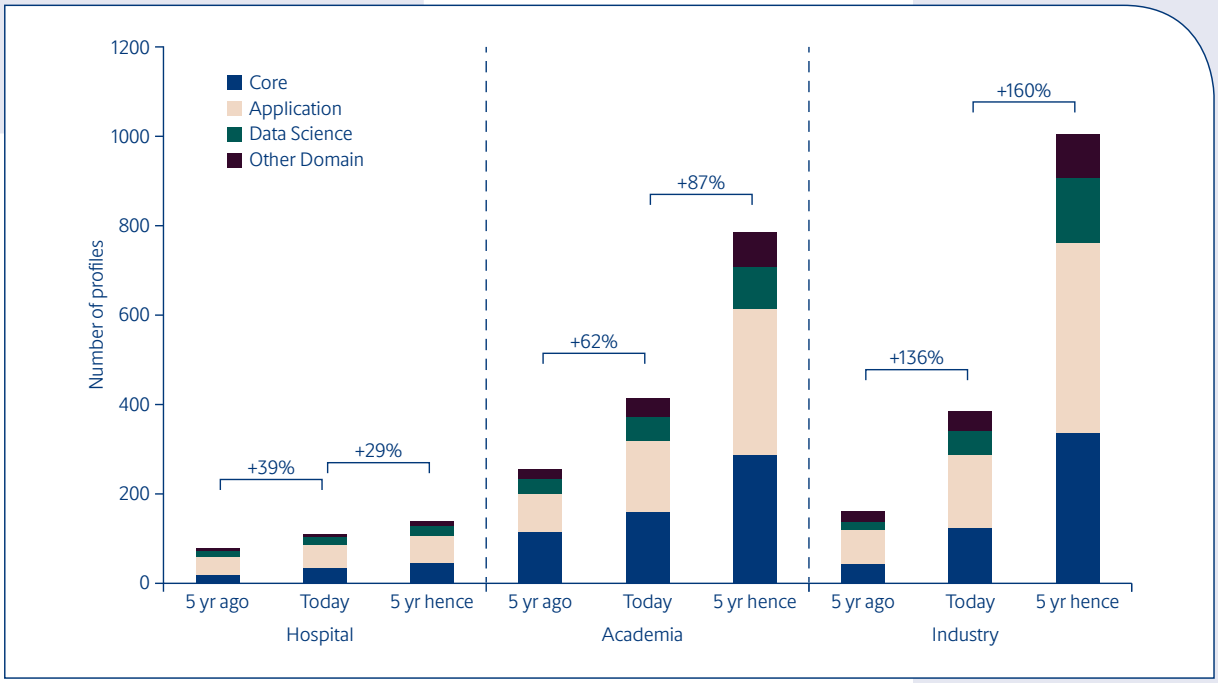
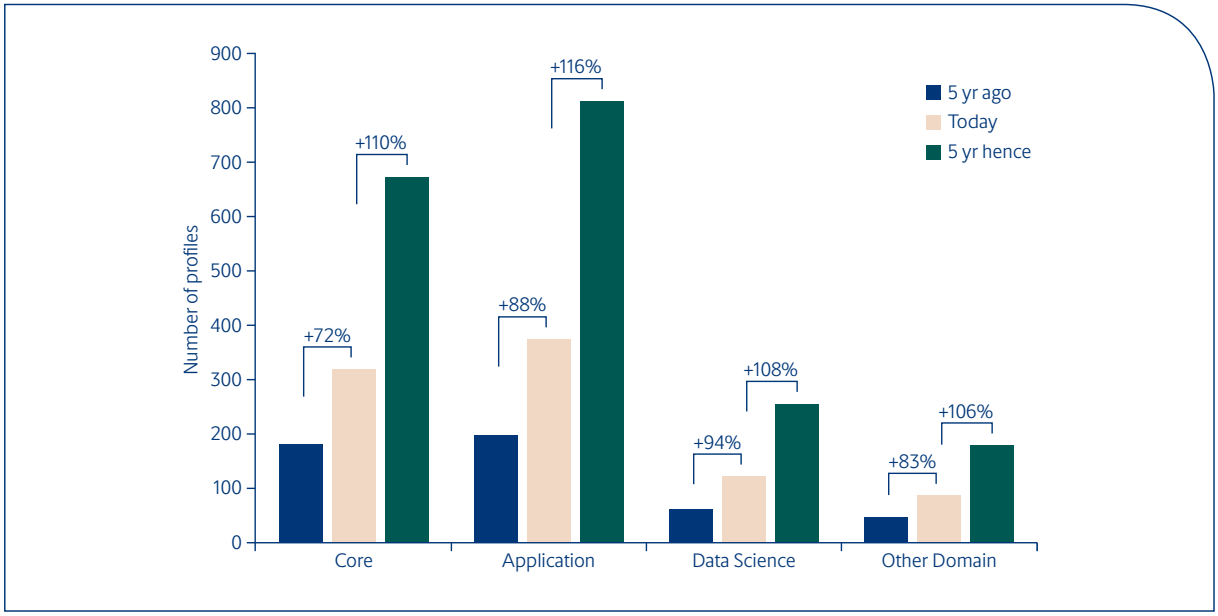


Figure 6. Increase over the past five years and expected increase in the coming five years, according to bioinformatic profile type across all sectors combined.



Demand within the Healthcare Sector

Several of the major Danish hospitals have established bioinformatic capabilities over the last decade in order to translate genomic mapping and analysis into better treatments targeted at individual patient needs (personalised medicine).

Examples include the establishment of a Unit for Genomic Medicine at Rigshospitalet, founded in 2010, a joint Genome Data Centre between Aarhus University Hospital and Aarhus University founded in 2016, and a Clinical Genome Centre at Odense University Hospital founded in 2014. Among other initiatives, these units collect samples from a variety of patients for a wide range of purposes (for example, collecting tissue samples to examine hereditary dispositions for certain cancers). Bioinformatic tools play a key part in the subsequent analysis of the data and form the basis for better screening, diagnosis and treatment.

This results in an increased need for bioinformaticians who can analyse and interpret large volumes of biological data and translate new insights into better treatments. In addition, interviewees emphasise that many current employees will need vocational education and training in order to incorporate standard bioinformatics tools into their patient care. Furthermore, the increased use of genomic analysis in standard treatments makes hospitals central providers of biological data, which needs to be stored properly and made accessible for further research, leading to a growing demand for data scientists in the healthcare sector.

While there is an increased demand for all four profiles between 2013 and 2023, the increase is not as steep as that seen and predicted in industry or academia. However, only departments who already use bioinformatics skills and profiles are included in the surveys. According to some of the interviewed hospital-based stakeholders, they expect an increase in the need for Application profiles and data scientists throughout the public care sector due to the introduction of personalised treatments. Thus, total demand is expected to be higher than presented here.

In the healthcare sector, the most significant increase is in the demand for core bioinformaticians and data scientists. The need for these profiles is expected to double over the surveyed ten-year period. In absolute figures, the demand for core bioinformaticians increases with approximately 50 profiles (from 160 today to almost 210 in five years). Likewise, the need for data scientists is expected to grow with 40 additional profiles (from 144 today to 184 in the next five years).

This development should be seen in light of the fact that healthcare professionals (including doctors) are rarely trained in bioinformatics and data analysis. If they are to gain valuable insights from the biological data produced, there is a need for profiles who know how to organise, analyse and interpret these data – and, most importantly, profiles who can support them in translating data-based knowledge into better and targeted patient treatment. There is also an increased demand for Application profiles and Other Domain profiles, but this trend is less pronounced.

Demand within Academia

Until recently, bioinformatics research was mainly carried out in a limited number of small research environments at major Danish universities. Bioinformatics was primarily seen as a tool for hypothesis testing by groups within specific areas such as genetics or cancer research. Correspondingly, the need for bioinformaticians was limited, and the few bioinformatics profiles had to span a broad competency gap between biology and data science.

However, bioinformatics is now becoming an established and independent field of research in its own right spanning basic, translational and applied research, and bioinformatic tools and methods are incorporated into a broad range of biological and medical research areas. Master's degree programmes in bioinformatics have been established at several universities and a growing number of students enrolled in other programmes are introduced to bioinformatics. Consequently, existing bioinformatics research environments are growing and new research centres spanning multiple faculties and hospitals are established (e.g. between Aarhus University and Aarhus University Hospital). In addition, new bioinformatics research environments are currently developing, for example, at the University of Southern Denmark.

As the scope of bioinformatics is expanding and the complexity of the research field is growing, the need for specialised profiles with bioinformatics competences is also growing rapidly. The dissemination of bioinformatics within biological and medical research also calls for profiles that have in-depth knowledge within their domain (e.g. certain disease therapy areas) and know how to utilise bioinformatic software as a tool for answering research questions.

Within academia, there is an increased demand for all four competency profiles, most strongly in an almost four-fold increase in Application profiles and Other Domain profiles between 2013 and 2023. Interviewed stakeholders expect to need just over 100 additional core bioinformaticians and 120 additional data scientists in the next five years. The increasing demand for Core Bioinformatics profiles should be seen in light of the current development of bioinformatics as an independent scientific discipline. This calls for profiles that can conduct high-level research and engage in interdisciplinary research collaborations (e.g. with biological and medical research groups) and who can educate and supervise students at both Master's and PhD levels.

Demand within the Life Science Industry

A growing part of the Danish life science industry is investing in improved data infrastructure and bioinformatics skills. However, for many companies these investments are relatively recent and, for some, it is still too early to say anything about specific effects, even among big pharmaceutical companies. To several of these companies, the bioinformatics department is to some extent regarded as a technical support service unit comparable to the IT department. To others, bioinformatics is an essential part of their R&D processes and provides the company with substantial competitive advantages. For example, bioinformatics tools can speed up the drug discovery process and make it less 'lab heavy'. Finally, a large proportion of the life science companies have not invested in bioinformatics but consider doing so in the near-future.

Common to all companies surveyed is that they expect the application of bioinformatics to accelerate. Some want to apply the latest bioinformatics methods to analyse their own data and combine them with external data, and a few of the most advanced companies expect to develop new strategies and business models based on bioinformatics analysis. They demand profiles who combine their core bioinformatics competences with a solid business sense, enabling them to link the company's investments in data, data-infrastructure and new technologies to the overall R&D strategy and business model of the company.

The expected increase in the application of bioinformatics among several companies indicates a sharp increase in industry demand for each of the competency profiles, a trend that is even more pronounced than the demand trend at hospitals and in academia. The demand for Core Bioinformatics profiles, Application profiles and Data Science & Software Design profiles is expected to more or less triple within the next five years, whereas the demand for Other Domain profiles is expected to double in the same period.

In the next five years, the surveyed companies expect their need for core bioinformaticians and data scientists to grow with approximately 450 and 470 additional profiles, respectively (in both cases, from approximately 300 profiles today to 750 profiles in five years). There is an increase of approximately 350 Application profiles and 230 Other Domain profiles expected in the same period. As these results do not cover all companies that apply bioinformatics now or in the future, the actual demand in five years is likely to be higher.

This general trend indicates that industry respondents have become aware of the importance of developing bioinformatics as part of their business. It also reflects that they have great expectations of the role of bioinformatics in life science industry in the near future.

Highest-rated Skills and Knowledge

As part of the survey, respondents were asked to rank the most important skills for each profile type. The top three competences for each type are summarised in Table 1.

Table 1. Highest rated skills and knowledge for each profile type.

	Top three most important skills		
	1	2	3
Core Bioinformatics	Knowledge on how to combine and integrate different types of biological data.	Understanding of bioinformatics' role in the scientific discovery process and interpretation of biological data	Programming and algorithm design to analyse and solve scientific problems within biology, including knowledge of several programming languages such as Python and R.
Application	Basic understanding of biology and in-depth knowledge within areas related to their discipline.	Understanding of bioinformatics' role in the scientific discovery process and interpretation of biological data.	Statistical research methods in a biological context.
Data Science & Software Design	Programming and algorithm design to analyse and solve scientific problems within biology, including knowledge of several programming languages such as Python and R.	Maintenance, security and scalability of databases and supercomputers.	Building databases for efficient storage of and searching in large and complex data.
Other Domain	Advanced understanding of mathematics and mathematical modelling.	In-depth knowledge in statistics.	Basic knowledge on and experience with application of large and complex data sets, e.g. in physics.

Source: IRIS Group's survey among stakeholders in industry, academia and healthcare. Core Bioinformatics profiles N=38, Application profiles N=37, Data Science & Software Design profiles N=35, Other Domain profiles N=25.
Note: The table lists the three skills within each profile as most respondents specified as "very important".

Respondents were given the opportunity to specify additional relevant competences. Desired competences for core bioinformaticians included good coding practice and solid biological data quality assessment, as well as the ability to communicate with data scientists about data challenges and provide a probable analysis and solution. For Application profiles, knowledge of which tools and methods to apply for a given problem was highlighted as key and the interpretation of biological data was highlighted as more important than understanding the role of bioinformatics in the scientific discovery process.

Perhaps influenced by recent changes in EU data protection laws, respondents also highlighted another key competence for data scientists: expertise in developing and applying data infrastructures in light of shifting demands and legal frameworks. For profiles from Other Domains, an interdisciplinary mindset was highlighted along with strong specialised skills in quantitative analytics and mathematical modelling.

Across all four profiles, respondents emphasised the need for good communicative and collaborative skills. Extracting insights from bioinformatics often requires a team of different educational profiles and specialisations who understand each other and work well together because they 'speak the same language'.

Supply of Bioinformatic Profiles

There are three ways to meet a growing demand for bioinformatic profiles:

(1) Education of appropriate profiles to appropriate degree levels;

(2) Recruitment of profiles from abroad;

(3) Vocational training and continuing education of individuals working in related fields.

The first of these is reviewed in the following section; the remaining two are discussed in the Key Challenges section.

Educational Throughput

Core Bioinformatics profiles, Application profiles, Data Science & Software Design profiles, and Other Domain profiles come from a wide range of educational backgrounds. Available study programmes were identified through desk research and interviews with managers from the educational programmes (Table 2; Appendix 1.2)

Table 2. Overview of the number of identified educational programmes according to bioinformatics profile.

	Copenhagen Area				Aarhus	Aalborg	Odense
	University of Copenhagen	Technical University of Denmark	IT University of Copenhagen	Roskilde University	Aarhus University	Aalborg University	University of Southern Denmark
Core Bioinformatics	1	1	–	–	1	–	1
Application	7	6	–	2	6	2	2
Data Science & Software Design	1	3	2	3	3	4	2
Other Domain	3	–	–	–	3	2	2

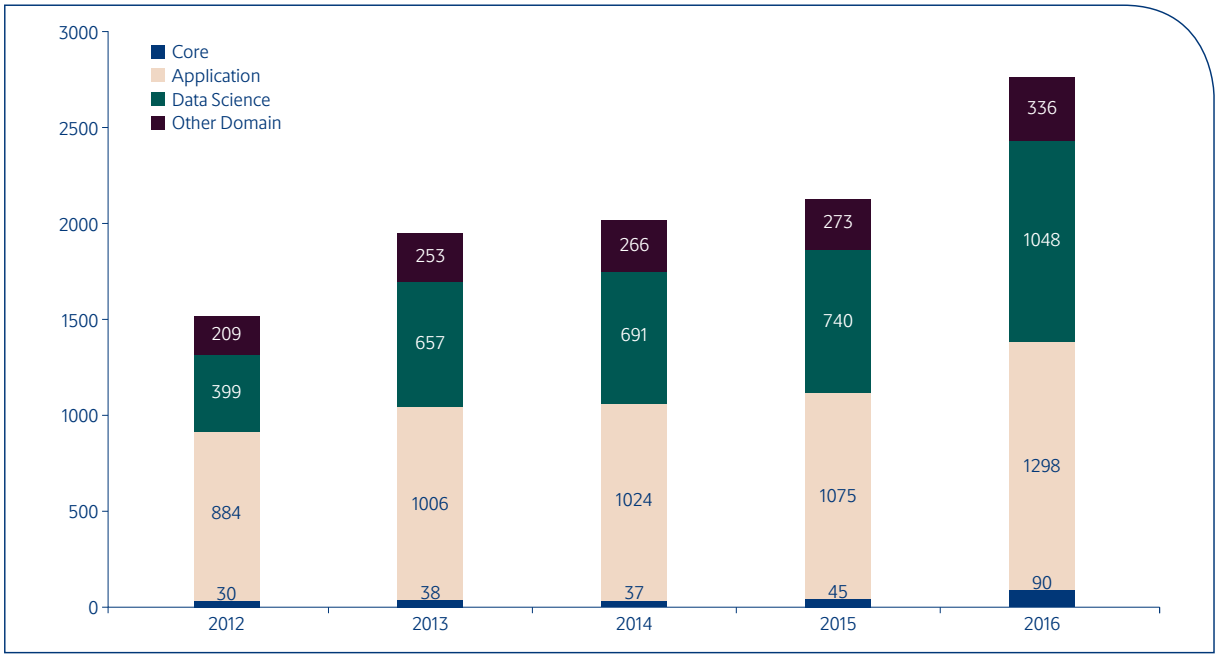
The majority of the educational programmes are located in the Copenhagen metropolitan area. The University of Copenhagen and the Technical University of Denmark both offer an educational programme in Core Bioinformatics and, together with Roskilde University, a total of 15 Application profile programmes (such as biochemistry, pharmaceutical sciences and quantitative biology; see Appendix 1.2 for a full list of programmes), are offered in the area. A total of nine Data Science programmes are offered across all universities in the Copenhagen area, including the IT University of Copenhagen.

Core Bioinformatics programmes are also offered at Aarhus University and the University of Southern Denmark and, together with Aarhus University, 10 Application programmes and nine Data Science programmes are offered outside of the Copenhagen area.

Other applicable domains include statistics, mathematics and physics and are offered in a total of 10 educational programmes across Denmark.

According to figures from the Danish Ministry of Higher Education and Science, the number of students admitted to the identified Master's degree programmes has steadily increased each year from 2012 to 2016 (Figure 7).

Figure 7. Number of students admitted to Master's degree programmes relating to the four bioinformatic profile types from 2012 to 2016.

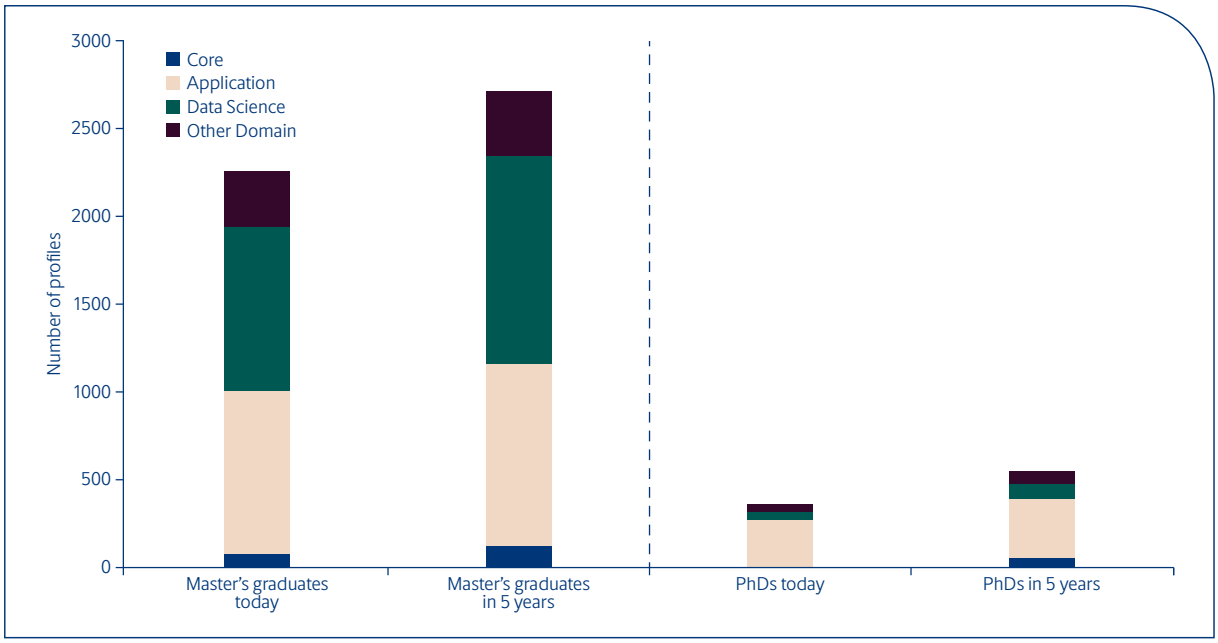


Source: Ministry of Higher Education and Science.

This increase is expected to continue into the near future with variability among profile types. The annual number of Core Bioinformatics profile Master's graduates to increase by 60% over the next five years, from 83 (of the 90 admissions in 2016) graduating this year to around 130 graduating in 2023 (Figure 7). The number of Data Science & Software Design graduates are also expected to increase by 27% (from approximately 931 to 1180 per year). Anticipated increases in annual graduates for Application and Other Domain profiles are less pronounced, at 11% (from approximately 930 to 1,030) and 15% (from approximately 320 to 370), respectively.

Study programme managers were also asked to project the number of PhDs with bioinformatic competences five years ahead. Here, an even more dramatic increase is expected in the Core Bioinformatics profile, with PhD graduations expected to rise 265% from 17 per year today to over 60 per year in 2023. Increases in PhDs among the other three profiles vary from 30% for Application, 44% for Other Domain and 70% for Data Science & Software Design profiles (Figure 8).

Figure 8. Annual number of Master's graduates (left) today and in five years' time and annual number of PhDs (right) today and in five years' time according to bioinformatic profile type.



Source: Ministry of Higher Education and Science; interviews with study programme managers.

Trends by Profile

Core Bioinformatics Profiles

There are four Danish Master's degrees in bioinformatics, one at each of four universities across Denmark, with the largest ones at the University of Copenhagen in central Copenhagen and at the Technical University of Denmark just north of Copenhagen. Intake has grown from 2012 through 2016, from a combined total of 30 students in 2012 to 90 in 2016 (Figure 7). In general, a relatively large proportion of graduates then continues on to PhD study (on average around 40%). The fairly small number of PhDs today reflect that the intake of Master's students in 2013 was very small. Since then, new Master's programmes have been established and more students are enrolled per year. The study programme managers expect the number of PhD candidates (academic and industrial) to more than triple within the next five years.

Application Profiles

Students can acquire competences matching the criteria for Application profiles at 25 available Master's programmes in Denmark (such as biochemistry, pharmaceutical sciences and quantitative biology; see Appendix 1.2 for a full list of programmes). The number of students admitted to Master's programmes supplying Application profiles has increased by approximately 45% from 2012 to 2016. An estimated two-thirds of all programmes relevant for these profiles have mandatory bioinformatics courses at either undergraduate or post-graduate level. The graduates from these programmes therefore all have some fundamental bioinformatics competences. Within the other programmes, bioinformatics is offered as an elective course. The introduction of bioinformatics courses to degree programmes such as microbiology or biochemistry has happened gradually over the last five years. The level and size of the courses vary between institutions, from five ECTS for the smallest courses to 15 ECTS for the most extensive ones. Some students also use bioinformatics methods in their Master's theses, but it is difficult to assess how many.

It is important to note that the number of graduates with relevant profiles differs considerably depending on the place of study. About a third of the interviewed study programme managers expect a moderate increase in the intake of Master's students over the next two-to-three years (graduating with the required skills in five years), a small number anticipate a decrease, and the majority of the remaining managers expect the number of admitted students to remain at the same level. The expectation is an increase in the supply from 900 Application profiles per year today, to 1000 annual graduates in five years.

The number of Application profiles with a PhD is also expected to increase. The current supply of PhDs with Application profiles is approximately 250 per year. Based on the increase in the intake of Master's students, the estimate is that this number will increase to approximately 330 in five years.

The large supply of Application profiles with integrated courses in bioinformatics reflects that study programme managers consider this to be a central field that most students of molecular biology and similar subjects should have a basic knowledge of. It is evident from the number of courses that great efforts have been made within degree programmes to introduce students to bioinformatics. This has been achieved in various ways. For example, biochemistry at the University of Copenhagen incorporates an introduction to both bioinformatics and statistics as mandatory Bachelor's courses. They also aim to integrate bioinformatics into other Bachelor's programmes with related content, where bioinformatics could be a relevant tool. Furthermore, students can choose thematic Master's level courses where bioinformatic methods are applied.

Some Master's programmes, such as biotechnology at Aalborg University, offer bioinformatics as an elective course and interested students can deepen their knowledge in the area through project and thesis work.

Data Science & Software Design Profiles

There are 18 programmes educating Data Science & Software Design profiles in Denmark (see Table 2 and Appendix 1.2). Despite the increase in students from 2012–2016, there continues to be great demand for graduates with data and software development competences and there is almost no unemployment among the graduates from these education programmes.

Eight out of the 10 biggest educational programmes for Data Science & Software Design profiles expect to increase their intake of students further within the next two-to-three years, leading to more graduates in five years' time. A few of these programmes, such as computer science at Aarhus University and data science at the IT University of Copenhagen, are expecting to more or less double their intake. Today, the supply of Data Science & Software Design profiles is over 900 a year and this figure is expected to grow by more than 200 over the next five years. Only relatively few of the Master's students that fit into this profile continue on to PhD studies (approximately 8%). Thus, the current number of PhDs is 50 per year and in five years this is expected to increase to 85.

Other Domains with Advanced Analytical Skills

'Other Domain' is a mixed category of profiles from a range of educational programmes providing advanced quantitative and statistical skills, which can be used for processing large biological datasets. There are 10 educational programmes supplying such domain profiles

(see Table 2 and Appendix 1.2). Statisticians, mathematicians and physicists play an important role in many of the bioinformatic research environments at universities and in the healthcare sector. Often, profiles from these domains play important roles in solving complex scientific challenges by using advanced quantitative methods.

The intake of Master's students in statistics, mathematics and physics increased by more than 50% from 2012 to 2016. Expectations are that the intake will increase further due to a growing awareness of the career paths among students and enhanced political focus on the need for skills in quantitative methods and mathematics.

The increase in the supply of statisticians, mathematicians and physicists is such that it should be possible to meet the growing demand for these profiles in the life science sector. The demand in the life sciences is expected to double over the next five years.

The interviewed study programme managers do not know how many graduates from these programmes take jobs within the life science industry. However, they believe it is very few. Thus, a key issue is to make the Master's and PhDs with these profiles more aware of the job opportunities and the impact they can make by choosing a career in the life sciences.

Confounding Factors

A significant number of the students admitted to the programmes reviewed in Denmark are international students. A study programme manager from the University of Copenhagen, for instance, reports that the share of international students was up to 79% in 2016. However, the managers of the four core programmes expect the share of international students to decrease over the next five years. Their reasoning is that a growing number of Bachelor's students at Danish universities are being introduced to bioinformatics, thereby becoming better equipped to compete with international students for the Master's programme places.

Gap Analysis

Supply Versus Demand

The demand for Core Bioinformatics profiles will more than double in the next five years. Surveyed stakeholders expect an increase in demand equal to approximately 350 Core Bioinformatics profiles. At today's rate of 80 graduates in bioinformatics per year, 415 core profiles will be available in five years. There is also an expected increase in the annual number of graduates, but it must be stressed that this survey does not cover the entire demand. New companies and research units, who apply bioinformatics, are likely to be established in the coming years. Furthermore, a significant proportion of Master's students in Core Bioinformatics profiles are from abroad. Therefore, it is very likely that supply of the Core Bioinformatics profiles will struggle to meet future demand.

The increasing demand for Application, Data Science & Software Design, and Other Domain profiles requires 440, 135 and 93 individuals in five years' time, respectively. Based on today's rates of graduates per year, there will be a good supply of such profiles, with graduation rates expected to increase further over time. However, these profiles are integral to a wide range of education programmes; for example, Application profiles include biochemistry and molecular biology graduates from the University of Copenhagen. Thus, while appropriate Application graduate profiles exist, competition for these profiles will exist outside of bioinformatics. Similarly, Data Science & Software Design profiles will be in good supply, but competition is even larger as it extends beyond life science into business sectors such as banking, marketing and social media.

Key Challenges

Based on stakeholder responses and interviews, there are six key challenges to ensuring an adequate supply of appropriate future bioinformatic skillsets and profiles in Denmark:

1. Funding of bioinformatics research and education;
2. Successful integration of bioinformatics into other programmes;
3. Collaboration between the life sciences and data sciences;
4. Provision of vocational training and education;
5. Retention and attraction of international talent;
6. Continued access to state-of-the-art research infrastructure.

1. Strengthening Bioinformatics Research and Education

Denmark has a number of strong bioinformatic research environments, which have evolved gradually over the last 25 years. The prospects for further expanding this research strength are promising. Industry, academia and the healthcare sector are all investing in enhanced bioinformatic capabilities.

On the supply side, the universities and study programme managers are preparing to address the increased demand. In recent years, a growing number of students have applied for the bioinformatics educational programmes, and expectations are that the supply of Master's graduates will increase by 60 percent and that the numbers of PhDs rooted in bioinformatics will more than triple over the next five years. Study programme managers from the institutions supplying Core Bioinformatic profiles report that the key challenges to realising the required increase are the lack of PhD grants and lack of supervisors for potential PhD students. These two factors may limit the intake of PhD students and be the critical issue impacting the feasibility of realising a threefold increase in the number of PhDs.

The opinion among most key stakeholders in academia is that there is a strong foundation of talented Master's students, but also a need for boosting the bioinformatics research environment with suggestions including:

- Additional support for senior researchers in bioinformatics and programmes to attract excellent researchers from abroad;
- Provide training opportunities for young talent through PhD and young investigator initiatives within bioinformatics (academic research and industrial PhDs).

Closer collaboration between the Danish bioinformatics environments, with respect to both research and educational programmes, is also highlighted as a key element in fostering enhanced specialisation and efficient use of existing knowledge and resources.

2. Integration of Bioinformatics into Other Programmes

Bioinformatics is applicable to a broad field of research within the life sciences. Therefore, it is important that researchers, Master's students and PhDs who work in the life science sector acquire an understanding of bioinformatics and how relevant techniques can be applied to and benefit their work.

Interviews with study programme managers indicate that, in recent years, a closer collaboration between the bioinformatic research environments and other relevant research groups (molecular biology, biochemistry, bioengineering etc.) has been promoted. However, it is emphasised that these efforts should be expanded as much as possible. Similarly, the supply of mandatory and elective courses in bioinformatics should be expanded to more life-science-related educational programmes and the application of bioinformatic competences should be strengthened within a broader field of public and private life science research.

THE MIT COMPUTATIONAL AND SYSTEMS BIOLOGY INITIATIVE

The MIT Computational and Systems Biology Initiative is a campus-wide education and research programme that connects biologists, computer scientists and engineers in an interdisciplinary approach to the systematic analysis of complex biological data. The initiative's underlying principle is the belief that quantitative analysis and modelling of biological data will bring about huge advances in the fields of medicine and pharma.

The initiative involves over 80 affiliated faculty members and the practical organisation of research and education is innovative. The initiative places equal emphasis on computer science and experimental biological research and researchers consider themselves a 'community of practice' where they work together in developing new approaches to the study of biological data.

Individual research teams are placed within their own departments (e.g. the Biology and Engineering Systems Divisions) and draw on the specialised knowledge of their own community. The initiative shares advanced research infrastructures, including data storage, high-performance computers, microscopes, etc. Furthermore, the faculty work in shared, multi-investigator, research collaborations and host a graduate education programme together, including training and supervision of PhD students.

By hosting an interdisciplinary graduate education programme that emphasises the study of biology from quantitative perspectives, the initiative also works to build a new generation of scholars with an expertise in solving complex biological questions through the use of quantitative biodata and advanced mathematical modelling.

Stakeholders interviewed suggest relevant efforts might include:

- Establishing stronger links between the bioinformatics environments and research groups within biological sub-disciplines;
- Establishing interdisciplinary research centres encompassing experimental research groups and bioinformatic researchers;
- Supporting a network and collaborative efforts between bioinformatic research centres and relevant stakeholders in industry and the healthcare sector; for example, through relevant student projects, co-financed PhDs, etc.

3. Collaboration Between Life Sciences and Data Sciences

While this analysis suggests a supply of data scientists and software engineers greatly exceeding the increased demand in life science over the next five years, the study programme managers emphasise that these profiles are in high demand in banking, insurance and various branches of industry. Competition for the best graduates is high and unemployment rates almost zero in this group. Due to this high demand, there is little incentive to include further specialisation in bioinformatics and related life-science subjects to the current curriculum.

Additionally, a further suggested challenge is that data science students themselves are generally part of an 'entrepreneurial culture' and wish to work at the frontiers of programming and software development. They do not consider life science software and programming as 'cutting edge' and do not see it as a particularly interesting career option.

The interviewed stakeholders recommend developing initiatives that target both students and research environments to encourage interest in bioinformatics. Approaches suggested include:

- Communicating the message about a professionally challenging and meaningful career in life science with the possibilities of changing healthcare and saving lives;
- Initiating internships, student projects and mentoring to show students what a career in life science or at hospitals can offer;
- Developing interdisciplinary research centres (such as Aarhus University's Bioinformatics Research Centre) where data scientists, software engineers and the biological sub-disciplines work together.

UNIVERSITY OF CALIFORNIA, SAN DIEGO: A CAMPUS HUB FOR DATA SCIENCE

UC San Diego has recently opened the Halıcıoğlu Data Science Institute. The intention is to create a central data science expertise hub, where data science specialists and software engineers can develop innovative programmes and methods to analyse the large amounts of data they receive from scientists across the entire campus. The idea is that scientists from all disciplines at the university get the opportunity to integrate data science into their respective research projects by drawing on the Institute's experts. Thus, many research fields get the opportunity to progress by analysing data they would otherwise be without means and expertise to do, and the data scientists and software engineers get the opportunity to wrestle with new fields and develop novel approaches to computer science.

The Institute hosts faculty, staff scientists and shared positions between the Institute and other departments. Data science students are part of the centre and projects will form part of the curriculum, giving them exposure to the potential in a life sciences career. In the coming years, the data centre will also create a Bachelor's in data science and a Master's degree, where students combine their data science interest with a specialization in a selected life science area of interest.

4. Provision of Vocational Training and Education

Survey respondents from all three sectors articulate a growing need for vocational training and education within bioinformatics, new bioinformatics tools and approaches. There is a growing demand for courses targeted at different audiences:

- General introduction courses where individuals with a background in biology or medicine can be introduced to the use of biodata and new bioinformatic tools and approaches. This type of course is of particular relevance for those working in industry or the healthcare sector;
- Advanced vocational training for researchers. Many of those working within research and development in industry and academia may not have updated insight on the latest technological advances in bioinformatics and how these can benefit their research. Thus, there is a need for more advanced vocational training. This would also strengthen their ability to supervise PhD students who use bioinformatic tools.

The supply of vocational training in bioinformatics in Denmark is limited and consists mainly of introductory courses focusing on specific software tools provided by commercial businesses. One problem is that individuals who possess the knowledge and skills required to develop and deliver appropriate vocational training courses are in very short supply. Another challenge is the difficulty in finding a viable business model for research-based vocational education and training. It is time-consuming to develop courses; the curriculum has to be continuously updated and it often requires a relatively large amount of senior resource to run courses at an appropriate level.

Support to develop a state-of-the-art supply of vocational training, suggested by interviewees, might include:

- Assisting with the design of courses;
- Trialling new forms of teaching activity with a focus on solving problems that researchers in industry, academia and the healthcare sector meet in their own research;
- Support for marketing and promotion to relevant audiences through conferences and meetings.

These activities could be based at one or two universities and, after an initial period, could continue without external funding.

5. Retention and Attraction of Bioinformatic Talent

The labour markets for bioinformatics profiles are international. Survey respondents estimate that close to 25 percent of employees currently working with biodata and bioinformatics in Denmark have an international background.

Similarly, the study managers from the programmes educating Core Bioinformatics profiles report that a large share of the Master's students in bioinformatics are from outside Denmark, in particular from countries in southern Europe. While they welcome an internationalisation of the programmes, they do also note that students are unlikely to remain in Denmark unless they find a job or a PhD position quickly following their graduation. Therefore, while it may seem there are enough Core Bioinformatics profiles to meet future demand, there is a risk that a substantial proportion of these will end up working outside Denmark. At the same time, there is also the risk that Danish-born talent leaves for employment abroad. Thus, it is important to ensure that talented students and PhDs from abroad are effectively matched with relevant job openings in the Danish labour market.

At the senior level, the greatest problems are in academia and hospitals where research environments are quite small, making it difficult to attract and retain international resource. Moreover, the smallest bioinformatics research environments are particularly fragile. If a single key senior researcher (Danish or international) chooses to leave, they lose a substantial part of their bioinformatics research and teaching capability.

Initiatives aimed at attracting and retaining international talent in academia and hospitals, suggested by interviewees, include:

- Increasing the number of '4+4' PhD programmes in bioinformatics. This is a particular way of organising the education where students have four years – including the last year of their Master's degree – to complete a PhD. This could lower the risk of unemployment and emigration from Denmark after graduation;
- Establishing internships and project work in industry, academia and at hospitals, where employers can get to know young bioinformatic talents.

Suggested initiatives at the senior level also include:

- Recruitment of one or more top-level international scientists and associated scientific staff. This could include initiatives focused on the development of a Core Bioinformatics research area where there is a potential for Denmark to further develop a research stronghold;
- Developing strategies for the retention of foreign senior scientists; for instance, by hiring early in their senior career stage and giving them responsibilities for the development of the Danish research environments.

6. Access to State-of-the-art Research Infrastructure

Many research projects and international research collaborations require access to supercomputers and advanced data-handling facilities. An example of a success

case is The Danish National Life Science Supercomputing Center, named Computerome: a high-performance computer facility specialised for life science. Computerome is physically installed at the Technical University of Denmark's campus in Risø (DTU Risø) and managed by a strong team of specialists from the university. Computerome is funded by grants from the Technical University of Denmark (DTU), University of Copenhagen (KU) and the Danish e-infrastructure Cooperation (DeiC). Users include research groups from all Danish universities and large international research consortia, as well as from industry and the healthcare sector.

Access to a fast, flexible and secure infrastructure and the ability to combine different types of sensitive data and perform analyses are key prerequisites for conducting bioinformatic research and participating in collaborative research with international scientists. Up-to-date supercomputers can also attract and retain talented individuals. The collaborative effort that led to the creation of Computerome is beneficial to the entire life science sector in Denmark. Relevant initiatives could be to:

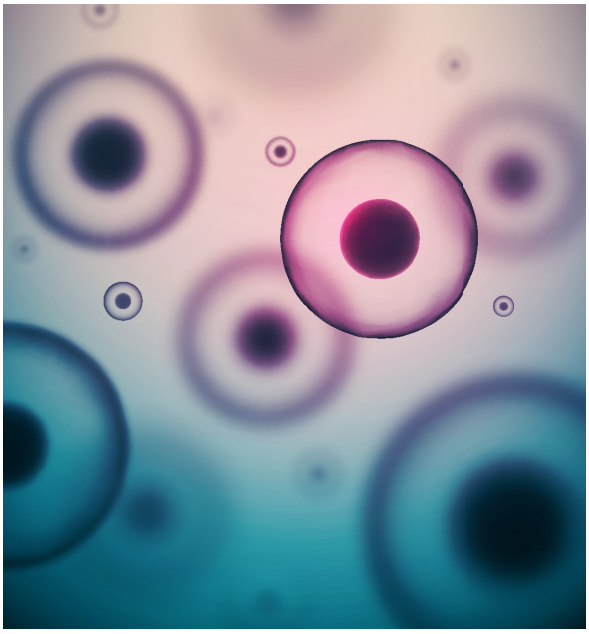
- Support for continuous technological updating of computer and data-handling facilities (estimated to be out of date every third year);
- Support and facilitate collaborative effort among key stakeholders when investing in basic research infrastructure to make the most of the total investments.

Concluding Remarks

The incorporation of bioinformatics into life sciences research has the potential to unlock and accelerate ground-breaking developments. Life science research is strong in Denmark, across the academic, industrial and hospital sectors, and individuals with bioinformatic competence profiles are already integral to this research activity. This analysis indicates that the number of such individuals has grown significantly over the past five years across all sectors and that stakeholders anticipate this growth to continue through the coming five years. Indeed, in academia and industry, anticipated accelerating growth will mean 87% and 160% more profiles will be required in five years' time, respectively.

Reflecting the increasing awareness of the importance of bioinformatics, the numbers of students enrolled in Danish university Master's programmes fostering bioinformatic competences has also increased over recent years. The numbers of both Master's and PhD graduates are anticipated to grow over the next five years, with the previously limited number of Core Bioinformatics graduates growing significantly. However, even though our analysis suggests that the growth of Core Bioinformatics profiles is approximately in line with the baseline anticipated growth in demand for them, it is very likely the supply of such profiles will struggle to meet actual future demand in Denmark. Therefore, a challenge for Core Bioinformatics is ensuring enough people are educated, including to PhD level.

For the remaining three bioinformatics profiles (Application, Data Science & Software Design, and Other Domain) there will certainly be more than enough graduates with the required skills versus demand. However, the challenge for these profiles is ensuring they are exposed to bioinformatics and interested in a career in the life sciences, with collaboration encouraged for both students and existing graduates alike. Similarly, Denmark needs to ensure it is positioned to attract and retain international talent, while ensuring talent within Denmark receives the best vocational training and has access to the necessary infrastructure.



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Appendices

1. Additional data

1.1 Identified centres of bioinformatics activity in Denmark

Copenhagen	Aarhus	Aalborg	Odense
Universities			
1. Bioinformatics Centre, University of Copenhagen 2. DTU Bioinformatics, Technical University of Denmark 3. Novo Nordisk Foundation Center for Protein Research, University of Copenhagen 4. Novo Nordisk Foundation Center for Biosustainability, Technical University of Denmark	1. Bioinformatics Research Centre (BiRC), Aarhus University 2. Centre for Integrative Sequencing (iSEQ) and the Genome Data Centre, Aarhus University 3. Centre for Integrated Register-based research (Cirrau), Aarhus University 4. Lundbeck Fourndation Initative for Intergative Psychiatric Research (iPSYCH), Aarhus University	Aalborg University, including research groups at: 1. Department of Chemistry and Biosciences 2. Department of Health Science and Technology 3. Department of Mathematical Sciences	University of Southern Denmark, including research groups at: 1. Department of Biochemistry and Molecular Biology 2. Department of Mathematics and Computer Science 3. Department of Public Health
Hospitals			
1. Rigshospitalet, Unit for Genomic Medicine 2. Rigshospitalet, Fase 1 Enheden 3. Hvidovre Hospital, Department of Clinical Mirobiology 4. Hvidovre Hospital, Department of Clinical Biochemistry 5. Hvidovre Hospital, MR-Forskningssektionen	1. Aarhus University Hospital, Department of Molecular Medicine (MOMA)	1. Aalborg University Hospital, Cancer Data Science Lab, Department of Haematology 2. Aalborg University Hospital, Unit for Molecular Diagnostics	1. Odense University Hospial, Clinical Genome Center 2. Odense University Hospital, Clinical Proteomics Center

1.2 Identified educational programmes according to bioinformatics profile type

University	Core Bioinformatics profiles	Application profiles	Data Science & Software Design profiles	Other Domain profiles
University of Copenhagen	Bioinformatics	Biology Molecular Biomedicine Biochemistry Biology Biotechnology Human biology Medicinal Chemistry Pharmaceutical Sciences	Computer science	Statistics Mathematics Physics
Technical University of Denmark	Bioinformatics and Systems Biology	Biotechnology Quantitative Biology and Disease Modelling Pharmaceutical Design and Engineering Life Science Engineering and Informatics Biomedical Engineering	Mathematical Modelling and Computation Computer Science and Engineering Digital Media Engineering	
Aarhus University	Bioinformatics	Biology (BSc+MSc) Molecular Biology (BSc+MSc) Molecular Medicine Agrobiology Biotechnology and Chemical Engineering	Computer Science Computer Engineering Electrical Engineering	Statistics Mathematics Physics
University of Southern Denmark	Computational Biomedicine	Biochemistry and Molecular Biology (BSc+MSc) Biomedicine (BSc+MSc)	Computer Science Software Engineering	Mathematics Physics
IT University of Copenhagen			Computer Science Software Development (design)	
Aalborg University		Biotechnology Medicine with industrial specialisation	Computer Science Health Technology (civiling.) Software Engineering (civiling.) Mathematical Technology	Mathematics Physics
Roskilde University		Medical Biology Molecular Biology	Computer Science (IT) Mathematical Computer Modelling Informatics	

1.3 Numbers of graduates (2018) from each programme

University	Programme	Graduates (2018)
Core Bioinformatics profiles		
Technical University of Denmark	Bioinformatics and Systems Biology	32
University of Copenhagen	Bioinformatics	29
University of Southern Denmark	Computational Biomedicine	11
Aarhus University	Bioinformatics	11
Application profiles		
University of Copenhagen	Pharmaceutical Sciences	151
Technical University of Denmark	Biotechnology	79
Aarhus University	Molecular Biology	67
University of Copenhagen	Biochemistry	65
Aarhus University	Biology	62
Aarhus University	Molecular Medicine	60
University of Copenhagen	Biology	48
Technical University of Denmark	Biomedical Engineering	48
University of Southern Denmark	Biomedicine	47
University of Copenhagen	Molecular Biomedicine	45
Data Science & Software Design profiles		
Technical University of Denmark	Information Technology	135
IT University of Copenhagen	Computer Science	120
IT University of Copenhagen	Software Development	116
Technical University of Denmark	Mathematical Modelling and Computation	102
University of Copenhagen	Computer Science	89
Aalborg University	Computer Science/Software Engineering	68
Technical University of Denmark	Digital Media Engineering	66
Aarhus University	Computer Science	62
Aarhus University	Computer Engineering	34
Roskilde University	Computer Science	23
Other Domain profiles		
University of Copenhagen	Physics	118
Aarhus University	Physics	56
University of Copenhagen	Mathematics	39
Aarhus University	Mathematics	39
University of Copenhagen	Statistics	22
Aalborg University	Mathematics	22
Aarhus University	Statistics	14
University of Southern Denmark	Physics	11
Aalborg University	Physics	9
University of Southern Denmark	Mathematics	8

2. Methodology

2.1 Interviewed demand stakeholders

Stakeholders were identified through desk research and peer recommendations. A total of 27 interviews were conducted, primarily with stakeholders from industry and academia.

Industry
1. Novo Nordisk, Department Manager Bioinformatics
2. LEO Pharma, Chief Data Scientist
3. Lundbeck, Director Bioinformatics
4. Brainreader, CTO
5. ME-TA, Director
6. Qiagen, Director Bioinformatics
7. Novozymes, Digital Strategist
8. Pcovery, Co-founder and CEO
9. CerCare, Managing Director
10. Blusense Diagnostics, CEO
11. Zealand Pharma, Chief Medical and Development Officer
12. Symphogen, CEO
13. Evaxion Biotech, Director Genomic Immuno-Oncology
14. Genomic Expression, CEO
15. Intomics, CEO
16. Roche Innovation Centre Copenhagen, Director, Project Excellence & Innovation
Academia
17. DTU Bioinformatics, Technical University of Denmark
18. DTU Bioinformatics, Technical University of Denmark
19. Bioinformatics Centre, University of Copenhagen
20. Bioinformatics Research Centre (BiRC), Aarhus University
21. Department of Molecular Biology and Genetics
22. Novo Nordisk Foundation Centre for Biosustainability, Technical University of Denmark
23. Novo Nordisk Foundation Centre for Protein Research, University of Copenhagen
24. ISEQ and the Aarhus Genome Centre, Aarhus University
25. Lund University, Faculty of Medicine
Hospitals
26. Rigshospitalet, Genomic Centre
27. Department of Molecular Medicine (MOMA), Aarhus University Hospital
28. Furthermore, IRIS Group has had shorter dialogues by phone and email with representatives from Aalborg University Hospital, Odense University Hospital and Hvidovre Hospital as a part of the mapping of research environments at hospitals.

2.2 Interviewed supply stakeholders

Student intake numbers from the education programmes identified (Appendix 1.2) were obtained from the Ministry of Higher Education and Science. Interviews were conducted with 28 study managers representing the most important Master's programmes including all Core Bioinformatics programmes, approximately 75% of Application programmes, approximately 50% of Data Science & Software Design programmes and one study manager covering two programmes from Other Domains.

University of Copenhagen
1. Programme manager Bioinformatics
2. Programme manager Biology
3. Programme manager Biochemistry & Bioinformatics
4. Programme manager Computer Science
5. Programme manager Human Biology
6. Programme manager Molecular Biomedicine
7. Programme manager Biology–Biotechnology
8. Programme manager Statistics
Technical University of Denmark
9. Programme manager Bioinformatics and Systems Biology
10. Programme manager Biotechnology
11. Programme manager Quantitative biology and Disease Modelling
12. Programme manager Pharmaceutical Design and Engineering
13. Programme manager Information Technology
14. Programme manager Mathematical Modelling and Computation
Aarhus University
15. Programme manager Bioinformatics
16. Programme manager Molecular Medicine & Molecular Biology
17. Programme manager Computer Science
University of Southern Denmark
18. Programme manager Computational Biomedicine
19. Programme manager Biochemistry and Molecular Biology & Biomedicine
20. Programme manager Computer Science
21. Programme manager Software Engineering
IT University of Copenhagen
22. Programme manager Computer Science
Aalborg University
23. Programme manager Medicine with industrial specialisation
24. Programme manager Computer Science & Software Engineering
25. Programme manager Health Technology
26. Programme manager Biotechnology
Roskilde University
27. Programme manager Molecular Biology & Computer Science
28. Programme manager Medical Biology