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Citation for the original published paper (version of record):

Nygård, Y., Geijer, C., Bettiga, M. et al (2026). Modular teaching for interdisciplinary education: Insights from a course in industrial biotechnology for lignocellulose-based processes. *New Biotechnology*, 94: 100-105.
<http://dx.doi.org/10.1016/j.nbt.2026.05.007>


N.B. When citing this work, cite the original published paper.

Contents lists available at [ScienceDirect](https://www.sciencedirect.com)

New BIOTECHNOLOGY

journal homepage: www.elsevier.com/locate/nbt

Modular teaching for interdisciplinary education: Insights from a course in industrial biotechnology for lignocellulose-based processes

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ARTICLE INFO

Keywords:

Modular learning
Interdisciplinary education
Course design
Biorefinery

ABSTRACT

Today's workforce must be capable of combining interdisciplinary concepts to meet future challenges and drive innovation. University education needs to stimulate such development and lay a foundation for life-long learning. One area that calls for interdisciplinary competences is the transition to a circular, bio-based economy that reduces dependence on fossil resources, supports climate-change mitigation, and enables the production of a broad range of sustainable products. Biotechnology plays a key role in this transition, and we must equip the next generation of engineers and scientists with a broad set of skills and knowledge to drive and navigate this research- and development-intensive field. Since 2009, we have offered a biennial, third cycle (PhD-level) course, titled Industrial Biotechnology for Lignocellulose-Based Processes. This course addresses all aspects from the field to the gate in discrete modules, covering biomass structure and analysis, enzyme technology, microbial cell factory design, fermentation processes, and associated sustainability and industrial considerations. We here share the motivation for creating the course, how it has developed over the years, and how students, teachers as well as the research community have benefited from it. We also offer insights on how similar broad and multidisciplinary courses can be designed in a modular fashion to accelerate advanced education in other critical fields.

Course conceptualization and initiation

Biotechnology continues to be a rapidly evolving field, where new knowledge and advanced methodology go hand in hand. The complexity of the field creates a growing need for educational formats that can integrate advances across multiple scientific and engineering domains. Our course—Industrial biotechnology for lignocellulose-based processes—is a five-day course that covers a broad area where progress depends on connecting fundamental biology with process engineering, sustainability, and system-level thinking. Alongside curiosity-driven research, society requires mission-oriented research capable of addressing grand challenges such as mitigating climate change and reducing dependence on fossil resources. Our course directly contributes to this agenda by focusing on the conversion of renewable lignocellulosic biomass into energy carriers, chemicals, and materials. The course structure is designed not only to teach core concepts but also to enable

mutual learning, as students and invited guest lecturers bring diverse expertise and perspectives. In doing so, the course enables networking among the students as well as the course instructors. We believe that this modular, integrative course concept is broadly transferable to other complex research fields, both established and emerging [1].

The course is hosted biennially by the Industrial Biotechnology research division at Chalmers University of Technology, Sweden, which has grown from a single principal investigator (PI) group established in 2008 into a collaborative multi-PI research environment with several independent research lines. We share laboratory facilities as well as a common organizational framework and mission: to advance bioeconomy-related knowledge and develop solutions that support society's transition from fossil dependence to a sustainable, bio-based future. To develop industrially viable solutions, a broad interdisciplinary knowledge base is needed. However, in 2008, there was a clear lack of postgraduate-level courses fully covering this area.

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<https://doi.org/10.1016/j.nbt.2026.05.007>

Received 16 March 2026; Received in revised form 13 May 2026; Accepted 13 May 2026

Available online 19 May 2026

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Consequently, we decided to develop an intensive PhD-level course designed to serve both our own and external students, as well as the wider research community, from academic scholars to industrial employees. The course was designed to give an overview of a wide range of topics relevant to the field, but not necessarily in great depth in every aspect, as the students entering the course would have highly diverse prior knowledge and backgrounds [2]. Moreover, the course was planned to include many opportunities for interactions and mutual learning among the course participants, both students and lecturers, with a poster exhibition, exercises and social activities.

Evolution of the course content

Lignocellulose is a complex and hierarchical material, chiefly consisting of polysaccharides (cellulose and hemicelluloses) and the aromatic polymer lignin [3]. In a classic biorefinery, the carbohydrates (mainly cellulose) are broken down through pretreatment and enzymatic hydrolysis [4] into the constituent monosaccharides (and process-related inhibitors [5]), which are then converted to products, such as ethanol, by microbial fermentation [6–9]. Hence, the course includes four core modules, covering: **I**) lignocellulose structure and analysis, **II**) lignocellulose-active enzymes, **III**) microbial cell factory design and **IV**) fermentation processes. The course begins with an introductory lecture to cover how the course modules come together to a biorefinery process concept. Throughout the course, examples are given how process steps together build an integrated biorefinery process.

The field of bioeconomy-related industrial biotechnology has developed tremendously since the course inception in 2009. At its launch, there was a strong focus on yeast-based bioethanol production from plant cell wall polysaccharides via cellulolytic and hemicellulolytic enzymes [10]. Over time, this initial focus has evolved to encompass broader biorefinery concepts (Fig. 1). Updates for module I have included the use of lignin as a source material, lignocellulosic biomass side-streams such as bark [11], and during some years also non-lignocellulosic algal biomass. Analytical techniques have advanced the ability to understand the composition and structure of the raw material streams [12]. For module II, updates include redox enzymes for lignin degradation, novel oxidative enzymes such as lytic polysaccharide monoxygenases (LPMOs, [13,14]) and the recently discovered metagenomic exo-acting cellulose oxidase CelOCE [15], including lectures by lead authors from these studies. As can be seen, the discovery of LPMOs coincided with an expansion on Module II (2015 edition), which also reflects a resurgence in research on biomass-active enzymes. For module III, updates include bacteria and filamentous fungi as cell factories [16,17], and new genetic editing tools such as CRISPR/Cas9 (discovered in 2012 [18]). The fermentation process module (IV) has been developed to address key issues for allowing efficient conversion at high substrate loadings, which include addressing the challenges with inhibitors [19,20]. Emerging topics related to the field, such as sustainability aspects of biorefineries [21,22], unconventional bioprocesses such as gas fermentation, and business aspects, especially in relation to start-up companies, have also become parts of the standard course

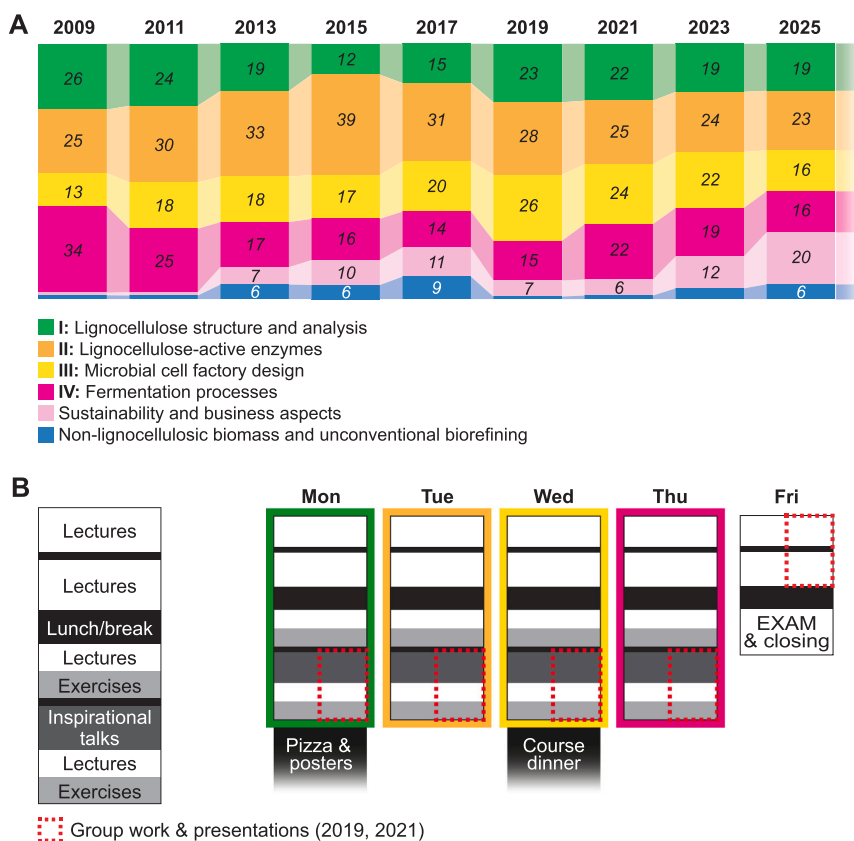


Fig. 1. Course evolution in terms of topics and generic schedule. A) The core pillars of the course (listed after bold numbers) have throughout its history been lignocellulosic biomass structure and analysis, lignocellulose-active enzymes, microorganisms and microbial cell factories, and fermentation processes. The size of each block here represents their respective proportional lecture and exercise time over the years, and numbers reflect the relative percentage (values below 5% have been omitted for clarity). Non-conventional biomass and unconventional biorefining refer mainly to algal biomass, gas fermentation and microbial electro-synthesis. B) The generic course schedule includes foundational lectures, primarily in the morning, and one to two exercises per day, as well as inspirational lectures. The colored outlines symbolize the main focus for each day (following the legend in A). The red dashed box indicates the time that was spent on teacher-assisted group work and presentations on the final day, during 2021 and 2023. Of note, the course duration has gone from six to five days, with the course initially starting on a Sunday.

curriculum over the years. Thus, the course retains the core aspects of biotechnological lignocellulose conversion but has a flexibility to adapt to recent advances.

Pedagogy and course design

The learning objectives of the course are listed in [Box 1](#), and while reaching them partly depends on the students' backgrounds, even students with limited prior experience in the field can normally complete the course. To be admitted, participants must be engaged in or have completed PhD studies or possess comparable industrial experience. Background literature, primarily review articles, is shared with students several weeks in advance and later referenced during the course, ensuring a constructive alignment between preparation and classroom discussions [23]. The emphasis of the teaching is on knowledge and skills that the students can directly benefit from in their own research projects. The teaching is dominated by traditional lectures, but also includes active learning elements such as quizzes, mini-problems, discussions in smaller groups, or small individual assignments, to stimulate and promote diverse types of learning [24]. While our requirement of course participants either performing or having recently performed active research in the field, it should be noted that the breadth of the course can be overwhelming for some students, especially for junior PhD students and those conducting research in areas somewhat peripheral to the central course themes. We try to mitigate this challenge by providing relevant course literature well in advance of the course, enabling participants to familiarize themselves with core concepts and terminology ahead of time.

The course was originally on-site only. During the pandemic (2021 edition), it was radically changed, going fully online with a reduction in the number of lectures to enable student group work projects (see below). The core modules of the course were, however, still retained, as well as inspirational talks on state-of-the-art developments. In the following years, the course was arranged in a hybrid format, but with on-site participation encouraged.

The structure of the course follows the four modules described earlier, with each module covered during its own dedicated day (with minor occasional deviations due to scheduling constraints) ([Fig. 1](#)). The fifth day is reserved for future outlooks, the course exam, and a final wrap-up. The course combines several key components: conceptual lectures that establish the scientific foundation, inspirational lectures that highlight cutting-edge research and industrial perspectives, group exercises that reinforce learning, formal assessment of student learning, and social activities for networking and fun. The intensive format of a

whole-week course is intentional; condensing the entire curriculum into five days of full-time engagement enables focus by limiting the typical juggling of experimental work, deadlines, and departmental obligations for the students. A drawback of this format can however be seen in a reduced energy level for some students during the last day(s) of the course. On a positive note, the format does offer a platform to develop essential "soft skills" critical for a research career, e.g. networking, peer-review, problem-solving, and representing one's organization in a professional setting away from the usual support networks of colleagues and supervisors.

Foundational and inspirational lectures

The foundational lectures provide key knowledge and concepts for each module and are primarily taught by the host university PIs, complemented by recurring external lecturers. Additional subtopics, such as sustainability, are integrated throughout the schedule to broaden the students' perspectives. While some of these lectures are relatively basic for students working directly in the same area, essentially no participants have prior knowledge on all of the topics covered in the course. As a result, students often report that sessions and modules outside their immediate expertise are among the most valuable, providing a much-needed overview of the broader field. Topics that will likely be included in the next rounds of the course are new AI-related tools useful for biotechnology [25], and emerging products such as bio-active or even living packaging materials [26].

The inspirational lectures in the course serve as a complement to the core teaching, offering a deeper dive into specific research areas and illustrating how the fundamental techniques and concepts are applied in cutting-edge academic and industrial R&D. They normally follow the foundational lectures, to make the content accessible also for the less experienced students. These lectures are of two main types, either presentations by prominent academic researchers on topics complementary to the course core focus, or by representatives from commercial actors, ranging from research institutes to startups and established companies. For the companies, detailed descriptions of processes, product development, optimization, or scale-up over time, including key challenges and how they were addressed, are expected. Clear instructions on the expectations (e.g. anticipated level and topics already covered during the course, importance of scientific details etc.) aid the invited lecturers to provide a good learning experience for the students. For newly invited industrial lecturers in particular, we prioritize discussions in advance, to align expectations and ensure that the lectures move beyond general company presentations and deliver content that is relevant to the course

Box 1

Learning objectives.

Overarching learning objective:

To develop a broad understanding of the full value chain covered in the course—from raw materials, through biological conversion methods, to final products—and to equip students with the ability to critically reflect on the role of biotechnology within the bioeconomy.

Specific learning objectives. After the course, the students should be able to:

- I:** Describe the complexity and composition of various lignocellulosic biomasses, and explain advanced methods used to characterize them.
- II:** Describe the main classes of enzymes acting on lignocellulosic biomass, their classification, and fundamental methods to assess their activities.
- III:** Critically compare technologies for microbial cell factory development and different microorganisms as production hosts.
- IV:** Demonstrate understanding of the theory underlying quantitative assessment of processes used for lignocellulose fermentation and different fermentation methods.
- V:** Describe other facets related to the core concepts, e.g. sustainability, systems perspectives, interdisciplinarity, and industrial perspectives and needs.

objectives. Some inspirational lectures are in the style of storytelling, for example describing how a startup company was initiated from a research idea and how it has navigated the startup landscape thus far. We see that the success of start-up companies originating from Chalmers and initiatives to support start-up activities such as the BioInnovation institute (BII) in Denmark have increased students' interest in business-related aspects of their own research. These examples provide concrete, experience-based, insights into industrial practice, innovation pathways, and opportunities for translating scientific results into real-world impact. The inclusion of different aspects of sustainability helps the students to get a better understanding of the potential societal benefits and pitfalls, enabling them to identify critical factors for realizing the green transition.

The foundational lectures are normally held on-site, while for inspirational lectures, online contributions are acceptable, which is particularly useful for speakers in other time zones and for reducing travel-related environmental impact. To maintain focus and encourage interaction, each session is kept concise (45–60 min), with frequent breaks in-between to foster informal discussions between students and instructors.

Group exercises

The course includes one or two exercises per day, each designed to reinforce the material presented in the preceding lectures and support contextual understanding (Fig. 1) [23]. The exercises often include think-pair-share assignments on given problems to foster discussions among the students, followed by joint reporting and whole-class discussion. Examples of topics covered include analytics, enzyme kinetics, microbial strain design strategies and calculations based on fermentation process variables, emphasizing direct application of the lecture content. Several exercises throughout the years have also been built around practical challenges brought directly from the students' own research. These sessions, where students might, for example, describe a difficulty in sample preparation or data interpretation, typically spark lively discussion and provide valuable feedback from peers and instructors.

During the pandemic in 2021, and in the 2023 course edition, the exercises were replaced by group projects in which students drafted a mock grant application, integrating topics from at least three course modules. Each group was paired with a teacher that acted as a mentor throughout the process. The projects were assessed through pitch-style presentations delivered to the full class at the end of the course, complemented by either a written report or a video presentation submitted after the course had ended. Although the group projects were generally appreciated by the students, in 2025 we returned to exercise-based assignments, to better directly gauge the students' grasp of the day's lecture content. Another reason for this reversion was that, despite asking the students to agree on the forms of collaboration on the first day, individual contributions to the project often became unbalanced, likely as the students had very short time to accommodate to each other's working style.

Exam and additional assessments of learning

On the final day of the course, we assess the students' learning through a traditional written exam (2009–2019) or an online multiple-choice question exam (2021–2025) to evaluate understanding of the foundational lectures and exercises. Most students pass the exam ($\geq 50\%$ correct answers; 30 questions in 60 min), and those who do not are offered an additional assignment. Admittedly, such assignments were more straightforward to design before the advent of AI-assisted tools. In the 2025 course edition, the students could additionally write an optional post-course reflective essay in addition to the exam for extra credits. This provided an opportunity to consolidate and articulate what they have learned from both the course content and the assigned

literature, scientifically as well as personally. In connection to the exam, we also request the students to fill in a course evaluation, where they are asked to describe their views of the course content and the different modules, list pros and cons, and then the collected information is shared among the teachers to guide the planning for the next iteration of the course. A common positive and general comment about the course is that it covers the full value-chain, from starting material to product, and that even students specializing in a certain module topic learn new things within that specific field. Data from the last course edition in 2025 showed an overwhelmingly positive response, with on-site participants responding with Very satisfied (5 out of 5, 70% of participants) or Quite satisfied (4 out of 5, 30% of participants) to the question "How would you evaluate your general satisfaction with the course?". Similar high levels of satisfaction have been consistently reported in previous years.

Social events

The course curriculum always includes a tour of the laboratories at the division of Industrial Biotechnology, and a poster session with pizza and refreshments during the first course evening. This setting enables students to network, become familiar with one another's research, and further develop their presentation skills. Moreover, a course dinner outside of campus is scheduled in the middle of the week. All teachers are encouraged to participate in these events, as well as in the joint lunches and coffee breaks, to allow for more opportunities for interaction, which we believe facilitates the appreciated course atmosphere.

Participants over the years

A total of 342 students working in 27 countries and more than 80 institutions (universities, institutes and companies) have so far participated in the course (2009–2025) (Fig. 2). While most are university PhD students, many postdocs and even PIs have taken the course over the years. Typically, a couple of participants from companies join each year. Naturally, the majority of the students originate from Swedish institutions (137 participants, 40%), of whom approximately half come from the host university. Our neighboring countries Denmark, Norway and Finland are also highly represented, as well as European countries, including Belgium, the Netherlands, Italy and Spain, but several students have come from non-European countries such as Brazil and India. The student body likely reflects both the networks of the PIs running the course and a strong emphasis on biotech (for lignocellulosics) in the countries of the participants. Indeed, when students are asked how they found out about the course, personal connections are often mentioned, and previous years' students and their supervisors are the best ambassadors for next years' editions. Regarding the students' backgrounds in terms of scientific topic, data from the last course edition where the students could give multiple answers, over half of the participants responded that they work with enzymes, a third that they work with fermentation, yet another a third that they work with microbial strain development, and a quarter that they work with bioprocesses or pre-treatment. These proportions have fluctuated somewhat over the years, but overall, a substantial number of students have been associated to each of the core module topics.

What's in it for us

The course is not only appreciated by the students but also by us as instructors. There are several reasons why we continue to offer it. Firstly, the course provides an opportunity to collaborate and strengthen our cohesion as a team, both during planning and execution of the course. It also gives us a reason to regularly discuss the latest research trends and update the teaching materials to ensure that the course remains relevant. Secondly, the course offers fantastic opportunities to invite guest lecturers from both academia and industry. These lectures not only

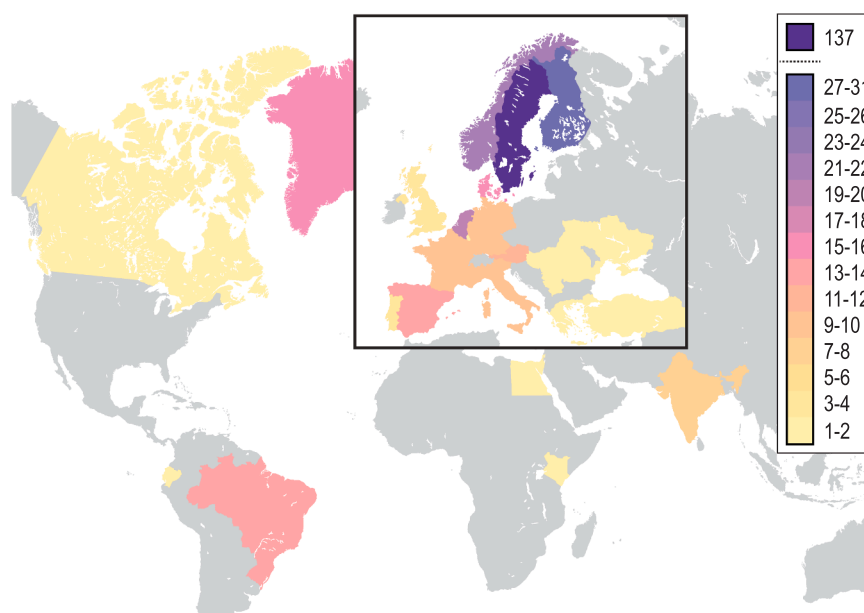


Fig. 2. Geographic distribution of course participants (2009–2025). The enlarged inset within the black frame shows the majority of Europe, from where most participants have come, and the color scale indicates the number of participants from each country. Note that the country affiliation here refers to where the participants studied or worked at the time of course participation, and not necessarily their nationality.

enrich the course but also help us build and maintain networks and collaborations, both new and existing. Finally, perhaps the greatest benefit of the course, is the chance of getting to know the students and postdocs who participate. In many cases, we have later welcomed participants back as visiting PhD students or researchers or even as new recruits to the division. This underscores the course's role in fostering lasting professional connections and its contribution to integrating emerging researchers into our research community, both at Chalmers and beyond.

Conclusions and future perspectives

The core aim of this course is to give future specialists in lignocellulose-based biorefineries a common understanding of the whole biorefinery process, and to favor communication and collaboration across the various disciplines. The combination of fundamental concepts and state of the art advancements in various fields thus cater both students with limited and deep expertise. Striking the right balance of depth vs breadth is a challenge. However, the design with intertwined lectures and group work and discussions promote engagement, learning and analytical thinking [27,28].

We see the modular format of the course being one of its main strengths, where the students know clearly what the focus of each day will be, and they can prepare accordingly. Furthermore, it is a strength when it comes to the course's adaptability, as each module can be adjusted to fit the current research front and focus of the course without causing major inconveniences. Consequently, the course has continued to evolve over the years, which we believe is why it attracts many students. We believe this format to be transferable to other similarly broad and interdisciplinary research areas, or rapidly changing fields, where a modular organization could facilitate dedicated focus and learning in select topics [29–31].

As guiding principles to transfer the course concept to other fields, we recommend the following key considerations:

1. Keep the number of core modules of the course to a minimum to avoid a fragmented curriculum. We suggest one or maximum two modules per day.

2. Arrange modules in a logical sequence, so that overarching terminology and concepts can be used throughout the course, such as biomass structure and composition in our case. Furthermore, the exercises should be closely aligned with their respective module.
3. Integrate fundamental and applied aspects. The foundational lectures provide a basis for the applied or inspirational lectures and furthermore enable linking theory to practice.
4. Design for future adaptability and continuous renewal. The modular structure should facilitate updating of individual modules, and even replacement in larger course reorganizations.
5. Foster interactions among the course participants, including both structured interactions in exercises and social informal settings, to stimulate discussion, networking, and ideally interdisciplinary thinking.

We believe that gaining a comprehensive overview of a broader research area helps students better frame their own research and fosters effective communication across disciplines, where establishing a common language is often a major barrier to collaboration. Equally important, we believe that our course format has proven effective in stimulating curiosity and highlighting the possibilities biotechnology offers for a future bioeconomy. These are key elements for cultivating the next generation of leaders in lignocellulose-based biorefineries who can contribute to the transition toward a circular economy.

CRedit authorship contribution statement

Yvonne Nygård: Writing – review & editing, Writing – original draft, Project administration, Investigation, Conceptualization. **Cecilia Geijer:** Writing – review & editing, Writing – original draft, Project administration, Investigation, Conceptualization. **Maurizio Bettiga:** Writing – review & editing. **Carl Johan Franzén:** Writing – review & editing. **Lisbeth Olsson:** Writing – review & editing. **Johan Larsbrink:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Investigation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial

interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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