7. Public Summary

The Engineering and Technology Institute Groningen (ENTEG) is the main research institute within the Faculty of Science and Engineering of the University of Groningen that conducts research on engineering science. ENTEG has focused on multidisciplinary engineering science and technology research with the aim to develop innovative and sustainable processes and products for society in three main research domains: Mechanical, materials & robotics engineering; Optimization, systems & control; and Sustainable chemical engineering & biotechnology. The institute has built strong partnerships with industry through public-private partnerships, knowledge transfer and valorization. The high-quality research in ENTEG is strongly embedded in the engineering educational curriculum at the faculty and aims at forming highly-skilled engineering scientists who will be key players in tackling current and future societal challenges. ENTEG has a unique position within the Netherlands as being the only engineering science institute operating within a comprehensive university.
Over the review period, ENTEG experienced a strong growth driven by societal and industrial demand, and stimulated by the strategic plan of the university and faculty to develop a stronger engineering profile of the University. The institute has a vivid, international community of 33 Principal Investigators (PI), 6 honorary / part-time professors, and over 160 PhD candidates and postdoctoral fellows. Further growth is expected with 9 additional PIs in the coming 1-3 years. ENTEG's scientific community prides itself on its diversity, with a notable increase in the percentage of female PIs, growing from 7% to 31%. The institute has fostered an inclusive and collaborative culture, embracing both a truly international environment and a culture of open science and open access publication.

ENTEG created a strong, multidisciplinary research portfolio covering fundamental to applied engineering sciences with a focus on societal challenges such as the transition towards digitalization, circularity and renewable energy. This has led to a significant increase in publications (from approx. 170 in 2017 to 270 in 2022), encompassing peer-reviewed scientific papers, conference proceedings, and PhD theses. Financially, the institute is in a healthy state, with annual spending nearly doubling since 2017 in line with staff growth. Its staff members have been successful in acquiring substantial external research funds, amounting to almost €32 million from a variety of sources including national and international research councils (e.g. NWO, ERC, H2020), regional funds (e.g. SNN), industrial partners, and government entities. Its research focus closely aligns with the EU's ambitions, allowing the institute to anticipate the development of a joint strategy for collaborative and European funding, enhancing its prospects for participation in EU projects.

ENTEG's research collaborations and funding from industry contribute to its high societal impact. The institute's cash flow income, primarily from contract research with industrial partners (more than 70% of third money income comes from contract research with industrial partners), demonstrates the trust that ENTEG gained, leading to a prominent role in supporting the innovation economy of the (North of the) Netherlands. Additionally, the number of patents (16) and the formation of start-up companies (6) further highlight the industrial and economic relevance of ENTEG's research.

Our educational programs are deeply intertwined with our research. ENTEG researchers significantly contribute to the training of young graduates, teaching in Bachelor's and Master's engineering degree programs such as Industrial Engineering and Management, Chemical Engineering, Mechanical Engineering, and Biomedical Engineering. Each year, over a hundred students undertake their research projects within our research units and our graduates find employment opportunities easily. To further enhance knowledge transfer to the industrial sector and to drive technological development, ENTEG will establish two Engineering Doctorate programs (Autonomous Systems and Sustainable Process Design) from September 2024. These post-master's programmes aim to train highly skilled design engineers and researchers with advanced expertise for the industry.

During the review period, ENTEG successfully improved its strategic positioning. This enhanced alignment, especially in terms of regional responsibility, valorisation orientation, sustainable development, and energy research focus, has strengthened the institute's relevance and ensured that its activities contribute effectively to broader strategic goals. With the arrival of young and highly talented PIs who bring fresh perspectives, enthusiasm, and energy to the institute and who have the potential to become future leaders in their respective fields, the ENTEG research team is strongly positioned for the future.

IID: Case Studies

1) Recycling rubbers

What should we do with the 1,5 billion old automobile tyres that are discarded worldwide? They are traditionally used as seesaw pads or swings in a monkey cage. Farmers utilise old tyres to secure silage tarpaulins. Car tyre granules make artificial turf fields playable, and the rest being incinerated. However, environmental constraints are making such uses increasingly challenging. Recycling the rubber in these tyres would be a good solution, but despite decades of research, no commercially viable way has yet been found to make new rubber from old car tyres. That is, until now.

The general problem of material recycling when dealing with rubbers lies in two main factors. On the one side the presence of chemical crosslinks between the chains factually hinders any melting and thus re-processability options as for thermoplastic materials. Furthermore, the presence of different kinds of rubber chains (as in car tires) often hinders high temperature processing due to undesired degradation reactions. Attempts to solve these problems via selective devulcanization have not resulted yet in commercial processes due to the costs and reactivity of the extrusion process (chemical devulcanization) or the long processing times (for example with enzymes).

The invention of the research group of F.Picchioni (WO patent Application WO2018/093260) takes advantage of the undesired degradation during extrusion (seen in many of our own research projects) instead of trying to avoid it. The general idea (see Figure C) is a 2-step process. In first instance the use of relatively high temperature and shear forces makes it possible to disrupt the entire network both at the crosslinking points and along the backbone to get an intermediate product characterised by relatively low viscosity (η).

FIGURE C: SCHEMATIC REPRESENTATION OF OUR PROCESS CONSISTING OF NETWORK DISRUPTION FOLLOWED BY BRANCHING TO OBTAIN THE DESIRED STRUCTURE.

In the second step a branching reaction induced by the use of a coagent X reconstitutes the chains in branched fashion thus achieving ideal viscosity values. The viscosity of the products constitutes here a pivotal parameter as it allows further mixing of the recycled rubber with thermoplastics or virgin rubber. The crucial point of this invention is the possibility to use branching agents (X in Figure C. that are completely safe, extremely cheap and environmentally friendly. Moreover both steps are carried out in reality in a single extrusion step. All these factors render this new technology extremely attractive from an industrial point of view.

The companies New Born Rubber and HoldingFP (Picchioni is involved in both companies) are now further developing the concept with the input from the researchers of the University. A test installation will be constructed and product technology will be developed. It recently has been awarded a substantial subsidy of more than €1.3 million and an NWO Take-off grant (40k). The team recently won the Entrance Award 2023.

The research of Picchioni was covered by UG, and it led to an outreach project on recycling of rubber together with FSE ScienceLinx for primary schools.

2) Ocean Grazer project

Research on the Ocean Grazer, a novel renewable energy harvesting and storage technology, is led by the research groups CMME (Prof.dr.Antonis I. Vakis and drs.Wout Prins, the inventor of the original concept) and DTPA (Prof.dr.Bayu Jayawardhana). The technology aims to exploit the unused potential of renewable ocean energy by developing innovative solutions that improve the efficiency of offshore wind farms and increase the energy yield per square kilometre [1-3]. This potential can be unlocked by combining various renewable energy sources such as wind, solar and wave energy at a given deployment location within hybrid devices that also feature on-site energy storage. The long-term goal of the research is to bring wave power to maturity via synergy with existing technologies and the smart sharing of infrastructure. The value of offshore energy sources can be increased considerably if the output can be made controllable and thus predictable: unique storage and wave control will coordinate the energy optimization processes within hybrid energy farms to dispatch energy in an optimal way, either directly to the electricity grid or in Power-to-Liquids and other processes. The team has been successful in developing the fundamental knowledge and underlying models [4], validated via experimental prototypes [5], which are used to realise our novel energy harvesting and storage technologies. They maintain close cooperation with their spin-off company Ocean Grazer B.V., whose CTO, drs. Marijn van Rooij, is a former member of the research team. There are ongoing collaborations with colleagues at the University of Groningen and elsewhere on topics ranging from hydrodynamics and fluid-structure interactions, to biomimetics, materials engineering, energy law and marine spatial planning. Due to its interdisciplinary nature, the Ocean Grazer project features in the Groningen Engineering Center, the Data Science and Systems Complexity theme, and the New Energy Coalition. The team received the inaugural Ben Feringa Impact Award of the University of Groningen in 2020, while they were nominated for the Huibregtsenprijs in 2021 and the Academic Startup Competition in 2019.

3) Conversion of waste biomass and plastic sources

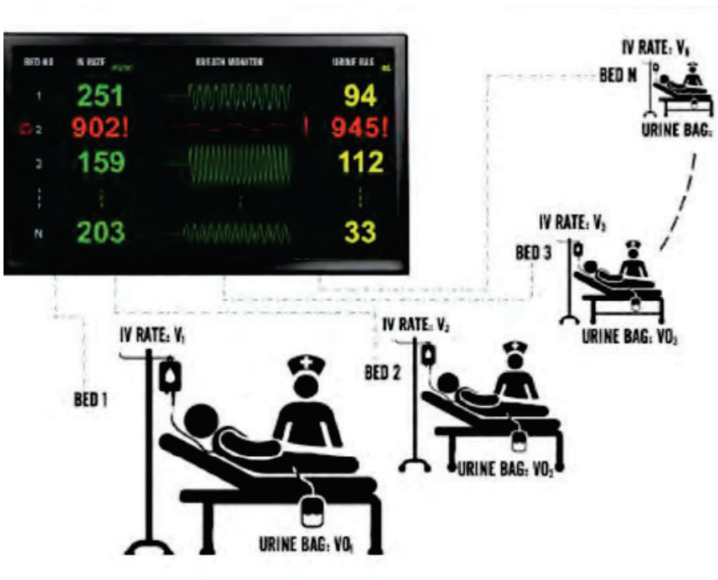
The research unit of Heeres is involved in the conversion of waste biomass sources (e.g. from agriculture and the paper and pulp industry) and waste plastics to biofuels and biobased chemicals, driven by the societal need to find alternatives for fossil-based feedstocks. In the group, the emphasis is particularly on the development of efficient chemo-catalytic conversion technology to obtain aviation fuels and specific important chemical intermediates (benzene, toluene, xylenes, BTX) for among others the plastics industry to provide non-fossil options for popular plastic products such as PET. The main technology used for this purpose is (catalytic) pyrolysis followed by catalytic upgrading using appropriate catalysts. Our main objectives are to bring the technologies from TRL levels 2-3 to at least 4 by demonstrating the concepts in dedicated continuous lab units including reactor and process design with special attention to carbon yields. In addition, fundamental studies for instance using model components are performed to obtain information on reaction pathways and catalyst stability, a major cost contributor. The team has successfully developed technology for BTX production from various biomass sources in close collaboration with the spin-off, BioBTX (video explaining the research). The latter has successfully scaled up the technology to pilot scale at the Zernike premises and will soon expand its activities to develop Europe's largest and most advanced plastic waste sorting plant for the chemical recycling industry in Delfzijl. Research interactions with the BioBTX and other commercial pyrolysis partners such as BTG (who focus more on fuels) have been strong and multiple joint research projects with regional (e.g. SNN), national funding (e.g. NWO) and international funding (e.g. H2020, ABC Salt) have been carried out. The research together with BIOBTX has led to 5 joint publications, a PhD-thesis, and multiple Master and Bachelor theses. The collaboration with BTG has so far led to 47 joint publications and at least 4 PhD-projects (1, 2, 3, 4).

FIGURE: BIOBTX PILOT PLANT AT ZERNIKE CAMPUS WITH RUG AND BIOBTX EMPLOYEES

4) Biomimetic Fish-Inspired Flow Sensors to Improve Patient Care in Hospitals

Ajay Kottapalli's research group focuses on nature-inspired biomimetic micro/nano electromechanical sensors (MEMS/NEMS) sensors and wearable electronics. One of the key pursuits of Kottapalli's research is to optimally translate the biological sensory functions found in nature into biomimetic electronic sensors for healthcare applications. The overarching research themes that encompass my research are advanced materials, smart industry and healthy living. A unique aspect of Kottapalli's research is to develop sensors with ultrahigh sensitivity, accuracy and real-life utility by imbibing designs of biological sensors in nature. The bio-inspired sensors developed in the team range from exploring cilia flow sensors in insects and neuromasts in fishes to whiskers in seals and the artificial sensors developed provide fundamental new insight into the hitherto unexplored sensing mechanisms of biological cilia sensors. Such biomimetic self-powered, sensitive, flexible, self-powered MEMS/NEMS and wearable sensor systems developed by the team find numerous applications in robotics healthcare and biomedical domains. The research team attracted traction in media and press in De Ingenieur, RUG Science Linx, AAAS Eureka Alert, Ukrant, Automatie magazine. More information about his research could be found through these videos: Seal whisker inspired sensors, Biomedical MEMS, Biomimetic MEMS sensors.

In one of the projects, in a pursuit towards enabling underwater vehicles with a capacity to manoeuvre with energy-efficiency in dark and turbid environments, the team built arrays of super tiny MEMS flow sensors that take inspiration from lateral-line organs on fishes. In a hydrodynamically challenging underwater environment, fishes are able to manoeuvre with high energy efficiency by gaiting trials as they go in schools. Blind fishes that survive in deep caves are able to "see" objects around through touch-at-a-distance sensing. Both the aforementioned feats are possible due to the lateral-line organ in fishes, which is essentially an array of flow sensors' called neuromasts which exist on the skin of the fish that constantly visualise and map the flow. Taking inspiration from the fish neuromast sensors, Kottapalli's team built tiny 3D printed polymer MEMS sensor arrays that mimic the functionality of the lateral-line. Due to the small foot-print, low-cost, biocompatibility, and ability to sense extremely low flows, these biomimetic MEMS sensors built by the team, in addition to robotics, also identified key applications in biomedical domain, where the team identifies their sensor technology to provide a breakthrough solution in patient vital flow management in hospitals.



Dr. Amar M. Kamat, a former postdoc working in Kottapalli's team was granted the NWO Take-off grant in 2020 through which he explored the commercial opportunities for such low-cost MEMS flow sensors in healthcare. The team filed a patent on the technology and thereafter created a start-up company, Sencilia, which was founded in 2020. Sencilia is an early-stage, investor-backed, deep-tech startup company based in Groningen, which develops nature-inspired sensing solutions through innovative fabrication methods to solve critical flow monitoring needs in hospitals. Fluid transfer, whether going into the patient (e.g. intravenous infusions) or coming out of the patient (e.g. urine), is a common feature in ICU's and requires constant monitoring. Currently, infusions and urine output are monitored manually by nurses, making the process error-prone and labour-intensive. In-line sensor measurement of vital clinical fluid flow rates, such as intravenous (IV) and urine output (UO), allows continuous and automated monitoring and can help reduce medication dosage errors, maintain appropriate fluid balance in the patient, and finally mitigate nurse workload. Nurses can thus use their time efficiently for patient care instead of on measurements and documentation. The biomimetic flow sensors prototypes created by the team were tested in IV infusion flow monitoring and urine drainage monitoring in the lab setting. The team is now conducting ex-vivo infusion monitoring tests on pig kidney models and is preparing to conduct in-human trials in the near future. Sencilia was one among the 11 European start-ups selected for the Medlim fast track accelerator programme in 2023. Sencilia also won the golden ticket to Draper University's Hero Training Program in Silicon Valley and was a part of the six companies chosen for the NOW Venture Challenge 2023 programme.

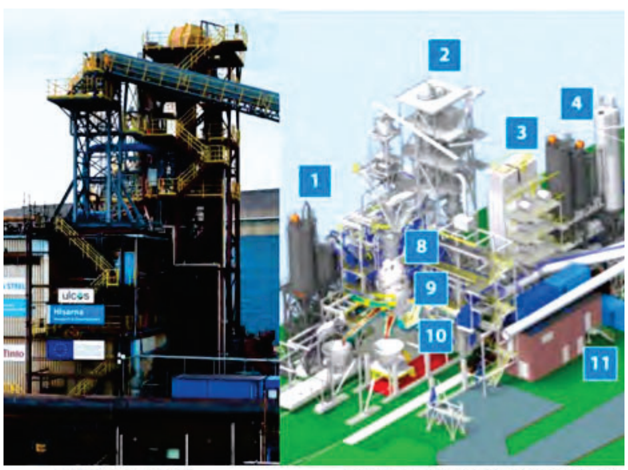
5) Data-driven and model-based control for the development of digital twins

The ubiquity of data from IoT sensors, actuators and machines, has offered the potential to develop accurate and agile digital twins of high-tech products and processes. Digital twins are digital represen-tations of cyber-physical systems and they are used in the real-time monitoring, control and optimization of the physical systems. The groups of Smart Manufacturing Systems and Discrete Technology and

Production Automation are leading researchers in this field. It has been financed through EU-SNN funding on Region of Smart Factories (1 PhD, 2016-2020), EU Marie Skłodowska-Curie COFUND (Grant 754315, 3 PhDs, 2016-2020), NWO-TTW Smart Industry project (2 PhD & 1 postdoc, 2017-2022), the flagship TTW Perspectief program on DIGITAL TWIN (17 PhDs & 2 postdocs, 2020-now) with Bayu Jayawardhana as the programme leader, and the MOOI-Heat is On project focusing on the application of digital twin to reduce of energy consumption in process industry. The results established the theoretical foundations for designing feedback control policies for complex dynamical systems based solely on the real-time data or the combination thereof with first principle models.

As one of the highlights, the research work in the group of Smart Manufacturing Systems has greatly advanced the state-of-the-art by providing an original fusion of control theory and data science via the introduction of a systematic technique to reduce control design to data-dependent convex optimization programs. The seminal paper by De Persis and Tesi on Formulas for data-driven control: stabilisation, optimality and robustness which has appeared in IEEE Transaction on Automatic Control, March 2020, lays down the framework and has been highly cited. Since its publication, it has been the most frequently accessed document for IEEE Transactions on Automatic Control. The results have drawn exceptional interest as highlighted by several invitations for plenary and semi-plenary talks, doctoral schools and invited seminars in top academic institutions, including CWI Amsterdam, ETH Zurich, EPF Lausanne, Imperial College London, KTH Stockholm, National Laboratory for Renewable Energies, Seoul National University, TU Delft, University of Oxford, University of Stuttgart.

As a byproduct of the project, several algorithms and software for the end-to-end automatic design of controllers from data have been produced and implemented in popular software packages, such as CVX and YALMIP. The recent paper of Andrea Bisoffi, Claudio De Persis, Pietro Tesi on Data-driven control via Petersen's lemma published in Automatica, has been the December 2022 Editors' Choice with the following motivation: "If you are looking for a well-articulated introduction to the current state of data-driven control, this cogent contribution is for you. [...] A key technical tool that permits the elegant, novel synthesis formulation is Petersen's lemma from robust control. [...] It will be fascinating to see these methods extended to dynamic output feedback and also to other classes of nonlinear systems."



HISarna plant Digital twin of HISarna plant

6) Using Systems and Control Theory to Mathematically Model Societal Change

Ming Cao and his research group have used systems and control theory, in combination with game theory, to develop and study mathematical models concerning networks of agents who interact with one another and make strategic decisions. A key application of such models is to study social diffusion, whereby an "innovation" such as a new product, technology, rumour, norm or behaviour spreads through a society to replace an existing status quo. In one of his projects, published in Nature Communications, he collaborated with psychologists from the Faculty of Economics and Business at the University of Groningen to study how social conventions, such as the way we greet each other, change over time. Experimental data gathered from human-bot team games revealed three basic rules that people tried to balance during social convention change: i) copy the most popular strategy, ii) stick with your current choice if possible, and iii) follow the trend if there is one. By incorporating these rules into a game-theoretic model, and using the experimental data for parametrisation, the team revealed using computational methods how a combination of these three individual-level rules allowed the model to predict real observed phenomena, such as how some social conventions can remain stable for long periods before suddenly and rapidly becoming replaced. It was also found that one way to create social change was the presence of enough "committed individuals" who pushed for the innovation, with quantitative results obtained on how many were "enough". Two articles covered this research, with many science websites subsequently re-sharing the articles as well.

In a second follow up project, Cao's team studied a similar decision-making and control model in more depth using rigorous mathematical analysis, to provide new insights into a fundamental problem. Namely, when promoting an innovation, traditional strategies relied on two key factors: ensuring the innovation is much better than the status quo and having enough innovators to lead the initial wave of adoptions. However, many innovations important to society, such as new sustainable technologies and practices, are lacking in these two aspects. Using the mathematical model, the team demonstrated that an effective strategy was to exploit a new "nudge" technique from social psychology called dynamic norms, which made people sensitive and aware of emerging trends and change. The team showed even a small nudge was enough to significantly reduce the need for the two traditional factors.
Cao's research is built on a strong mathematical modelling framework, but has important societal applications. These range from fundamental knowledge discovery on when, why and how societal change occurs through social diffusion, and more immediate applications such as the adoption of innovations and practices that are important for our efforts against the climate crisis. For the latter, Cao has been collaborating with researchers in psychology, economics, and urban planning to explore applications in sustainable behaviours and practices, and interventions to boost the adoption of such behaviours.

7) Smart Circular Alliance

Major breakthroughs will be required to prepare our industrial sector for the future. Smart digitalization and circularity will be key and essential for success. By initiative of ENTEG (Profs. Heeres, Scherpen, Euverink, and Post) and with support of the University of Groningen and under the heading of the University of the North, PricewaterhouseCoopers helped us to explore the need for creating a centre of expertise. The inventory demonstrated that the combination of both disciplines is unique and has ample opportunities for the industry in the Northern region.
ENTEG staff (Heeres leading the initiative as project enabler) now aims to bring the project to the next level under the name Smart Circular Alliance. SC-Alliance aims to create a centre of expertise on technological developments in the field of Smart Industry and Circular Economy. Smart Industry and circular economy can, if being combined, pose additional value propositions and since the Northern region of the Netherlands has a strong chemical, process, manufacturing and agri-food industry, it has lots of opportunities for Smart Industry and Circular Economy initiatives. By creating a centre of expertise, we aim to stimulate R&D activities and to strengthen the regional industry. We aim to:

- give UG and its partners within the Alliance the opportunity to stand out as a frontrunner of industrial innovation and research and education in the field of Smart Industry and Circular Economy.
- Future-proofing the industry in the Northern region by innovation through the entire value chain ('more with less') and the exchange of knowledge.
- Retaining talent in the Northern Netherlands by offering high quality education and job opportunities. Currently several brainstorming sessions are organised together with key (industrial) players in the field to set-up an innovation agenda.