Research self-assessment 2007-2012
Preface

In the past two decades the Department of Mechanical Engineering at TU/e has changed from a department focusing mainly on (short-term) practical work for industry into one with a strong discipline-oriented backbone, working closely together with industry to address major challenges in the field. This policy has been further extended in the present assessment period. The department is now grouped around three disciplinary fields: one focusing on mechanics and materials, the second focusing on systems, dynamics and control, and the third focusing on heat and flow. These fields aim to integrate fundamentals, design and manufacturing. The interaction between research and education, the high-profile industrial network and the sustained healthy funding level all help to make the department an exciting environment for students and visitors from academia and industry.

The goal of the research assessment is partly to look back and evaluate the performance of the department and its groups over the past six years. But it is also a time to look ahead to the future, to assess the changes that we expect to face, and to advise on the right actions for further improvements. This feedback will be of great value for our strategy, for the organisation of the department, and for achieving the profile of international excellence that we aim for.

As Dean of Mechanical Engineering, I would like to express my appreciation for the work of the Assessment Committee. We look forward to receiving their findings, and to putting them into practice in our drive for continuing improvement.

Philip de Goey
Dean
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Section A: Mechanical Engineering Department TU/e
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1. General information. Mission statement

1.1. Global data

The department of Mechanical Engineering is one of the nine departments of Eindhoven University of Technology (TU/e). The department was established at the founding of the university in 1956. Current staff numbers are 162, including 14 full professors, 11 part-time professors, 24 associate professors, 33 assistant professors and 76 administrative and technical support staff. There are approximately 1155 engineering (BSc and MSc) students, 157 PhD students and 21 postdocs. The department’s current annual budget is approximately 23 M€, about 50% of which is obtained from external funding.

1.2. Industrial context

The industrial surroundings of the department are characterised by an exceptionally high concentration of high-tech industry and research & development laboratories, which are all competitive on a global scale. Within the supply chain, large companies focus on carefully selected core technologies, while small and medium-sized enterprises concentrate on subsystem analysis, design and manufacturing. This has a significant impact on our research and education programme, since our graduates must be able to function effectively in the industrial context of today and tomorrow. In fact they must be able to work at ever-higher levels of abstraction, using the most modern analysis and design tools, and to sustain this during their professional careers.

1.3. Historical context

Since the mid-1990s, the structure of the Mechanical Engineering department has gradually evolved into an institute covering three educational and research tracks: one with a focus on mechanics and materials (CEM), a second with a focus on systems, dynamics and control (DSD), and a third with a focus on heat and flow (TFE). The aim of the tracks is to integrate fundamentals, design and manufacturing. In each of these tracks several groups collaborate in the educational programme and often share lab research facilities and technicians. All research groups are conceptually and methodologically oriented, rather than exclusively focused on either applications or fundamentals.

1.4. Result of previous assessment

In the previous evaluation period 2002-2007, the average evaluation score of the Mechanical Engineering department of TU/e was 92.5% (4.61), compared with 80.7% (4.03) for Delft University of Technology and 73.8% (3.69) for the University of Twente, while TU/e’s average score across all departments was 82.5%.
1.5. Mission statement

Within this industrial and historical context, the mission of the Mechanical Engineering department of TU/e can be stated as:

- To carry out long-term, generic, world-class research within the mechanical engineering domain on carefully selected topics that fall within the research profile areas of the university, and that match the technological interests of high-tech, internationally oriented industry in the Netherlands and especially in the Eindhoven region.
- To realise an education and research programme with a balanced combination of fundamental and application aspects, thereby aiming at providing industry with scientifically educated and application-driven engineers who are optimally equipped to address future challenges.

2. Leadership and Management

2.1. Organisational structure

The organisational structure of the department is shown in Figure 1. The Departmental Board, appointed by the Executive Board of the university, consists of the Dean, the Vice-Dean and the Managing Director. Two advisors, the Director of Education and a student representative, also attend the weekly Board meetings. The Dean is ultimately accountable for the entire management, in which the Managing Director covers all matters concerning personnel and organisation, financial administration, services and accommodation.

The department has a professional managerial structure including direct communication between the Departmental Board and the individual research groups, with no intermediate level. In addition, several research groups share laboratory facilities and supporting staff. The department has an educational institute to organise the educational programmes, and its own management support sections for human resources, finance, computing, accommodation and maintenance. All major administrative support systems are integrated university-wide.

2.2. Advisory bodies

The Departmental Board has a number of advisory bodies that play a role in its decision-making procedures:

- the Departmental Council, which has to approve major organisational and educational changes as well as the annual budget,
- the Full-time Professor Board, which meets bi-weekly to share information and discuss important strategic choices of the department,
- the standing Advisory Committee for Research, which advises the Departmental Board on policies in quality control of research,
- the standing Committee for Education, which advises on educational policies and on the educational programme,
- the Examination Board, which is an independent committee that decides on all formal matters related to examinations and diplomas
- the Appointment Advisory Committee, which advises on the appointment and promotion of academic staff.
2.3. Allocation of funds

The department's total annual budget of direct funding (see Table A.2.2 in Section 5.1) is split into five parts:

- Staff salaries that are directly funded by the department (56%)
- Funds needed for education and administrative tasks (28%)
- Discretionary funds for new research initiatives (3%)
- Funds assigned to the research groups for exploitation (3%)
- Funds for support of laboratory infrastructure and other facilities (10%).

The first two items are funded at departmental level, covering the largest part (84%) of the direct funding. This creates long-term stability in the department's personnel policy.

Next, the Departmental Board decides, usually after advice from the Advisory Committee for Research, on limited discretionary funds to start new, promising research lines, or to give incentives for basic research.
The amount of funding assigned to the research groups for exploitation is mainly output-driven. Funding from governmental agencies such as NWO (Netherlands Organisation for Scientific Research), FOM or the Technology Foundation STW, from Leading Technology Institutes (Materials Innovation Institute, Dutch Polymer Institute), European projects or innovation programmes (HTAS, Peaks in the Delta, IOP, PointOne and ESI) and from industry is directly managed by the research group that acquired the project (projects funded by research grants and contract research). The department does not impose overhead on these grants. Groups can use this overhead for other research and lab facilities. In selected situations, the department invests in its laboratories to support the research groups by providing them with a proper research infrastructure.

2.4. Communication

The major communication channel is through the bi-weekly meetings of the Departmental Board and the full professors. Subsequently, each group leader communicates on a regular basis with his/her group. A news page on the department website provides relevant up-to-date newsflashes.

In addition, the department organises the following annual meetings:

- Between the Board and each group leader to discuss personnel development and career planning.
- Between the Dean and each group leader to evaluate the performance of the group leader and research group.
- An annual ‘Day on Research’ at which the scientific staff (professors, associate professors and assistant professors) meets to discuss research highlights on a chosen theme, offering a platform to new faculty members to present their research plans.
- An annual ‘Day on Education’ to discuss the most recent developments regarding changes in university and department policy on education, new curricula and educational tracks.

3. Strategy and policy

3.1. Choices made concerning research

The strategy adopted by the department is to maintain its proven excellence in research quality, research relevance and research output in a balanced combination with its state-of-the-art teaching and education of substantial numbers of BSc and MSc students. The department strives for excellence above critical mass, in both research (order 150 PhD students) and education (order 250 freshmen).

As a result, the members of the research staff are always actively involved in the educational programmes. Typically, 40% of the time is spent on research, 40% on educational tasks and 20% on other tasks such as personal development and administrative tasks. As a guideline, each (assistant/associate) professor supervises 3 PhD students and several Bachelor’s and Master’s students. PhD students are encouraged to participate actively in the international research community and to interact with their peers, by contributing to international symposia/congresses and publishing in refereed journals. As an indication with regard to the envisaged output quantity, PhD students are expected to publish 1 paper in a refereed journal per year.
To enhance the impact of our research on society, the department is increasingly focusing on promoting research valorisation. The ME Board therefore encourages the creation of an innovative departmental spirit in which innovations are developed, spin-off companies are initiated and supported, and from which creative student teams (e.g. on robotics and solar vehicles) emerge.

The Departmental Board adheres to a flexible strategy, which is responsive to internal and external developments. The Board recognises the increase in workload of the tenured scientific staff through the need for growing external funding, by the publication pressure and, importantly, by the increasing number of freshmen and the substantial changes in the teaching curriculum as a result of the introduction of the Bachelor College due to the University's new educational policy. A number of full professors are (in the process of) retiring, and the Departmental Board has anticipated these changes by early appointment of successors, making use of extra funding by the so-called 3TU CoEs – Centres of Excellence (prof. Van Brummelen, prof. Heemels), by the EEI – Eindhoven Energy Institute (prof. Smeulders) and by promotion of excellent internal candidates to the personal or full professor level (prof. Peters, prof. Anderson).

In view of the existing financial constraints of the direct funding, choices have been made and priorities set in which the emphasis lies on the systematic strengthening of the senior tenured scientific staff. In the period 2007-2012 the number of full professors increased from 9 to 14, and the number of associate professors from 16 to 24. This has resulted in smaller and easier-to-manage research groups.

3.2. Changes with respect to the research groups

Organisational and personal changes in different research groups during the assessment period show the dynamic character of the department. Structural changes and new appointments were in line with the department’s general strategy, which is to keep the quality standards high while adequately facing and adapting to the challenges of a modern society.

- **Chair Microsystems**
  Prof. Dietzel started in 2004 as full professor in *Micro- and Nano-scale Engineering*, but decided in 2006 for a career switch by joining the Holst Centre, a close cooperation between IMEC and TNO in the area of micro-fabrication. In the transition period, 2006-2012, he remained affiliated with the department through a part-time appointment, with prof. Van Steenhoven as temporary section head. He joined the TU Braunschweig in 2013, after which the name of the section was simplified to *Microsystems* and – after an international competition – prof. Den Toonder was appointed as full professor of this new group.

- **Chair Structure and Rheology of Complex Fluids**
  In anticipation of the retirement in 2014 of prof. Meijer, who chaired the large Polymer Technology group, the Departmental Board decided in 2012 to split the group into Polymer Solid Mechanics and Polymer Fluid Mechanics. The former, which continues under the original name Polymer Technology, is led by prof. Meijer and focuses more on structure-property relationships in polymers. The second group is headed by prof. Anderson and focuses on the flow of complex fluids, with applications in polymers in the development of novel polymer processing technologies and in devices in for example lab-on-a-chip, polymeric membranes and fuel cells.
• Chair *Hybrid and Networked Systems*
  Within the framework of the 3TU CoE for High Tech Systems, prof. Heemels was appointed in 2010 as the chair of the new Hybrid and Networked Systems group. The research focus is on hybrid cyber-physical systems with both continuous and discrete dynamics and on control methods of highly complex systems using rapidly advancing communication technologies. The group was merged with the Control Systems Technology group headed by prof. Steinbuch in 2013.

• Chair *Manufacturing Networks*
  In anticipation of the retirement in 2011 of prof. Rooda, chair of the Systems Engineering group, the department appointed prof. Baeten in 2010 to cover the Systems Engineering research area. The section was further strengthened by the appointment of prof. Adan on the related Manufacturing Networks chair. In 2011 prof. Baeten accepted the prestigious position of director of the CWI in Amsterdam (Centre for Mathematics and Computer Science). The Systems Engineering group was merged with that of prof. Adan into a new research group focused on the investigation of machines in (network) environments, with the emphasis on their operational performance and their effect on the environment. Examples are warehousing systems, road traffic, semiconductor wafer factories and hospitals, but also complex multi-processing machines such as wafer steppers.

• Chair *Energy Technology*
  Within the framework of the EEI, Eindhoven Energy Institute, the new Engineering Thermodynamics for Energy Systems research group was established in 2010 with prof. Smeulders as chair, with the objective of later succeeding prof. Van Steenhoven, head of the Energy Technology group. This was made effective by mid-2012. The research focus is on enhanced thermal transport and small-scale energy systems for thermal storage and conversion, separation and cooling.

• Chair *Multi-scale Engineering Fluid Dynamics*
  Within the framework of the 3TU CoE for Multi-scale Phenomena, prof. Van Brummelen started the new Multi-scale Engineering Fluid Dynamics group in 2009. The research focus is on mathematical-physical models and advanced numerical techniques for multi-scale flow problems.

• Chair *Numerical Methods in Engineering*
  In May 2007 prof. De Borst succeeded prof. Van Campen as Dean of the department. The Executive Board of the university simultaneously appointed him as distinguished university professor and granted him the privilege of setting up a new small research group on Numerical Methods in Engineering, with applications in solids, fluids and interaction phenomena. However, prof. De Borst was offered a prestigious chair at the University of Glasgow in 2011 and decided to leave TU/e. The still small research group was discontinued, and the two remaining faculty members joined other neighbouring groups. Prof. De Goey took over his duties as Dean from May 2011.

### 3.3. Embedding of the research at university and national levels

Embedding at university level concentrates on the three Strategic Research Areas chosen and on three Interdepartmental Master's programmes. Nationally, the focus is on three Centres of Excellence, two Leading Technology Institutes and six Graduate Schools.
The surroundings of TU/e in Eindhoven are well-known for their high concentration of high-tech related industry (ASML, Philips, NXP, FEI, DAF), referred to as ‘Brainport’. The Intelligent Community Forum (ICF) identified Brainport as the ‘world’s smartest region’ in 2011. In view of this, TU/e adopted a strategy of aiming its development towards a university with a ‘High-Tech Systems and Materials’ focus. TU/e’s vision is to achieve the highest quality levels in research and education, with high relevance for industry and society. In doing so, the university aims to support society and industry with engineers and researchers who are optimally equipped to address our future challenges. The three cross-departmental Strategic Areas have been introduced to address the major societal challenges of ‘Energy’, ‘Mobility’ and ‘Health’. Each of these Strategic Areas has developed a roadmap for future research in relation to industry. The department is also active in these Strategic Research Areas, as shown in the next table.

**Table 1. Contribution to TU/e Strategic Research Areas**

<table>
<thead>
<tr>
<th>Area</th>
<th>Energy</th>
<th>Health</th>
<th>Mobility</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>PhD input*</td>
<td>32%</td>
<td>12%</td>
<td>21%</td>
<td>35%</td>
</tr>
</tbody>
</table>

* Based on all PhD positions and vacancies, as counted in 2011

Automotive Technology (AT) related to the Strategic Area ‘Mobility’, in collaboration with the departments of Electrical Engineering, Chemical Engineering and Chemistry, Industrial Design, Industrial Engineering & Innovation Sciences, and Mathematics & Computer Science.

Sustainable Energy Technology (SET), a 3TU programme related to the Strategic Area ‘Energy’, in collaboration with the departments of Applied Physics, Chemical Engineering and Chemistry, Electrical Engineering, Built Environment and Industrial Engineering & Innovation Sciences.

Systems & Control (S&C), a 3TU programme related to the ‘High-Tech Systems and Materials’ profile of TU/e in collaboration with the department of Electrical Engineering.

**University level: Top research institutes**

Prof. Van Brummelen is director of the Eindhoven Multi-scale Institute. This institute combines and coordinates research on multi-scale modelling within TU/e.

**National level: 3TU Centres of Excellence and 3TU.Research Centres**

The three Dutch universities of technology – the University of Twente, TU Delft and TU/e – collaborate in the 3TU joint venture to coordinate research and education in technical engineering sciences in the Netherlands. In 2005 the Dutch government awarded 50 M€ to the three universities of technology to set up the inter-university Centres of Excellence (CoEs). The ME department participates in the following three CoEs:

- High-Tech Systems,
- Sustainable Energy Technologies,
- Multiscale Phenomena (in Fluids and Solids).
The department acts as commissioner for the 3TU Centre of Excellence on Multiscale Phenomena, and research groups within the department have also been chosen to participate in the CoE on High-Tech Systems (CST chair prof. Steinbuch is the Scientific Director) and Sustainable Energy Technologies. In addition, the Master's programmes S&C and SET are given jointly with Master's programmes at TU Delft and the University of Twente, and are therefore referred to as 3TU Master's programmes. From 2014 new 3TU.Research Centres will be installed, and in some of these the department again plays a central role.

- National level: Leading Technological Institutes
  At national level the department substantially participates in two Leading Technology Institutes (TTIs or LTIs):
  - Dutch Polymer Institute (DPI), in which Polymer Technology participates, and
  - Materials Innovation Institute (M2i) in which Mechanics of Materials participates.
  The LTIs provide substantial external industrially oriented research funding, with a structural link between the research carried out by the participating groups and industry.

- National level: Graduate Schools
  All research in the department is embedded in six nationwide graduate schools and one local graduate school. All graduate schools have been accredited by the Royal Netherlands Academy of Arts and Sciences (KNAW) and provide a forum for inter-university exchange of information and coordination of the research:
  - Engineering Mechanics (solid and structural mechanics; commissioner: Department of Mechanical Engineering TU/e)
  - JM Burgerscentrum (JMBC, fluid mechanics)
  - Dutch Institute of Systems and Control (DISC)
  - Institute for Programming and Algorithms (IPA)
  - Graduate School on Process Technology (OSPT)
  - BETA research school for operations management and logistics
  - Eindhoven Polymer Laboratories (local research school; commissioner: department of Mechanical Engineering, TU/e)
  The graduate schools serve as a common platform for the development of PhD courses (which are normally given by professors of all participating universities and are accessible to all PhD students). Courses are often organised in collaboration with other graduate schools and also support the international profile of the research area.

### 3.4. Education at BSc and MSc level

The Mechanical Engineering Bachelor's programme is part of the Bachelor College of TU/e and consists of a broad disciplinary basis in mathematics and three major learning lines in Mechanics & Materials, Dynamics & Control and Energy & Flow. The faculty members of the department provide most of the teaching elements in the Bachelor's programme.

The Mechanical Engineering Master's programme consists of 5 Master's tracks:

- Computational and Experimental Mechanics (CEM),
- Dynamical Systems Design (DSD),
- Thermo-Fluids Engineering (TFE),
- Automotive Engineering Science (AES),
- Micro- and Nanotechnology (MuNT).
As well as the 3 main tracks CEM, DSD and FTE, which result from the cooperation between research groups and are materialised in 3 large laboratory infrastructures, 2 research themes and Master’s tracks are defined: AES and MuNT. These are consistent with the regional industrial focus aligned with the Strategic Areas chosen at university level, and establish extra links between the different research groups participating in the main tracks. The department also plays a leading role in the national MSc excellence track Fluid and Solid Mechanics.

4. Researchers and other personnel

4.1. Researchers

Table A.2.1 shows the composition of the scientific, visiting and supporting staff for the entire department. Typically, until recently, all established research groups consisted of a full professor and four to five assistant and/or associate professors, a part-time professor, a few technicians (shared with other research groups), a secretary plus temporary scientific personnel (PhD students and postdocs). New research groups tend to be smaller in size.

<table>
<thead>
<tr>
<th></th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tenured staff</td>
<td>18.0</td>
<td>19.4</td>
<td>20.4</td>
<td>20.5</td>
<td>21.2</td>
<td>22.5</td>
</tr>
<tr>
<td>Non-tenured staff</td>
<td>14.6</td>
<td>16.3</td>
<td>17.3</td>
<td>18.4</td>
<td>23.5</td>
<td>21.7</td>
</tr>
<tr>
<td>(mainly postdocs)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PhD students</td>
<td>67.1</td>
<td>71.5</td>
<td>75.8</td>
<td>96.0</td>
<td>101.7</td>
<td>115.1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>99.7</strong></td>
<td><strong>107.3</strong></td>
<td><strong>113.5</strong></td>
<td><strong>134.9</strong></td>
<td><strong>146.4</strong></td>
<td><strong>159.3</strong></td>
</tr>
<tr>
<td>Supporting staff</td>
<td>15.4</td>
<td>16.5</td>
<td>17.1</td>
<td>17.1</td>
<td>16.9</td>
<td>16.7</td>
</tr>
<tr>
<td>Visiting fellows</td>
<td>10.0</td>
<td>5.6</td>
<td>2.5</td>
<td>4.6</td>
<td>6.2</td>
<td>11.2</td>
</tr>
<tr>
<td><strong>Total staff</strong></td>
<td><strong>125.0</strong></td>
<td><strong>129.4</strong></td>
<td><strong>133.1</strong></td>
<td><strong>156.7</strong></td>
<td><strong>169.5</strong></td>
<td><strong>187.2</strong></td>
</tr>
</tbody>
</table>

Completely in line with our strategy, see Section 3.1, we have successfully increased the tenured research staff by 25%, despite the fact that the total direct funding has remained almost constant, see Section 5. The number of PhD graduates has increased by a factor of almost 2 during the evaluation period. This is a result to be proud of, and apart from continuous hard work of the existing staff is due partly to the growth of several relatively young groups and the creation of some new groups, see Section 3.2. Currently, the PhD student/tenured staff ratio (based on research fte) has reached a value of 5, which is equivalent to an average of 2.5 PhD students per tenured scientific staff member, close to the long-term goal of 3 PhD students per staff member as mentioned in Section 3.1. The technical supporting staff/tenured staff ratio has decreased from 0.85 to 0.75.

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1 Tenured scientific and supporting staff members (with 1.0 fte appointment) are involved for 0.4 fte in research, postdocs and PhD students spend 0.8 fte on research.
4.2. Recruitment, tenure and promotion

- For the recruitment of new full professors, the Departmental Board appoints an expert advisory committee chaired by the Dean and consisting of at least four full professors, the Director of Education and a number of external experts from other departments within the university and from other universities, both in the Netherlands and abroad.
- The department has for many years had an active policy of appointing scientifically oriented part-time professors from industry (providing a structural link with industrial applications), from technological institutes (such as TNO, the Netherlands Organisation for Applied Scientific Research), and from other universities (in particular from abroad). The aim of these appointments is to introduce industrial experience into the research and education. For the recruitment of the part-time professors, who have an appointment period of four years with a possible extension, similar committees as for full professors are adopted.
- The department has extended this policy to also appoint part-time assistant and part-time associate professors from research institutes and industry. Currently, 11 part-time professors, two part-time associate professors and five part-time assistant professors have been appointed, for example from Shell, Philips, DSM, ASML, ECN, TNO, FOM, University of Twente, Delft University of Technology, Lund University, Cambridge University and University of Amsterdam.
- For recruiting new faculty members and for evaluating temporary faculty members for whom tenured positions are envisaged, as well as for promoting assistant professors to the rank of associate professor, the department appoints an advisory committee consisting of three full professors, the Director of Education and at least one member from another TU/e department or another university. New faculty members are in principle given a temporary appointment for a four-year period, after which the tenure procedure starts.
- After a positive recommendation by the committees, the Departmental Board decides and if required (in case of full and associate professors) prepares a proposal for the Doctorate Board of the university. The Executive Board of the university will finally confirm the appointment only after a positive recommendation by the Doctorate Board.

4.3. Development and evaluation

All new scientific staff attends a number of courses on management, presenting, research, education and teaching.

- A general management course aimed at improving leadership skills for professionals.
- Courses that include didactic training, presentation techniques, design of new courses, design of examinations and tutor and mentor training, as well as language courses.
- Requirements for teaching are met by the University Teaching Qualifications (UTQ), which is a set of basic teaching qualifications for university teaching personnel, as agreed on in the Netherlands and for which rules are defined at 3TU level. At present, 3 years after the UTQ introduction, 32% of the scientific staff have qualified for UTQ, while another 10% have subscribed to the UTQ.
- With respect to research, training programmes in project management are offered on request.
- The department encourages financed sabbatical leaves by faculty members every five years. A stay abroad is considered important for international contacts, research refreshment and internal promotion.
- An annual evaluation of all personnel is performed covering both performance and job satisfaction. Full integration of education and research in the tasks of the tenured scientific staff is considered essential.
4.4. PhD students

- PhD students can allocate up to 20% of their time to further education and professional development. Most inter-university courses are organised by the (national) graduate schools, offering course packages from 20-30 EC. Most PhD students in the department are embedded within such a school. In addition, the university offers a set of personal development (PROOF) courses (for example Dutch, writing articles in English, career development etc.). All courses are financed by the research groups.

- PhD students gain experience in giving talks and presenting posters at national meetings and workshops organised by the local research groups and graduate schools, and at the international level by presenting at conferences. English is the working language of the national meetings to prepare the PhD students as well as possible, and also because of the substantial number of international PhD students.

- Evaluation: PhD students write a progress report after their first year, which is followed by a go/no go decision with respect to the following 3 years.

- In the assessment period, 90% of the enrolled PhD students finished their PhD successfully, 12% of the students finished within 4 years, 71% within 5 years, 7% within 6 years and 1% within 7 years. 8% of the PhD student contracts have been discontinued, while 2 of them are still ongoing.

- The average duration of the PhD period is 4 years and 4 months, only slightly above the nominal 4 years and well below the national average. Due to administrative procedures, the thesis defence is usually 3 months after the end of the 4-year PhD contract. Graduated in 4-<5 years should therefore be interpreted as: the PhD work, including writing the thesis, is finished in 4 years. Accordingly, prior to the start of the defence the draft thesis is sent to the committee for approval (1 month), after which 2 months are required by the PhD regulations (approval by the Doctorate Board; thesis printing etc.). This period is 3 months in total, and obligatory according to the regulations governing the conferral of doctor's degrees at our university.

- Only a small but increasing fraction of the enrolled PhD students have been admitted on the basis of an external scholarship (for example the China Scholarship Council). The majority of the students have been employed with a regular PhD salary at the university or on the payroll of FOM or M2i. For these students the sources of funding in 2013 were:

  - Direct funding 13%,
  - Research funding 33%,
  - Contract funding 54%.

7% of the PhD students were female.
<table>
<thead>
<tr>
<th>Starting year</th>
<th>Male</th>
<th>Fem</th>
<th>Total</th>
<th>≤ 4</th>
<th>4 - 5</th>
<th>5 - 6</th>
<th>&gt; 6</th>
<th>Total graduated</th>
<th>Not yet finished</th>
<th>Discontinued</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>20</td>
<td>4</td>
<td>24</td>
<td>4 / 17%</td>
<td>17 / 71%</td>
<td>2 / 8%</td>
<td>1 / 4%</td>
<td>24 / 100%</td>
<td>- / - %</td>
<td>- / - %</td>
</tr>
<tr>
<td>2004</td>
<td>28</td>
<td>3</td>
<td>31</td>
<td>3 / 10%</td>
<td>20 / 65%</td>
<td>5 / 16%</td>
<td>- / - %</td>
<td>28 / 90%</td>
<td>- / - %</td>
<td>3 / 10%</td>
</tr>
<tr>
<td>2005</td>
<td>18</td>
<td>-</td>
<td>18</td>
<td>2 / 11%</td>
<td>12 / 67%</td>
<td>2 / 11%</td>
<td>1 / 6%</td>
<td>17 / 94%</td>
<td>- / - %</td>
<td>1 / 6%</td>
</tr>
<tr>
<td>2006</td>
<td>16</td>
<td>3</td>
<td>19</td>
<td>2 / 11%</td>
<td>15 / 79%</td>
<td>1 / 5%</td>
<td>1 / 5%</td>
<td>19 / 100%</td>
<td>- / - %</td>
<td>- / - %</td>
</tr>
<tr>
<td>2007</td>
<td>24</td>
<td>1</td>
<td>25</td>
<td>2 / 8%</td>
<td>20 / 80%</td>
<td>1 / 4%</td>
<td>- / - %</td>
<td>23 / 92%</td>
<td>- / - %</td>
<td>2 / 8%</td>
</tr>
<tr>
<td>2008</td>
<td>25</td>
<td>-</td>
<td>25</td>
<td>5 / 20%</td>
<td>18 / 72%</td>
<td>- / - %</td>
<td>- / - %</td>
<td>23 / 92%</td>
<td>1 / 4%</td>
<td>1 / 4%</td>
</tr>
<tr>
<td>2009</td>
<td>36</td>
<td>4</td>
<td>40</td>
<td>3 / 8%</td>
<td>18 / 45%</td>
<td>3 / 8%</td>
<td>- / - %</td>
<td>24 / 60%</td>
<td>16 / 40%</td>
<td>- / - %</td>
</tr>
<tr>
<td>2010</td>
<td>30</td>
<td>3</td>
<td>33</td>
<td>1 / 3%</td>
<td>1 / 3%</td>
<td>- / - %</td>
<td>- / - %</td>
<td>2 / 6%</td>
<td>31 / 94%</td>
<td>- / - %</td>
</tr>
<tr>
<td>2011</td>
<td>29</td>
<td>4</td>
<td>33</td>
<td>- / - %</td>
<td>- / - %</td>
<td>- / - %</td>
<td>- / - %</td>
<td>- / - %</td>
<td>33 / 100%</td>
<td>- / - %</td>
</tr>
<tr>
<td>2012</td>
<td>29</td>
<td>4</td>
<td>33</td>
<td>- / - %</td>
<td>- / - %</td>
<td>- / - %</td>
<td>- / - %</td>
<td>- / - %</td>
<td>33 / 100%</td>
<td>- / - %</td>
</tr>
<tr>
<td>2013</td>
<td>13</td>
<td>3</td>
<td>16</td>
<td>- / - %</td>
<td>- / - %</td>
<td>- / - %</td>
<td>- / - %</td>
<td>- / - %</td>
<td>16 / 100%</td>
<td>- / - %</td>
</tr>
</tbody>
</table>

4.5. Postdoc positions

- Postdocs are generally appointed for a 2-year period. They are offered the same possibilities to take courses as PhD students.

4.6. Technical support

- Technical staff are embedded in the laboratories, shared by several related research groups. The research groups share a joint responsibility for their technicians, which enhances flexibility and efficiency and allows the ratio of technical staff to scientific staff to be kept low.
- Tracks have joint, well-equipped workshops for quick adjustments and building of small experimental set-ups.
- For the design, engineering and construction of high-tech or complex equipment, the university operates the Equipment and Prototype Centre (EPC), a workshop which is well equipped for high-precision machining for mechanical constructions and design, and for stable, easy-to-align support structures.
5. Resources, funding and facilities

5.1. Overview of funding in 2007-2012

Table A.2.2. Funding at institutional and programme level

<table>
<thead>
<tr>
<th>Funding: (k€/%)</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>64%</td>
<td>62%</td>
<td>58%</td>
<td>58%</td>
<td>56%</td>
<td>49%</td>
</tr>
<tr>
<td>Research grants</td>
<td>2.036</td>
<td>2.171</td>
<td>2.904</td>
<td>3.405</td>
<td>3.773</td>
<td>4.570</td>
</tr>
<tr>
<td></td>
<td>11%</td>
<td>11%</td>
<td>13%</td>
<td>15%</td>
<td>17%</td>
<td>20%</td>
</tr>
<tr>
<td>Contract research</td>
<td>4.766</td>
<td>4.941</td>
<td>6.201</td>
<td>6.485</td>
<td>5.840</td>
<td>7.258</td>
</tr>
<tr>
<td></td>
<td>25%</td>
<td>26%</td>
<td>29%</td>
<td>28%</td>
<td>27%</td>
<td>31%</td>
</tr>
<tr>
<td>Total funding</td>
<td>18.948</td>
<td>18.930</td>
<td>21.755</td>
<td>23.326</td>
<td>22.021</td>
<td>23.239</td>
</tr>
<tr>
<td></td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

• The direct internal government funding allocated by the university Executive Board fluctuates in time due to forced central cost-cutting actions leading to decreasing funding. This is compensated by a rising budget through the growing number of PhD theses and MSc diplomas, and by direct support for excellent new groups by the university Executive Board.

• External funding by research grants and contracts almost doubled in the evaluation period (125% increase in research funding and 50% in contracts). This illustrates the increasing strength of the groups in terms of valorisation and collaborations with industry.

• Meanwhile the external funding ratio has reached the value of 50% of the total funding of the department. The success of our groups in attracting external funds partially compensates the limited and decreasing direct government funding.

• At present, the net effect of the direct funding for Dutch universities is that the government provides the salaries of the permanent faculty members and supporting staff, and the costs of the buildings that are empty but including heating and lighting. All other funds are to be acquired externally.

• To promote the acquisition of external projects, the Departmental Board has adopted a policy of not levying overheads on the additional funding that ultimately provides the infrastructure and temporary manpower needed to actually carry out the research.

5.2. Housing and infrastructure

• The research groups have an excellent laboratory infrastructure. In the assessment period the department and its groups have substantially renewed the experimental facilities, partly from the direct funding budget. The department also finances an in-house ICT support group.

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2 Direct funding is defined here as all funds acquired from the TU/e Executive Board. This is spent after splitting it into five categories as indicated in Section 2.3, and therefore does not correspond to the total direct funding at programme level because it also contains funding for educational and organisational costs.

3 Research grants are defined as funding from National Science Foundation (NWO/FOM/STW) and ERC.

4 Contract research is defined here as funds related to EU (FP6/7), Economic Affairs, LTIs and industry.
• The department acquired considerable extra funds of approximately 7 M€ to substantially improve the working conditions by introducing air, light and space in the 25 year-old building. An extra amount of approximately 1200 m² of office space for scientific staff, students and PhD student was created within existing facilities. In addition, the physical connections between the north and south wings of our buildings were enlarged and opened up to improve mutual contacts and interactions between researchers in different disciplines and laboratories.

6. Research output and quality

6.1. Publications and citations

• Journal publications
The number of journal publications has increased by an average rate of almost 10% per year over the last period, leading to a total increase of 64% from 2007 to 2012. In the same period the tenured scientific staff also increased by 25%. This indicates an increase in the number of journal publications per scientific research staff member (fte) per year from 6.7 to 8.8. The number of PhD theses per scientific research staff (fte) per year shows a somewhat lower increase from 1.55 to 1.65.

<table>
<thead>
<tr>
<th>Publications</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>6 year total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Academic publications</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refereed articles</td>
<td>128</td>
<td>166</td>
<td>165</td>
<td>175</td>
<td>148</td>
<td>205</td>
<td>987</td>
</tr>
<tr>
<td>Conference proceedings</td>
<td>166</td>
<td>171</td>
<td>191</td>
<td>153</td>
<td>159</td>
<td>129</td>
<td>969</td>
</tr>
<tr>
<td>PhD theses</td>
<td>28</td>
<td>24</td>
<td>22</td>
<td>19</td>
<td>29</td>
<td>33</td>
<td>155</td>
</tr>
<tr>
<td>Books</td>
<td>-</td>
<td>1</td>
<td>2</td>
<td>5</td>
<td>1</td>
<td>4</td>
<td>13</td>
</tr>
<tr>
<td>Book chapters</td>
<td>19</td>
<td>6</td>
<td>23</td>
<td>19</td>
<td>11</td>
<td>15</td>
<td>93</td>
</tr>
<tr>
<td>Total academic publications</td>
<td>341</td>
<td>368</td>
<td>403</td>
<td>371</td>
<td>348</td>
<td>386</td>
<td>2217</td>
</tr>
<tr>
<td>Patents</td>
<td>17</td>
<td>14</td>
<td>10</td>
<td>8</td>
<td>6</td>
<td>3</td>
<td>58</td>
</tr>
<tr>
<td>Total research output</td>
<td>358</td>
<td>382</td>
<td>413</td>
<td>379</td>
<td>354</td>
<td>389</td>
<td>2275</td>
</tr>
</tbody>
</table>

• Citation analysis
The world average citation impact of the ME department as a whole, according to the CWTS bibliometric studies, is up to 35% above world average, MNCS=1.35 in the period 2002-2011. The MNCS indicator of the department’s publications shows a slight decrease from 1.40 in the period 2002-2005 to 1.26 in the period 2008-2011. The total impact of the research related to the MNCS multiplied with the total output strongly increased, due to the strong increase in the number of journal papers. The department publishes in journals of high impact as shown by the journal impact factor MNJS=1.21 in the period 2001-2011, remaining virtually constant over time.
6.2. Scientific reputation

National and international scientific recognition of the department is related to the recognition and reputation of the faculty members, as shown by the large number of awards, memberships of editorial boards, presented in the self-evaluation reports by the programmes. Some important examples are:

- Prof. De Goey (CT, 2010) is the recipient of the STW-Simon Stevin Meester Award;
- Prof. Heemels received a Vici grant (CST, 2010);
- Three researchers, dr. Lefeber (MN, 2007), dr. Van Oijen (CT, 2011) and dr. Hoefnagels (MM, 2012), have received a Vidi grant;
- Three researchers, dr. Van der Zee (MEFD, 2010), dr. Van Dommelen (MM, 2008) and dr. Verhoosel (MEFD, 2011), received a Veni grant; in 2013 two more Veni grants were received by dr. Oomen and dr. Felici, both CST;
- Dr. Bellouard (2012) and dr. Luttge (2011) received an ERC starting grant;
- Prof. Geers was appointed Euromech Fellow (2012) and received the Advanced ERC grant (2013);
- Prof. Steinbuch was appointed Distinguished university professor (2013).

7. Societal relevance: quality, impact and valorisation

7.1. Societal quality and impact of the research

To enhance the quality and maximise the societal impact of our research, the policy of the department is to focus strongly on the following areas:

- Contribution to research on major societal challenges
- Enhance interaction between research and education
- Collaboration with industry

**Societal impact: Strategic Research Areas**

Mechanical Engineering is actively involved in TU/e's Strategic Research Areas (SA), with 65% of the PhD students working in areas related to these three areas. ME is the leading department of the Smart Mobility and the Energy Strategic Areas. Prof. Steinbuch is one of the coordinators of the Smart Mobility Strategic Area, while prof. Smeulders is Scientific Director of the Eindhoven Energy Institute and prof. de Goey is theme leader Future Fuels in the associated Energy Strategic Area.

**Societal impact: enhance interaction between research and education**

- In recent years it has become clear that society needs more distinct profiles among the engineers we educate. The TU/e Executive Board has therefore decided to introduce the TU/e Bachelor College, which integrates the Bachelor's education at TU/e. One of the key ideas is that students can more broadly design their own educational track and their own career path, enabling combinations of several disciplines and skills. So far this has been quite successful, as the inflow of students has increased significantly (e.g. from 180 in 2011 to 250 in 2013 in the ME Bachelor's), and the study efficiency has also increased.
• The ME department has introduced three new cross-disciplinary Master’s programmes: Automotive Technology (AT), Sustainable Energy (SET) and Systems & Control (S&C). AT and SET fit well with the Smart Mobility and Energy Strategic Areas. A new Bachelor’s in Automotive Engineering has also been started in 2011 by the Electrical Engineering department, with a strong contribution by ME to create a full educational AT curriculum. A two-year PDEng programme in Automotive Systems Design has been launched by the Mathematics & Computer Science department, again in close collaboration with the ME department. Prof. Steinbuch is director of the Graduate Program Automotive Systems (Master’s AT & PDEng ASD).

• New cross-disciplinary research topics within these fields are currently being initiated throughout TU/e to support these new educational lines.

• The 3TU S&C Master’s has been introduced to educate students in the high-tech systems field, again in line with the goals of the industry within Brainport.

Societal impact: collaborations with industry
Mechanical Engineering actively participates in the following consortia:

• **Brainport**, the local industrial clustering in the South-East Brabant region. The establishment of Brainport inspired Philips Electronics to establish the new High-Tech Campus, and TNO Industry to move from Delft to Eindhoven to integrate its research and development activities on the TU/e campus. More recently, Solliance (TNO, TU/e, Holst Centre and ECN) and DIFFER (FOM institute for fundamental energy research of fusion and solar fuels plan to move to the TU/e campus soon) are examples of new joint initiatives that create opportunities to enhance collaborations with industry.

• The **Leading Technological Institutes** in polymers (DPI) and materials (M2i), which were initiated through an industrial initiative and finally selected for relevance and past performance.

• **Strategic Partnerships** with strong industrial parties like DSM (joint institute InSciTe), ASML (joint High-Tech Equipment Institute, prof. Steinbuch is one of the co-ordinators), DAF and Shell.

• Top Sectors such as **Energy, High-Tech Systems and Materials**, new funding models by government to finance innovative research in collaboration with industry.

It is clear that the research groups each have their own industrial networks, which are increasing in strength as shown by the growth in contract and research funds by almost a factor of 2.

7.2. Valorisation of the work

The department actively encourages faculty members in the valorisation of their research activities. The acquired strong valorisation potential is apparent from the increasing level of collaborations with industry within the different groups, and this is also shown by the increase in external funding. Additionally, the department follows an active policy of initiating, accommodating and supporting spin-offs companies and student teams. This policy has been instrumental in acquiring strong external visibility, in triggering successes of student teams and in initiating a significant number of spin-off companies:
• 3 successful student teams:
  1. Tech United, the world champions in the Middle Size League of the RoboCup 2012 robot soccer competition
  2. URE, University Racing Eindhoven

• 8 newly created spin-offs in the current evaluation period:
  1. IME Technologies (dr. van Helvoirt MSc/R. Solberg MSc)
  2. Sorama (dr. Scholte/Locht MSc MBA)
  3. Progression Industry (dr. M. Boot/Arts MSc)
  4. Fistuca (J. Winkes MSc)
  5. Heat Power (dr. H. Ouwerkerk)
  6. Express Precision Engineering (dr. E. Bos/E. Treffers MSc)
  7. Optimal Forming Solutions (dr. S. Boers)
  8. Medical Robotics (dr. G. Naus/dr. T. Meenink/M. Beelen MSc)

8. Strategy

The description of our strategy starts with a short evaluation of the actions resulting from the previous evaluation, and continues with plans for continuation and plans for the future, based on a SWOT analysis.

8.1. Strategy followed since the previous evaluation

The committee appointed for the research evaluation in 2002-2007 shared the following observations for the ME department of TU/e:

• Department shows excellent leadership.
• Department has a very good structure in terms of divisions, labs and themes.
• Labs and facilities are world class with the highest standard.
• There are good collaborations between the groups.
• The plan to appoint 3 to 4 new professors was appreciated.
• Micro-systems and Numerical Methods in Engineering are important new fields.
• The programmes are well supported by TU/e (direct funding).
• Research funding is moderate and could improve.
• Societal relevance is very good.
• Academic reputation is mostly excellent, the output also.
• Staff/student ratio is high.
• Attention for high-risk, curiosity-driven research.

As a follow-up to these comments, the Departmental Board initiated the following actions:
• In line with the plans, new sections on Micro-Systems, Multi-scale Engineering Fluid Dynamics and Structure and Rheology of Complex Fluids were established.
• 7 new full professors were appointed in the evaluation period, while only 2 full professors retired.
• Initiatives and efforts have been undertaken to increase research funding, which resulted in an increase of the research funds by 125%.
• The scientific staff have been increased by 25%. However the number of students increased even more.
• Until recently, 1-2 direct funded PhD students were funded per group to initiate high-risk, curiosity-driven research. Due to direct funding limitations, this policy was discontinued in 2012. On the other hand, the increase in the research funded by ERC, Veni-Vidi-Vici and STW provides new possibilities in this respect.

8.2. Continuation strategy

Additionally, the department initiated the following plans to form a continuous solid basis on which the research and education within the department is established:

• The Polymer Technology chair holder, prof. Meijer, will retire in April 2014 and measures have been taken to continue this successful programme. In addition to the appointment of prof. Anderson as chair of the Polymer Fluid Mechanics in January 2012, a procedure has been started for a new chair in Polymer Solid Mechanics. Until a suitable candidate is found, prof. Peters, to whom a personal professorship chair on Rheology has been granted, can and will act as temporary section chair. In the meantime the Polymer Solid Mechanics group has been strengthened by the tenure appointments of dr. Hütter and dr. Van Breemen.
• The Process Technology chair holder, prof. Brouwers, will retire in October 2014. A procedure will be started soon to attract a new highly qualified chair holder. Prof. Kuerten, part-time professor at the University of Twente and associate professor in the Process Technology group, will temporary chair the group until a new successor is in place.
• A new chair position will be created in between the CST and DCT sections of the DSD track. This will help spreading the teaching and research.
• Despite the increasing number of full professors, the pressure on the group management tends to remain high due to the increasing administrative workload. Time for the professors to focus on their own further development therefore tends to be limited. To improve this situation, the department started the policy of appointing more personal professors embedded in the research groups. As well as having greater responsibility for their own research, these personal professors will assist the section chairs in their research and managerial tasks. Highly qualified staff are available in the department.
• In 2013 an industrial advisory board was appointed with key players from the Dutch industry. Their recommendations will be used to formulate future policy measures to further strengthen the research and education.

8.3. Strategy for the future based on SWOT analysis

The following SWOT analysis forms the basis of the additional strategic plans for the future.

Major Strengths of the department:

General
• The department is proud that its research and education are strongly interconnected. This provides optimal conditions for the educational tracks within the Mechanical Engineering programme and for commissioning the 3TU MSc programmes on Sustainable Energy Technology and Systems & Control, as well as for the interdepartmental Automotive Technology programme.
Excellent personnel and stimulating culture

- The department has dedicated, highly motivated and well-qualified staff.
- A stimulating positive academic atmosphere with open communication lines and a collaborative attitude in research and education is present among the professors and the scientific staff. The more open and transparent renovated Gemini buildings also contribute to the positive atmosphere.
- The research groups are discipline-oriented, rather than application-oriented, and therefore have a high resilience to rapid changes in subject areas that are en vogue in government and/or industry. The past has shown that our organisation is capable of adapting in a smooth, flexible way to new challenges and opportunities, for example the need for discipline-oriented research groups and more inter-disciplinarity, while preserving their own clear identities.
- The flat organisational structure with a manageable number of research groups results in optimal efficiency, good and fast communication, and a sense of shared responsibility.

Finance

- The financial situation is sufficiently strong and solid, with a sound and increasing share of external funding, while the support organisation is lean and efficient.

Excellent research

- The research is at an excellent level from both a scientific (see CWTS citation analysis) and an application point of view, as a result of our close relationships and interactions with industry.
- The tremendous innovation potential of the research is evidenced by the large number of innovations, spin-off companies and successful student teams initiated.
- The laboratory facilities are mostly world-class, and are frequently upgraded or renewed.

Strong external participation

There is a strong participation, and in many cases leadership, in two of the four nationwide Leading Technological Institutes, and in three of the six 3TU Centres of Excellence. The strong participation in the Strategic Areas of the university indicates that the department and its professors play a key role in the strategic agenda of the TU/e.

Strong connection with industry and research institutes, both nationally and internationally.

As main Weaknesses of the Department, we note:

- In line with governmental policy on gender equality, the TU/e Executive Board has formulated quantitative goals for the appointment of female researchers by the department. The number of female (assistant/associate/full) professors is growing, but is still lower than desired despite the measures taken so far.

Opportunities are:

- Funding structures to appoint female researchers: e.g. at TU/e level, WISE (Women in Science) grants are available, which support them with 50% of their salary costs.
- The use of high-tech facilities and knowledge in the Brainport region. Expertise within industrial parties can be used to strengthen our research and evaluation further.
- Opportunities for collaborative research funding (Horizon2020 & KIC) and personal grants (ERC) at EU level. Due to our successes in national funding, the participation in EU funding communities leaves room for extension. EU funding could become more important in the future because of the decreasing national funding possibilities.
The upcoming move of the DIFFER institute on fundamental energy-related research to the TU/e campus.

**Threats are:**
- Decreasing direct and research funding at national level. In addition, the changing innovation climate in the Netherlands is causing a gradual shift of the funding agencies towards more applied research. This tends to act as a barrier to fundamental, high-risk and curiosity-driven research, which is the typical incubator for new, long-term applications.
- The research quality has proved to be stable in the evaluation period as shown by the (minor decrease in the) MNCS citation index. A further rapid increase in future output could lead to dilution effects and a decreasing quality.
- The recent growth of the scientific staff has been insufficient to fully compensate for the increasing student numbers. Due to the pressure on the direct funding sources it remains difficult to attract the required additional talented staff to compensate for this growth. However, there is still some room for new appointments.

Based on the SWOT analysis, our **Strategy** will also address the following advices:

- Apply the knowledge in the department to start more spin-off companies.
- Use our strong connections with industry to join more collaborative research funding initiatives at EU level.
- Encourage and coach promising young faculty members to apply for personal grants, which will reduce pressure on direct funding if successful. The experience gained with personal grants (Veni-Vidi-Vici & ERC) will be helpful in this initiative.
- Stabilise the output around values of 2.5 students/scientific staff member, 1 journal paper and 1 refereed proceedings paper per year per PhD student on average to focus more on quality and to enable an increase of the citation indicators.
- Focus more on the appointment of female faculty members. The department started an open competition in 2013 among the new research groups for attracting at least one excellent young female young researcher each year.
Section B: Documentation regarding the programs
TU/e 1: Control Systems Technology
TU/e 1: Control Systems Technology

1. Objective(s) and research area

1.1. Vision, mission and objective(s) of the programme

Our vision is that the major societal needs and challenges require a significant contribution by the Engineering Sciences in general and system theory, control engineering and mechatronics in particular. In our Control Systems Technology (CST) group we have chosen strategic focuses on applications in Energy (fusion plasmas), Health (robotics for care and cure), Smart Mobility (connected cars and clean vehicles) and High-tech Equipment (mechatronics), thereby creating natural links with the Brainport region Eindhoven and far beyond.

The mission of the CST group is to develop new methods and tools in the area of Systems Theory, Control Engineering and Mechatronics. The research focuses on understanding the fundamental system properties that determine the performance of mechanical engineering systems, and exploiting this knowledge for the design of the high-tech systems of the future. In particular, the research programme concentrates on performance-driven control and systems design, and develops robust and data-driven control theory, hybrid and networked systems theory, optimisation techniques and mechanical design principles aimed at high-performance motion systems, robotics, vehicle powertrains and control of plasma fusion as application areas.

The objective is to realise our mission by taking an internationally leading role in research, combining this with inspiring education for our students and actively supporting and initiating valorisation through spin-off companies as well as direct co-operation with industry.

1.2. Strategy

Inspired by our vision, mission and objective, our strategy aims at attaining leadership in research as well as playing an active role in education and co-operation with our surrounding high-tech industry. This strategy has proved highly successful in many aspects. In particular, we are proud to welcome each year an impressive number (40-50/year) of undergraduate students eager to finish their MSc studies in our group. All Master’s students participate in our research projects, and a large number of our PhD students are recruited from this group. As an important supplier of human capital and knowledge for the (global) high-tech industry, we have an extremely healthy portfolio of research projects, well spread over national (STW, FOM), international (EU) and bilateral (Industry) funding. While being this successful, we keep focused on investing in the quality of our people, who are our main asset.

1.3. Research area and subprogrammes

Our overall research strategy is focused on performance-driven design and control. The performance of a controlled system is defined as the extent to which the actual behaviour of the
system matches the intended behaviour, while being subject to disturbances acting on the system and variations in system dynamics. Performance requirements can be related, for instance, to the accurate tracking of a set-point (motion) or to the energy utilisation (hybrid vehicles). Fundamental properties that determine and possibly limit performance can be found in both external sources (disturbances acting on the system) and internal sources (system properties, controller properties, quality of sensors and actuators etc.). Only by an integrated design of both the mechatronic (hardware) system and the (software) controller can the highest performance requirements be achieved.

The engineering question underlying the design problem of high-performance systems is how to find the best combination of controller and system realisation such that the performance requirements are achieved for all prescribed situations (disturbances and system variations). The scientific question is how to exploit (model-based) insights into the fundamental properties of the system for systematic analysis and design, leading to a significant increase in the achievable performance. It is clear that the engineering question has a strong interrelationship with the scientific question, in which the former has the role of validation and inspiration for new directions of research. The research is structured in 5 subprogrammes.

1.3.1. Model-based Control, identification and Design of Motion Systems
Increasing performance requirements in motion systems necessitate taking the flexible, dynamic behaviour of these systems explicitly into account. New approaches are being investigated to exploit multiple additional actuators and sensors to actively compensate for system deformations. The increasing requirements justify an increased model dimensionality, complexity and accuracy, and associated control solutions. To enable this, we develop numerically reliable identification methods for complex systems with high-order dynamics and a large number of inputs and outputs. By connecting identification and robust control we can non-conservatively account for model uncertainty, and appropriately account for the system environment, such as by disturbance identification. New techniques based on identification and iterative learning control are being developed to accommodate reference-induced errors. Finally, the development of design principles for the mechanical design of high-tech systems, such as ultra-thin stages and adaptive optics systems, focuses on the research question of how to design for stiffness with high reproducibility and manufacturability, and sometimes for low cost and low thermal sensitivity. Applications are in the high-tech systems industry (ASML, Philips, Océ, FEI, various SMEs).

1.3.2. Hybrid and Networked Control Systems
In the design of many engineering systems it is no longer possible to develop the control system in isolation. Next-generation high-tech systems require tight coordination between computation, communication and control elements (the ‘cyber’ part) on the one hand, and physical processes such as heating, cooling, motion, vibrations etc. (the physical part) on the other hand. Despite the need for integrated design of these so-called cyber-physical systems (CPSs), the corresponding scientific disciplines have predominantly been developed independently. This separation of disciplines can no longer be sustained and urgently needs to be bridged. The CST group has taken up this tremendous challenge that has led to a strong scientific track record and a position as a key player in the field of CPSs in general and in (wireless) networked control systems (NCSs) in particular. Inspired by highly relevant applications including intelligent traffic systems with (wireless) vehicle-to-vehicle and vehicle-to-infrastructure communication, and resource-aware control for lithographic systems and automotive systems, new foundations have been developed for distributed control of physical systems over shared communication networks and resource-aware (event-triggered) control. These contributions are recognised worldwide as
highly innovative and ground-breaking. The mathematical modelling of NCS and CPS require both discrete and continuous model ingredients leading to an overall hybrid system description. The CST group provides important fundamental developments in the area of hybrid systems that directly connect to the essential challenges in the NCS and CPS applications. The methods are being developed in close co-operation with leading industries such as NXP, TNO Automotive, ASML, Technolution, FEI, Honeywell, Ford etc.

1.3.3. Robotics for Care and Cure
The Robotics for Care and Cure subprogramme aims to advance the state-of-the-art in robotics in health-related applications. To enable robots to perform a wide variety of household tasks we are investigating the cognitive abilities of domestic service robots. We have initiated the FP7 RoboEarth programme, in which a framework for a learning database for robots is being developed. For both the domestic (care) as well as the medical (cure) application field our group realises world-class design of high-performance robots (MidSize Turtle, Amigo, Sofie, PRECEYES, MicroSure etc). The use of predictive models during the design allows a highly integrated design process in which all relevant phenomena from different disciplines are taken into account, thereby also connecting to the subprogrammes 1.3.1 and 1.3.2. The success of this approach is evidenced by becoming world champion robot soccer in 2012, and the design of the eye-surgery robot PRECEYES, which can perform procedures that were not possible before. Finally, control synthesis methods for haptic master-slave systems are being investigated that can deal with uncertainty in operator and environmental conditions. In cure applications, the resulting controllers will allow the robot to copy the surgeon's movements and force at the same time, for a wide variety of surgeons and patients. In this field we have broad co-operations with medical academic hospitals and SME industries.

1.3.4. Automotive Powertrains
Driven by stringent legislation for CO2 and other pollutant emissions, the automotive industry faces enormous challenges to find a cost-efficient balance between drivability and energy-efficiency. The introduction of advanced fuel-efficient low-emission engine concepts requires closed-loop combustion control to enhance transient performance of the engine. Ultimately, this research is heading towards integrated powertrain control, in which energy and emissions management of the overall powertrain is fully integrated. Moreover, the research on slip control of Continuously Variable Transmissions (CVT) and new high-tech powertrain concepts for hybrid and electrical drive trains for passenger cars and commercial vehicles is resulting in new innovations. In particular, the hybridisation of automotive powertrains leads to challenging research questions regarding technology, topology and control design. Concurrent and integrated design from component to system level (co-design) enables significant gains in performance and cost reduction. To derive an efficient co-design method, the theoretical concepts of multidisciplinary optimisation and optimal control methods are adopted in combination with scalable models and adaptive surrogate modelling. The search for computational efficient optimisation techniques has led to contributions to optimal control theory. Many of the research results have been experimentally validated in our Automotive lab. The methods are also being implemented at DAF Trucks, Punch Powertrain, TNO Automotive, Bosch Transmissions and other industrial automotive partners.

1.3.5. Control of fusion plasmas
The future operation of the world’s largest nuclear fusion reactor ITER in France requires significant advances in control methods for fusion plasmas. Our main orientation is on the control of magneto-hydrodynamic instabilities and the control of distribution of the current density in the plasma, using new sensor designs, system identification and control oriented
modelling. Innovative control solutions for so-called MHD instabilities have been developed and tested in the TEXTOR (Jülich, Germany) and TCV (Lausanne, Switzerland) experimental fusion devices. The unique properties of the control-oriented plasma simulation code RAPTOR has allowed applications in state reconstruction, prediction and feedback controller design for the plasma current density profiles. A Veni grant has been gained for this work. An analysis method has been developed to determine the plasma boundaries from optical images, and the method has been applied in offline analysis of the boundaries of JET and MAST plasmas. Extended by spectroscopic data, the method can resolve the plasma equilibrium. In addition, a two-camera hyper-spectral imaging system has been developed and applied to plasma position control at TCV. The imaging is also expected to be applied to real-time observation of the state of the diverted plasma for exhaust control. Next to the plasma control activity, funding for 2 Goal Oriented Trainees (GOT-ITER) has been obtained in competition to work on the remote maintenance of ITER subsystems. Here, a strong link exists with the haptics activities within the Robotics subprogramme.

2. Composition of the research staff at programme level

In the past years we have seen a slight increase in tenured scientific staff from 2.2 to 2.7 fte, while in the same period the number of PhD students doubled (from 12.9 fte in 2007 to 24.3 fte in 2012). To cope with this increase in PhD numbers, which expresses our success with respect to the continuous increase in funding, we decided in early 2010 to hire more postdocs to support the advisory work of the tenured staff. A significant increase in non-tenured staff resulted; see the second line in Table 2.1a which also includes our new part-time professors. The CST group was one of the first to add non-tenured part-time researchers from industry at the assistant and associate professor levels. This was boosted by the knowledge workers arrangement (KWR), in which the CST group played an important initiating and stimulating role (see Section 8). The supporting staff include technicians who are instrumental for our five labs (Automotive, Motion, Construction & Mechanism, Medical Robotics BV and Robotics labs), and also include a programme manager for robotics. Table 2.1 shows an overview of the composition of the CST staff.

| Table 2.1a. Composition of research staff at programme level (fte) |
|-------------------|---|---|---|---|---|---|
|                  | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 |
| **TU/e 1: Control Systems Technology** |
| Tenured staff     | 2.2  | 2.4  | 2.3  | 2.6  | 2.6  | 2.7  |
| Non-tenured staff | 1.3  | 1.9  | 2.1  | 4.8  | 8.3  | 5.0  |
| PhD students      | 12.9 | 16.6 | 18.7 | 21.9 | 22.2 | 24.3 |
| **Total research staff** | **16.4** | **20.9** | **23.1** | **29.3** | **33.1** | **32.0** |
| Supporting staff  | 2.5  | 2.8  | 2.8  | 3.2  | 3.2  | 2.8  |
| Visiting fellows  | 7.8  | 4.0  | 0.1  |  -   |  -   | 0.9  |
| **Total staff**   | **26.7** | **27.7** | **26.0** | **32.5** | **36.3** | **35.7** |
Table 2.1b. Composition of research staff at programme level (numbers)

<table>
<thead>
<tr>
<th></th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TU/e 1: Control Systems Technology</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tenured staff</td>
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<td>7</td>
<td>7</td>
<td>7</td>
<td>7</td>
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<tr>
<td>Non-tenured staff</td>
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<td>6</td>
<td>5</td>
<td>13</td>
<td>15</td>
<td>8</td>
</tr>
<tr>
<td>PhD students</td>
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<td>25</td>
<td>30</td>
<td>33</td>
<td>33</td>
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<td><strong>Total research staff</strong></td>
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<td>42</td>
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<td>8</td>
<td>7</td>
<td>7</td>
<td>8</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>Visiting fellows</td>
<td>11</td>
<td>5</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>2</td>
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<tr>
<td><strong>Total staff</strong></td>
<td>51</td>
<td>50</td>
<td>51</td>
<td>61</td>
<td>63</td>
<td>57</td>
</tr>
</tbody>
</table>

3. Research environment and embedding

3.1. National positioning

**Internal TU/e**

The CST group co-operates actively with the Dynamics and Control (D&C) group, sharing several of the laboratory facilities: the DCT (Motion) laboratory, the AES (Automotive) lab, the Robotics lab and the Construction and Mechanisms lab. In addition, research co-operation exists with the Combustion Technology group within the department.

The group has joint research projects with various others groups within TU/e, such as the Plasma Fusion group (Applied Physics), the Electro-Mechanics, Electronic Systems and the Control Systems groups (all Electrical Engineering), the Human Technology Interaction group (Innovations Sciences) and the System Architecture and Networking group (Computer Science).

We participate in all three strategic areas, and have a pioneering role in the strategic area Smart Mobility. We were one of the founding fathers of the new Automotive educational programmes (BSc, MSc, PDEng). Steinbuch is the Director of the TU/e Graduate Program Automotive Systems. We are co-founder of the new TU/e High Tech Systems Center.

Through our RoboCup activities (Mid Size League, @Home) as well as by our support for the Automotive student teams (URE, Solar Team Eindhoven), we are initiating and promoting a large number of activities within TU/e, with both research and outreach impact.

**Dutch position**

The CST group actively participates in the Dutch Institute on Systems and Control (DISC) research school. Members of the group regularly act as teachers of PhD courses for DISC.

The group is a member of the 3TU.Centre of Excellence for Intelligent Mechatronic Systems, now called the 3TU Research Centre High-tech Systems (Delft, Eindhoven, Twente). Steinbuch has been the Scientific Director of this Centre since its start in 2006.
The CST group plays a far-reaching role in setting the research agenda in the Netherlands in the areas of High-tech Systems (PointOne innovation programme) and Automotive (HTAS\(^1\)), and recently the Top Sector HTSM\(^2\). Steinbuch is a member of the Executive Board of HTSM and a member of the Board of AutomotiveNL. The group is an active research partner for the Embedded Systems Institute (TNO).

The CST group was one of the initiators of the Dutch RoboNED network, a research network for robotics in the Netherlands that brings together SMEs, larger companies and knowledge institutes.

The CST group also was one of the initiators of a recently approved STW Perspectief Program on Cyber-Physical Systems throughout the Netherlands (29 PhD students) with important contributions from industries such as ASML, Océ, Philips, FEI, NXP, Technolution and many others.

### 3.2. International positioning

The CST group actively participates in the relevant international communities such as the Control Systems Society of the IEEE as well as the various technical committees of IFAC. As a group, we play a very active and recognized role at the two major conferences in the control systems field: ACC and CDC, but also at specific conferences related to system identification (SysID), mechatronics, hybrid systems (HSCC, ADHS) and networked control systems (NECSYS). In fact, in 2012 the IFAC Conference on Analysis and Design of Hybrid Systems (ADHS) was organised in Eindhoven (Heemels general chair). In addition, our various editorial roles for top journals underline the group’s commitment to and importance for the control and mechatronics community. Within the precision technological area we are active participants in the Euspen conference, including contributions by demos.

The CST group participates in various EU projects such as R3COP, R5COP, Artemis, WIDE, MOBYDIC etc. We are the PI of the EU project RoboEarth (4.5 M€). The group participates in the Network of Excellence HYCON\(^1\), and its predecessor HYCON, a network around the theme of Hybrid Control Systems, which comprises more than 20 universities and research institutes.

During the past period we established a strong position for our group in the international plasma fusion community, and we participate through FOM-DIFFER in the activities of the European Fusion Development Agreement (now EUROFUSION). We organised two control-oriented fusion workshops (Eindhoven and Leiden) with the participation of all leading groups in this area. Strong evidence of our growing success in this research field is our increasing role in the European experimental programmes, reflected in the application of our control solutions at European Medium Sized Tokamaks (ASDEX-Upgrade, TCV), in the Japanese Stellerator LHD and in ITER and its successor DEMO.

During the past years we have been very active and successful in the RoboCup community, being a finalist in the Mid Size League for 6 consecutive years, and becoming world champion in 2012. This has resulted in the organisation of the RoboCup World Championships (chaired by Van de Molengraft) and the RoboCup Scientific Conference in Eindhoven in 2013. RoboCup 2013 attracted 40,000 visitors and the queen of the Netherlands as guest of honour.

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\(^1\) High-Tech Automotive Systems

\(^2\) High-Tech Systems and Materials
In the reporting period, several guests were hosted in the CST for longer research visits (>3 months): Egon Geerardyn (VUB, Oct.-Nov. 2012), Dr. C. Fontaine (University of Valenciennes, France, Sept.-Nov., Feb.-Apr. 2012), Prof. Jamal Daafouz (July 2008, Apr. and July 2010, Mar.-Apr. 2011, Feb. 2013) and prof. Pierre Riedinger (Feb.-July 2012) both of the University of Nancy, France, and Dr. Jan Richter (Oct. 2007-Feb. 2008) of Bochum University, Germany.

The group maintains sustained scientific collaborations with several recognised research teams (which have resulted in joint publications and shorter visits): Herman Bruyninckx, KU Leuven, Belgium; Jamal Daafouz and Romain Postoyan, University of Nancy, France; Sebastien Delprat, University of Valenciennes, France; Alain Bouscayrol, University of Lille, France; Lino Guzzella and Raffaello D’Andrea, ETH Zürich, Switzerland; Oliver Zweigle, Universität Stuttgart, Germany; Andy Teel and João Hespanha, University of California, Santa Barbara, USA; Carlos Silvestre, Instituto Superior Tecnico, Lisbon, Portugal; Abhyudai Singh, University of Delaware, USA; Håkan Hjalmarsson and Cristian R. Rojas, KTH Stockholm, Sweden; Egon Geerardyn and Johan Schoukens, VUB Brussel, Belgium; Adrian Wills and Brett Ninness, University of Newcastle, Australia; Jan Lunze, University of Bochum, Germany; Dragan Nesic, University of Melbourne, Australia; Alberto Bemporad, IMT Lucca, Italy.

Most faculty members of the group have spent longer research periods (>3 months) abroad: KU Leuven (Van de Molengraft), ETH Zürich (Hofman), EPFL Lausanne (Felici), KTH Stockholm (Oomen), University of Newcastle (Oomen), UCSB, Santa Barbara (Heemels).

4. Quality and scientific relevance

The CWTS analysis covers 132 papers (total number of journals is 177, see Table 5.1). The most important MNCS number is 1.49.

4.1. Most significant results/highlights

With respect to our quality, an important recognition is the prestigious Vici grant for Heemels, awarded in 2010. Because the proposals were written and submitted in the reporting period, we are also proud to mention the two Veni grants for Oomen and Felici that were awarded in 2013. Also, in the reporting period we started our work on the control of fusion plasmas, and we are proud to mention the important role we gained in the international plasma research community as an engineering group among the predominantly physics groups. This important role is evidenced by the fact that we were granted 6 FOM sponsored PhD students. Furthermore, the plenary lectures given at the SYSID 2012, MSC2013 and the ACC 2013 by Steinbuch, the (semi-)plenary lectures by Heemels at NMPC 2012 and ECC 2014, and the session on plasma control at the European Fusion Physics Workshop led by De Baar all further confirm the international visibility of our research results. The design and realisation of the unique eye surgical robot PRECEYES, which is now close to the next (industrial) phase, has attracted a lot of attention worldwide. Last but not least, we became World Champion in Robot Soccer in 2012!
4.2. Key publications


4.3. Number of articles in top 10% and top 25% of publications relevant to the discipline

Of the analysed papers by the CWTS citation analysis, 17% are in the top 10%, and 40% are in the top 25%. This shows our impact is well above the world average.

4.4. Most important books or chapters of books


5. Output

5.1. Number of publications

The output of the CST group in the reporting period is shown in Table 5.1. The average number of refereed journal papers equals 30/year. The ratio refereed journal papers/conference papers is 0.6 (177/315). The ratio of journal papers and research staff (fte, line 1 in Table 2.1a), yields the number 1.2 (177/155) which is indeed above our set-point of at least 1.0. The number of PhD theses equals 5/year resulting in almost 6 journal papers (177/31) per thesis. However, given an average (and target!) of 3 journal papers per PhD, this number of 6 indicates that we also generate scientific output independent of our PhD student projects. This includes contributions from our scientific staff, our master’s students and postdocs. The number of patents meets our ambition and contributes to our valorisation.

Table 5.1. Number of academic publications and other research output

<table>
<thead>
<tr>
<th>Publications</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>6 year total</th>
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<tr>
<td>Academic publications</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refereed articles</td>
<td>22</td>
<td>32</td>
<td>32</td>
<td>30</td>
<td>26</td>
<td>35</td>
<td>177 (54)</td>
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<tr>
<td>Conf. papers</td>
<td>70</td>
<td>63</td>
<td>69</td>
<td>48</td>
<td>34</td>
<td>31</td>
<td>315 (83)</td>
</tr>
<tr>
<td>PhD theses</td>
<td>8</td>
<td>3</td>
<td>4</td>
<td>7</td>
<td>6</td>
<td>3</td>
<td>31</td>
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<td>Book chapters</td>
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<td>9</td>
<td>6</td>
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<td>23 (9)</td>
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<td>Total academic publications</td>
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<td>546 (146)</td>
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<td>Patents</td>
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<td>6</td>
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<tr>
<td>Total research output (3)</td>
<td>107</td>
<td>100</td>
<td>115</td>
<td>91</td>
<td>68</td>
<td>71</td>
<td>552 (147)</td>
</tr>
</tbody>
</table>

(#) numbers between brackets represent papers in collaboration with other groups.

5.2. Number of PhDs (completed and in progress)

Table 5.2 shows the PhD efficiency by analysing the data of PhD students who started in the previous and current period. The gender issue has attracted our attention in the recent years, and we are attracting more female PhD students (currently 2). We experienced 1 student (out of a total of 56 PhD students) who stopped (after two years). Overall, 7 students managed to hold the formal defence within the 4-year period. The average length of the PhD period is 4.3 years until concept completion, and 4.6 years until the defence. The numbers reduce to 4.2 and 4.5, respectively, if we compensate for the additional 6 months (approved by the Departmental Board) that 6 PhD students were granted because of their active participation in the RoboCup activities.

All our PhD students take part in the ‘PROOF’ programme, which is a training series on professional skills such as technical writing in English, presentation techniques, planning skills, coaching of MSc students etc.
Table 5.2. PhD students

<table>
<thead>
<tr>
<th>Starting year</th>
<th>Enrolment (male/female)</th>
<th>Total</th>
<th>Graduated after (years)</th>
<th>Total</th>
<th>Not yet discontinued</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>M</td>
<td>F</td>
<td></td>
<td>≤ 4</td>
<td>4- ≤ 5</td>
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<tr>
<td>2003</td>
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<td>2012</td>
<td>6</td>
<td>-</td>
<td>6</td>
<td>-</td>
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</tr>
</tbody>
</table>

6. Resources

6.1. Overview of the various sources of funding

The CST group has a very healthy financial position. The research funding that we have gained amounts to 13.3 M€, which is on average 2.2 M€/year. This is approximately 20% of the direct/indirect funding acquired by the Mechanical Engineering department, which we realise with only 13% of the department’s tenured staff. Table 5.2 shows a research funding ratio of 897 k€/fte tenured staff.

Table 6.1. Funding at programme level

<table>
<thead>
<tr>
<th>Funding</th>
<th>2007 k€</th>
<th>2008 k€</th>
<th>2009 k€</th>
<th>2010 k€</th>
<th>2011 k€</th>
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<td>13.3</td>
<td>262</td>
<td>15.4</td>
<td>326</td>
<td>13.3</td>
</tr>
<tr>
<td>Industry &amp; contract research</td>
<td>1275</td>
<td>86.7</td>
<td>1464</td>
<td>84.6</td>
<td>2124</td>
<td>86.7</td>
</tr>
<tr>
<td>Total funding</td>
<td>1470</td>
<td>100</td>
<td>1709</td>
<td>100</td>
<td>2450</td>
<td>100</td>
</tr>
</tbody>
</table>

It is interesting to note the increase in the public/industry funding ratio, up to 1/3 in 2012. This ratio was a point of attention raised by the previous assessment committee. It is now clearly above our target of 1/5, and is mainly due to the Vici of Heemels and our new FOM funding. STW funding is on target. Within the industrial and contract research, we are happy to have a number of industrial partners that are willing to fund our research through bilateral agreements (without additional governmental support, thereby demonstrating the apparent and direct relevance of our research). The CST group is also very active within various EU projects and programmes.
6.2. Research facilities & investments

The Motion (DCT) laboratory. The DCT laboratory is a joint laboratory of the CST and D&C groups. It provides a combined educational and research facility for MSc and PhD student projects. In the past few years we have used an H drive pick-and-place system, an RRR robot manipulator, industrial pick-and-place units, a 1-DOF medical manipulator with force feedback etc. The (mechanical and electrical) technical staff provide support and create a stimulating environment for PhD and MSc students to carry out experiments in the Motion lab. The real-time hardware, data acquisition and measurement equipment includes EtherCAT-based portable data-acquisition systems that enable students to use their own notebook computers as real-time control processors, as well as dSpace and SigLab systems.

The Automotive Engineering Science (AES) laboratory. The renovated AES lab facility was opened in September 2003. Since then, with the help of TU/e, Paccar and other parties, we have been able to renew and extend many automotive testing facilities. These include an up-to-date controlled drum facility that enables reproducible fuel consumption testing at full vehicle scale and various tyre test facilities. A powertrain test rig is used to test new algorithms for CVT control, and it was used extensively for the Empact project, a new EM actuated and slip controlled CVT transmission.

The Constructions and Mechanisms (C&M) laboratory. The Constructions and Mechanisms laboratory is led by dr. Rosielle, who is working in both the CST and D&C groups. In this laboratory about 6-8 PhDs and 10 MSc students specialise in the design and construction of machines, instruments and robotic systems.

The Robotics laboratory. Because of the successful growth of the robotics activities, we opened a new Robotics lab in 2011 combining our haptics as well as our RoboCup activities and RoboEarth project activities. The lab has a playing field for the Mid Size RoboCup and a simulated hospital room for RoboEarth and domestic environments for @Home. Also all robotics related MSc and PhD students are located in an office area close to the experiments.

Medical Robotics B.V. Labs. Close to the C&M lab, we started the Medical Robotics B.V. Lab in 2012, with the Sofie Master-Slave robot for minimally invasive surgery, the eye surgical PRECEYES robot and the new MicroSure robot for reconstructive surgery. The lab is a common undertaking of the spin-off MRT BV and the CST group.
7. Academic reputation

More information is provided in the appendices.

**Prof.dr.ir. M. Steinbuch**
- Distinguished University Professor (2013+)
- Editor-in-Chief IFAC Mechatronics (2008+), Editor-at-Large European J. of Control (2004-2008)
- Member Scientific Advisory Board Linz Center for Mechatronics.

**Prof.dr.ir. W.P.M.H. Heemels**
- Associate Editor ‘Automatica’ (2009+) and ‘Nonlinear Analysis: Hybrid systems’ (2006-2010, 2014+)
- Vice-chair of the IFAC Technical Committee on Networked Control Systems (since 2011)
- Member EUCA (Administrative Council of the European Union Control Association) (2009-2011)
- General chair of IFAC ADHS 2012, IPC chair of IFAC NECSYS 2013, IPC co-chair ECC13
- Organiser and founding father of a successful series of biannual international PhD schools on hybrid and networked systems (since 2003 educating over 500 PhD students worldwide)
- Various IPC: HSCC07, ACC08, CDC08, HSCC08, ACC09, CDC09, HSCC09, ADHS09, HSCC10, CONET10, NECSYS12, NMPC12, CPSN13, ICCPS14, ECC14, WC14, CDC14.

**Dr.ir. M.J.G. van de Molengraft**
- Associate Editor IFAC Mechatronics (2008-2012)
- Member of the IFAC Technical Committee on Mechatronic Systems (2008+)
- Guest Editor of Special issue on Advances in intelligent robot design for the RoboCup Middle Size League, IFAC Mechatronics
- Guest Editor of Special issue Towards a World Wide Web for robots, IEEE Robotics and Automation Magazine

**Dr.ir. A.G. de Jager**
- Member IFAC Technical Committee 2.5 on Robust Control.

**Dr.ir. T. Hofman**
- Associate Editor Int. Journal of Electric and Hybrid Vehicles (2006+)
- IPC: CVT2010, VPPC 2009
- Co-organiser with prof. J. Gover (Kettering University, USA) on special session on ‘Future jobs in automotive engineering’ with new education demands for the future at the IEEE VPPC (2009).
- Member of the Modélisation Énergétique et Gestion d’Énergie des Véhicules Hybrides et électriques (MEGEVH) group, French network on Hybrid Electric Vehicles (HEVs).
Prof. dr. M. de Baar
- Leader ITER-NL work package 2: tearing mode control with and remote handling of ITER Upper port Electron Cyclotron Current Drive launcher (2007-2013)
- Member EFDA Scientific and Technical Advisory Committee (since 2011)
- Groupleader at FOM institute DIFFER.

Dr. ir. F. Willems
- Invited lecture at Workshop on Open Problems & Challenges in Automotive Control, UCLA Berkeley, CA, USA, 2011
- Organiser and tutorial lecture ‘Model-Based Powertrain Control for Diesels: An Industrial View’ at American Control Conference, Montreal, Canada, 2012
- Invited lecture at International Advanced Engine Control Symposium, Tianjin, China, 2011
- Member of IFAC Technical Committee Automotive Control.

Dr. ir. T. Oomen
- Guest Editor of Special issue on Precision Motion Control, IFAC Mechatronics.

Dr. ir. M. Heertjes
- Guest Editor of special issue on Precision Motion Control, IFAC Mechatronics and of special Issue on Performance of Nonlinear Control Systems, International Journal of Robust and Nonlinear Control, Volume 23, Number 10, July 2013
- Organiser and chair of the invited sessions ‘Advances in High-Precision Motion Stages’ at ACC 2013, Washington DC, and ’Control of High-Precision Motion Stages’ at ACC 2012, Montréal, Québec, Canada.

Awards
- Ngo Dac Viet won the best paper prize for the paper *Predictive Gear Shift Control for a Parallel Hybrid Electric Vehicle* at VPPC2011, Chicago.
- STW ‘Simon Stevin Gezel’ 2011 award for the PhD work of Linda van den Bedem of the Medical Robot Design ‘Sofie’.
- Hugo van de Brand won the Shell Master prizes for physics (2012).
- Cum laude PhD (top 5%) for M.C.F. Donkers (promoter: W.P.M.H. Heemels)
- Maurice Heemels received a personal VICI grant (1.5 MEuro) from NWO/STW in 2010
- Best performance award Systems & Control Benelux meeting 2007; Ir. Gert Witvoet
- ‘Van der Hoek Constructeurs’ 2007 award Rob van Haendel MSc thesis
• ‘Van der Hoek Constructeurs’ 2009 award Raimondo Cau MSc thesis
• KIVI Best thesis Mechanical Engineering award 2012 for Frank Boeren
• 2nd place, Aart-Jan van der Hoeven, Eric Bergshoeff, Emilia Silvas, Theo Hofman, Plug-in Hybrid Electric Vehicle (PHEV) Benchmark competition; IFAC Workshop on Engine and Powertrain Control, Simulation and Modeling, E-COSM 2012, IFP, Paris, France
• 2nd place Hybrid TukTuk Battle by ENVIU between the Dutch and Indian Universities organised at SRM University, Chennai, India (2009)
• RoboCup World Champion Mid Size League Robot Soccer 2012 (Mexico), 2nd in 2008 (China), 2nd in 2009 (Austria), 2nd in 2010 (Singapore), 2nd in 2011 (Turkey), 2nd in 2013 (Netherlands)
• RoboCup @Home 3rd in 2013 (Netherlands)

8. Societal relevance: quality, impact and valorisation

8.1. Societal quality of the work

Innovation programmes. The CST group participated in the IOP Precision Technology innovation programme, the Programme for High-tech Systems and the Mechatronics workgroup of the Point One Innovation programme (PPP, a > 100 M€ programme). Here, we discussed the future roadmaps of high-tech systems with OEMs and SMEs and made a significant contribution to these discussions as co-writer of the semicon/mechatronics/health and robotics roadmaps. The same holds for the PPP HTAS for the Automotive sector, in which we initiated research and education innovations (see next section). We also contributed significantly to the forming of the new Top Sector approach and had many discussions with the Ministry of Economic Affairs.

Knowledge workers arrangement (KWR). During the crisis of 2008, we initiated the idea of hosting industrial researchers and engineers within knowledge institutes to prevent unemployment. We came up with this idea in November 2008, and it was realised in early 2009 by the Dutch government in a 200 M€ programme for about 1500 engineers. Within our group we hosted 20 people from industry for about 1.5 years. Of these, 15 were from a single project (DAF Trucks and its suppliers) on the development of hybrid trucks. This was a perfect example of how engineers from industry can efficiently take time to do research and benefit from the knowledge available in our group. It also led to a successor in the form of an HTAS-funded research project with 4 PhD students at TU/e (2 in CST). In the same spirit we have been involved in KWR projects with Océ, Philips, ASML and various SMEs, as well as a number of follow-up projects. From this KWR period, we were also active in appointing part-time researchers from industry as part-time assistant or associate professors within our group.

Outreach. The robotic activities gave ample opportunities to show the relevance of technology and engineering for solving societal problems. With our RoboCup team we visited many primary schools to show children our robots. We were on Dutch national television many times, and we organised the Dutch RoboCup Open in 2012, as well as the RoboCup World Championships in Eindhoven in 2013. The latter event attracted an audience of more than 40 million viewers worldwide.

With our eye surgery robot PRECEYES we participated in the BBC Horizon broadcast on Robotics (2012), with millions of viewers worldwide. We also gave a TEDx ‘Binnenhof’ talk about our surgical robot, with an audience including the present king and queen of the Netherlands.
Electric Driving: Policy and Outreach. In the reporting period we started our activities, together with the D&C group and EE, in electric driving. As a result, Steinbuch became a member of the Dutch National Formula-E Team (FET), a group of stakeholders advising the Dutch government. Since then, many interviews have appeared in newspapers and professional journals, and on national radio and television. Steinbuch actively started a blog on these subjects (> 225k views since the start), and a Twitter account (> 5k followers), thereby promoting the inflow of students into the educational programs.

8.2. Societal impact of the work

Human Capital. Our most prominent and relevant contribution to society is formed by our students. In the reporting period more than 200 Master's students and 30 PhD students finished their studies within our group and started to work in industry or institutes. Our research is instrumental in providing them a good environment to prepare themselves for a professional life. Nowadays, having a degree from our group is seen by our surrounding industries and institutes as a mark of quality.

Medical Robotics. With our activities in medical robotics we are able to make more medical doctors aware of the possibilities of modern technology, and we see an increasing number of partnerships of CST with medical academic hospitals.

High-tech Industries. Our research results are being used in industry, for example: feed forward tuning and learning control (ASML, Philips, Océ), energy management (DAF, TNO), control of transmissions (Bosch, Punch Powertrains) and friction compensation (FEI).

Automotive Education. Our group was the initiator of a complete new line of education within TU/e: a new Bachelor's in Automotive (hosted by EE), a new Master's in Automotive Technology (hosted by ME) and a new PDEng in Automotive Systems Design (hosted by Computer Science). This is the first multidisciplinary programme, hosted by various departments and focusing on systems engineering, a long-standing wish of industry. Related to these developments, the group has also been active in making the link with the vocational education (MBO/HBO), realising a unique and frequently cited example of interconnecting innovation programmes and Top Sector research with education.

8.3. Valorisation of the work

Supporting Industry. Using the many contacts with industry we transfer knowledge through our people (MSc, PDEng and PhD level, see above), as well as direct transfer in projects. Examples are given above. In addition, we have already for many years been giving courses for industry ‘Motion Control’, ‘Advanced Motion Control’, and ‘Iterative Learning Control’ (in the reporting period > 1000 man-course-days). We have also given parts of these courses in Denmark and Switzerland. This has given us a respected and well-known position as the motion group.

Start-up Companies. As shown by Table 5.1, we are active in patents, primarily to support our spin-off activities. The CST group initiated IME Technologies BV, with two of our former students, with the aim of forming a short-term oriented consultancy activity around the section to enable fast transfer of knowledge to industry. The ME department liked the idea, and enlarged the initiative to department level. The CST group started also Medical Robotics Technologies (MRT) BV,
a 100% TU/e owned company as an incubator for new commercial activities in this field. The eye surgery robot will be launched soon as the new start-up PRECEYES BV. In the coming year we will transfer MRT BV into CST Innovations BV, with the original idea of acting as incubator and enabling short-term knowledge transfer to industry. We achieved a number of STW Valorisation Grants.

**Entrepreneurial Activities.** The CST group encourages its members to take roles in society, for non-profit organisations as well as in consultancy or entrepreneurial activities. For all these activities the members follow the formal ethical rules of TU/e.

### 9. Viability

The strong embedding within the TU/e as well as with the high-tech and automotive industry, and with the international physics plasma fusion society, enables us to attain a healthy amount of funding, well balanced between the various sources. We are able to continue our policy of being critical of what to do and with whom. In fact the funding gained also gave us the opportunity to invest in new (‘free’) PhD and postdoc projects, as well as in new start-ups such as MRT BV.

The groups’ structure is well-balanced in terms of young and mature researchers, as well as scientific and engineering capabilities. The younger people are encouraged to write their plans in the form of personal research grants, in 2010 we gained a Vici (Heemels) grant and in 2013 we were able to gain 2 Veni grants (Oomen and Felici). At the same time we gained EU funds, and we will continue to pursue this. For the coming period we will appoint a few new part-time full professors (one of them being prof. Herman Bruyninckx, KUL, Belgium) to balance the workload and to further improve our international visibility and/or our industrial embedding. Another significant opportunity will be the new TU/e institute the High-Tech Systems Center (HTSC), of which the CST group is one of the founding fathers.

### 10. SWOT analysis

Restating our objective from Section 1 to realise our mission (develop new methods and tools in the area of Systems Theory, Control Engineering and Mechatronics) by taking worldwide leadership in research, and combining this with inspiring education for our students, and by actively supporting and initiating valorisation, we see the following SWOT items for our group:

**Strengths**
- We now have a healthy balance between funding obtained in competition (indirect funding) and direct funding, see also the remark of the previous assessment.
- We have improved our journals/PhD ratio by a factor 2, compared with the previous assessment.
- We have a strong reputation in our research fields.
- We have further strengthened our role for the high-tech industry (doubled the funding).
- We continue to be attractive for students.
Weaknesses
• The CST group has become large, which make the internal co-operations less trivial
• Because we have so many MSc students within our own group, we are less eager to receive master students from other (international) groups
• Our gender diversity needs to be improved.

Opportunities
• We can benefit greatly from the TU/e focus on high-tech systems for the coming years
• We can benefit from the development of the Automotive Campus in Helmond
• We are in a very strong position to gain funding related to ITER and to the control design of its successor
• We are in a strong position to contribute to the need to make valorisation not only a ‘buzzword’, but also to contribute to the wealth of the Brainport region by our Human Capital agenda and our start-up initiatives.

Threats
• We are concerned about the Top Sector approach by the Dutch government. The move from specific towards generic funding leaves little money for demand-driven research. In addition, the appropriate processes for the allocation of funding have not (yet) been identified/implemented.
• Our size (20% of the ME external funding, 35% of the ME students, with 13% of the ME staff) creates an imbalance within the ME department.

11. Strategy for the coming period

Table 11.1. Strategy for the coming period

<table>
<thead>
<tr>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Opportunities</strong></td>
<td><strong>Weaknesses</strong></td>
</tr>
<tr>
<td>• participate in the new TU/e HTSC(^3)</td>
<td>• appoint new part-time full professors</td>
</tr>
<tr>
<td>• increase our role for ITER</td>
<td>• actively recruit female researchers</td>
</tr>
<tr>
<td>• participate in the Automotive Campus</td>
<td>• invest in CST as a group</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Threats</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>• generate ideas and influence policy-making on the Top Sector approach</td>
<td>• rethink the structure of the ME department and look for enlargement of the DSD part, i.e. define a new chair</td>
</tr>
<tr>
<td>• rethink the distribution model of MSc students within our department</td>
<td></td>
</tr>
</tbody>
</table>

\(^3\) High-Tech Systems Center
TU/e 2:
Dynamics and Control
1. Objective(s) and research area

1.1. Vision, mission and objective(s) of the programme

The mission of the programme is to conduct high-level research in the area of Dynamics and Control, with the emphasis on modeling, analysis and control of mechanical and mechatronic systems. Nonlinear dynamics and control, acoustics and robotics are among the focal areas of the programme. Fundamental research is combined with numerical tools and supported by dedicated laboratory experiments. Teaching at undergraduate and graduate levels, in the spirit of Humboldt, is a key integral part of the mission of the programme, to provide students with state-of-the-art knowledge of and skills in Dynamics and Control, certainly in the high-tech region that Eindhoven represents. This is a key scientific field which is relevant to many advanced applications, and is fostered by the development of the latest technologies in these application areas. Particularly the constantly increasing requirements for the efficiency, accuracy and reliability of these systems make it necessary to unravel detailed dynamic models for analysis, to develop advanced numerical tools for simulation, to develop automation strategies and to provide validation experiments. Although high-tech systems form a strong motivation of the group, the ultimate objectives are:

- to carry out world-class research in this field,
- to combine this with excellent teaching and courses at both Bachelor's and Master's levels in mechanical engineering, tailored to both the scientific state-of-the-art and the industrial state-of-practice,
- and to address societal and valorisation aspects of the research.

It is our vision that fulfilling our objectives makes key contributions to general research challenges, but particularly to the technological and societal challenges that we face from both industry and society.

The Dynamics and Control group takes its responsibility in teaching courses at BSc and MSc levels, including the compulsory courses in Dynamics (BSc, year 1), Mechanical Vibrations (BSc, year 2) and Applied Design Principles (BSc, year 3). A complete list of courses is given in the Appendix. In the period 2007-2012, 142 MSc students graduated in the Dynamics and Control group in Mechanical Engineering, Systems and Control or Automotive Technology.

1.2. Strategy

The Dynamics and Control group was established in 2000, and new staff were recruited in the subsequent years. The research programme is organised in a number of sub-themes, which will be described in detail later. Since its formation, the following steps are used as markers in the development of the group:
• Renew and update the teaching curriculum in dynamics and (nonlinear) control for the Bachelor's and Master's students in Mechanical Engineering
• Develop and support a research programme in Dynamics and Control that meets today's requirements and contains both fundamental and industrial appeal and challenges
• Renew and update the laboratory facilities to match the research and teaching goals
• Appoint new staff in accordance with the desired research and teaching goals

We have actively continued our development along the above lines, particularly encouraged by the positive feedback from the last research assessment. In fact, in the present period the group is involved in the new BSc programme in Mechanical Engineering (now in its 2nd year), the new MSc in Automotive Technology, the new MSc in Systems and Control, and the new BSc in Automotive Technology (now in its 3rd year), and finally the newly established PDEng in Automotive Systems Design. In addition, substantial developments have taken place in the field of robotics (for which a new robotics laboratory has been created), partly inspired by the activities around the RoboCup robot soccer world championship.

The dynamic properties of mechanical systems almost always involve physical and geometrical nonlinearities, possibly a large number of degrees of freedom with interactions between them, and often also a relatively high speed of operation. The combination of these properties easily leads to difficulties in modeling and analysis, and thereby also in successfully implementing a model-based controller design in practice. This is the basic challenge throughout the research in the Dynamics and Control group. Clearly, the ambition of the group is to work at the forefront of today's technology, and to aim at a highly recognisable research stature not only within the department, but also in the Netherlands and internationally. Against this background, the group focuses on the research areas such as those listed in the next subsection.

MSc and PhD projects are supervised using an ‘umbrella format’, in which in most cases a PhD student (or postdoc) acts as daily supervisor of an MSc student, while one of the permanent staff members are the daily supervisors of PhD students. About once a month a project team meeting is scheduled with the group head reviewing the project with MSc and PhD students.

Once a year the Dynamics and Control group together with the Control Systems Technology group organises a 24-hour off-campus DCT day for all staff, PhDs and technicians, during which intensive discussions about the development and future of the groups are held in a highly motivating environment. As well as the technical discussions for all participants and a poster competition, social activities are also an important part of this 24-hour meeting to further support teambuilding.

The Dynamics and Control group participates in the national research schools Engineering Mechanics (EM) and Dutch Institute on Systems and Control (DISC). Both research schools provide advanced graduate courses for PhD students in the broad area of dynamics and control. Both research schools have been accredited by the Royal Netherlands Academy of Arts and Sciences (KNAW). In 2012 and 2011 respectively, members of the group played an active role in the curriculum of EM and DISC. Almost all PhDs participate in the teaching programmes of EM and DISC.
1.3. Research area and sub-programmes

The Dynamics and Control group focuses on the following research themes:

1. Nonlinear dynamics of mechanical systems
2. (Structural) acoustics and noise control
3. Nonlinear control of Mechanical (motion) systems, synchronisation and robotics
4. Vehicle dynamics, tyre dynamics and control
5. Mechanical design

1. Nonlinear dynamics of mechanical systems

The analytical, numerical and experimental study of complex (nonlinear) mechanical systems, such as those experiencing friction or impact phenomena as well as those with a large number of degrees of freedom, are key activities in this sub-theme. Such systems play an essential role in the modeling and analysis of advanced mechanical systems. The research on these nonlinear phenomena is highly relevant to engineering applications (e.g. high-performance/high-precision systems, nonlinear cutting processes in drill strings, and high-speed milling, hybrid control systems, micro electro mechanical systems, vehicle dynamics etc.). The strength of the research in this theme is the combination of theoretical techniques and numerical tools for analysis with dedicated experimental studies, which jointly provides insight into how to tame or exploit nonlinearity in the design of mechanical systems.

2. (Structural) acoustics and noise control, optimisation

This sub-theme deals with structural vibrations and the associated sound radiation. Our research addresses, in particular, Near-field Acoustic Holography (NAH) and, more specifically, improving the accuracy and resolution of NAH and extending the formulation to localising sources in the presence of reflecting surfaces, temperature gradients or transient events. Benchmark applications are found in automotive (tyre-road noise), and in vibration detection for high-precision motion stages. The focus is on the one hand on numerical/computational tools for acoustic models, and on the other hand on the experimental validation of those tools, for example in the anechoic laboratory.

3. Nonlinear control of motion systems, synchronisation and robotics

In the nonlinear control area, the emphasis is on problems related to (i) stability, stabilisation and performance of nonlinear/non-smooth control systems; (ii) synchronisation/coordination of mechanical systems; and (iii) embedded and networked control of mechanical systems. There is particular interest in applications in robotic systems (such as teleoperation). Other fields of applications pursued in collaboration with industry are the control of high-precision motion systems, temperature control for lab-on-chips, and high-tech manufacturing and resource exploration processes. Here too the theoretical developments are combined with and supported by experimental validation in the robotics and DCT lab.

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 Jointly with Control Systems Technology
4. Vehicle dynamics, tyre dynamics and control
In the last five years an extensive effort has been made to conduct advanced research in this area, in collaboration with extensive laboratory testing equipment and vehicles from the AES lab. The research focus is on improved tyre dynamics modeling (beyond the standard tyre models), modeling and analysis of articulated (long and heavy) vehicles (LZVs), and building and developing an electric research vehicle for energy-efficient aspects in EVs. A subject that is intimately linked to the previous subject is the theme of ‘Connected Car’, in which cooperative and autonomous driving is investigated to support improved traffic flows on highways and increased fuel efficiency.

5. Mechanical design
The Constructions and Mechanisms subgroup focuses on a range of research questions in mechanical design. Design projects on position accuracy form a substantial part of the group’s work.

The above research themes provide a coherent representation of state-of-the-art research in the field, and although listed as separate lines there are often cross-links between the themes, for example nonlinear dynamics is linked to nonlinear control, and both are used in the robotics and vehicle dynamics application domains. Likewise, tyre-road noise forms an important research topic, and requires expertise in both acoustics and tyre dynamics.

Together, the general research objective of the Dynamics and Control Technology group is the study of all aspects related to the dynamics and control of high-performance mechanical systems. This covers the full range of topics such as design, modeling and analysis of systems, controller synthesis, signal analysis and performance analysis.

2. Composition of the research staff at programme level

Table 2.1a. Composition of research staff at programme level (fte)

<table>
<thead>
<tr>
<th></th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>TU/e 2: Dynamics and Control</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tenured staff (1)</td>
<td>1.6</td>
<td>2.1</td>
<td>2.2</td>
<td>2.2</td>
<td>2.2</td>
<td>1.9</td>
</tr>
<tr>
<td>Non-tenured staff (2)</td>
<td>0.4</td>
<td>0.4</td>
<td>0.6</td>
<td>0.5</td>
<td>0.5</td>
<td>0.2</td>
</tr>
<tr>
<td>PhD students (3)</td>
<td>7.1</td>
<td>7.5</td>
<td>8.6</td>
<td>12.0</td>
<td>13.4</td>
<td>13.6</td>
</tr>
<tr>
<td>External PhD students</td>
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<td>0.9</td>
<td>2.0</td>
<td>1.9</td>
<td>2.6</td>
<td>4.0</td>
</tr>
<tr>
<td>Postdocs</td>
<td>0.4</td>
<td>1.6</td>
<td>1.6</td>
<td>1.3</td>
<td>0.3</td>
<td>1.4</td>
</tr>
<tr>
<td><strong>Total research staff</strong></td>
<td><strong>10.3</strong></td>
<td><strong>12.5</strong></td>
<td><strong>15.0</strong></td>
<td><strong>17.9</strong></td>
<td><strong>18.9</strong></td>
<td><strong>21.1</strong></td>
</tr>
<tr>
<td>Supporting staff</td>
<td>5.7</td>
<td>5.3</td>
<td>5.9</td>
<td>5.0</td>
<td>5.6</td>
<td>5.4</td>
</tr>
<tr>
<td>Visiting fellows</td>
<td>0.5</td>
<td>0.3</td>
<td>0.3</td>
<td>0.5</td>
<td>0.5</td>
<td>1.3</td>
</tr>
<tr>
<td><strong>Total staff</strong></td>
<td><strong>16.5</strong></td>
<td><strong>18.1</strong></td>
<td><strong>21.2</strong></td>
<td><strong>23.4</strong></td>
<td><strong>25.0</strong></td>
<td><strong>27.9</strong></td>
</tr>
</tbody>
</table>

2 Jointly with Control Systems Technology
Table 2.1b. Composition of research staff at programme level (numbers)

<table>
<thead>
<tr>
<th>TU/e 2: Dynamics and Control</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
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<td>PhD students (3)</td>
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<tr>
<td><strong>Total research staff</strong></td>
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<td><strong>28</strong></td>
<td><strong>34</strong></td>
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<td>1</td>
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<tr>
<td><strong>Total staff</strong></td>
<td><strong>33</strong></td>
<td><strong>34</strong></td>
<td><strong>36</strong></td>
<td><strong>43</strong></td>
<td><strong>50</strong></td>
<td><strong>52</strong></td>
</tr>
</tbody>
</table>

3. Research environment and embedding

3.1. National positioning

Internal TU/e
Within the department, as stated above, the Dynamics and Control group collaborates with the Control Systems Technology group, sharing several of the laboratory facilities, notably the DCT laboratory, the AES lab, the Robotics lab and the Construction and Mechanisms lab. In addition, research cooperation exists with the Systems Engineering group, the Combustion Technology group, the Polymer Technology group and the Energy Technology group within the department. Cooperation has also been established with the Embedded Systems Institute (ESI) at TU/e. There are also other collaborations, for example with the groups of prof. Gert-Jan van Heijst (Applied Physics), prof. Kees van Hee (Computer Science), and prof. Elena Lomanova, prof. Henk Corporaal, prof. Paul van den Hof and Siep Weiland (Electrical Engineering). In all cases the collaboration is evidenced by joint MSc and PhD students and resulting joint papers.

In 2012 TU/e defined its main research areas in terms of three Strategic Areas: Health, Energy and Smart Mobility. The group is particularly active in the latter two areas. Some highlights of our contribution to these strategic areas will follow later.

National position
The Dynamics and Control group actively participates in the research schools Engineering Mechanics (EM) and Dutch Institute on Systems and Control (DISC). The quality of EM and DISC is underlined by the accreditation every 5 years of these graduate schools by the Royal Netherlands Academy of Arts and Sciences (KNAW), of which the latest evaluations took place in 2012 and 2011. Members of the group regularly act as teachers of PhD courses for EM and DISC. In addition, several of the group members have participated in courses set up by PAO (Post-Academic Education), KIVI (Royal Institute of Engineers in the Netherlands).
The group has been active and very successful in acquiring project funding nationally under the innovation programmes IOP Precision Technology, HTAS (High Tech Automotive Systems, sponsored by the Ministry of Economic Affairs via Agentschap NL), Point One (National platform for high-tech systems, sponsored by the Dutch Ministry of Economic Affairs) and Peaks in the Delta (sponsored by the Ministry of Economic Affairs via Agentschap NL), STW and NWO. Since 2012 the national innovation programmes have been discontinued, and newer forms of industrial-university collaboration are under development.

### 3.2. International positioning

#### International cooperation

The Dynamics and Control group and specifically members of the group are extensively involved in various international collaborative projects, ranging from various EU projects to more formal alignments with international institutions. In the review period a growing number of PhD students with their own funding have joined the group (CSC, China and CONACyT, Mexico). As well as the formalised collaborations, group members have extensively collaborated with fellow scientists resulting in joint journal and conference publications. A list of the main collaborators is given below.

At EU level, the group participates in the HYCON 2 Network of Excellence and its predecessor HYCON 1, a network around the theme of Hybrid Control Systems, which comprises more than 20 universities and research institutes.

Dynamics and Control of Hybrid Mechanical Systems (DyCoHyMS) was a joint project sponsored by NWO (Netherlands Organisation for Scientific Research) and its Russian counterpart RBFR, in which the group cooperates with researchers from St. Petersburg and Nizhny Novgorod with the aim of creating novel (experimental) results in the area of synchronisation and coordination of multiple mechanical systems. The project has been completed with a symposium and the publication of a joint book. The group participated with the CST group in the EU project WIDE on the decentralised and wireless control of large-scale systems.

After earlier scientific visits, dr. Ines Lopez was appointed in 2011 as visiting professor at the KTH Royal Institute of Technology, Stockholm, Sweden, in the field of acoustics, showing our strong potential in this area. This appointment has created a strong collaboration between KTH and our group in the broad area of vibrations and acoustics.

Dr. Nathan van de Wouw has built up a valued international network as shown by his (sabbatical) visits: 2012: Visiting MTS professor, University of Minnesota, Minneapolis, USA (invited by prof. E. Detournay); 2009-2010: Visiting professor at the Electrical and Electronic Engineering Department, University of Melbourne, Australia (invited by prof. D. Nesic); 2007: Visiting researcher in the Drilling Geomechanics group at CSIRO Petroleum, Perth, Australia (invited by prof. E. Detournay); 2006-2007: Visiting professor at the Center for Control, Dynamical Systems, and Computation, University of California, Santa Barbara, CA, USA (invited by prof. J.P. Hespanha). Co-organiser of the Second International Colloquium on ‘Nonlinear dynamics and control of deep drilling systems’ at Eindhoven University of Technology, Eindhoven, 2012.

Prof. Henk Nijmeijer has extensive long-term collaborations worldwide, as shown by numerous joint publications. In cooperation with NTNU Trondheim, Norway, this has resulted in 3 jointly organised specialised workshops with highly cited book proceedings. He is an advisor to the Norwegian CESOS project. Similarly, he is advisor to the Aihara Innovative Modelling project, Tokyo, Japan (since 2011), strengthening the cooperation with Japan.

Dr. Rob Fey cooperates with Dr. Amit Shukla (Miami University, Ohio, USA) in the field of discontinuous dynamical systems. There have been scientific visits, joint journal publications and a joint guest editorship for a Special Issue in the journal Nonlinear Dynamics in 2011.
Dr. Alessandro Saccon has active research collaborations with prof. A. Pedro Aguiar (University of Porto, Porto, Portugal), prof. Alessandro Beghi (University of Padova, Padova, Italy), prof. John Hauser (University of Colorado, Boulder, CO, USA), prof. Robert Mahony (Australian National University, Canberra, Australia), prof. António Pascoal (Instituto Superior Técnico (IST), UTL, Lisbon, Portugal), prof. Giorgio Picci (University of Padova, Italy), and prof. Jochen Trumpf (Australian National University, Canberra, Australia).

Dr. M. Heertjes, who is part-time affiliated with the DC group, and whose main appointment is at ASML, acted as Guest Editor of the Special issue on Precision Motion Control, IFAC Mechatronics Several international researchers have visited the Dynamics and Control group for longer periods. A list of visitors is given in the appendix.

The CWTS analysis covers a total of 131 papers with a MNCS score of 1.39 which is well above the world average.

4.1. Most significant results/highlights

Research highlights

**Sound Imaging** is a wide-spread powerful technique to localise sound sources in all kinds of machines and devices ranging from mobile phones to trains. Our research focuses on Near-field Acoustic Holography (NAH) and, more specifically, on improving the accuracy and the resolution of NAH and on extending the formulation to localising sources in the presence of reflecting surfaces, temperature gradients or transient events. The group has been active in the area of NAH for an extended period, and this has resulted in several publications, patents and a highly successful start-up company Sorama.

**Synchronisation and Cooperation of Mechanical Systems** has been the subject of research from the start of the group in 2000. This work has close links with several of the other research themes of the group, and numerous publications, conferences, conference sessions and workshops have been organised featuring our work. Some dedicated laboratory facilities have been developed to illustrate the potential; this is partly the case in collaboration with external international labs showing long-distance cooperation and synchronisation. The work on Huygens’ synchronisation is also shown regularly to a wider audience, including the National Science Quiz 2012.

**Networked Control Systems** are (physical) systems controlled over a communication network such as a wireless network or the internet. The control of systems over such a network has a broad range of advantages: firstly, in some applications such as vehicular ‘platooning’, control can only take place over a wireless network; secondly, large-scale systems typically need the communication of control commands and sensor readings over large distances, and thirdly, reduced wiring can be highly beneficial, for example in high-precision mechatronics. Networked control therefore has high potential in many applications of societal and industrial relevance. However, unavoidable uncertainty aspects of communication networks (such as delays, information loss, scheduling constraints and data-rate constraints) threaten the reliability of using such networks in time- and safety-critical applications. The Dynamics and Control group has pioneered the development of techniques for the analysis and design of controllers that can reliably operate over a communication network despite the inherent uncertainties of the network. This research effort has led to several research projects and a large number of highly-cited publications in top journals. Subsequently, these fundamental system-theoretical developments
have been applied in practice, for example in the scope of vehicular platooning and the remote control of robotic systems and teleoperation. The related experimental benchmarking has been done in collaboration with both national and international academic and industrial partners, and underlines the feasibility and potential of networked control in these important applications. Moreover, the maturity of the work in this field has also allowed us to set up postdoc courses on the topic of Networked Control Systems in the Dutch Institute of Systems and Control (DISC).

4.2. Key publications


4.3. Number of articles in top 10% and top 25% of publications relevant to the discipline

From the CWTS analysis it follows that 16% of the papers fall in the top 10% class and 39% are in the top 25% class.

4.4. Most important books or chapters of books, insofar as applicable


5. Output

5.1. Number of publications

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<th>Publications</th>
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<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
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<td>18 (5)</td>
<td>23 (5)</td>
<td>26 (12)</td>
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<td>-</td>
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<td>36 (16)</td>
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<td><strong>Total academic publications</strong></td>
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<td><strong>73 (19)</strong></td>
<td><strong>86 (26)</strong></td>
<td><strong>64 (16)</strong></td>
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<td><strong>Total research output</strong></td>
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<td><strong>74 (22)</strong></td>
<td><strong>73 (19)</strong></td>
<td><strong>86 (26)</strong></td>
<td><strong>64 (16)</strong></td>
<td><strong>67 (19)</strong></td>
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(¹) numbers between brackets represent papers in collaboration with other groups

5.2. Number of PhDs (completed and in progress)

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6. Resources

6.1. Overview of the various sources of funding

Table 6.1a. Funding at programme level [k€]

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<th>Funding</th>
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<th>2011</th>
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<td>Direct funding (1)</td>
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<td>Public grants (2)</td>
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<td>382</td>
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<tr>
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<td>753</td>
<td>918</td>
<td>1106</td>
<td>850</td>
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<td>1580</td>
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</table>

Table 6.1b. Funding at programme level [%]

<table>
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<th>2011</th>
<th>2012</th>
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</thead>
<tbody>
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<td>7%</td>
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<td>Public grants (2)</td>
<td>26%</td>
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<td>25%</td>
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<tr>
<td>Industry &amp; contract research (3)</td>
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<td>69%</td>
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<tr>
<td>Total funding</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
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</tbody>
</table>

6.2. Earning capacity

Table 6.2. External funds used/acquired in the period 2007-2012

A detailed description of projects and research grants is given in the appendix.

6.3. Research facilities & investments

Facilities
The Dynamics and Control group shares the following laboratory facilities in the Mechanical Engineering Department:

The Motion (DCT) laboratory
The DCT laboratory is a joint laboratory of the Control Systems Technology and Dynamics and Control groups. It provides a combined educational and research facility for MSc and PhD student projects. Laboratory facilities are regularly replaced by newer set-ups to warrant a state-of-the-art laboratory for research that also accommodates today’s educational needs. In the past years a large variety of test set-ups has been exploited in the DCT laboratory. Some of the equipment is replaced over time by newer facilities or, depending on the project, have been removed. The technical staff (mechanical and electrical) provide support and create a stimulating environment for PhD and MSc students to carry out experiments in the DCT lab. The real-time hardware, data acquisition and measurement equipment includes dSpace and Beckhoff systems, SigLab measurement systems as well TU/e DACS systems that enable students to use their own notebook computers as real-time control processors.
The Automotive Engineering Science (AES) laboratory

The renovated AES lab facility was opened in September 2003. Since then, with the help of TU/e, Paccar and other parties, we have been able to renew and extend many automotive testing facilities. These facilities include an up-to-date controlled drum facility and various tyre test facilities. Also a number of test vehicles have been acquired for various purposes, including a fully converted electric VW Lupo EL, with as ‘donor vehicle’ a VW Lupo 3L, as well as a fully instrumented cooperative driving DAF truck. A powertrain test rig is used by the CST group for testing new algorithms for CVT control.

The Constructions and Mechanisms (C&M) laboratory

The Constructions and Mechanisms laboratory is led by dr. Rosielle, who is working both within the Control Systems Technology group and the Dynamics and Control group. In this laboratory about 6-8 PhDs and 10 MSc students specialise in the design and construction of machines, instruments and robotic systems.

The Robotics laboratory

Because of the successful growth of the robotics activities, we opened a new Robotics lab in 2011 combining our haptics, RoboCup and RoboEarth project activities. The lab has a playing field for the RoboCup Middle Size League and a simulated hospital room for RoboEarth and @Home. Also all MSc and PhD students are located in an office area close to the experiments.

7. Academic reputation

Each of the group members has been invited regularly to give presentation of the work at international conferences and institutes. We have also been involved in the organisation of international workshops and meeting sessions.

Reputation of the group members

Short summaries of the group’s permanent staff are given below. For further information and cv’s of other long-term associates, please see the appendix and the Mechanical Engineering site at www.tue.nl/universiteit/faculteiten/faculteit-werktuigbouwkunde/de-faculteit/medewerkers/ per-afdeling/ep-tab/501/

Symposium 2008, Co-initiator of the 3TU Centre of Competence High Tech Systems on Intelligent Mechatronic Systems together with prof P.M.H. van den Hof (TUD) and prof S. Stramigioli (UT) 2008 (10MEuro), Co-organiser Workshop Synchronisation, Leiden 2012, Keynote speaker at various conferences on dynamics, synchronisation and control.

Dr. R.H.B. (Rob) Fey, MSc (49) received his MSc degree (cum laude) in 1987 and his PhD degree (Shell Study Prize) in 1992, both from Eindhoven University of Technology (TU/e). From 1992-2002 he worked for the TNO Netherlands Organisation for Applied Scientific Research in Delft. In 2002, he joined the group as an Assistant Professor. His research field is nonlinear dynamics (nonlinear vibrations, stability and bifurcation analysis, synchronisation, non-smooth systems, MEMS). He published 39 refereed journal papers, 16 refereed book chapters, and 26 refereed conference papers. H-index: 10 (Scopus), 8 (WoS). He was co-advisor of 4 PhD theses. Since 2012 he has been member of the editorial board of the Journal of Vibration and Control. In 2011 he was guest editor for the journal Nonlinear Dynamics. Since 2011 he has been member of the Technical Committee for Vibrations of the IFToMM.

Dr.ir. P.C.J.N. (Nick) Rosielle (57) has been associate professor since 1996. His research is in mechanical design. He has supervises six PhD students and typically ten Master's students per year, largely in the Control Systems Technology Group, and in part also in the Dynamics and Control Group (e.g. Robotic master design by R. Hendrix, next-generation humanoid mechanics design). In the review period, dynamic positioning related subjects in their relation to design have emerged. Repeated Industrial Funding for the lithography related PhD work on precision positioning systems such as: wafer stage design in relation to control, reticle stage design, adaptive optics for EUV, whereas STW funding tends to be sought more in the medical related subjects (robotic surgery: laparoscopic surgery robot design, eye robot design, reconstructive plastic surgery robot design. Some smaller projects contributing to industries in the region for designer training.

Dr. A. (Alessandro) Saccon (36) joined the group in 2013 as assistant professor. He received a PhD degree in control system theory from the University of Padova, Italy, in 2006, and was awarded by the Politecnico di Milano with the Claudio Maffezzoni best PhD thesis award. Until August 2009 he held a research and development position at the University of Padova in joint collaboration with the motorcycle racing company Ducati Corse. Before joining TU/e, he held a postdoc research position at the Instituto Superior Técnico, Lisbon, Portugal, sponsored by the Portuguese Science and Technology Foundation (FCT). Dr. Saccon has held visiting positions at the University of Colorado, Boulder (2003 and 2005), at the California Institute of Technology (2006), and at the Australian National University (2011). His research interests are focused on modeling, simulation, analysis and control of complex and highly manoeuvrable mechanical systems. Recent work has focused on the development of optimal constrained motion planning strategies for multiple autonomous robotic vehicles. His H-index, according to WoS, is 3.

Drir. N. (Nathan) van de Wouw (42) gained his MSc degree with honours and PhD degree in Mechanical Engineering from TU/e, Eindhoven, the Netherlands, in 1994 and 1999, respectively. From 1999 until 2013 he has been affiliated with the Department of Mechanical Engineering of TU/e in the Dynamics and Control group as an assistant/associate professor. In 2000, Nathan van de Wouw worked at Philips Applied Technologies, Eindhoven, the Netherlands, and in 2001 he worked at the Netherlands Organisation for Applied Scientific Research (TNO), Delft, the Netherlands. He has held positions as a visiting professor at the University of California, Santa Barbara, USA, in 2006/2007, at the University of Melbourne, Australia, in 2009/2010, and at the University of Minnesota, USA, in 2012 and 2013. Nathan van de Wouw has published a large
number of journal and conference papers and the books ‘Uniform Output Regulation of Nonlinear Systems: A convergent Dynamics Approach’ with A.V. Pavlov and H. Nijmeijer (Birkhauser, 2005) and ‘Stability and Convergence of Mechanical Systems with Unilateral Constraints’ with R.I. Leine (Springer-Verlag, 2008). His H-index is 15 in Web of Science and 19 in Scopus. He is currently an Associate Editor for the journal ‘Automatica’. His research interests are the analysis and control of nonlinear/non-smooth systems and networked control systems with a wide range of applications, such as vehicular platooning, mechatronics/robotics, and resource exploration. His research is performed in collaboration with international industries such as ASML, Philips, Shell, Statoil, FEI Company, Bosch Rexroth B.V., Tomax, ESA/ESTEC, Dutch Space, Assembleon etc.

**Prof.dr.ir. I. (Ines) Lopez Arteaga** (44) is head of the Material and Structural Acoustics group at the Marcus Wallenberg Laboratory for Sound and Vibration Research (MWL) and vice-director of the Odqvist Laboratory for Experimental Mechanics at KTH Royal Institute of Technology (Sweden), where she has been appointed as visiting professor. She has been part-time affiliated associate professor in the Dynamics and Control group since 2002. Ines Lopez Arteaga received her degree in Mechanical Engineering at the University of Navarra in San Sebastian (Spain) in 1993, where she gained her PhD in 1997. From 1999 to 2001 she worked as researcher, mainly in the field of railway noise, at Centro de Estudios e Investigaciones Tecnicas, CEIT (Spain) and in 2001 she moved to the Netherlands to work in the Technical Analysis group of DAF Trucks on cabin acoustics until she joined TU/e. Her research field is vibro-acoustics and her main interests are tyre/road noise and vibration and inverse acoustics. She has published more than 70 papers in refereed journals and refereed proceedings and several patents. She is subject editor for the Journal of Sound and Vibration and member of the board of directors of the International Institute of Acoustics and Vibration (IIAV). Journal publications: 15, Patents: 3, Conference publications: 43, H-index= 6 (Scopus), 5 (WoS).

**Dr.ir. I.J.M. (Igo) Besselink** (47) studied mechanical engineering at Delft University of Technology from 1985 to 1990 and graduated with credit in the field of vehicle dynamics. Thereafter he joined Fokker Aircraft and became responsible for the analysis of landing gear design loads and stability. In 1996 Igo joined TNO Automotive in Delft (later Helmond) and was responsible for tyre simulation software development and projects related to vehicle dynamics. Igo gained his PhD degree from TU Delft in 2000 on the analysis of shimmy stability of aircraft main landing gear. In 2002 Igo started as a part-time lecturer at TU/e. Here he started to develop and teach courses on vehicle dynamics, initiate research activities and laboratory facilities. In 2008 Igo took up a full-time position as assistant professor at TU/e. Research interests include tyre modeling, dynamics of commercial vehicles, vehicle control and battery electric vehicles. He has 12 journal publications, 25 conference papers. Web of science: H-index: 4 (18 items)

**Prof.dr. H.J. (Hans) Zwart** (53) studied mathematics at the university of Groningen from 1978 to 1984. At the same university he gained his PhD degree in 1988 under the supervision of prof.dr. R.F. Curtain. After his PhD, he joined the Applied Mathematics department of the University of Twente. Since 2000 he has been associated professor, and since May 2011 he has been part-time professor in the DC group. His research interests include controller design for physical systems and the analysis of the underlying models. Examples of these are pool boiling and climate control. He has written 3 books and more than 70 journal articles and a similar number of conference publications. The 1995 book written together with prof.dr. R.F. Curtain has become the standard reference in the field of distributed parameter systems. He has won several best teaching awards. Web of science: H-index is 12. Several MSc students and staff members have contributed to the reputation of the group through the following awards:
8. Societal relevance: quality, impact and valorisation

Regarding the societal quality of research the programme will provide information in terms of the three aspects.

8.1. Societal quality of the work

The group has continued to build an extensive network of industrial relations with research projects and student thesis work done in close collaboration and financed via collaborative funding programmes from STW, NWO and programmes sponsored by the Ministry of Economic Affairs. (IOP Precision Technology, HTAS, Point One, Peaks in the Delta). Collaborations with the industrial partners – and within which area – are shown in the figure below.
8.2. Societal impact of the work

MSc and PhD students from the group have easily found their way in industry and academia. The fairly large number of MSc students in the evaluation period have easily found jobs in the high-tech industry in Eindhoven or, more broadly, in the Netherlands. Several of the PhD students have decided to follow academic careers at prestigious institutes such as KTH Stockholm, NTNU Trondheim, ETH Zurich, Bandung and further afield.

Knowledge Workers Arrangement (KWR). During the crisis of 2008, the DC group was involved in the idea of hosting industrial researchers and engineers within knowledge institutes to combat unemployment. In particular, the DC group has hosted researchers from DAF and MTT (Micro Turbine Technology), and several of them have spent some period of time in the group.

8.3. Valorisation of the work

Electric vehicles Together with the Delft University of Technology and the University of Twente, TU/e was involved in the ‘Car of the Future’ project, initiated by the Netherlands Society for Nature an Environment. As a result of this project the DC group decided to engineer and build a road-legal battery-powered electric vehicle using a VW Lupo 3L as a donor car for follow-up of this project. In 2011 the electric Lupo was first shown to the public at the AutoRAI show, and participated in the Challenge Bibendum competition in Berlin, Future Car Challenge in the UK and Clean Week event at the circuit of Zolder in Belgium. This initiative led to great exposure in news media and on television, but it also lead to a very powerful research line with several MSc and PhD students. It has resulted in the development of other electric vehicles such as an electric Formula Student racing car and the world’s first four-seat solar car STELLA (see also the appendix for further information on this subject).
**Nearfield Acoustic Holography** has been a subject of study for a long time. As well as the research challenges, we have been involved right from the beginning with the very successful start-up venture Sorama, which was founded by former PhD student Rick Scholte in 2009. The start-up phase was passed successfully by winning 1st and 2nd STW valorisation grants of 25 kEuro and 200 KEuro respectively, as well as by several joint patents. Sorama, which uses an acoustic camera and various scanning facilities, is growing rapidly in size and for that reason has recently moved from the Mechanical Engineering building, but ties are still close.

**Humanoid Robotics** has been an active research area of the group, and has participated annually in the world championship robot soccer as part of the larger activities of Tech United, a student team working on our humanoid robot Tulip. This research involving the promotion of technical and exact sciences has a major societal impact.

**Rose b.v.** is a start-up company that resulted from the Tele-service Robotics project in which, together with industrial partners and colleagues from Computer Science, a robot for care of the elderly has been developed and tested in a care environment. This venture, with support from an insurance company, aims at further development of control software and architecture in a concrete care environment, as well as building early experience of such robots in care.

### 9. Viability

The Dynamics and Control group started in 2000, and in the previous research assessment the group proven itself to have excellent viability despite its relatively short history. In the assessment period we have shown this activity to be sustainable by gaining substantial funding, from both indirect funding and contract research sources, showing appreciation for the more fundamental and industrial/application side of our activities. Alessandro Saccon was recently appointed as assistant professor in the group, strengthening the robotics and nonlinear control activities. Group members are encouraged to write personal research plans (sponsoring EU and or national), as well as to obtain joint EU projects. Another significant opportunity will be the new TU/e institute: High-Tech Systems Center (HTSC), of which the DC group and the CST group are both among the founding fathers.

### 10. SWOT analysis

**Strengths (internal dimension)**
- Good team of researchers with strong fundamental backgrounds and broad experimental experience, and with a good research output.
- Well-equipped state-of-the-art laboratories: DCT lab, Robotics lab, Automotive Engineering Science lab.
- Constant stream of talented MSc students supporting the research of the group and leading in a natural way to future industrial contacts.
- Good balance between industrial and fundamental projects.
Weaknesses (internal dimension)
- The group recruits a good mix of talented students, both from our own education as well as internationally, and preferably of mixed gender.
- The group strives for a larger number of international projects, particularly with the changing Dutch funding systems. The group was able to acquire 2 EU projects in 2013, underlining the fact that the team is perfectly capable of making such a switch.

Opportunities (external dimension)
- The Eindhoven region is very strong regarding high-tech systems and equipment. This offers ample opportunities for joint projects in Dynamics and Control with leading industrial partners; the new High-Tech Systems Center is a clear initiative of this kind.
- The demand for further automation is seen everywhere in society, due partly to the advancement of new sensor and actuator technology, novel communication technologies and lower-cost computational resources. Most of our research is relevant to this area.
- The competences for integrating fundamental (mathematical) research in combination with advanced numerical/simulation tools and experimental/industrial benchmarking remains our core domain.

Threats (external dimension)
- The Dutch landscape for research financing is rapidly changing, making it more difficult to acquire funding for fundamental research; such research is nevertheless essential for the group.
- The need to avoid an excessively one-sided perspective in projects, in other words the overall portfolio of projects should cover more fundamental academic work as well as more industrially oriented projects.
- In the previous research assessment the group's education was commended as the 'best education of the world for dynamics'. With the ongoing changes at the university level regarding the Bachelor and Master College, it remains a real challenge to keep the quality of education at that level.
- Initiating new research always has some risk, and some avenues may therefore be less successful than others.

11. Strategy for the next period

Table 11.1. Strategy for the next period

<table>
<thead>
<tr>
<th></th>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opportunities</td>
<td>After its start in 2000, the group has played a significant role in educating MSc and PhD students. Many of them are now working in the high-tech industry and provide excellent contacts for future collaborations.</td>
<td>Collaboration with strategic partners, particularly within the TU/e Strategic Areas, can be useful to become better prepared in positioning the group to apply for strategic funding.</td>
</tr>
<tr>
<td>Threats</td>
<td>The group has built up an excellent international status which helps to attract international students at both at MSc and PhD levels, partly with their own funding. This allows a sustainable and healthy mix of 'own' and external students.</td>
<td>To resolve instabilities in the funding of more fundamental research projects, stronger participation in external projects is planned – for example through EU funding, but also to attract funded PhD students and postdocs from abroad.</td>
</tr>
</tbody>
</table>
TU/e 3: Manufacturing Networks
1. Objective(s) and research area

1.1. Vision, mission and objective(s) of the programme

Our vision in Manufacturing Networks (MN) is that managing the growing complexity of manufacturing systems requires significant contributions from the interdisciplinary research at the interface of operations research, engineering optimisation, control theory, computer science and design science. The mission of our group is to provide education and to conduct research at this interface, with a particular focus on manufacturing systems and networks. The objective is to develop new methods and computational tools to support and improve the design and control of systems and networks, and to present results in international conferences, followed by their publication in highly rated international journals.

1.2. Strategy

After the retirement of prof. Rooda in 2011, continuation combined with renovation of the research group was aimed at and realised by the appointment of two new professors: prof. Adan, with a background in stochastic operations research, and prof. Fokkink, with a background in formal methods. The new strategic choice of placing stronger emphasis on fundamental research and its connection to tool development was underlined and strengthened by expanding the research staff with the appointments of dr. Reniers, also with a background in formal methods, and ir. Hendriks, scientific programmer.

The group members share their common interest in interacting parallel processes, in either a discrete-event or a continuous-time modeling framework, with a particular focus on performance analysis, control and system design. The research strategy is based on the SEA concept: Science, Engineering, and Application. The science part reflects the fundamental research that is firmly grounded in formal and rigorous methods from mathematics and computer science. The engineering part refers to the development of software tools founded on this scientific basis. The application part of the research activities includes validation of the newly developed methods and tools in industrial applications and teaching.

The applications provide a continuing source of inspiration for new research and educational activities. The application domain is high-tech systems, for example including (semiconductor) manufacturing, warehousing and baggage handling. The strategy is to expand this domain by including healthcare and road traffic, in line with the TU/e strategic areas of Health and Smart Mobility.
1.3. Research area and subprogrammes

The research of the Manufacturing Networks group is positioned at the interface of operations research, engineering optimisation, control theory, computer science and design science, and encompasses the following four topics:

- **Performance analysis:** This topic aims to develop modeling and analytical and simulation methods, grounded in the theory of stochastic processes, queueing networks and timed automata, to evaluate system performance in terms of throughput, flow times, timeliness and reliability.
- **Engineering optimisation:** This topic aims to develop optimisation methods for multidisciplinary and simulation-based design, with particular focus on system decomposition, coordination, approximation, aggregation and meta-modeling.
- **Controller design:** This topic aims to develop methods for the design of network controllers and supervisory controllers, including discrete-time and continuous-time optimal control, model predictive control, nonlinear control, adaptive and robust control, supervisory control synthesis and hybrid observers.
- **Systems design:** This topic aims to develop model-based systems engineering methods to support systematic design and improvement of complex engineering systems. Techniques for model checking of functional and performance requirements, model transformations, simulation-based visualisation and design structuring play a central role in this research topic.

Many mutual connections exist between these topics. The common focus is the development of novel modeling methods, which drives the development of and is supported by compiler-based computer languages for:

- Modeling and simulation of discrete-event systems (Chi language),
- Optimisation and system design structure (Psi language),
- Supervisory controllers (CIF language).

2. Composition of the research staff at programme level

The MN group has one full professor (group leader), one part-time professor, six assistant/associate professors, two scientific computer programmers (MSc and PhD), three supporting staff members (laboratory, secretary, organisation and education) and one part-time scientist from TNO. PhD researchers are associated with one of the research topics mentioned. The duration of postdoc appointments varies between one to three years. Researchers from abroad regularly visit our group for periods ranging from one week to half a year.
### Table 2.1a. Composition of research staff at programme level (fte)

<table>
<thead>
<tr>
<th></th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
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<td>TU/e 3: Manufacturing Networks</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tenured staff</td>
<td>2.3</td>
<td>2.3</td>
<td>2.3</td>
<td>2.2</td>
<td>2.7</td>
<td>2.7</td>
</tr>
<tr>
<td>Non-tenured staff</td>
<td>1.6</td>
<td>2.8</td>
<td>3.2</td>
<td>2.5</td>
<td>1.8</td>
<td>1.0</td>
</tr>
<tr>
<td>PhD students</td>
<td>8.7</td>
<td>6.1</td>
<td>4.9</td>
<td>4.4</td>
<td>3.6</td>
<td>3.2</td>
</tr>
<tr>
<td>Total research staff</td>
<td>12.7</td>
<td>11.2</td>
<td>10.4</td>
<td>9.1</td>
<td>8.1</td>
<td>6.9</td>
</tr>
<tr>
<td>Supporting staff</td>
<td>1.6</td>
<td>2.1</td>
<td>2.1</td>
<td>2.7</td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td>Visiting fellows</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.6</td>
<td>1.5</td>
</tr>
<tr>
<td>Total staff</td>
<td>14.3</td>
<td>13.4</td>
<td>12.5</td>
<td>11.8</td>
<td>11.4</td>
<td>10.1</td>
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<tr>
<td>External PhD student</td>
<td>0.1</td>
<td>0.3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

### Table 2.1b. Composition of research staff at programme level (numbers)

<table>
<thead>
<tr>
<th></th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>TU/e 3: Manufacturing Networks</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tenured staff</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>8</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>Non-tenured staff</td>
<td>5</td>
<td>5</td>
<td>6</td>
<td>6</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>PhD students</td>
<td>14</td>
<td>12</td>
<td>7</td>
<td>7</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Total research staff</td>
<td>25</td>
<td>23</td>
<td>19</td>
<td>21</td>
<td>18</td>
<td>15</td>
</tr>
<tr>
<td>Supporting staff</td>
<td>6</td>
<td>6</td>
<td>7</td>
<td>9</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Visiting fellows</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Total staff</td>
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<td>30</td>
<td>26</td>
<td>30</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>External PhD student</td>
<td>1</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

In this period we had one external PhD student, not on our pay-roll. He finished his PhD successfully.

### 3. Research environment and embedding

#### 3.1. National positioning

The MN group has a unique position within the mechanical engineering domain in the Netherlands. The mix of concepts from mechanical engineering, mathematics and computer science has resulted in research that clearly distinguishes MN from related university groups in the Netherlands, in and outside mechanical engineering.
Within the university there are close contacts with the following groups:

- Stochastics (Mathematics), which focuses on the study of systems operating in the presence of randomness. There are two joint PhD projects in the area of stochastic processes and queueing theory.
- Model Driven Software Engineering (Computer Science), which develops methods and tools for high-quality software systems.
- Operations, Planning, Accounting and Control (Industrial Engineering) in the manufacturing and service sectors. We have a joint research project on the design of robust and flexible service systems and we plan to start a joint PhD project on build-to-order manufacturing.

At the national level, collaborations exist with the groups:

- Stochastic Operations Research and the Formal Methods and Tools (University of Twente).
- Stochastics (CWI, Amsterdam). We have a joint PhD project on error bounds for Markov Chains.
- Logistics and Operations Management (Erasmus University). We have a joint PhD project on stochastic modelling of warehousing systems.
- Structural Optimisation and Computational Mechanics (University of Delft).

The research of the MN group is embedded in the following research schools:

- Engineering Mechanics (EM), a KNAW-recognised national inter-university research school.
- Institute for Programming Research and Algorithmics (IPA), a KNAW-recognised national inter-university research school on programming research and algorithmics.
- Landelijk Netwerk Mathematische Besliskunde (LNMB), a Dutch network on the mathematics of Operations Research.
- Institute for Business Engineering and Technology Application (BETA), a KNAW recognised inter-university research school on operations management and logistics.

The group actively participates in:

- EURANDOM, the leading European institute on Stochastics, which has its centre at TU/e.
- EIRICT, the Eindhoven Institute for Research on ICT.

### 3.2. International positioning

The MN group was involved in the following European research projects (see also Section 6.2):

- Hycon (FP6),
- Con4Coord (FP7),
- Multiform (FP7),
- Hycon-2 (FP7).

In all these projects, the contribution of the group was on the development of an open source environment for model-based design of supervisory controllers for hybrid and timed embedded systems. These contributions to European projects reflect the international standing of the methods and software developed for systems design and control. As of 2011 the group is involved in the People Marie Curie Actions International Research Staff Exchange Scheme (FP7-PEOPLE-2011-IRSES) ‘Mobility between Europe and Argentina applying Logics to Systems’ for international exchange of research. The focus is on the application of logics to systems, and more specifically on both theoretical and applicative work on supervisory control synthesis.
techniques. As from October 2013, the group participates in the FP7 project ‘CPSoS – Towards a European Roadmap on Research and Innovation in Engineering and Management of Cyber-physical Systems of Systems.’

Around 40% of our journal papers in 2007-2012 were co-authored by international researchers, reflecting active international collaboration. Our international network is intensively used to provide internships to the steady inflow of Master’s students. To facilitate internships we are currently setting up a student exchange program with HKUST School of Engineering. We have strong ties with:

- **University of Arizona.** From 2006-2010, prof. Armbruster has been part-time professor in the MN group. He collaborates with dr. Lefeber on modeling and control of manufacturing lines. Lefeber has spent several working visits in Arizona.
- **University of North Carolina.** Prof. Adan spent a one-year sabbatical and several working visits at UNC, teaching and collaborating with prof. Kulkarni on various stochastic models. Kulkarni spent his sabbatical at TU/e.
- **University of Haifa.** Prof. Weiss collaborates with prof. Adan on infinite matching and multi-skilled service systems, and with dr. Lefeber on networks with infinite virtual buffers. He regularly visits EURANDOM at TU/e. Prof. Adan also collaborates with prof. Perry on stochastic models.
- **University of Queensland,** where dr. Lefeber spent a working visit collaborating with dr. Nazarathy, a former postdoc researcher in our group and now assistant professor at this university. They are writing a book together on control theory and matrix-analytic theory.
- **University of Stellenbosch.** Dr. Etman spent a sabbatical at this university. He collaborates with prof. Groenwold on sequential approximate optimisation methods for structural optimisation.
- **St. Petersburg State University.** Dr Pogromsky regularly visits and spends sabbaticals at this university to collaborate with prof. Leonov and prof. Matveev on stability and control problems.
- **Technical University of Dortmund.** In several European research projects there has been close collaboration with prof. Engell. This collaboration continues in the FP7 project CPSoS referred to above.

### 4. Quality and scientific relevance

#### 4.1. Most significant results/highlights

**Performance analysis:** A powerful aggregate modeling method has been developed for discrete-event systems (PhD projects of Kock, Veeger and partly Andriansyah, financed by STW, NXP and Senter). A complex manufacturing network, workstation or machine system is modeled as a simplified queuing system by means of effective process times. The effective process time distribution is obtained from simple arrival and departure events measured at the boundaries of the system to be aggregated, without the need to quantify the various details of the system. Based on this concept of aggregate process times, new analytical tools have been developed to predict the performance of discrete and continuous manufacturing lines. The projects have resulted in **eight** journal publications, a best paper award at the SiMUL 2009 conference and an invited paper at the 2011 Winter Simulation Conference of INFORMS. Further exploration of this method is an active line of research.
Engineering optimisation: A novel optimisation method, called the Augmented Lagrangian Coordination (ALC) method, has been developed for the distributed design optimisation of engineering systems (PhD project and postdoc work by Tosserams, financed by MicroNed). Distinguishing aspects of the ALC method compared with existing multidisciplinary design optimisation methods are the high degree of flexibility in setting up the coordination structure while respecting disciplinary design autonomy, and the mathematical rigour. The project has resulted in nine journal papers in highly rated engineering journals, which have received considerable international attention and many citations. This work acts as a stepping stone for our recent efforts to study coordination of distributed system design in concert with design structuring methods. The first paper resulting from this research is the best cited one of the Structural and Multidisciplinary Optimization journal in 2006.

Model-based Engineering of Supervisory Control: A framework for model-based engineering of supervisory control has been developed and implemented in an Eclipse-based open source development environment. This framework covers the complete development chain consisting of modeling of uncontrolled systems and requirements, synthesis of supervisors, simulation-based validation, testing, verification and implementation via automatic code generation/implementation. Development started with the publication on the formal Chi language (best cited paper of JLAP in 2006). The research has resulted in two PhD theses (Schiffelers and Nadales Agut) and fourteen journal papers. After improving and employing the language in European and industrial projects, it evolved in the CIF formalism. Over the years the quality of the toolset has improved to a level that has led to the initiation of new projects to achieve a breakthrough in industrial adoption by major high-tech industries.

Control of manufacturing systems: Controller design for flow networks of switching servers with setup times is the topic of the research project of dr. Lefeber (postdoc work by Nazarathy, PhD projects of van Zwieten and Fleuren), who was awarded an NWO Vidi grant for young talented researchers who are among the top in their research areas. The distinguishing feature of this project is that network control policies are derived from desired network behaviour (instead of the other way round). An important application and source of inspiration is the control of urban traffic networks. So far, this project has resulted in four journal papers and seven refereed conference papers.

4.2. Key publications


### 4.3. Number of articles in top 10% and top 25% of publications relevant to the discipline

It follows from the CWTS study that the MN group is a productive group, with 6% of the group’s papers among the top 10% and 22% among the top 25%, which represents a good level. The MNCS value is 0.78, which is a somewhat low score, but this is also true for the CI-coverage of 51%. The results of the bibliometric analyses should therefore be treated with extreme caution, as indicated in the CWTS study.

### 5. Output

**5.1. Number of publications**

Table 5.1. Number of academic publications and other research output

<table>
<thead>
<tr>
<th>Publications</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>6 year total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Academic publications</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refereed articles</td>
<td>11   (6)</td>
<td>15 (4)</td>
<td>13 (4)</td>
<td>25 (9)</td>
<td>21 (13)</td>
<td>23 (10)</td>
<td>108 (46)</td>
</tr>
<tr>
<td>Conference papers</td>
<td>25   (4)</td>
<td>25 (5)</td>
<td>33 (10)</td>
<td>19 (7)</td>
<td>37 (15)</td>
<td>32 (8)</td>
<td>171 (49)</td>
</tr>
<tr>
<td>PhD theses</td>
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<td>7</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>4 (2)</td>
<td>16 (2)</td>
</tr>
<tr>
<td>Book</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>Book chapters</td>
<td>9    (1)</td>
<td>-</td>
<td>7 (4)</td>
<td>3 (1)</td>
<td>5</td>
<td>4 (2)</td>
<td>28 (8)</td>
</tr>
<tr>
<td>Total academic publications</td>
<td>46   (11)</td>
<td>48 (9)</td>
<td>55 (18)</td>
<td>50 (17)</td>
<td>64 (28)</td>
<td>63 (24)</td>
<td>326 (105)</td>
</tr>
<tr>
<td>Patents</td>
<td>3    (2)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1 (1)</td>
<td>-</td>
<td>4 (3)</td>
</tr>
<tr>
<td>Total research output</td>
<td>49   (13)</td>
<td>48 (9)</td>
<td>55 (18)</td>
<td>50 (17)</td>
<td>65 (29)</td>
<td>63 (24)</td>
<td>330 (108)</td>
</tr>
</tbody>
</table>

(#) numbers between brackets represent papers in collaboration with other groups.
5.2. Number of PhDs (completed and in progress)

### Table 5.2. PhD candidates

<table>
<thead>
<tr>
<th>Starting year</th>
<th>Enrolment (male/female)</th>
<th>Graduated after (years)</th>
<th>Total</th>
<th>Not yet finished</th>
<th>Discontinued</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>F</td>
<td>≤ 4</td>
<td>4-≤ 5</td>
<td>5-≤ 6</td>
</tr>
<tr>
<td>2003</td>
<td>3</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2004</td>
<td>6</td>
<td>-</td>
</tr>
<tr>
<td>2005</td>
<td>1</td>
<td>-</td>
<td>1</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>2006</td>
<td>3</td>
<td>-</td>
<td>3</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>2007</td>
<td>1</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>2008</td>
<td>2</td>
<td>-</td>
<td>2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2009</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2010</td>
<td>1</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2011</td>
<td>1</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2012</td>
<td>2</td>
<td>-</td>
<td>2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2013</td>
<td>1</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The average duration of promotion is 4 year. The defense of the only non-finished candidate (Theunissen) starting in 2006 is scheduled in June 2014.

6. Resources

6.1. Overview of the various sources of financing

### Table 6.1. Funding at programme level

<table>
<thead>
<tr>
<th>Funding</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>k€</td>
<td>%</td>
<td>k€</td>
<td>%</td>
<td>k€</td>
<td>%</td>
</tr>
<tr>
<td>Direct funding</td>
<td>50</td>
<td>12</td>
<td>50</td>
<td>19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Public grants</td>
<td>100</td>
<td>17</td>
<td>134</td>
<td>19</td>
<td>134</td>
<td>19</td>
</tr>
<tr>
<td>Industry &amp; contract research</td>
<td>476</td>
<td>83</td>
<td>560</td>
<td>81</td>
<td>560</td>
<td>81</td>
</tr>
<tr>
<td>Total funding</td>
<td>576</td>
<td>100</td>
<td>694</td>
<td>100</td>
<td>694</td>
<td>100</td>
</tr>
</tbody>
</table>
### 6.2. Earning capacity

**Table 6.2. Distribution external funds used/acquired in the period 2007-2012**

<table>
<thead>
<tr>
<th>Project</th>
<th>Start</th>
<th>End</th>
<th>Sponsor</th>
<th>Partners</th>
<th>Funding k€</th>
</tr>
</thead>
<tbody>
<tr>
<td>STW Adopt DWO 5328</td>
<td>01-10-00</td>
<td>31-12-09</td>
<td>STW</td>
<td>NXP Semiconductors, CQM</td>
<td>278</td>
</tr>
<tr>
<td>NWO 612064205</td>
<td>11-10-02</td>
<td>11-05-07</td>
<td>NWO-EW</td>
<td>CWI, VU</td>
<td>312</td>
</tr>
<tr>
<td>Tangram TSIT2026</td>
<td>01-03-03</td>
<td>01-01-08</td>
<td>NL SENTER BSIK</td>
<td>ASML, Embedded Systems Institute (ESI), Radboud University Nijmegen</td>
<td>411</td>
</tr>
<tr>
<td>STW.EWV.6462</td>
<td>01-06-04</td>
<td>01-05-12</td>
<td>STW</td>
<td>NXP, CQM, Steelweld</td>
<td>185</td>
</tr>
<tr>
<td>HYCON – van Beek</td>
<td>26-08-04</td>
<td>14-09-08</td>
<td>EU FP6</td>
<td>University Dortmund (TUDO), Sienna University</td>
<td>60</td>
</tr>
<tr>
<td>Microned – Etman</td>
<td>01-09-04</td>
<td>01-01-10</td>
<td>TU Delft Faculteit R</td>
<td>TU Delft</td>
<td>200</td>
</tr>
<tr>
<td>Frans Maas</td>
<td>01-02-05</td>
<td>01-02-09</td>
<td>Frans Maas Groep N.V., Koninklijke</td>
<td>Frans Maas</td>
<td>176</td>
</tr>
<tr>
<td>Darwin</td>
<td>01-10-05</td>
<td>01-10-10</td>
<td>NL Senter BSIK</td>
<td>Philips Healthcare, ESI</td>
<td>540</td>
</tr>
<tr>
<td>Philips – C. Veeger</td>
<td>01-06-06</td>
<td>01-06-10</td>
<td>NXP Semiconductors</td>
<td>NXP Semiconductors</td>
<td>263</td>
</tr>
<tr>
<td>PSA HNN-M. Hendriks</td>
<td>01-07-06</td>
<td>30-06-10</td>
<td>PSA HNN</td>
<td>PSA HNN</td>
<td>224</td>
</tr>
<tr>
<td>Falcon Rooda</td>
<td>01-10-06</td>
<td>01-10-11</td>
<td>NL Senter BSIK</td>
<td>ESI, Vanderlande</td>
<td>221</td>
</tr>
<tr>
<td>Twins (point one)</td>
<td>01-01-07</td>
<td>31-12-09</td>
<td>EU ITEA 2</td>
<td>Océ, NBG, Neopost</td>
<td>303</td>
</tr>
<tr>
<td>Vidi Lefeber</td>
<td>01-01-08</td>
<td>01-01-13</td>
<td>NWO-EW</td>
<td>–</td>
<td>406</td>
</tr>
<tr>
<td>CON4COORD</td>
<td>01-05-08</td>
<td>01-09-11</td>
<td>EU FP7</td>
<td>CWI, Océ, HNN-PSA</td>
<td>416</td>
</tr>
<tr>
<td>MULTIFORM-W</td>
<td>01-09-08</td>
<td>01-06-12</td>
<td>EU FP7</td>
<td>TUDO, ESI, Aalborg University</td>
<td>310</td>
</tr>
<tr>
<td>HYCON2 – van Beek</td>
<td>01-09-10</td>
<td>01-09-14</td>
<td>EU FP7</td>
<td>TUDO, IMT Lucca</td>
<td>60</td>
</tr>
<tr>
<td>NWO Prothos</td>
<td>15-08-11</td>
<td>08-07-15</td>
<td>NWO-EW</td>
<td>–</td>
<td>201</td>
</tr>
</tbody>
</table>

### 6.3. Research facilities & investments

**FESTO DIDACTIC flow line** consists of four didactic training stations (input, test, process and storage) consisting entirely of industrial-grade components and including various types of pneumatic and electrical actuators. This training system is used for educational and research purposes related to supervisory control synthesis, integrated in model-based engineering processes. The flowline serves as demonstrator and validator of the CIF tooling which is being developed for MBE. We recently purchased new FESTO DIDACTIC components (40 k€), including a transport robot (Robotino). This new set-up with automatic transportation also offers possibilities for performance-related projects.
**Liquitrol** is a prototype developed for education and research purposes. The prototype is a liquid-based emulator of manufacturing network processes, consisting of several electric pumps and liquid reservoirs. The electric pumps emulate a manufacturing machine behaviour, while the liquid reservoirs serve as buffers. This prototype permits an easy and intuitive way of studying manufacturing control techniques and performance for several network topologies.

### 7. Academic reputation

**Ivo Adan** gained his PhD in 1991. He has been full professor in the field of Manufacturing Networks since July 2011. He serves on the editorial boards of Statistica Neerlandica, Queueing Systems, Mathematical Methods of Operations Research and Probability in the Engineering and Informational Sciences. He is guest editor of Queueing Systems on the topic of Queues in Healthcare. He has been area editor (Stochastic Models and Simulation) of the Asia Pacific Journal of Operational research and guest editor of Annals of Operations Research on the topic of Polling Systems. Ivo Adan is a senior fellow of the EURANDOM European research institute. He was member of PCs of NET-COOP, SIGMETRICS, SMCTools and MAM. He was the co-chair of the PC of the INFORMS Applied Probability Conference (Costa Rica, 2013). He is board member of the Dutch LNMB network and he served on the board of the BETA research school. He is co-recipient of the best paper prize in Design and Manufacturing of IIE Transactions in 2009.

**Pascal Etman** gained his PhD in 1997. He is associate professor in the field of engineering optimisation, and joined the MN group in 1997. In 2010 he gave an invited lecture on Approximated Approximations for Sequential Convex Programming at the symposium held on the occasion of the honorary doctorate of prof. Bendsoe (Liege, Belgium). He was visiting scientist with Philips Semiconductors Nijmegen in 1998; visiting professor at the University of Michigan in 2001; visiting professor at the University of Pretoria in 2005; and visiting professor at the University of Stellenbosch in 2006. He has co-authored 38 journal papers. During the period of 2007-2012 he advised 4 PhD students: Andriansyah, Kock, Tosserams and Veeger. He is co-recipient of the SIMUL 2009 best paper award.

**Erjen Lefeber** gained his PhD in 2000. He is assistant professor in the field of control of manufacturing networks. In 2009 he was awarded an NWO Vide grant for young talented researchers who are among the top 5% in their research areas. He was guest editor for a special issue of Physica A: Statistical Mechanics and its Applications. He was co-organiser of a one-month EU Thematic Institute on Information and Material Flows in Complex Networks in Goldrain, Italy. He has been a visiting scientist with Philips Semiconductors Nijmegen in 2001, and visiting professor at Boston University in 2003. He has co-authored 22 journal publications, 49 conference papers (22 refereed) and 11 book chapters. He advised 2 PhD students (Hendriks, van Eekelen), and is currently advising 2 PhD students (van Zwieten, Fleuren).

**Alexander Pogromsky** gained his PhD in 1994. He is assistant professor in the field of control of manufacturing networks. He is associate editor of Mathematical Problems in Engineering (until September 2013) and International Journal of Advanced Robotic Systems. He was 18th IFAC World congress technical adjoint editor and TPC member of the 24th and 25th Chinese Conference on Decision and Control. In 2013 he gave a plenary talk on IFAC Conference on Manufacturing Modeling, Management and Control. In 2011-2012 he was invited as a visiting professor/project leader to the Department of Mathematics and Mechanics of the St. Petersburg State University. He participated in the CONCOORD EU FP7 project. He has co-authored 28 journal publications, 10 book chapters and one book. During the period 2007-2012 he advised 3 PhD students (van den Berg, Ivanov, Starkov).
Bert van Beek gained his PhD in Electrical Engineering in 1993. He is assistant professor in the field of Systems Engineering. He has been associate editor of SIMULATION: Transactions of the SCS. He has given 10 international invited presentations, including the keynote at the Industrial Simulation Conference ISC 2007, a plenary presentation at the 15th International Workshop on Formal Methods for Industrial Critical Systems (FMICS 2010), and a joint invited industrial/academic presentation at the Industry Day at the Formal Methods Week 2009. He has been actively involved in several European projects, leading four work packages: ITEA2 Twins on hardware-software co-design, FP7 C4C on coordination of control, FP7 MultiForm on tool integration, and the Networks of Excellence HYCON on hybrid control, where he was a member of the executive committee, and HYCON2 on highly complex and networked control. During the period 2007-2012 he advised 2 PhD students (Nadales, Theunissen).

Asia van de Mortel-Fronczak gained her PhD in Computer Science in 1993. Since 1997 she has been assistant professor in Systems Engineering, with specific interest in specification, design, analysis and verification of supervisory machine control systems. She was actively involved in an NWO Open Competition project, an ITEA project and an NL Senter BSIK project. She co-authored 11 journal papers, 6 book chapters and 24 conference papers. She advised 8 PhD students (4 of whom finished during the period 2007-2012).

Michel Reniers gained his PhD in Computer Science in 1999. He is associate professor in the field of model-based systems for supervisory control as of August 2010. He has been editor of ISRN Software Engineering since August 2011. He has been co-chair for SOS 2011 and EXPRESS/SOS 2012, PC member of SOS 2010, EXPRESS/SOS 2013, BFMA 2011-2013 and ARSSIR 2011. He was involved in the organisation of several events of the Research School IPA and of SIREN 2010 // NL. He has been involved in several national and international projects, including two ITEA projects, two NWO Open Competition projects, one STW project, and recently, in an FP7 project on Cyber-physical Systems of Systems, as a work package leader on Engineering and Management of Cyber-physical Systems of Systems. He has authored 24 journal publications, one book, 8 book chapters and over 70 conference and workshop papers. He has advised 6 PhD students.

8. Societal relevance: quality, impact and valorisation

8.1. Societal quality of the work

Societal contributions are realised through:

- Intensive collaboration with industry through internships, MSc projects and PhD projects. This provides a continuing source of inspiration for new research that is relevant to industry. We will therefore continue to maintain and strengthen our industry network.
- Our group actively supports the vivid MN Alumni Association. The yearly meetings of the growing alumni network are used for presenting new research developments and getting feedback from industry.
- Our policy is also to participate on a regular basis in workshops or symposia attracting industrial companies (like the Bits&Chips and ETFA conferences), and to publish articles in professional journals.
8.2. Societal impact of the work

Our postdocs and PhD students found positions in industry and academia:

<table>
<thead>
<tr>
<th>Postdoc researchers</th>
<th>Current position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dr. Q. Li</td>
<td>Statoil, Norway</td>
</tr>
<tr>
<td>Dr. Y. Nazarathy</td>
<td>University of Queensland, Australia</td>
</tr>
<tr>
<td>Dr. M. Petreczky</td>
<td>Maastricht University</td>
</tr>
<tr>
<td>Dr. R. Su</td>
<td>Technical University of Singapore</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PhD students</th>
<th>Current position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dr.ir. R. Andriansyah</td>
<td>NXP, Eindhoven</td>
</tr>
<tr>
<td>Dr.ir. R.A. van den Berg</td>
<td>Vanderlande Industries, Veghel</td>
</tr>
<tr>
<td>Dr.ir. R. Boumen</td>
<td>ASML, Veldhoven</td>
</tr>
<tr>
<td>Dr.ir. N.C.W.M. Braspersning</td>
<td>ASML, Veldhoven</td>
</tr>
<tr>
<td>Dr.ir. J.A.W.M. van Eekelen</td>
<td>Vanderlande Industries, Veghel</td>
</tr>
<tr>
<td>Dr.ir. M.P.M. Hendriks</td>
<td>Quintiq, 's-Hertogenbosch</td>
</tr>
<tr>
<td>Dr. E. Ivanov</td>
<td>ASML, Veldhoven</td>
</tr>
<tr>
<td>Dr. I.S.M. de Jong</td>
<td>ASML, Veldhoven</td>
</tr>
<tr>
<td>Dr.ir. A.A.A. Kock</td>
<td>Weir Minerals, Venlo</td>
</tr>
<tr>
<td>Dr. D.E. Nadales Agut</td>
<td>Océ-Technologies, Venlo</td>
</tr>
<tr>
<td>Dr.ir. R.R.H. Schiffelers</td>
<td>ASML, Veldhoven</td>
</tr>
<tr>
<td>Dr. K. Starkov</td>
<td>ASML, Veldhoven</td>
</tr>
<tr>
<td>Dr.ir. S. Tosserams</td>
<td>Océ-Technologies, Venlo</td>
</tr>
<tr>
<td>Dr.ir. C.P.L. Veeger</td>
<td>OM Partners, Belgium</td>
</tr>
</tbody>
</table>

8.3. Valorisation of the work

The transfer of knowledge and valorisation of research results is achieved through:

- Former postdoc researchers, PhD and MSc students currently working in industry;
- Scientific and professional publications;
- Software tools (Chi, Psi, CIF);
- Project meetings, presentations, and internships by MSc and PhD students. For example:
  - Development of a real-time data-mining tool for assembly plants of NXP (internship). This tool may become a standard tool for all assembly plants of NXP.
  - A novel chain length monitoring system for poultry processing plants of Marel (MSc project), demonstrating the potential of condition monitoring.
  - Automatic generation of real-time PLC controllers for baggage handling systems of Vanderlande Industries (MSc project), convincing industry to adopt this model-based approach and to co-fund further research and implementation.

and through patents:


9. Viability

The group has a considerable output of MSc and PhD students, many of them currently working in industry. This indicates that there is a steady and strong demand for mechanical engineers with a background in manufacturing and systems engineering. The need for research in this domain is also apparent from the European and national projects acquired by the group, see Table 6.2. The Netherlands is renowned for designing, developing and manufacturing high-tech equipment that is smart, accurate and efficient. It is also famous for its logistics network and performance. The ambition of the top sectors High Tech and Logistics is to make high-tech equipment even smarter, smaller and more efficient, and to make logistics activities even more efficient and sustainable. Considering its past earning performance and its current multidisciplinary composition, the group is well equipped to successfully contribute to these ambitions.

10. SWOT analysis

Strengths
• The group has a steady enrolment of MSc students.
• The focus of the group is on fundamental research; it has a strong record in stochastic modelling and analysis, engineering optimisation and formal methods.
• Increased output of journal publications (from 0.85 per fte per year in the previous period to 1.2 in the current period).
• The multidisciplinary composition of the group, with backgrounds in mechanical engineering, mathematics, computer science and electrical engineering.

Weaknesses
• The group is currently running a somewhat too small number of externally funded research projects. We intend to improve this aspect with high priority in the very near future, see also Section 11.
• We publish in computer science oriented fora, which are for a large part (competitive and refereed) conference proceedings, and these are of limited value in the engineering context.

Opportunities
• The Brainport area forms a fertile biotope for industrial contacts.
• The interest of OEMs to become technology service provider instead of equipment provider increases the pressure on the design of systems that are robust and flexible.
• The complexity of engineering systems requires an interdisciplinary approach at the interface of systems engineering, operations research, engineering optimisation, (supervisory) control theory, materials design, product and process design, and software engineering.
• For safety-critical systems, extra care should be taken to ensure that these systems operate safely in their environment. This requires a rigorous development process, which is offered by model-based engineering and synthesis of supervisory controllers.

• The growing urbanisation increases the pressure on the available infrastructure. The availability of planning and floating car data offers opportunities to develop new dynamic control concepts for traffic flows to alleviate this pressure.

• Programmes initiated by the top sectors and the Horizon 2020 programme offer opportunities for the group as enabler for more sustainable products and production.

Threats
• Rapid changes of group leaders and researchers in recent years, resulting in a group that has a relatively large number of permanent staff members and has been through a turbulent transition period.
• Fundamental research on novel methods for manufacturing and systems engineering design has a long time horizon before industrial acceptance.

11. Strategy for the coming period

The strategy of the group is to initiate new research along the four research lines Performance, Optimisation, Control and Design, as outlined in Section 1.3. According to the SEA concept, this will be grounded on a solid scientific and industrial base. The group aims to achieve this by intensifying and extending its contacts with industry and academia. In the Performance research line, we are building an interest group on the design of robust and flexible service systems. For Control we are building an interest group on urban traffic flow management, and intend to focus on the algorithmic development of supervisory control synthesis for the tool set CIF. Participation in the FP7 project ‘CPSoS – Towards a European Roadmap on Research and Innovation in Engineering and Management of Cyber-physical Systems of Systems’ raises the opportunity to build an academic and industrial network that is capable of influencing European research policy and attracting funding for projects on CPSoS. Within the Optimisation and Design research lines we have initiated cooperation with TNO (Sander Gielen) on systems design in the context of complex materials systems, and LED lighting systems in particular. The aim is to initiate projects on multi-level and multi-scale network modeling and optimisation methods supporting complex systems design. To build a solid industry base for our research, we have also changed our policy regarding MSc projects: the majority of MSc projects are now carried out with industrial partners, to identify the main challenges that industry is facing, to transfer knowledge (for instance generated in PhD research projects) and to explore opportunities for new research projects. In our group, we try to create an inspiring research environment striving for quality, originality and applicability. With a proper balance and a stimulating and enjoyable research and teaching environment, we believe this creates the true basis for success in the coming period.
## Table 11.1. Strategy for the coming period

<table>
<thead>
<tr>
<th>Opportunities</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Trend towards OEMs becoming technology service providers</td>
<td>• Broaden our research scope on modeling methods towards developing new technology. We think of systems-integrated intelligence, in which models become part of the machine</td>
</tr>
<tr>
<td>• Increase in complexity of engineering systems</td>
<td></td>
</tr>
<tr>
<td>• Demand for safety-critical systems</td>
<td></td>
</tr>
<tr>
<td>• Increased availability of industrial data</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Threats</td>
<td></td>
</tr>
<tr>
<td>• Cooperation with TNO</td>
<td>• Strive for quality, originality and applicability</td>
</tr>
<tr>
<td>• Build industry consortia</td>
<td>• A stimulating, enjoyable research environment</td>
</tr>
<tr>
<td>• Horizon 2020 and top sectors</td>
<td>• Balance in research and teaching</td>
</tr>
</tbody>
</table>
1. Objective(s) and research area

1.1. Vision, mission and objectives of the programme

In view of the continuous increase in world energy demand, our vision is that combustion will remain the main energy conversion process, even in the far future when fossil fuels are depleted, since heavy transport by road, air and water needs dense energy carriers, in other words liquid fuels.

An important factor in today’s combustion is the shift to ultra-clean and highly efficient ‘low-temperature’ combustion methods. The second important issue is related to the fuel aspects: we will see increased use of biofuels, and in the longer term the emergence of sustainable solar fuels. Either way, it remains of the utmost importance to optimise combustion devices, now in combination with different fuel formulations to minimise undesired emissions and maximise thermal efficiency. With the current level of development of practical combustion systems, further improvements will depend on details of the combustion-system and fuel-composition combination. More accurate and efficient models are required, and these need to be validated.

The mission of the Combustion Technology (CT) group is twofold: Develop new fundamental knowledge and understanding of reacting flows, and develop sophisticated models for practical combustion systems especially suited to incorporate the fuel chemistry.

These objectives can only be reached by combining advanced experimental set-ups, state-of-the-art diagnostic tools and numerical approaches of the highest scientific quality. Fundamental insights are incorporated into numerical models which, in turn, are used to guide the development of emerging ultra-clean and efficient combustion concepts and determine the optimal fuel properties to facilitate them. Long-term strategic research programmes with industrial partners have been established, and this also ensures that tools and knowledge are disseminated to industry and society.

1.2. Strategy

Our strategy is based on the philosophy that a systematic approach towards improved combustion models and concepts should be based on a thorough understanding of the physical and chemical processes involved right down to the smallest scales. We focus on detailed analyses of the smallest reacting structures available, referred to as laminar flamelets, and their interaction with the flow field, turbulent structures, acoustic waves and electrical fields. At a fundamental level of combustion technology, we focus on two main research themes comprising:

a. the main combustion regimes in current use (indicated as FLAMES), as well as

b. new, promising developments for future combustion systems (indicated as FLAMELESS).
FLAMES involve well-defined, spatially delimited reaction fronts, while FLAMELESS combustion takes place in a more diffuse mode, in which the heat release is widely distributed. The field of FLAMELESS combustion\(^1\) is relatively new: combustion takes place in lower-temperatures regimes where kinetics and transport time scales become comparable, enabling near-zero emissions and high efficiencies. These regimes differ fundamentally in the chemical pathways involved, as well as in the way that control over the process is achieved.

### 1.3. Research disciplines and application areas

These themes are approached both by experiments on dedicated setups as well as by detailed numerical multi-scale models combining fluid dynamics, mass/heat transport and combustion chemistry. Models are validated experimentally, where we include both advanced laser diagnostic methods as well as classic analysis methods such as exhaust gas analysis. These disciplines are combined to cover new developments in a broad range of applications, three of which can be considered as the focus applications of the CT group:

a. Internal combustion engines,

b. Small-scale domestic heat & power systems, and

c. Gas turbines.

In all cases experiments form the basis for the development of detailed model descriptions in terms of combustion models at various scales. These models are based on one of the most popular current combustion models, the Flamelet-Generated Manifold (FGM) approach that was developed in the CT group. While the CT group initially focused on fundamental but relevant combustion problems, it was decided to bridge the gap with more applied research in the current evaluation period, by setting up a new strategy of collaborations with industry, e.g. by intensifying our industrial network and improving our innovative power, while maintaining the links with our strong fundamental research base.

### 2. Composition of the research staff at programme level

#### 2.1. Total number of employees in each job category

The CT group was founded in 2001 by the appointment of prof. Philip De Goey as full professor and section chair, and saw a period of gradual growth from 2001-2009 to reach the steady state with a current tenured staff composition of 1 full professor and 5 assistant/associate professors. The profiles of the assistant and associate professors are well matched to the range of disciplines needed to support the group's vision and strategy.

- Dr. Rob Bastiaans on model development for turbulence-chemistry interaction,
- Dr. Nico Dam on laser-diagnostic measurement technique applications,
- Dr. Carlo Luijten on sprays and combustion engine experiments,
- Dr. Jeroen van Oijen on multi-scale detailed/reduced combustion model development, and
- Dr. Bart Somers on unsteady fuel-sensitive combustion engine model development.

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\(^1\) Examples are Premixed Charge Compression Ignition (PCCI) and Partially-Premixed Combustion (PPC) in engines and MILD combustion in gas turbines and furnaces.
Recently, dr. Luijten left for industry and the resulting vacancy is still open. To support laser diagnostics as well as combustion chemistry during the start-up phase of the programme, well known experts prof. Alden (0.2 fte, 2005-2009) and prof. Konnov (1.0 fte, 2007-2009) have been appointed as part-time and visiting professors. To further support the introduction of future fuels in combustion engines and the application of ultra-clean (low-temperature) combustion techniques in engines, part-time professors have been appointed. In order of appointment these are prof. Baert (0.4 fte, 1996-2008), prof. Kalghatghi (0.2 fte, 2008-2010) and prof. Johansson (0.2 fte, 2011-2015), all well-known experts in their fields. The number of PhD students has meanwhile grown to a steady state of around 20; the number of postdocs varies from 3-5. Apart from the core of experienced tenured research staff, a lean supporting staff group has been appointed, shared with three other chairs within the thermo-fluids engineering lab of the department, to support the intensive laboratory research characterised by many large and complicated set-ups. To enable intensive collaborations with industry, employees from our spin-offs and from some outside companies have been given offices close to or within the CT group. They are in some cases tied more strongly to the CT group by part-time appointments. For example dr. Michael Boot, CTO of Progression Industry, has been appointed as part-time assistant professor and innovation manager in the CT group.

**Table 2.1a. Composition of research staff at programme level (fte)**

<table>
<thead>
<tr>
<th></th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tenured</td>
<td>2.0</td>
<td>2.1</td>
<td>2.2</td>
<td>2.3</td>
<td>1.9</td>
<td>1.8</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-tenured</td>
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<td>4.0</td>
<td>2.7</td>
<td>3.4</td>
<td>3.7</td>
</tr>
<tr>
<td>PhD students</td>
<td>7.3</td>
<td>7.4</td>
<td>6.7</td>
<td>13.9</td>
<td>14.7</td>
<td>13.0</td>
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<tr>
<td>Total research staff</td>
<td>13.3</td>
<td>13.5</td>
<td>12.9</td>
<td>19.0</td>
<td>20.0</td>
<td>18.5</td>
</tr>
<tr>
<td>Supporting staff</td>
<td>1.2</td>
<td>1.6</td>
<td>1.7</td>
<td>1.6</td>
<td>1.6</td>
<td>1.8</td>
</tr>
<tr>
<td>Visiting fellows</td>
<td></td>
<td></td>
<td></td>
<td>0.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total staff</td>
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<td>15.1</td>
<td>14.6</td>
<td>20.6</td>
<td>22.3</td>
<td>21.9</td>
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</tbody>
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**Table 2.1b. Composition of research staff at programme level (numbers)**

<table>
<thead>
<tr>
<th></th>
<th>2007</th>
<th>2008</th>
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<th>2010</th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
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<td>Tenured</td>
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<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-tenured</td>
<td>11</td>
<td>10</td>
<td>9</td>
<td>5</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>PhD students</td>
<td>15</td>
<td>11</td>
<td>13</td>
<td>20</td>
<td>20</td>
<td>22</td>
</tr>
<tr>
<td>Total research staff</td>
<td>31</td>
<td>27</td>
<td>28</td>
<td>31</td>
<td>33</td>
<td>35</td>
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<tr>
<td>Supporting staff</td>
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<td>6</td>
<td>6</td>
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<tr>
<td>Visiting fellows</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Total staff</td>
<td>35</td>
<td>33</td>
<td>34</td>
<td>36</td>
<td>42</td>
<td>44</td>
</tr>
</tbody>
</table>
3. Research environment and embedding

The CT group is the largest academic combustion research group in the Netherlands, with a strong (inter-)national position. The group is embedded in the following local, national and international organisations.

3.1. National positioning

Local
- **TFE** – Thermo-Fluids Engineering Lab, jointly with the Energy Technology (TU/e-5, Smeulders) Process Technology (TU/e-6, Brouwers en Kuerten) and Multi-scale Engineering Fluid Dynamics (TU/e 7, Van Brummelen) sections. These sections have a long tradition of collaboration with a joint lab equipped with state-of-the-art infrastructure, facilities, supporting staff and set-ups of the highest quality. These groups offer the joint Master's track Thermo-Fluids Engineering.
- **Eindhoven Energy Institute (EEI) of TU/e** – Prof. De Goey is one of the founding fathers of the EEI to coordinate all the Energy-related research within TU/e, and he is theme leader ‘Future Fuels’, one of the 4 major themes within the EEI.
- **Strategic Area Energy of TU/e** – The EEI is the backbone of the Strategic Area Energy, one of the three TU/e Strategic Areas (Energy, Mobility and Health), in which TU/e aims to address the major societal challenges. The CT group largely contributes to the SAE with many projects on clean and efficient energy conversion and fuels.
- **Strategic Area Mobility of TU/e** – The CT group is also one of the major players in the Strategic Area Mobility, with many projects on future fuels and engines.

National
- **SUNET** – 3TU Centre for Sustainable Energy Technology, one of the 3TU Centres of Excellence (CoE); research at this centre focuses on sustainable production of energy. Biofuels and biomass conversion is a major theme; prof. De Goey is theme leader biofuels and co-chair of the TU/e part of the CoE.
- **JM Burgerscentrum** – The JMBC is the national fluid mechanics research school; PhD students working on fundamental problems in combustion are members of JMBC.
- **OSPT** – The national graduate school on process technology; PhD students and postdocs working in the area of biofuels are members of OSPT.
- **NVV** – The Dutch flame research organization; CT group members have been board members of the NVV.
- **STW** – The Technology Foundation of the NWO (Netherlands Organisation for Scientific Research). Prof. De Goey was chairman of the Clean and Efficient Combustion Platform (STW-SZV), and was founding father and programme leader of the STW Perspectief programme Clean Combustion Concepts (STW-CCC). The CT group contributes with 7 projects within CCC.
3.2. International positioning

International consortia

- **EU** – Prof. De Goey is member of the ENGITECH committee for the Engineering Sciences, one of the 6 scientific committees which supports ‘Science Europe’ (Assembly of all European Science Foundations) in the formation of European research policy and framework programme development; prof. De Goey was also coordinator of the industrial committee of the Marie Curie exchange network Aether (Aero- and Thermo-acoustics). The CT group contributes to different projects in the framework programmes (Opticomb, H2IGCC, Combina, Strela, Timecop, Fuelube) and Marie Curie networks (Aether, Efficient Engine, FuelLube).

- **ETN** – European Turbine Network; dr. Bastiaans is Chair of the Fuel-Flexibility workgroup.

- **ECN** – Engine Combustion Network, a worldwide collaboration to improve engine knowledge. Dr. Somers participates with the high-pressure cell on the experimental part and the FGM-methodology on the numerical part of this work. CT is the only institute worldwide that contributes on both aspects.

- **Society of Automotive Engineers (SAE)** – CT has contributed actively to SAE since 2008.

- **Combustion Institute (CI)** – The international scientific community focusing on combustion science and technology. Prof. De Goey participates in the management of the CI, has been member of the board of directors since 2004, was coordinator and colloquium co-chair of the ‘laminar flames’ colloquium in 2006 and 2008, and has been member of the programme advisory committee since 2008, member of the editorial committee since 2008, and associate editor of the most prestigious journal ‘Proceedings of the Combustion Institute’ (ProCI) of the Institute and editor-in-chief (together with prof. Sick, USA) since 2010. Dr. Bastiaans is chair of the Dutch section of the CI.

International long-term collaborations established with the following top groups

- Prof. Peters (RWTH Aachen, sabbatical of prof. De Goey & dr. Van Oijen, joint publications, exchange of MSc students and postdocs and a joint STW project)
- Prof. Pitsch (CTR Stanford & RWTH Aachen, dr. Van Oijen and dr. Bastiaans were visiting professors at CTR and joint publications)
- Prof. Konnov, prof. Aldén & prof. Johanssen (Lund University of Technology, Sweden, joint projects, exchange of students, joint publications and part-time professors of CT)
- Dr. Cant (Cambridge University, exchange of DNS codes and students, joint publication)
- Prof. Maas, prof. Bockhorn & prof. Class (KIT Karlsruhe, joint projects in KIC innoEnergy + joint publications)
- Dr. Consul (University of Catalonia, sabbatical in our group and joint publication)
- Dr. Lyle Pickett & dr. M Musculus (Sandia National Labs, Livermore, USA, visit of our PhD students Meijer MSc and Leermakers MSc, joint publications)
- Dr. C. Angelberger & dr. G. Bruneaux (IFPen Paris, France, sabbatical of dr. Somers, hosting of PhD students Meijer MSc and Bekdemir MSc, joint publications)
- Prof.dr. R. Cracknell (Shell GS, Thornton, UK, hosting of our postdoc Zixin, joint publications)
- Prof. Seshadri & prof. Williams (UCSD, exchange of 8 MSc students, joint publications)
- Prof.dr. Xi Jiang, (Lancaster University, visiting professor at TU/e in 2008, joint publications)
- Dr. V.B. Akkerman, (Princeton University, visiting researcher at CT in 2007, joint publications)
- Dr. M. Day, (Berkeley, visiting scientist at CT in 2012, joint publication)
- Dr. F.M. Pereira, (Rio Grande do Sul University, Brazil, visiting ass. professor at CT in 2012)

In addition, we hosted several visiting PhD students (dr. W. Irrazabal Bohorquez from ITA Brazil, J. Galle MSc from Ghent University, and A. Wehrfritz MSc from Aalto University).
4. Quality and scientific relevance

The CT group has grown into a leading research group in several areas within the international combustion community. Five significant contributions, connected to the five key publications of section 4.2, are:

1. The CT group developed the well-known heat-flux method (see highlight 1 and key publication 1),
2. The CT group developed the well-known FGM method (see highlight 2 and key publication 2),
3. More recently, CT has focused on future fuel combustion using ultra-clean combustion concepts (see highlight 3 and key publication 3),
4. The CT group developed the first quantitative theory for the influence of flame stretch and curvature on premixed flames; this theory is also used as basis for FGM (see key publication 4),
5. The CT group is well-known for its expertise in the analysis and control of flame-acoustic interactions (see key publication 5).

4.1. Most significant results/highlights

The first three contributions referred to are highlighted below.

1. Heat-flux method
The heat-flux method is a method to stabilise planar premixed adiabatic flames, primarily used to measure the adiabatic burning velocity, a fundamental property of reacting mixtures. The method was introduced in 1993 by De Goey and has been developed and improved further over the years by CT. It is currently recognised as one of the most accurate ways to measure the adiabatic burning velocity of flames. Workshops organised by the group in 2011 and 2012 attracted a high level of interest (key information can be found on www.heatfluxburner.org). The number of groups using this technique is rapidly increasing, and currently stands at more than 10, with most of the burners being manufactured by CT. CT has published 21 journal papers over the years, with a total of 578 citations in Web of Science (which makes an average 27.5 citations per paper), with a strong increase in the citation rate after 2008.

2. Flamelet Generated Manifolds
Reliable computational models, which accurately predict combustion dynamics and emissions, are essential enablers for cost-effective design of optimised combustion devices. Detailed comprehensive reaction mechanisms promise the most accurate description of the reaction kinetics but require excessive computational power, effectively prohibiting their application in simulations of industrial combustors and engines. The flamelet generated manifold (FGM) method, which was developed by the CT group, addresses this problem by reducing the computational demands of the chemistry model by orders of magnitude while maintaining accuracy. Ever since its initial development for premixed laminar flames, the CT group has systematically analysed and extended the FGM method for nearly all combustion regimes. Based on the underlying flamelet/flame stretch theory (see key publication 4), new (turbulent) FGM models have been developed, and these have been shown to accurately predict combustion
processes in engine applications and gas turbine combustors. These results have been published in 40 journal papers with 425 citations in Web of Science. The key paper with 90 citations is the most cited paper of that year in CST. The capabilities of the FGM method have not gone unnoticed: More than 20 academic and industrial research groups (for example Siemens and Rolls-Royce) that we know of use FGM. The recent availability of FGM in the commercial CFD codes FLUENT, FINE and STAR-CCM+ will further boost its application in combustor development.

3. Future Engines and (their) Fuels
Research and development on combustion engines focuses on clean combustion concepts (e.g. HCCI, PPC, LTC) and new clean fuels. There is a strong interaction between both combustion concepts and their (optimal) fuels. This is exactly the focus of CT, which aims to understand the interplay between fuel and combustion concept. The approach taken is a combined numerical and experimental approach. At the fundamental level (high-pressure) burners are available to study pure fuel combustion properties. More towards the application, a state-of-the-art high-pressure optical accessible constant-volume cell has been developed to study engine spray combustion and the interaction with fuel properties in great detail. On the more practical side, the facilities are completed by a series of optical and full metal engines to perform studies on the impact of fuels on the combustion mode (flames or flameless) and the resulting emissions and efficiencies. The facilities compare very well with the best in the world. The experimental activities are complemented by the development of efficient yet detailed combustion models for engines. On the basis of dedicated experimental data, the FGM method has been successfully extended to combustion in engines. CT is a well-established member of a strong international consortium on engine combustion (ECN, www.sandia.gov/ecn) with world-leading institutes such as SANDIA, ANL and IFPen. The world-leading expert on flameless concepts (HCCI/PPC) Bengt Johansson is a part-time professor at CT.

The combined numerical and experimental approach reflects our strong belief that only the combination of high-quality numerical work and state-of-the-art experiments will provide the necessary knowledge base to develop clean fuel/engine concepts. This approach leads to a new perspective towards fuels and engines: can we reverse-engineer the engine’s ‘favourite drink’ through a detailed understanding of combustion? The desired combustion behaviour is then translated into the required fuel properties, which in turn are translated into the best-matching molecular composition of the fuel, preferably derived from a sustainable source. This has already led to a spin-off company Progression Industry and the patented future fuel component ‘CyclOx’.

In close cooperation with the catalysis group of prof. Hensen/van Santen in the TU/e Chemical Engineering department, viable production pathways from biomass are currently being studied to actually produce ‘Cycllox’. To bridge the gap between science and the market, funding has been raised and permits recently granted to realise ‘Elixer’ at TU/e, a pilot-scale fueling station operated as living lab, with our experimental (bio)fuel.
4.2. Key publications


4.3. Citation Analysis

The CT group mainly publishes in key combustion journals with high impact, such as ProCI, Combustion&Flame and Fuel. As an example, in the evaluation period the CT group published 15 papers in ProCI, a journal with a very low acceptance rate of around 35% resulting in high-quality published papers. This strategy is reflected in and in line with the relatively high journal impact factor of the CT group, which is significantly above world average in the field of combustion (MNJS=1.41). The citations of our papers, MNCS, give the following picture:

Table 4.1. Field average citation impact, for more information, see Appendix 2.3.

<table>
<thead>
<tr>
<th>Field</th>
<th>Publications</th>
<th>Citations/Publication</th>
<th>MNCS²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat-flux</td>
<td>13</td>
<td>26.5</td>
<td>3.05</td>
</tr>
<tr>
<td>Flames</td>
<td>73</td>
<td>11.2</td>
<td>1.40</td>
</tr>
<tr>
<td>Laser Diagnostics</td>
<td>27</td>
<td>6.5</td>
<td>0.75</td>
</tr>
<tr>
<td>Future fuels &amp; Engines</td>
<td>17</td>
<td>5.2</td>
<td>0.60</td>
</tr>
<tr>
<td>Total</td>
<td>117</td>
<td>9.2</td>
<td>1.06</td>
</tr>
</tbody>
</table>

² It is assumed that cites/paper scales with MNCS, because papers from all categories are published in the same journals, such as C&F, ProCI, CST, Fuel.
The CT group has a high citation impact related to its traditional more fundamental and highly recognised fields, *laminar flames* and *turbulent flames (Flames)*, with a field average score of \( \text{MNCS}=1.40 \). For the *heat-flux* related papers (part of the *flames* field), it is even \( \text{MNCS}=3.05 \). However, the group’s relatively new research areas of *laser diagnostics, future fuels & engines* still have a lower international visibility. These research areas have a high (industrial) relevance, but academic recognition in the international context will take time. Due to this generally slow take-up of results in classical engineering sciences, and since MNCS is now measured with an emphasis on fast citations in the early years after publication, the average weighted citation impact factor of all the CT group’s contributions is lower, at \( \text{MNCS}=1.06 \). However, considering the unique character of the group’s research approach in these new fields, and our unique set of experimental and numerical facilities, we are confident that the impact in these areas will strongly increase in the future.

5. Output

5.1. Number of publications

Fully in accordance with our original goal of one journal publication per PhD student per year, the number of journal publications gradually increased to reach a steady state in 2009 at an average of about 20 journal publications per year. The larger numbers in the uneven years (2009, 2011, 2013) reflect the biannual character of the International Symposium on Combustion, at which we frequently present our latest results. The number of PhD theses increased to about 5 per year as a result of the steady increase in projects. This is an excellent number given the size of our group in terms of tenured staff. To intensify our interaction with the automotive industry, we decided to publish more often in SAE and to focus more on patents, compared with the previous evaluation period.

Table 5.1. Number of academic publications and other research output

<table>
<thead>
<tr>
<th>Publications</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>6 year total</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Academic publications</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refereed articles</td>
<td>17 (12)</td>
<td>22 (14)</td>
<td>22 (11)</td>
<td>15 (7)</td>
<td>18 (9)</td>
<td>16 (7)</td>
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<td>26 (18)</td>
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<td>SAE articles*</td>
<td>1 (1)</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
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<tr>
<td>Refereed conf. papers</td>
<td>22 (11)</td>
<td>8 (3)</td>
<td>18 (5)</td>
<td>10 (2)</td>
<td>23 (7)</td>
<td>10 (5)</td>
<td>91 (33)</td>
<td>11 (5)</td>
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<td>PhD theses</td>
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<td>2</td>
<td>3</td>
<td>3</td>
<td>6</td>
<td>19</td>
<td>4</td>
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<tr>
<td>Book chapters</td>
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<td></td>
<td>1</td>
<td>1</td>
<td></td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Total academic publications</td>
<td>47 (24)</td>
<td>31 (17)</td>
<td>47 (17)</td>
<td>33 (9)</td>
<td>51 (21)</td>
<td>39 (14)</td>
<td>248 (102)</td>
<td>52 (25)</td>
</tr>
<tr>
<td>Patents</td>
<td>2</td>
<td>3</td>
<td></td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>Total research output</td>
<td>49 (24)</td>
<td>34 (17)</td>
<td>47 (17)</td>
<td>34 (9)</td>
<td>54 (21)</td>
<td>40 (14)</td>
<td>258 (102)</td>
<td>56 (25)</td>
</tr>
</tbody>
</table>

* SAE (Society of Automotive Engineers): refereed technical papers, seen as most important in the field of combustion engines, especially in relation with interaction with industry.
(#) numbers between brackets represent papers in collaboration with other groups.
5.2. Number of PhDs

The CT group only hosted PhD candidates with employee status during the evaluation procedure. One student, M. Tian MSc, who started in September 2012, is funded by a Chinese CSC scholarship. Three students, dr. Verhoeven, dr. Haseli and dr. Bekdemir, finished within 4 years and the rest finished within 5 years, most of them within a few months after their official PhD appointment of 4 years. The 16 PhD students stated in table 5.2 finished their PhDs with an average duration of 54 months (for the input data, please see to the table in Appendix 3.5). Former PhD student dr. Seykens took a little more than 5 years to finish his PhD, as he started working in industry when his four-year appointment completed. Dr. Bekdemir was granted a PhD diploma cum laude (top 5%); 1 out of 16 graduates was female (dr. Verhoeven). In addition, 11 out of 14 finished PhD students have Dutch nationality. The ratio of Dutch PhD students currently enrolling is lower. At present 7 of the 22 (+ 3 visiting) PhD students in the group have Dutch nationality, and 3 are female. Note that the thesis defense is usually 2 months after the end of the 4-year PhD contract. Graduated in 4-<5 years should therefore be interpreted as: PhD work, including writing the thesis is finished in 4 years. Accordingly, prior to the start of the defense the thesis is sent to the printer and subsequently to the committee members to read. This takes 2 months.

Table 5.2. PhD students

<table>
<thead>
<tr>
<th>Starting year</th>
<th>Male/female</th>
<th>Total</th>
<th>≤ 4</th>
<th>4- ≤ 5</th>
<th>5- ≤ 6</th>
<th>6- ≤ 7</th>
<th>&gt; 7</th>
<th>Total graduated</th>
<th>Not yet finished</th>
</tr>
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<tbody>
<tr>
<td>2003</td>
<td>2M 0F</td>
<td>2</td>
<td>-</td>
<td>-</td>
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<td>-</td>
</tr>
<tr>
<td>2004</td>
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<td>3</td>
<td>-</td>
<td>1</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>2005</td>
<td>1M 0F</td>
<td>1</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>2006</td>
<td>1M 1F</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>2007</td>
<td>4M 0F</td>
<td>4</td>
<td>-</td>
<td>4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td>2008</td>
<td>1M 0F</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>2009</td>
<td>4M 0F</td>
<td>4</td>
<td>-</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>2010</td>
<td>8M 1F</td>
<td>9</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>2011</td>
<td>1M 0F</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>2012</td>
<td>3M 1F</td>
<td>4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4</td>
</tr>
<tr>
<td>2013</td>
<td>6M 1F</td>
<td>7</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>7</td>
</tr>
<tr>
<td>Total</td>
<td>34M 4F</td>
<td>38</td>
<td>3</td>
<td>11</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>16</td>
<td>22</td>
</tr>
</tbody>
</table>
6. Resources

6.1. Overview of the various sources of funding

Total funding of the CT program is presented in table 6.1. Direct funding originates for example from the Centre of Excellence SUNNET, while the PhD students M. Andrade de Oliveira, S. Delhaye and L. Zhou were funded directly by the department. The total funding reached an average of around 1.7 M€ per year. The total indirect funding raised by CT amounts to 17% of the ME departments total, while the research funding amounts to 29% of the ME departments total.

Table 6.1. Funding at programme level

<table>
<thead>
<tr>
<th>Funding</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>k€</td>
<td>%</td>
<td>k€</td>
<td>%</td>
<td>k€</td>
<td>%</td>
</tr>
<tr>
<td>Direct funding</td>
<td>187</td>
<td>16</td>
<td>129</td>
<td>11</td>
<td>254</td>
<td>14</td>
</tr>
<tr>
<td>Research funding</td>
<td>466</td>
<td>40</td>
<td>392</td>
<td>34</td>
<td>868</td>
<td>50</td>
</tr>
<tr>
<td>Contract funding</td>
<td>510</td>
<td>44</td>
<td>640</td>
<td>55</td>
<td>633</td>
<td>36</td>
</tr>
<tr>
<td>Total funding</td>
<td>1.163</td>
<td>100</td>
<td>1.161</td>
<td>100</td>
<td>1.755</td>
<td>100</td>
</tr>
</tbody>
</table>

6.2. Earning capacity

Table 6.2 gives a breakdown of the contract and research funding to further illustrate the origin of the external funds acquired by the CT group. These numbers demonstrate a significant growth in valorisation projects and projects fully funded by industrial partners. Note that almost all EU and Economic Affairs projects include industrial partners, accounting for 10-25% of the financial support which is provided. Similarly, STW funds also include around 10-25% of financial support by industrial partners.

Table 6.2. Distribution of external funds over several sources in the period 2007-2012

<table>
<thead>
<tr>
<th>Funding</th>
<th>2007 (%)</th>
<th>2008 (%)</th>
<th>2009 (%)</th>
<th>2010 (%)</th>
<th>2011 (%)</th>
<th>2012 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Research funding</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valorisation (STW)</td>
<td>2</td>
<td>6</td>
<td>12</td>
<td>14</td>
<td>13</td>
<td>6</td>
</tr>
<tr>
<td>STW (OTP / Perspectief)</td>
<td>98</td>
<td>94</td>
<td>88</td>
<td>86</td>
<td>87</td>
<td>94</td>
</tr>
<tr>
<td>Total research funding</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Contract funding</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valorisation (other)</td>
<td></td>
<td>-</td>
<td>5</td>
<td>8</td>
<td>16</td>
<td>34</td>
</tr>
<tr>
<td>European Union</td>
<td>36</td>
<td>44</td>
<td>49</td>
<td>46</td>
<td>34</td>
<td>25</td>
</tr>
<tr>
<td>Economic Affairs</td>
<td>28</td>
<td>34</td>
<td>38</td>
<td>33</td>
<td>24</td>
<td>12</td>
</tr>
<tr>
<td>Industry</td>
<td>36</td>
<td>22</td>
<td>8</td>
<td>13</td>
<td>26</td>
<td>29</td>
</tr>
<tr>
<td>Total contract funding</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>
6.3. Use of research facilities

Labs and experimental facilities
- The laboratories of the CT group are part of the TFE Lab and consist of a ‘Combustion/Laser Lab’ and a ‘Future Fuels/Engines Lab’. The ‘Combustion/Laser’ Lab involves two closed rooms (acoustic room and laser-lab) and a large open space with testbenches for small-scale experiments. The Future Fuels/Engines Lab consists of 8 engine cells containing a range of linked set-ups for running experiments to relate fundamental issues of basic flame structures to practical engine systems (high-pressure/atmospheric burner set-ups, a constant volume vessel (EHPC), two single-cylinder optical engines, a single-cylinder metal engine and a six-cylinder engine).
- A broad range of sophisticated laser-diagnostic equipment and cameras is available, e.g. for PIV, LIF, LII, Raman spectroscopy, and other spectroscopic experiments.

Computer and numerical facilities
- We have available 2 large computer clusters of 736 and 384 computing cores with 235 Tb of RAID 6 storage. For scientific calculations we have access to the national infrastructure with the new Bull supercomputer, named Cartesius (when fully installed the peak performance will exceed 1Pflop/s). In addition, we have access to large-scale data files of LBNL in Berkeley, USA, funded by DOE.
- The group develops and disseminates new sophisticated and efficient models for laminar and turbulent combustion. Methods are based on RANS, LES and DNS concepts in 1D-3D environments. Many of the models are based on the FGM concept.
- The most important code is CHEM1D, our fundamental 1D basis code. It can handle complex kinetics and complex transport. It is used for modeling a broad range of 1D flame structures, and is our basic tool to generate FGM manifolds with reduced chemistry information. CHEM1D is currently used by around 25 research groups in academia and industry (e.g. Rolls-Royce, TU Darmstadt, Imperial College).
- A series of subroutines are made available for implementation of the laminar and turbulent FGM approach in academic and commercial CFD codes. Widely-used commercial codes and open-source solvers are used. These include: Ansys Fluent & CFX, CD Adapco’s Star-CCM+, STAR-CD, COMSOL and OpenFOAM and our in-house research codes (both low-Mach as well as fully compressible). FLUENT also built in an FGM version themselves, while CD Adapco will follow soon. Implementations of FGM are also being developed by Dacolt, CFD Progetti and NUMECA (in their code FineOpen for modeling, mainly, gas turbines). In our own lab progress is made with simulations of real ICE engines and gas turbines, including high pressures and varying pressures, heat loss and preferential diffusion effects.

7. Academic reputation
The (inter)-national visibility and reputation of CT staff members is evidenced by the large number (41!) of awards (see Appendix 2.4 and website) and the international positioning of the CT group (see Section 3.1). Only the most significant signs of scientific recognition are mentioned here, for more detailed CVs please see appendix 1.
• As well as full professor and dean, prof. De Goey is also visiting professor at BIT in Beijing and has a central position in the international community, the Combustion Institute (CI).
• De Goey is active editorial board member of 4 journals and has been Editor-in-Chief of ProCI, one of the two most prestigious combustion journals, since 2010 (shared with prof. Sick), after being associate editor for several years.
• De Goey received the Simon Stevin Meester 2010 award, the highest Dutch award in Technical Sciences (500,000 euros), for ‘the outstanding way in which he is able to couple fundamental research to practical applications’.
• Dr. Dam is visiting scientist at LUT, Lund, dr. Somers is guest lecturer and visiting professor at IFP, Paris, and dr. Van Oijen and dr. Bastiaans have both been visiting professors at Stanford University. Dr. Van Oijen was awarded the prestigious VENI (2003) and VIDI (2010) grants.
• The part-time professors, prof. Konnov, prof. Aldén and prof. Johansson, are all highly respected researchers in their fields of kinetic mechanism development, laser-diagnostics in combustion and clean combustion concepts in engines, respectively.
• Prof. Kalghatghi has a strong position in fuel-engine interaction and has his main position in industry (Shell and later Saudi Aramco).
• Prof. Baert has his main position at TNO Automotive and is lector at Fontys University of Applied Sciences.
• Dr. Boot is a promising young entrepreneurial researcher with a position as innovation manager/assistant professor in the CT group, and as CTO at Progression Industry who has already received many awards and grants.

8. Societal relevance: quality, impact and valorisation

At present, more than 80% of the current energy consumption involves some form of combustion. As well as energy production, more than 30% of the energy is consumed by facilitating transport. Due to the required energy density, the combustion of liquid fuels will remain important for (heavy) transport by road, water and through the air. In addition, the equipment and processes involved will need to meet increasing demands on efficiency, emissions and fuel flexibility. The aim of the CT research programme is to deliver new (fundamental) knowledge to bridge the gap between science and applications, and to contribute significantly to the above future technological demands.

8.1. Societal quality and impact of the work

The policy followed by the CT group to disseminate new knowledge, insights and models to industry and society is by means of, for example, publications, active participation in and coordination of symposia, workshops, project/programme committees and other scientific and organisational panels, but also by using various levels of collaboration:
• Long-term fundamental research projects/programmes on precompetitive exploratory topics, involving new ideas for investigating clean, efficient and stable combustion, funded by industry and/or the science foundation (STW), and guided by at least one but mostly more industrial parties, e.g. Philips, Bosch, Rolls-Royce, Siemens, Polidoro, DAF, Delphi, Shell, TNO, Sensata, Volvo and Wärtsilä: 60%

3 To improve the links with the automotive industry we decided to enhance our visibility within the SAE society and increase the SAE publication rate (see Table 5.1).
• Close collaborations with networks of companies on precompetitive problems such as the series of projects with ‘Centre for Noise in Boilers’ consisting of Atag, Remeha, Bekaert, AWB and Honeywell, and SMO ‘Dutch Engines Education Centre’ consisting of DAF, Shell, Oronite, TNO and Benteler: 15%

• Close collaboration with a number of companies on joint, more practical combustion systems. Specifically, this concerns the development of innovative burners together with MTT Micro-turbines using a joint laboratory set-up, joint (PhD-level) research with Shell on a Shell optical engine set-up in our engine lab, and similar activities with DAF. Staff and scientific equipment are shared with these companies in these projects, and they also deal with practical issues, leading to joint publications and patents: 15%

• Close collaboration with spin-off companies Fistuca and Progression Industry, in which joint projects are carried out at the CT laboratory facilities, while staff and scientific tools are shared and applied in practice, leading to joint publications and patents: 10%

In all cases we strive for long-term strategic collaborations with our industrial partners, which is shown by the long-term major funding from these partners. As a research group, we are continuously in discussion with our academic and industrial partners. Apart from participation in the international networks like ENGITECH and CI, the group is locally involved in several discussion groups and institutes, such as the Dutch Section of the CI (currently chaired by dr. Bastiaans), the Dutch flame research association NVV (CT staff participate in the board) and the STW-SZV platform for Clean and Efficient Combustion (initiated and chaired in the past by prof. De Goey; this platform initiated the 6 Meuro CCC Perspectief programme, also chaired by De Goey). In addition, De Goey is member of the advisory board of the Engineering School of Aalto University in Finland, and has been member of the advisory boards of the companies OWI in Aachen and MTT Micro-turbines. Finally, CT’s group members are also active in many review panels of research programmes and projects.

8.2. Valorisation of the work

Direct dissemination of knowledge has been strengthened in recent years by partly shifting the strategy from scientific/technological research to direct innovation. This is achieved in several ways:

A. Spin-off companies

Two spin-off companies have been started:

• Fistuca BV (3.5 fte) was started in 2008 by J. Winkes MSc to develop a clean and efficient DC (double-combustion) Pile Driver and the LP Vibratory Hammer, a well-controllable, low-maintenance and fuel-efficient vibratory hammer, both for the onshore market. Inspired by previous developments, BLUE technology was developed with the offshore wind market leaders. BLUE promises to drive down the price of offshore wind and the ecological impact of installing these foundations, see www.fistuca.com.

• Progression Industry BV was founded in 2009 by dr. M. Boot to valorise the various engine and fuel innovations developed during his PhD period in the CT group. Of the three technologies in question, WEDACS, PFAMEN and CyclOx, the latter is the most mature. In 2013, Maersk Oil Trading placed a 10 year order for 50 ktons/annum of this biofuel. This order is now being used to attract funding to construct a commercial-scale bio-refinery in the Rotterdam area. WEDACS, a waste energy recovery technology, is currently in the final phase of development, funded by a 2.5 M€ EU project in cooperation with among others Volvo Car Corporation. The PFAMEN project, an alternative fuel injector design, was stopped in 2012
due to fundamental technological hurdles and referred back to the scientific drawing board. Progression Industry has 5 employees, see www.progression-industry.com.

B. Innovations and patents
The following innovations have been launched:

- A novel porous injector PFAMEN with Progression Industry BV (PI).
- A new ultra-clean oxygenated fuel CyclOx with PI.
- A Waste-Energy Driven Air-Conditioning System WEDACS with PI. Patents have been filed to protect the inventions and many awards and prizes have been won.
- The DC pile driver of Fistuca has also been introduced together with CT group members.
- With the high-tech company MTT (Micro Turbine Technology BV), new sophisticated burners such as a plasma-assisted combustor, Mitre burner, catalytic burner, mild combustor and recuperative burner are currently being developed. CT staff members participated in 2 patents, and more are expected to follow. One newly developed burner is used in the current prototype micro-turbine, and another one will be used in the next-generation micro-turbines.
- Together with Dovre a new ultra-clean updown woodstove has been invented. A first prototype is built by Dovre.

C. Valorisation Grants
Eight STW valorisation grants have been awarded:

- 2 for PFAMEN (1st phase with 25 k€ and 2nd phase with 200 k€),
- 2 for CyclOx (1st and 2nd phase),
- 2 for WEDACS (1st and 2nd phase) and
- 2 for DC-Pile Driver (1st and 2nd phase).

The CT group is one of the two most successful groups in the Netherlands in this respect. An innovation grant by SenterNovem has been awarded to CT for testing the updown woodstove.

D. Scientific tools
- The heat-flux method has been optimised for application by other users. Currently, more than 10 institutes and industrial partners use the method and most of them have purchased the burner system from our group.
- An FGM toolbox including CHEM1D is available to generate reduced mechanism databases, together with a set of subroutines to couple the approach to CFD solvers. About 25 institutes have purchased CHEM1D and companies including Rolls-Royce and Siemens use the FGM method in their codes to develop gas turbines.

4 WEDACS and related projects has been transferred to Energy Technology Section, for which they are a better fit.
9. Viability

The group is very well positioned for the future in terms of staff, labs and finances, but there are also some threats.

**Staff**
- Most of the administrative and part of the managerial tasks of prof. De Goey are carried out by dr. Vogels-Verhoeven, CT's project manager appointed specifically for these tasks. In this way, and because of the high level of experience of the remaining research staff, prof. De Goey has sufficient time to focus on his (inter-)national scientific tasks within CT (0.5 fte), next to his appointment as dean of the department.
- The vacant assistant professor position on ‘Engine Experiments’ is expected to be filled in the near future. Two promising PhD students in the final stage of their studies are interested in this position.
- The CT group has an active research staff with expertise in the necessary disciplines of interest. However, we feel that more extensive expertise in the field of chemical kinetics may become important, especially if fuel chemistry aspects become even more important. Knowledge in this field can be imported by our strong collaboration with prof. Konnov from Lund as in the current evaluation period, and the established collaboration with prof. Curran from NUI Galway on automotive fuels.
- So far, it has not been easy to fill our PhD/postdoc positions. We also strive for an increase in the number of Dutch (and female) candidates, especially from our own group (on average 15 MScs per year). However most Master's students are interested in industrial careers and, – conversely, industry shows a high level of interest. By organising discussions and presentations (CT lunches), attended by both PhDs and MScs, we hope to appoint more of our own MScs as PhDs.

**Laboratories**
- The labs are of top quality and have all the necessary equipment. For maintenance, replacement and improvement of set-ups and measurement equipment such as lasers and engine systems, the CT group invests around 400 k€/year, which is possible thanks to the group's strong funding base.
- The supporting TFE staff have experience in all disciplines (electronics, mechanics, engines, design, optics and fabrication) for future support of staff and students in the lab.

**Funding**
- Due to the declining direct financing budget, the budget for travel, maintenance and lab infrastructure has to be shifted more towards research and contract funds. We have been successful in gaining the necessary funds, and after a strong increase in the funding rate during the initial phase of the programme a steady rate of around 1.7 M€ per year has been reached.
- However, to strengthen our future funding rate, we have for the past few years been focusing more on European funding, such as KIC-EIT, again with great success.

10. SWOT analysis

The committee of the previous research assessment was very positive, and praised the at that time young group for its strong Quality (4.5) and Viability (5). We were encouraged to prepare more journal and conference papers, and were recommended to fulfil the need for expertise in
the fields of atomisation, kinetics and laser-diagnostics. For this latter reason CT recruited two
new staff members, dr. Luijten and dr. Dam, while prof. Konnov was temporarily appointed. Since
then prof. Konnov and dr. Luijten have left the group, and the vacant tenured position of dr.
Luijten is expected to be filled in the near future.

In accordance with the recommendations of the previous assessment committee, the output per
tenured staff member in terms of publications has been increased significantly compared with
the previous period, when the programme was still in the start-up phase with the necessary
investments in terms of money and time. To further strengthen the Relevance of the CT group,
several major steps have been taken by incorporating a new strategy to collaborate with industry,
and by creating a climate of innovation within the group. In addition, the industrially relevant
research environment has attracted more new students, many new industrial partners and new
projects, and has enhanced the outreach of the group. This can be seen for example in the large
number of innovations and valorisation grants.

Strengths

• A research area with high societal relevance is the core business of the CT group.
• Research on fundamentals and applications always goes hand-in-hand. The outstanding way
  in which fundamentals and practical applications are combined has been recognised by the
  Simon Stevin Meester Award committee.
• The group has unique research facilities in the field of numerical modeling as well as for
  experiments.
• The expertise covers a broad range of applications, and investigations use a well-balanced
  set of disciplines within combustion science and technology.
• A high level of research is achieved by combining theory with sophisticated numerical and
  experimental tools. This is reflected in the quality of the output in high-impact journals (such
  as Combustion & Flame, ProCI, Fuel).
• The strategy to intensify collaboration with industry, including the use of joint laboratory set-
  ups and staff, appears to be successful. Its impact is shown by the large number of awards
  and innovation grants, the increasing number of patents and the success of the new spin-off
  companies.
• The CT group has a strong position in research funding (STW) and a large number of contract-
  funded projects, indicating our intensive contacts with industry.

Weaknesses

• A relatively slow take-up of our research results; for example it took 15 years before the
  success of the heat-flux method was acknowledged.
• Developing and building the engines/future-fuels lab with a well-balanced set of testing
  facilities required the investment of time during which the group was slightly less visible. The
  application of new laser-diagnostic methods such as high-speed LIF/PIV/phosphorescence
  appeared to be a real challenge, given the very high-pressure engine-like conditions. Our
  approach, together with the experimental and numerical facilities, are now unique. This is not
  yet fully recognised by the international research community, and as a result the CT group’s
  overall citation score is considered low given our reputation and our high citation scores in
  the fundamental parts of our research. However, it is expected that in the longer term this
  ‘start-up problem’ will automatically disappear.
Opportunities

• The ever-increasing demand for cleaner and more efficient production of energy is driving market parties to a more in-depth knowledge of the fundamental aspects of combustion processes. Fuel flexibility, future fuels like ‘synfuels’ (fuels synthesised from fossils and bio-sources) and longer-term future ‘solar fuels’ (fuels directly storing solar energy by reversing the combustion reaction) pose exciting challenges for combustion equipment and processes.

• The knowledge available within CT can also be used in other application areas in the field of reacting flows, such as fuel cells, Chemical Vapour Deposition and fuel production without losing our conceptual focus.

Threats

• Chemical kinetics expertise in the group is limited and may become more important.

• Due to the increase of PhD students (the CT group currently employs 22 PhD students and 3 visiting PhDs, 8 of them started in 2013), and the vacancy for a full-time staff member, the workload of the staff members is high.

• It remains a challenge to fill the job vacancies for postdocs, PhD students and technical staff with highly qualified candidates. Master’s students prefer to join industry instead of taking PhD positions.

11. Strategy for the coming period

Opportunities due to strengths of the programme

• Using our recently introduced strategy to accommodate joint in-house research with industry (MTT, Shell, DAF) could enable more intense collaborations with existing and new industrial partners, also opening the way to additional sources of research funding.

• To strengthen our funding capacity even further, we have for the past few years been focusing more on European funding, such as Horizon2020, ERC and EIT. We already participate in EU projects and we have had our first successes with EIT (2 large KIC InnoEnergy projects). However our policy is directed towards even stronger participation in European funding in the future, since national funding possibilities are decreasing.

• Continuous and successful application of experiments, theory and numerical modeling, also combining fundamentals with applications, may open the way to strengthen our research further, also in other application areas. This might be especially effective if our unique set of experimental and numerical research tools is adequately used.

Opportunities that may help overcoming weaknesses

• We are using the approach of combining fundamentals with applications and experiments with theory and numerical approaches, also in the areas of fuels and engines. This approach will most probably lead to enhanced international visibility and higher citation impact, also in these areas.

• This effort will be supported by a more eager attitude to worldwide dissemination of our scientific results, e.g. by enhancing our participation in international conferences and symposia. Active involvement of dr. Vogels-Verhoeven as project manager and dr. Boot as innovation manager in the dissemination of science will enhance our outreach, and may contribute to a faster renewal of the strengths and qualities within the CT group. Examples are the organisation of workshops, colloquia, consortia and websites, like that recently introduced for the heat-flux method.
Reduce threats using strengths

- Our strong position in the combustion community will be used to start strategic collaborations with other strong groups inside and outside TU/e, for example to allow the import and/or use of chemical kinetics knowledge to reach our future goals. As an example, we are intensifying our collaboration with the Chemical Engineering department of TU/e by the organisation of a joint ‘Future Fuels and Chemicals Lab’.

Threats and how to reduce weaknesses

- The staff workload is high, but the staff vacancy is expected to be filled in 2014, which should lead to a reduction in the workload.
- To enhance the quality and speed of filling open positions for PhD students, we are also including Master’s students in our internal research community; this will give our students a better view of the pros and cons of an academic career.
TU/e 5: Energy Technology
1. Objective(s) and research area

1.1. Vision, mission and objective(s) of the programme

The mission of Energy Technology (ET) is to develop new methods and tools for the extraction, conversion, transportation, storage and use of energy, targeted towards yielding highly efficient (sustainable) energy systems while mitigating side-effects on humans, nature and the environment. An equally important objective of the research programme is to contribute to the scientific and engineering education of undergraduate, graduate and postgraduate students.

1.2. Strategy

Scope: Energy Technology focuses on two fundamental research lines, Enhanced Thermal Transport and Small-Scale Energy Systems. Within these research lines application domains are defined and regularly evaluated. This allows us to maintain a long-term perspective while being flexible in application domains. New applications Thermochemical and Phase Change materials, LNG systems and Hydraulic fracturing were recently developed. This also means that other applications are to be discontinued (see Table 1.1).

Means: We choose to operate in collaborative structures. We develop multidisciplinary research activities funded by government, industry (Shell, GDF Suez, Wintershall, Total, Baker-Hughes) and the EU. We collaborate intensively with other universities and institutions (KTH Stockholm, TU Delft, Utrecht University, Maastricht University) and research groups within TU/e and the Mechanical Engineering department (see Table 3.1).

Resources: Human capital is the key to success. Over the past evaluation period, we appointed young scientists (dr. Speetjens, dr. Nedea) to tenured positions and attracted senior researchers for new research lines (dr. Huyghe). Also, prof. Smeulders was appointed as group leader as successor to prof. Van Steenhoven, and research reorientation of senior staff (dr. Rindt and dr. De Lange) took place. Moreover, part-time professors from industry (prof. Dam, prof. Veringa, prof. Zondag) were appointed to work on the new applications.

1.3. Research area and subprogrammes

The research programme of the Energy Technology group consists of two research lines and three application domains (see Table 1.1).
Table 1.1. Composition of research programme

<table>
<thead>
<tr>
<th>Research lines</th>
<th>Application domain</th>
<th>Separation</th>
<th>Cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enhanced Thermal Transport</td>
<td>Thermochemical and Phase Change materials*</td>
<td>CO₂ separation, LNG systems*, Hydraulic fracturing*</td>
<td>Cooling of electronics and turbine blades**, Microsystems cooling</td>
</tr>
<tr>
<td>Small-scale Energy Systems</td>
<td>Photovoltaic/Thermal systems, Thermochemical biomass conversion</td>
<td>Not pursued</td>
<td>Thermal comfort, Heat exchanger fouling**</td>
</tr>
</tbody>
</table>

* New application
** Application discontinued

The fundamental research lines are Enhanced Thermal Transport and Small-Scale Energy Systems. Application domains are Thermal Storage & Conversion, Separation, and Cooling:

**Thermal Storage & Conversion**

The research on seasonal solar heat storage in the built environment focuses on the reversible sorption process of water vapour into thermochemical materials like crystalline salt hydrates. For latent seasonal heat storage one option is to make use of so-called sugar alcohols. Some sugar alcohols show large supercooling properties and can be stored at relatively low temperatures, minimising heat losses to the environment. Energy storage densities of thermochemical and phase change materials are typically 3 to 5 times larger than sensible heat storage using water. In this relatively new research topic both optimised materials and reactors/systems are being developed. To simulate the processes at the molecular level, bond order force fields are being developed using Density Functional Theory calculations and implemented in ReaxFF (Reactive Force Fields). Controlled reactor experiments are carried out to study the hydration/dehydration behaviour of various sorption materials under different process conditions, and numerical models are being developed based on the continuum approach using commercial software.

A photovoltaic/thermal (PV/T) collector delivers both electricity and heat, with solar cells generating the electricity and acting as the absorber for the heat at the same time. This research focuses on the optimisation of the absorption factor of solar cells for PV/T applications and how to optimise the electrical and thermal yield of systems with PV/T collectors.

**Separation**

In the gas chain, gas contaminant separation is of vital importance for LNG production, but also for example for the exploitation of sour gas fields. The process of condensation in expanding gas streams is investigated numerically by means of MD simulations that can be compared with the results from Pulse Expansion Wave Tube experiments.

The research on hydraulic fractures has recently been started. Enhanced heat and gas recovery from fracture networks is investigated numerically by means of chaotic advection dynamics and spectral analysis. This research aims at boosting the performance of geothermal and shale-gas reservoirs by designing optimal heat and mass throughflow scenarios. This research is complemented by fracture mechanics propagation studies on the basis of FEM (partition-of-unity) methods. Currently 5 PhDs have already been appointed in this domain.

**Cooling**

For turbine blades, an experimental and numerical effort focused on the boundary layer transition process at high turbulence levels and later the study was extended to the influence of
small particles. Also investigated was the effect of production inaccuracies of cooling channels on the cooling effectiveness. In the latter study it was shown that a well-positioned anomaly increases the cooling performance by 100%. For electronics cooling the focus was mainly on the influence of heat input or a near-wake disturbance on the transition mechanisms of wake-flows. For a cylinder flow it is shown that a relatively low heat input or the insertion of a thin wire in the near-wake region will lead to a drastic change in the laminar-to-turbulent transition behaviour. The above studies are both experimental (SPIV, PTV, LIF) and numerical (DNS, LES, SEM) in nature.

In addition, cooling in microsystems is analysed. For example, electro-kinetic flow forcing is used to enhance thermal transport in micro-fluidic devices. Also investigated are micro-pulsating heat pipe principles and evaporative cooling (based on MD and DSMC-techniques).

2. Composition of the research staff at programme level

The Energy Technology group was headed by Anton van Steenhoven until 1-7-2012 (appointed in 1990). Currently the group, headed by David Smeulders, has 6 tenured researchers, 3 part-time professors, 19 PhD students and 3 post-docs. BSc students (about 15/year) and MSc students (about 15/year) contribute to the research programme. The joint Thermo Fluids Engineering (TFE) Laboratory is manned and equipped together with the Combustion Technology (CT) and Process Technology (PT) groups.

2.1. Total number of employees in each job category

Energy Technology aims to have 3-4 PhDs per tenured staff member to ensure that staff have sufficient time for guidance of the individual students, education and new funding acquisition. Including external PhDs, this ratio rose from 2 to 3.3 from 2007 (when 2 new staff members started) to 2012. After a consolidation in 2012, 6 new PhDs are appointed in 2013.

Table 2.1a. Composition of research staff at programme level (fte)

<table>
<thead>
<tr>
<th></th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
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<td>2.4</td>
<td>2.1</td>
<td>2.5</td>
<td>2.5</td>
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<tr>
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<td>2.2</td>
<td>1.3</td>
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<td>5.5</td>
<td>9.0</td>
<td>9.5</td>
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<tr>
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<td>12.8</td>
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<tr>
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<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
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<tr>
<td>Visiting fellows</td>
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<td>0.5</td>
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<td>Total staff</td>
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<td>11.8</td>
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Table 2.1b. Composition of research staff at programme level (numbers)

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<th>2010</th>
<th>2011</th>
<th>2012</th>
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</thead>
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<td></td>
<td></td>
<td></td>
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<td>6</td>
<td>6</td>
<td>5*</td>
<td>6*</td>
<td>6</td>
</tr>
<tr>
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<td>1</td>
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<td>7</td>
<td>9</td>
<td>8</td>
<td>14</td>
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<tr>
<td><strong>Total research staff</strong></td>
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<td><strong>14</strong></td>
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<td>3</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td><strong>Total staff</strong></td>
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<td><strong>21</strong></td>
<td><strong>23</strong></td>
<td><strong>24</strong></td>
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<td>External PhDs**</td>
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<td>2</td>
<td>3</td>
<td>4</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>

* excluding dr. De Lange, who is acting Director of Education.
** appointed elsewhere in TU/e

3. Research environment and embedding

3.1. National positioning

The Energy Technology group is a member of, or has strong formal ties with, the following institutions and groups:

- TU/e, Eindhoven University of Technology. Joint research projects with other groups and departments within TU/e are summarised in Table 3.1. From 2007-2012 prof. Van Steenhoven also temporarily headed the MNSE group.
- EEI, the Eindhoven Energy Institute, combines the energy research at Eindhoven University of Technology. Prof. Smeulders is Scientific Director of the EEI and of the strategic area Energy.
- JMBC, the J.M. Burgerscentrum Research School for Fluid Dynamics, provides a platform for the fluid dynamics research in the Netherlands and is very successful in organising joint PhD courses for the entire Dutch fluid dynamics community. From 2012 prof. Van Steenhoven has been chair of the newly established yearly award for best thesis in Fluid Mechanics.
- 3TU.Centre for Multiscale Phenomena is a Center of Excellence for research on fluids and solids at smaller scales. ET is selected to participate in this center and our optical equipment for 3D PTV and LIF, to accurately determine fluid velocities, concentrations and temperatures, is funded by it.
- FOM, the Foundation for Fundamental Research on Matter promotes, co-ordinates and finances fundamental physics research in the Netherlands. Prof. Van Steenhoven was Coordinator of the Program on Turbulence and its role in Energy Conversion Processes (with projects at 4 universities). Prof. Smeulders now heads 3 FOM-projects within the framework of the FOM-Shell Computational Science Program for Energy Research.
- ECN, the Energy Research Centre of the Netherlands. Collaboration on sustainable energy led to the exchange of staff (dr. Van Helden, dr. Zondag) and a joint PhD student (mrs. Ferchaud) at ECN within the framework of ADEM (an innovation lab for energy materials with ECN, TU/e, TU Delft and UT). Prof. Van Steenhoven is theme coordinator for heat transport materials.
- TKI Gas, the Topconsortium Knowledge and Innovation within the Dutch gas sector, provides grants for discovery, development and deployment projects from government and industry funding. Prof. Smeulders is board member of TKI Gas.
• TKI EnerGo, the Topconsortium Knowledge and Innovation for the built environment. Prof. Smeulders is board member of TKI EnerGo.
• Maastricht University. Collaboration with Maastricht University led to staff exchange (dr. van Marken Lichtenbelt) and several joint PhD students at Maastricht (mrs. Van Ooijen and mr. Kingma).

Table 3.1. External postdocs and PhDs (appointed elsewhere in TU/e)

<table>
<thead>
<tr>
<th>Host</th>
<th>Postdocs</th>
<th>Co-advisor</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP*</td>
<td>J. Znaien</td>
<td>Speetjens</td>
<td>•</td>
<td>•</td>
<td></td>
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<tr>
<td>BMT**</td>
<td>A. Dawid</td>
<td>Nedea</td>
<td>•</td>
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### PhDs

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<tr>
<th>TU/e 11</th>
<th>R. Derks</th>
<th>Frijns</th>
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<th>•</th>
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<tbody>
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<td>TU/e 2</td>
<td>R. v. Gils (HTAS)</td>
<td>Speetjens</td>
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<td>TU/e 11</td>
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<tr>
<td>TU/e 8</td>
<td>O. Gorodetskyi</td>
<td>Speetjens</td>
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<td>AP*</td>
<td>O. Baskan (STW)</td>
<td>Speetjens</td>
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<td>TU/e 11</td>
<td>T. Ahmed (STW)</td>
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<td>TU/e 6</td>
<td>B. v.d. Plas (SHELL)</td>
<td>Speetjens</td>
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</tr>
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<td>TU/e 11</td>
<td>C. Nie (NanoNextNL)</td>
<td>Frijns</td>
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<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
</tbody>
</table>

Total PhDs: 123466

* Applied Physics
** Biomedical Technology

3.2. International positioning

The group has international connections with:
• EU, the FP7 framework projects ‘Sugar Alcohol-based Materials for Seasonal Storage Applications’ (SAMSSA, project leader: dr. Nedea) and ‘Gas Flows in Micro-Electro-Mechanical Systems’ (GASMEMS, project leader: dr. Frijns).
• European Graduate School for Sustainable Energy Technology, in which European top universities join forces in energy research (DTU, TUM, Lausanne, TU/e, project leader: dr. Rindt).
• KTH, dr. De Lange spent a sabbatical there and coordinates a joint PhD project with the group of prof. Dan Heningson on boundary layer instabilities.
• TU Darmstadt, dr. Frijns spent a sabbatical there and collaborates with prof. Peter Stephan on micro-scale processes.
• University of Colorado at Boulder. Dr. Moskovsky from the group of prof. James Meiss visited us on a Fulbright grant to work on the numerical modeling of laminar mixing in close cooperation with dr. Speetjens.
• University of California, Santa Barbara. Dr. Speetjens spent a sabbatical there and collaborates with prof. Mezic on laminar mixing.
• PAS, the Polish Academy of Science. Two postdoc researchers (dr. Stanczyk and dr. Ostrowski) visited us on a PAS grant to collaborate on the biological modeling of thermal comfort. Prof. Van Steenhoven is member of the International Advisory Board of IPPT of PAS.
• International Energy Agency, dr. Rindt is working group leader within the SHC task 42 on Compact Thermal Energy Storage.
• EUROTHERM, an organisation which promotes European cooperation in Thermal Sciences and Heat Transfer. In 2008 the Energy Technology group, together with the group of prof. Van der Meer in Twente, organised the European Thermal Sciences Conference in Eindhoven. Prof. Van Steenhoven is the present President of Eurotherm.
• International Centre for Heat and Mass Transfer is a worldwide forum for heat and mass transfer scientists and engineers. Prof. Van Steenhoven is member of the Executive Board and member of the Award Committee. He is also Regional Editor for the related International Heat Transfer Conference (IHTC-15) in Kyoto in 2014.
• ERCOFTAC, a scientific association of academic and industry groups in the areas of flow, turbulence and combustion. Dr. De Lange is an active SIG member in the Flow Transition group, and prof. Van Steenhoven was deputy chairman of the scientific program committee.

4. Quality and scientific relevance

4.1. Most significant results/highlights

Cooling of electronics and turbine blades
The most remarkable finding for the flow behind a cylinder is that a disturbance by heating or by a thin wire led to an early 3D transition with respect to the undisturbed case, with secondary vortices having a spanwise wavelength of about two times the cylinder diameter. This is of importance for convective cooling of electronics. Moreover, heating resulted in thermal plumes escaping from the primary vortices, also with a similar wavelength, while for a thin wire a period-doubling character is found. Current cooling research is generalised towards microsystems, in which latent heat and electrokinetic forcing are also investigated.

For engine turbine blade cooling, the effect of production inaccuracies of cooling channels on the cooling effectiveness was investigated. It was shown that a well-positioned anomaly increases the cooling performance by 100%. The numerical work was performed in close collaboration with KTH in Stockholm. The above flow transition research has successfully been published in many research papers in J. Fluid Mech., Physics of Fluids, Int. J. of Heat and Mass Transfer, Experiments in Fluids, and Int. J. of Heat and Fluid Flow.

Thermochemical and phase change materials
This relatively new application started in 2007 with a Master's study. At the end of 2013 7 PhD students were appointed on this topic. The work is carried out in close collaboration with ECN by joint supervision of several PhD students (prof. Zondag from ECN has been appointed as part-time professor at TU/e). Close contacts exist with prof. Van Duin (Penn State University) who is the initiator of the reactive force field model. The results obtained within this research line are integrated into IEA SHC task42 (International Energy Agency Solar Heating and Cooling) on Compact Thermal Energy Storage in which dr. Rindt is leader of the working group on Numerical Modeling. Finally the good contacts that have been established Europe-wide have led to participation in the FP7 project SAM. SAA (Sugar Alcohol based Materials for Seasonal Storage Application). The research has already led to 5 journal papers and a new method to efficiently optimise the ReaxFF force field, a new generation MD force field to model reactive chemical systems based on the bond order concept.
Thermal comfort

Thermo-regulatory systems are of paramount importance for medical applications and in the built environment. In close collaboration with the Human Biology group in Maastricht, a thermophysiological model, ThermoSEM, is being developed that can be used to predict the heat transfer, temperature distribution in the human body and the individual thermal perception. It consists of a multi-segmental passive model and an active thermoregulation model based on neurophysiology. This model has been successfully applied for modeling individual thermal comfort, but is also successfully applied for modeling the thermal management during medical treatment such as open-heart surgery (in collaboration with the Amsterdam Medical Centre) and during dialysis (in collaboration with the Maastricht Medical Centre). The dialysis research has led to a new research project funded by the Dutch Kidney Foundation, in which dialysis procedures are optimised and individualised by means of advanced sensor techniques. Within the Eindhoven Energy Institute, a new project was recently granted on thermo-regulatory systems in the built environment.

4.2. Key publications


4.3. Number of articles in top 10% and top 25% of publications relevant to the discipline

The CWTS study shows that the Energy Technology group had 3% of papers in the top 10% and 21% in the top 25% journals, and an Mncs of 0.79. A more in-depth analysis using Web of Knowledge shows the following:

1. The Mncs value is somewhat low compared with our previous evaluation in spite of the fact that our citation rate has increased recently (see Figure 4.1). This is due to our 2009 research reorientation. Note in Figure 4.1 that the output is not constant over time. The dip in 2009 reflects this reorientation towards heat storage applications.
2. The scientific communities of porous media and heat transfer are relatively small (see Table 4.1) and relatively slow in citations. In Figure 4.1, a delay of about 4 years is clearly visible between publications and citations.

3. Our 2009 applications Thermochemical and Phase Change materials and Thermal comfort are not yet fully mature and need more time to become visible in good journals. This influenced the result.

4. We note that our papers appear in above-average journals per field. This is supported by the 1.08 value for Mnjs.

![Figure 4.1. Publications and citations according to Web of Knowledge (as at 1-11-2013)](image)

<table>
<thead>
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<th>Topic</th>
<th>Application</th>
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<th>C-sc-2013</th>
<th>CPP</th>
<th>Journals</th>
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<td>Biomass</td>
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<td>Solar Energy: 3</td>
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<td>Fouling</td>
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<td>Powder Technology: 3</td>
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<td>Transport in Porous Media: 4</td>
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<td>Convective cooling</td>
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Microsystems Cooling

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| Thermochemical materials

Biological Systems

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Total

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<th></th>
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<th>134</th>
<th>900</th>
<th>6.72</th>
</tr>
</thead>
</table>

4.4. Most important books or chapters of books


5. Output

5.1. Number of publications

The Energy Technology group published 76 refereed journal articles in the review period, which leads to a ratio of 1.26 per research fte, which is well above the aimed value 1.

Table 5.1. Number of publications and other research output

<table>
<thead>
<tr>
<th>Publications</th>
<th>2007</th>
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<th>2009</th>
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<td>7 (3)</td>
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<td>16 (6)</td>
<td>23 (8)</td>
<td>25 (11)</td>
<td>14 (6)</td>
<td>14 (7)</td>
<td>17 (4)</td>
<td>109 (42)</td>
</tr>
<tr>
<td>PhD theses</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>2 (1)</td>
<td>5 (4)</td>
<td>4 (3)</td>
<td>19 (8)</td>
</tr>
<tr>
<td>Books</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2 (1)</td>
<td>5 (1)</td>
</tr>
<tr>
<td>Book Chapters</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>2 (1)</td>
<td>4 (4)</td>
</tr>
<tr>
<td>Total academic publications</td>
<td>32 (7)</td>
<td>42 (14)</td>
<td>35 (14)</td>
<td>30 (13)</td>
<td>32 (17)</td>
<td>43 (23)</td>
<td>214 (88)</td>
</tr>
<tr>
<td>Patents</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total research output</td>
<td>32 (7)</td>
<td>42 (14)</td>
<td>35 (14)</td>
<td>30 (13)</td>
<td>32 (17)</td>
<td>43 (23)</td>
<td>214 (88)</td>
</tr>
</tbody>
</table>

(#) numbers between brackets represent papers in collaboration with other groups.
5.2. Number of PhDs appointed at ET (completed and in progress)

In the period 2003-2008, 1.6 PhD/y was appointed on average. All PhD students have graduated after 4-5 years. The PhD appointment rate has increased strongly after 2008.

### Table 5.2. PhD students

<table>
<thead>
<tr>
<th>Starting year</th>
<th>Enrolment (male/female)</th>
<th>Total (male + female)</th>
<th>Graduated after (years) ≤ 4</th>
<th>4-≤ 5</th>
<th>5-≤ 6</th>
<th>Total graduated</th>
<th>Not yet finished</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>-</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>2004</td>
<td>2</td>
<td>3</td>
<td>-</td>
<td>3</td>
<td>-</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>2005</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>1</td>
<td>-</td>
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<td>-</td>
</tr>
<tr>
<td>2006</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>2007</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>2008</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2009</td>
<td>4</td>
<td>4</td>
<td>-</td>
<td>2</td>
<td>-</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>2010</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>2011</td>
<td>5</td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>2012</td>
<td>2</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>2013</td>
<td>4</td>
<td>2</td>
<td>6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>6</td>
</tr>
</tbody>
</table>

6. Resources

6.1. Overview of the various sources of funding

The funding of the Energy Technology group showed a 26% increase from 2011 to 2012, owing to a substantial increase in EU research grants and contract research. In the period 2007-2012 the average annual funding was 584 k€.

### Table 6.1. Funding at programme level

<table>
<thead>
<tr>
<th>Funding</th>
<th>2007 k€</th>
<th>2007 %</th>
<th>2008 k€</th>
<th>2008 %</th>
<th>2009 k€</th>
<th>2009 %</th>
<th>2010 k€</th>
<th>2010 %</th>
<th>2011 k€</th>
<th>2011 %</th>
<th>2012 k€</th>
<th>2012 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct funding (1)</td>
<td>47</td>
<td>12</td>
<td>21</td>
<td>5</td>
<td>119</td>
<td>26</td>
<td>177</td>
<td>30</td>
<td>131</td>
<td>19</td>
<td>125</td>
<td>14</td>
</tr>
<tr>
<td>Research grants (2)</td>
<td>161</td>
<td>40</td>
<td>161</td>
<td>35</td>
<td>94</td>
<td>21</td>
<td>106</td>
<td>18</td>
<td>124</td>
<td>17</td>
<td>114</td>
<td>13</td>
</tr>
<tr>
<td>Research grants (EU)</td>
<td>7</td>
<td>2</td>
<td>82</td>
<td>18</td>
<td>82</td>
<td>18</td>
<td>82</td>
<td>14</td>
<td>112</td>
<td>16</td>
<td>184</td>
<td>20</td>
</tr>
<tr>
<td>Contract research (3)</td>
<td>189</td>
<td>46</td>
<td>190</td>
<td>42</td>
<td>157</td>
<td>35</td>
<td>228</td>
<td>38</td>
<td>340</td>
<td>48</td>
<td>471</td>
<td>53</td>
</tr>
<tr>
<td><strong>Total funding</strong></td>
<td><strong>404</strong></td>
<td><strong>454</strong></td>
<td><strong>452</strong></td>
<td><strong>593</strong></td>
<td><strong>707</strong></td>
<td><strong>894</strong></td>
<td><strong>707</strong></td>
<td><strong>894</strong></td>
<td><strong>707</strong></td>
<td><strong>894</strong></td>
<td><strong>707</strong></td>
<td><strong>894</strong></td>
</tr>
</tbody>
</table>
6.2. Earning capacity

Table 6.2. Examples of external funds used/acquired in the period 2007-2012

<table>
<thead>
<tr>
<th>Name</th>
<th>Project</th>
<th>Start Date</th>
<th>End Date</th>
<th>Sponsor</th>
<th>Three most important partners for the programme</th>
<th>External funding k€ (entire funding period)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot wakes</td>
<td></td>
<td>04/2004</td>
<td>12/2010</td>
<td>FOM</td>
<td>TUD, UT</td>
<td>320</td>
</tr>
<tr>
<td>VENI Nedea</td>
<td></td>
<td>02/06</td>
<td>02/2009</td>
<td>STW</td>
<td>ENEA, Philips</td>
<td>200</td>
</tr>
<tr>
<td>GASMEMS</td>
<td></td>
<td>10/2008</td>
<td>10/2012</td>
<td>EU FP7</td>
<td>7 Universities and 3 companies</td>
<td>400</td>
</tr>
<tr>
<td>ADEM</td>
<td></td>
<td>09/2010</td>
<td>09/2014</td>
<td>EZ</td>
<td>TUD, UT, ECN</td>
<td>328</td>
</tr>
<tr>
<td>Upstream</td>
<td></td>
<td>08/2012</td>
<td>08/2014</td>
<td>SHELL</td>
<td></td>
<td>170</td>
</tr>
<tr>
<td>Integrated micro-fluidic cooling</td>
<td></td>
<td>06/2011</td>
<td>09/2015</td>
<td>STW</td>
<td>Holst Centre, Philips, ASML</td>
<td>565</td>
</tr>
</tbody>
</table>

6.3. Use of research facilities

Labs and experimental facilities

- The laboratories of the Energy Technology group are part of the TFE lab and consist of a Laser Lab, a Large-Scale Facilities (LSF) Lab, and a Gas Dynamics Lab. In the Laser Lab, 3D PIV and PTV experiments are carried out for heat and flow diagnostics. In the LSF Lab, dedicated experimental set-ups are constructed for research on thermal storage, thermochemical biomass conversion and hydraulic fracturing. The Gas Dynamics Laboratory is equipped with a Pulse Expansion Wave Tube and an Expansion Cloud Cell for rapid decompression experiments for nucleation and condensation phenomena.

- The Energy Technology group and the Transport in Permeable Media group of the department of Applied Physics have recently founded the Darcy Laboratory for fundamental energy research in permeable media. The new Darcy Lab is built for flow visualisation experiments in permeable media by means of state-of-the art MRI, CT, and XRD techniques, and required capital expenditures of more than 1 M€.

Computer and numerical facilities

- For very large numerical simulations the national super computer facilities in Amsterdam can be used. Moreover, two Linux clusters are available for development, testing and less demanding simulations. The difference between the two is the number of nodes attached, memory available per core, and type of cpu. The fastest node consists of two octacore Intel Xeon E5-2630 processors and has 256 gigabyte memory.

- The group intensively uses Reactive Molecular Dynamics software like ReaxFF (Reactive Force Fields), GROMACS (GROningen MAchine for Chemical Simulations), and PumMa (a TU/e parallel molecular dynamics tool for biochemical systems).

- The group developed and disseminated an in-house developed hybrid Molecular-Dynamics/Direct-Simulation-Monte-Carlo code, which can be used for upscaling.

- The group uses Monte Carlo methods to simulate chemical reactions (using Kinetic Monte Carlo) combined with heat and flow in small geometries (based on the Boltzmann and Enskog equation).
A variety of commercial software is available at the Linux clusters. In addition open-source and in-house codes are used. Commonly used packages are: Ansys Fluent & CFX, CD Adapco STAR-CD & STAR-CCM+, Centaur, Numeca Fineopen and OpenFOAM.

7. Academic reputation

The Energy Technology group has established a firm national and international reputation as is reflected in the following summary of positions of our senior staff:

Prof.dr.ir. D.M.J. Smeulders
- Scientific director of the Eindhoven Energy Institute (EEI),
- Board member of the Dutch ‘top sector’ TKI EnerGO,
- Board member of the Dutch ‘top sector’ TKI Gas,
- Board member of the DPS (Dutch Petropysical Society),
- Chairman of the Dutch national Program Council Small-Scale LNG (2012),
- Scientific director of the Delft University Geotechnology Laboratory (2006-2010),
- Guest lecturer at ETH Zurich (Switzerland, 2007-2009),
- Guest editor of ‘Transport in Porous Media’ (2010-2012),
- Member of ASA (Acoustical Society of America), SPE (Society of Petroleum Engineers), SAE (Society of Automotive Engineers), SEG (Society of Exploration Geophysicists), EAGE (European Association of Geoscientists & Engineers).

Prof.dr.ir. A.A. van Steenhoven
- President of the EUROTERM Committee (2010-2014, www.eurothermcommittee.eu),
- Chairman 5th European Thermal Sciences Conference, May 2008, Eindhoven,
- Member Executive Committee of International Centre of Heat and Mass Transfer and member of the Prize and Honours Committee (2010-2014),
- Deputy chairman (2004-2008) and member of the Scientific Program Committee of ERCOFTAC (2002-2012) and Coordinator of the SIG on Bio-Fluid Dynamics and Heat Transfer of ERCOFTAC,
- Dutch Representative in the General Assemblies/Scientific Councils of:
  - ICHMT: International Centre for Heat and Mass Transfer (since 1991),
  - AIHTC: Assembly of International Heat Transfer Conferences (since 1996) and editor for Benelux and Scandinavia in 2008 and 2014,
  - EUROTERM Committee for European Thermal Sciences (since 1997),
  - ExHFT: Experimental Heat Transfer, Fluid Flow and Thermodynamics (since 2009),
- Member International Advisory Board of Institute of Fundamental Technological Research (IPPT) of Polish Academy of Science, 2005 to date,
- Member of the ‘Royal Holland Society of Sciences and Humanities’ (since 1992),
- Theme coordinator Heat Transfer in ADEM-programme (ECN-3TU), since 2008.

Dr. C.C.M. Rindt
- Work group leader 'Numerical Modeling' within the IEA SHC task42 ‘Compact Thermal Energy Storage’,
- Member international scientific committee of Eurotherm Seminar 99 ‘Advances in Thermal Energy Storage’,
• Internal coordinator of the research topic on Heat Storage, 2007,
• Project coordinator of one FOM-project on ‘Flow transition behind a wire-disturbed cylinder wake flow’, 2007-2011,
• Board member of the Section of Energy and Heat Technology of the Royal Netherlands Association of Engineers (KIVI), 2006 to 2012.

Dr.ir. H.C. de Lange
• Director of Education Dept. Mechanical Engineering,
• Member Advisory Board for the SENTER-Novem project ‘CO2-tool’,
• Member ERCOFTAC Special Interest Group (SIG33) ‘Transition Mechanisms, Prediction and Control’,
• Member Centre of Excellence for Industrial Gas Turbines (CE-IGT),
• Member European Turbine Network (ETN).

Dr.ir. J.M.R.J. Huyghe (as from April 2013)
• Member of Poromechanics committee of American Society of Civil Engineers ASCE,
• Member of the editorial Board of Biorheology,
• Member of the editorial Board of Transport in Porous Media,
• Member of the Solid Mechanics Conference Committee, of the European Mechanics Society (2012-2018),
• Project coordinator of project AGM-modelling with Procter and Gamble,
• Project coordinator of FP7-project GENODISC: Disc degeneration linked pathologies: novel biomarkers and diagnostics for targeting treatment, prevention and repair (2008-2012),
• Project coordinator of STW-project MuST-POROMULT, computational poromechanics of hydraulic fracture, 2008-2013.

Dr.ir. A.J.H. Frijns
• Co-chairman 1st European Conference on Gas Micro Flows, 2012,
• Work Package leader GASMEMS (EU, Marie-Curie Initial Training Network), 2008-2012,
• (Co)-organizer GASMEMS summer schools and workshops, 2009-2011,
• Treasurer of the 5th European Thermal Sciences Conference, May 2008, Eindhoven,
• Member of STW-jury (OTP – 299), 2011,
• Project coordinator STW-project ‘Integrated micro-fluidic cooling in laminated flexible microsystems’,
• Project coordinator Kidney Foundation ‘Individualization of dialysis treatment by continuous monitoring of electrolytes by novel optical sensor Technologies’.

Dr.ir. M.F.M. Speetjens
• Lead organizer Lorentz Center (LC) workshop ‘Physics of Mixing’, 2011,
• Guest editor special issue ‘Advances in Applied Mechanics’ on LC workshop, 2012,
• Board member of the ‘Section of Energy- and Heat Transfer Technology of the Royal Netherlands Association of Engineers (KIVI)’,
• Project coordinator FOM-Shell project ‘GEOCHAOS – Geoscience meets chaos’, 2014-2017,
• Project coordinator STW-project ‘Lagrangian mixing analysis of heat transfer: a new way for thermal optimisation’.
Dr.ir. S.V. Nedea
• Work package leader SAM.SSA (2012-2014),
• Principle investigator GASMEMS (EU, Marie-Curie Initial Training Network), 2008-2012,
• Project coordinator NWO-VENI project ‘Novel hybrid simulations for heat transfer at atomistic level’, 2005-2009,

8. Societal relevance: quality, impact and valorisation

8.1. Societal quality of the work

The research group is active on several elements of the energy chain: extraction (geothermal energy, shale gas, fracturing), conversion (photovoltaic/thermal systems, thermochemical treatment of biomass) and storage (thermochemical and phase change materials). In all elements there is productive interaction of societal stakeholders: scientists through knowledge dissemination, public through participation in debates (EnergyDays), industry through participation in consortia, and government through participation in the Dutch ‘top sectors’. And of course the main stakeholders are our students (both MSc and PhD), who quite easily find positions in industry.

8.2. Societal impact of the work

As outlined in the European Strategic Energy Technology Plan (SET-Plan), energy technologies will be crucial to successfully combat climate change and to secure world and European energy supply. Achieving the Europe 2020 and 2050 targets and visions on greenhouse gas emissions, renewable energy and energy efficiency will require the deployment of more efficient and new technologies:

• **Photovoltaic/Thermal combi-panels.** The research on PV/T combi-panels focuses on the optimisation of the overall efficiency, also taking into account the specific combi-panel concept and the total system design. The most crucial parameter is the thermal absorption factor of the solar cells used. This research was funded partly by ECN and partly by SenterNovem, and was carried out in close co-operation with Shell Solar. DimarkSolar PV/T combi-panels are currently undergoing performance tests in our laboratory. Within a new ‘top sector’ project, manufacturing concepts of PV/T combi-panels are investigated in co-operation with several small and medium-sized enterprises.

• **Thermal Storage.** The research on thermal storage focuses mainly on the development of optimal materials, reactors and systems. We collaborate closely with the Energy Research Centre of the Netherlands (ECN) through joint supervision of 3 PhDs and the part-time professorship of prof. Zondag. Dissemination of knowledge takes place through participation in IEA SHC task 42 on Compact Thermal Energy Storage and the KIC InnoEnergy on Heat storage.

• **Hydraulic Fracturing.** The research on hydraulic fracturing aims at boosting the performance of shale reservoirs by creating pathways in the rock structure. Fracture initiation and propagation is investigated within the 2F2S industry consortium, in which EBN, GDFSuez, Total, Baker-Hughes and Wintershall acknowledge the industry demand for better fracture predictability for unconventional gas production.
8.3. Valorisation of the work

The way to generate societal and industrial impact is through valorisation. Valorisation takes place through our Valorisation Grants, STW users’ committees, the KIC MTT project which is directly targeted towards market deliverables, and the EOS-LT INTEWON users’ committee. We participate in the public debate through the Eindhoven Energy Institute. Knowledge dissemination takes also place through direct industry contacts and through the Dutch ‘top sectors’.

9. Viability

Resource management
Through the sabbatical leaves, (inter)national cooperation and active participation in networks and conferences the Energy Technology group constantly strives for improvement of the research. The steady growth of the success of our long-term research programme shows the returns on investment of this policy. Other positive indications are the rapid success of the new research on cooling in microsystems and the strong growth in the number of PhDs in recent years (see Figure 9.1).

Available infrastructure
ET benefits from an excellent experimental infrastructure. In this respect optical techniques for velocity measurements, temperature profiles and particle size detection are complemented by state-of-the-art pressure sensors (piezo-electric, piezo-resistive, high-temperature resistive). In addition, dedicated technical equipment is designed, manufactured and maintained in our own workshops. The computational infrastructure is excellent and has recently been substantially extended by the implementation of a new parallel computer cluster. Available routines comprise Molecular Dynamics (MD), Direct Simulation Monte Carlo (DSMC), Direct Numerical Simulations (DNS), Large Eddy Simulation (LES), Spectral Element Method (SEM) and (Extended) Finite Element Modeling (X)FEM.

Figure 9.1. Number of PhDs per application domain
Innovative capacity
Since 2007 we have defined new applications Thermochemical and Phase Change materials (2008), LNG systems (2011) and Hydraulic fracturing (2012), in which the knowledge and expertise of the group members can be challenged. Significant external funding has been acquired within these domains. New staff have been appointed in these domains: Speetjens (mixing flows & advection dynamics, 2007), Nedea (molecular dynamics, 2008), Zondag (heat storage, 2010), Dam (LNG, 2012) and Huyghe (fracture mechanics, 2013). This has resulted in a substantial increase in the number of PhDs (see Figure 9.1). Interesting to note is the balance between the different application domains in 2013. The new application domain on Separation has rapidly matured over a 3-year period without compromising the others.

10. SWOT analysis

Strengths (internal dimension)
Our strengths are:

- The fundamentally-oriented research on Enhanced Thermal Transport gives us a strong international position in the Heat Transfer community, which has led to a strong increase in citations (250% relative to the previous period), a high number of publications in fundamentally-oriented journals and an increased visibility at an international level (EUROTHERM, ERCOFTAC, ICHMT, AIHTC and IEA).
- We are active in fields that have great societal and technological relevance, and the application of acquired knowledge to Small-scale Energy Systems is an integral part of our research. Examples involving both fundamentals and application are Thermochemical biomass conversion and Thermal comfort.
- There is a strong interaction between experimental and numerical analyses using (optical) measurement techniques and (open) software tools, which has resulted in a good infrastructure for both approaches. The design of small-scale energy systems includes construction, realisation and testing. All this has led to well-equipped test facilities in the laboratory.

Weaknesses (internal dimension)

- Energy Technology in itself encompasses a very broad field of research. Our research effort is divided among various topics (chosen along the predefined research lines and application domains), ranging from fundamentally-oriented towards application-oriented approaches with a strong interaction between experimental and numerical work. This may result in less focus and insufficiently connected research activities, which is disadvantageous for our external visibility. Embedding of new research topics along the predefined research lines and application domains is indispensable and requires constant attention. As a result of this we have ended the research on Cooling of electronics and turbine blades and Heat exchanger fouling. Although very successful, new applications Thermochemical and Phase Change materials, Hydraulic fracturing and LNG systems are considered more viable.
- The period 2008-2009 was an exciting one in which new staff joined the programme from other research areas (dr. Nedea and dr. Speetjens) and there was a reorientation of senior staff (dr. Rindt started the heat storage research line and dr. de Lange became educational programme director and head of the educational office). This created opportunities to thoroughly renew our research lines. The number of publications per research fte is well above 1, and the number of citations per paper is about 6. Although this value is not so different from that of our peer groups, the Mncs as found by CWTS is somewhat lower. As the
new research lines are well on track now and results are becoming increasingly visible, we expect the CPP values to rise in the coming period.

**Opportunities (external dimension)**
- The awareness that the use of energy-efficient systems and renewable energy technologies will be essential in mitigating global climate change has increased tremendously in the past few years. The group's expertise connects well with current/future needs and developments in the fields of energy, for example the definition of 9 top sectors (of which energy is one) and 3 TU/e-wide strategic areas (energy, health and mobility). In addition, the increasing visibility of the Eindhoven Energy Institute (with prof. Smeulders as Scientific Director) will lead to strong networks within TU/e and at national level. All this offers great opportunities to strengthen the group's position and realise new research projects.
- The Energy Technology group has expanded recently, bringing in complementary expertise. The new chair of the group (prof. Smeulders) will further strengthen the research and initiate new projects related to CO₂ Separation and Hydraulic fracturing, which perfectly fit in the research line on Enhanced Thermal Transport. New senior researchers (prof. Dam and dr. Huyghe) have recently been appointed.
- A new application domain has been established on Thermal Storage with a senior staff member (dr. Rindt) as research coordinator, and a new part-time professor in this field (prof. Zondag from ECN) has been appointed. Up to now 7 PhD projects have been started on subjects ranging from the molecular scale up to the reactor scale. Because of this broad scope, other staff members (dr. Nedea and dr. Speetjens) are involved in the supervision of the PhD students because of their specific expertise.
- The approach to engineering problems using micro-scale and multi-scale modeling techniques is becoming increasingly important. New research topics have been formulated for Microsystems cooling (dr. Nedea and dr. Frijns) and for Thermal Storage (dr. Nedea and dr. Rindt), based on the development of Molecular Dynamics (MD) modeling techniques. This has already resulted in numerous publications in high-ranked journals. The type of MD simulations is strongly related to similar activities in the Chemical Engineering and Biomedical Engineering departments.

**Threats (external dimension)**
- Over-reliance on industry funding threatens to lower the scientific impact of long-term research, and may reduce research efforts and output. This may potentially damage the longer-term scientific reputation of the group. Efforts have been successfully undertaken to define new research topics with both a fundamentally-oriented and an application-oriented character. Examples are the new research topics on Microsystems cooling and Thermal Storage (started since 2008 and still growing), Hydraulic fracturing and CO₂ separation with which our output in high-ranked journals is secured.
- The tendency of Dutch funding agencies towards research programmes and formation of consortia makes the realisation of smaller-scale individual research projects more difficult. This may in particular affect research staff at more junior levels, since realisation and formation of consortia typically requires networks at full-professor level. This applies to an even larger extent to European funding sources. Here the formation of consortia is even more important than at the national level.
11. Strategy for the next period

**Scope:** Our strategy for the coming period is to expand our research on Cooling, Separation, and Thermal Storage & Conversion as illustrated in Figure 9.1. The research on Cooling of electronics and turbine blades and Heat exchanger fouling is no longer pursued.

**Means:** This expansion can be achieved by consortium-building in emerging technologies to limit both threats (declining project funding) and weaknesses (too little focus). We have shown that we can successfully attract increasing numbers of PhDs, staff and funding for our research.

**Resources:** This expansion will be implemented by the current research staff which has been significantly increased over the review period (prof. Smeulders, prof. Dam, prof. Veringa, prof. Zondag, dr. Huyghe, dr. Speetjens and dr. Nedea have been newly appointed).

**Table 11.1. Strategy for the coming period**

<table>
<thead>
<tr>
<th></th>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Threats</strong></td>
<td>- Consortium-building against declining project funding.</td>
<td>- Consortium-building in emerging technologies limits both threats (declining project funding) and weaknesses (too little focus).</td>
</tr>
</tbody>
</table>
TU/e 6: Process Technology

1. Objective(s) and research area

1.1. Vision, mission and objective(s) of the programme

The mission of the Process Technology group is fourfold:
- Gain insight into the fundamental phenomena underlying the mechanics of process technology;
- Apply this insight to model and predict the behaviour of relevant unit operations;
- Use this knowledge to develop new technological concepts;
- Educate the new generation of engineers in this field.

The research programme therefore ranges from fundamental problems in physics and mechanics of process technology to the conceptual development of new technologies. Fundamental research focuses on turbulence, phase-transitional flow, rotating fluid flow and subsurface flow. New technologies concentrate on rotational phase separation, wall-desublimation techniques and condensed rotational separation. In our vision innovative contributions can be made by a combination of experimental, theoretical and numerical methods covering the full range of length scales – from microscopic, where the basic phenomena in turbulence and heat and mass transfer play a role, right up to the large industrial scale.

The objective of the group is to combine a high scientific level with a strong focus on challenging questions from industry and society, and to prepare the new generation of students in this field for future industrial and societal needs.

1.2. Strategy

Process industry accounts for one-third of the gross national product of the Netherlands. Dutch companies active in this field are among the world’s largest, e.g. Royal Dutch Shell, AkzoNobel, Unilever and DSM, and they are supported by a network of engineering and manufacturing companies. Research and education in the section benefit from and contribute to the strong base of process industry in the Netherlands.

We apply scientific principles to develop methods and models to support the advance of innovative and the improvement of existing technologies, at the same time increasing our fundamental understanding of key problems in mechanics of process technology, such as turbulent dispersion and phase-transitional flow. We aim for a combined experimental and numerical approach, wherever possible enabling direct validation of developed methods.

We strive for a good balance between different sources of external funding. In the past period we received almost equal funding directly from industry and from public grants, which are mostly from the Technology Foundation STW through their Open Technology Program. In this way we...
also maintain a good balance between more fundamental and more applied research. To adjust to the changing Dutch policy on research funding, we are broadening our funding strategy to special programmes such as ISPT and HTSM.

Education of students at all levels, BSc, MSc and PhD, is achieved by a well-tuned course programme in fluid mechanics, heat transfer and their applications, in collaboration with adjacent groups in the department, by special advanced courses offered by the Dutch Research Schools on fluid mechanics and process technology and by our contacts with industry, which offer good opportunities for on-site training.

1.3. Research areas and subprogrammes

The research activities in the group are performed by a combination of experimental, theoretical and numerical methods and focus on the phenomena that play a prominent role in the mechanics of process technology and are important for Dutch industry. This is reflected in the four research areas defined in the programme:

1. Statistical Turbulence and dispersion. Theoretical methods are applied to gain insight into the nature of turbulence and turbulent dispersion. Numerical simulation and experimental techniques have been used to validate the developed models. Particle-laden flows are studied by means of DNS, LES and 3D PTV.

2. Phase Transitional Flow: Innovation in two-phase processes and equipment through analysis, experiments and numerical simulation (condensing heat exchangers/expanders, evaporation and droplet growth). A multi-scale method, based on and validated by dedicated experiment and numerical simulation, is being developed.

3. Rotating Fluid Flow: increasing our understanding for the further development of rotating equipment (Pumps, Rotational Particle Separator, Gas-Centrifuges). A combination of experimental methods and numerical simulation is used for this purpose.

4. Sub Surface Flow (since 2012): experiment and analysis of non-Newtonian flow to extract energy from the earth (geothermal, oil & gas) through the experimental study and development of proppant fluids. A new lab facility is being built for this research area.

The insights gained in these research areas are applied to develop new technological concepts, in particular the inception and development of new processes and equipment. Examples are Condensed Rotational Separation, the Wall Desublimator and the Snow Sweeper.

2. Composition of the research staff

At present the group consists of 6 scientific faculty members (2 fte research capacity):

- **Full professors**: prof.dr.ir. Bert Brouwers (64), prof.dr. Michael Golombok (54; part-time, also at Shell)
- **Associate professors**: dr. Cees van der Geld (59), prof.dr. Hans Kuerten (52; also part-time full professor at University of Twente)
- **Assistant professors**: dr. Bart van Esch (48), dr.ir. Erik van Kemenade (46)

The group supervises on average 10-12 PhD students and postdoc researchers and 10-15 MSc students.
The scientific staff combine expertise in mathematical, numerical and experimental techniques with a thorough understanding of the relevant physical phenomena in turbulence, multi-phase flow and rotating fluid flow and experience in practical design. Most of our projects require joint activities by the team members in which there is strong interaction between these specialisations. These interactions also take place with members of adjacent groups and with industrial partners. When the required specialisations are not readily available in our group, guest researchers are invited from our network.

The supporting staff consist of three technicians, one of whom also manages the computer clusters used for numerical simulations, and one secretary. All technicians have held various positions in industry (Philips, Vialle).

**Changes in the evaluation period**

Prof.dr. Ingwald Obernberger (part-time full professor) left the group in 2007.

**Table 2.1a. Composition of research staff at programme level (fte)**

<table>
<thead>
<tr>
<th></th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TU/e 6: Process Technology</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tenured staff</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Non-tenured staff</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.2</td>
</tr>
<tr>
<td>PhD students</td>
<td>5.9</td>
<td>7.1</td>
<td>7.7</td>
<td>8.8</td>
<td>7</td>
<td>7.5</td>
</tr>
<tr>
<td><strong>Total research staff</strong></td>
<td>7.9</td>
<td>9.1</td>
<td>9.7</td>
<td>10.8</td>
<td>9</td>
<td>9.7</td>
</tr>
<tr>
<td>Supporting staff</td>
<td>1.0</td>
<td>1.3</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Visiting fellows</td>
<td>0.5</td>
<td>0.9</td>
<td>1.6</td>
<td>2.2</td>
<td>1.2</td>
<td>3.1</td>
</tr>
<tr>
<td><strong>Total staff</strong></td>
<td>9.4</td>
<td>11.3</td>
<td>12.5</td>
<td>14.2</td>
<td>11.4</td>
<td>14.0</td>
</tr>
</tbody>
</table>

**Table 2.1b. Composition of research staff at programme level (numbers)**

<table>
<thead>
<tr>
<th></th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TU/e 6: Process Technology</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tenured staff</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Non-tenured staff</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>PhD students</td>
<td>10</td>
<td>12</td>
<td>12</td>
<td>13</td>
<td>11</td>
<td>13</td>
</tr>
<tr>
<td><strong>Total research staff</strong></td>
<td>15</td>
<td>17</td>
<td>17</td>
<td>18</td>
<td>16</td>
<td>19</td>
</tr>
<tr>
<td>Supporting staff</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
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<tr>
<td>Visiting fellows</td>
<td>2</td>
<td>4</td>
<td>5</td>
<td>7</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td><strong>Total staff</strong></td>
<td>21</td>
<td>25</td>
<td>26</td>
<td>29</td>
<td>24</td>
<td>31</td>
</tr>
</tbody>
</table>
3. Research environment and embedding

3.1. National positioning

• The Process Technology group is one of the groups in the Thermo-Fluids Engineering cluster of the department. The participating groups share a common laboratory including the technicians and high-performance computer clusters. In addition, they share expertise in experimental techniques and they collaborate in teaching courses at Bachelor and Master level.

• The group participates in the research schools JMBC (J.M. Burgerscentrum for fluid mechanics and OSPT for process technology, and actively collaborates with groups at the University of Twente.

• The group is involved in a number of projects funded by the Dutch Technology Foundation STW in which collaboration with the Department of Applied Physics, the University of Twente and Wageningen UR University & Research centre takes place. These projects are financially supported by and involve active collaboration with Dutch industry, e.g. Philips Research, Shell, DAF, Océ and Stork. In several cases this collaboration has resulted in joint journal publications.

• Royal Dutch Shell has financed 8 PhD projects carried out in the group on condensed rotational separation and subsurface flow and has provided the group with experimental equipment.

• In cooperation with EMC and AMC, research on boiling phenomena occurring during endovenous laser ablation is studied experimentally and numerically and financed by EMC. This research has resulted in a number of publications.

3.2. International positioning

• The group is and has been involved in several European collaboration projects and COST Actions, in which also industries from abroad participate. Group members act as work-package manager or cluster manager in some of the COST Actions.

• BASF has financed a PhD project on high-pressure safety valves. Collaboration with BASF on this topic and on gravitational pressure drop in adiabatic two-phase flow has resulted in several publications in scientific journals.

• Collaboration with Brazil has led to a PhD project at TU/e funded by CAPES and an official bilateral exchange agreement between TU/e-W and Univ. Federal de Santa Catarina, with 2 proposals involving postdocs and PhD students guided by our group, in the ‘Sciencias sem Fronteiras’ framework which was established in 2013 to strengthen the collaboration.

• Contacts with leading Chinese Universities in the field of hydraulic turbines and pumps have resulted in joint research and an exchange of visiting scientists. Formal collaboration agreements have been established with Tsingua University in Beijing and the National Key Research Center of Fluid Machinery Engineering at Jiangsu University in Zhenjiang.

• Together with Institut de Mécanique des Fluides de Toulouse (IMFT) measurements have been performed in microgravity and supergravity during parabolic flights with a single bubble generator and nearly uniform flow approaching a growing bubble. The analysis of the measurements was carried out in Eindhoven and published in Physics of Fluids.

• Collaboration with groups from several countries has resulted in joint articles on benchmark problems for DNS and LES of particle-laden turbulent flow.
4. Quality and scientific relevance

4.1. Most significant results/highlights

**General Statistical Description of Turbulent Flow and Dispersion**

We developed a universal description for turbulent dispersion using large Reynolds number theory, and implementing asymptotic expansions with the inverse of the Kolmogorov constant as small parameter. The theory replaces conventional semi-empirical expressions by fit factors. Predictions of this description are confirmed by in-house results of DNS at moderately high Reynolds number in channel flow, and by 3D PTV in pipe flow. This work has been published in Phys. Rev. E., Phys. Fluids, Theor. Math. Phys. The theory was very recently extended to a closed system of equations describing all main statistical parameters determined by the large scales of turbulence. The statistical descriptions provide a new basis for assessing turbulent flow and dispersion in nature and technology.

A subgrid model has been developed for large-eddy simulation of particle-laden turbulent flow. It is based on a combination of approximate deconvolution and an additional stochastic forcing, whose properties have been found to be universal, i.e. independent of Reynolds and Stokes numbers. This work has been published in several papers in Phys. Fluids and has been frequently cited.

**Phase transitional flow**

We have succeeded in deriving expressions for the inertia forces on deforming and growing bubbles with the aid of a variational approach (*J. Fluid Mech.*), and we have applied these expressions in a method to assess and predict the forces on a growing boiling bubble (*Phys. of Fluids*). Prediction of heat transfer in the nucleate boiling regime is preferably based on mechanistic modeling (*J. Heat Mass Transfer*), and in such models the detachment size of boiling bubbles is a key parameter (*Int. J. of Heat and Mass Transfer*). The model developed is essential in the prediction of this size. In addition, a diffuse interface model has been developed (*Int. J. of Multiphase Flow*) that automatically accounts for changes in the topology of interfaces and for heat and mass transfer. Dedicated experiments with e.g. PIV and PTV are used to validate predictions of steam injection (*J. Fluid Mech.*), boiling bubble interaction (*Phys. of Fluids*) and flow pattern transitions. A similar approach has successfully been followed in studies of endovenous laser ablation (EVLA) (*European J. of Vascular and Endovascular Surgery*) and of the manufacturing of biosensors (*J. of Colloid and Interface Sc.*).

**Flow in rotating machinery**

Experimental work on fluid induced forces revealed that rotor-stator interaction in mixed-flow pumps causes fluid forces that can lead to a backward-whirling impeller. This was previously anticipated theoretically, but never confirmed experimentally. Based on numerical and experimental analyses we concluded that pumps operating at non-uniform suction flow experience a considerable lateral force on the impeller. It explains a formerly not understood type of damage in ship propulsion systems. Wakes behind the rotor blades turn out to contribute significantly to the magnitude and phase of the hydrodynamic damping forces. Their contribution to torsional and axial vibrations of the shaft system was quantified (*J. Fluids Eng.-Trans. ASME, Int. J. Maritime Eng., Marine Techn.*).

Numerical calculations of the internal flow of pumps identified the primary cause of damage to fish. This was validated by dedicated experiments involving live fish. Guidelines for the selection and operation of pumps for pumping stations were derived (*J. Fluids Eng.-Trans. ASME*).
4.2. Key publications


4.3. Number of articles in top 10% and top 25% of publications relevant to the discipline

Of the scientific articles 5% are in the top 10% and 17% in the top 25% of publications relevant to the discipline. The MNCS value of our group of 0.7 is below world average. We evaluated our citation scores on the basis of Web of Science. The two figures below show the number of publications (left) and citations (right) of the tenured staff members of the group in the period 2001-2012.

- The number of citations (corrected for self-citations and without 2013) per publication equals 3.14, which is close to the value of 2.82 reported by CWTS over the same period.
- From 2010 onwards the number of articles published in SCI journals increased significantly. This increase was continued in 2013.
- There is a delay of approximately 5 years in the number of citations. The increase in the number of publications since 2010 is therefore not yet visible in the number of citations.
- In some fields of research (for example direct numerical simulation and large-eddy simulation of particle laden flow), the number of citations per year is significantly higher (between 6 and 10) than in others.
- Our papers appear in above-average journals per field. This is supported by the 1.02 value for MNJS in the citation report.
- The number of citations per publication is related to the size of the research community. For some of the fields in which we work the community is small.
5. Output

5.1. Number of publications

Table 5.1. Number of scientific publications and other research output

<table>
<thead>
<tr>
<th>Publications</th>
<th>2007 (1)</th>
<th>2008 (3)</th>
<th>2009 (8)</th>
<th>2010 (2)</th>
<th>2011 (0)</th>
<th>2012 (4)</th>
<th>6 year total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Academic publications</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refereed articles</td>
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<td>9</td>
<td>12</td>
<td>11</td>
<td>10</td>
<td>16</td>
<td>68</td>
</tr>
<tr>
<td>Conference papers</td>
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<td>6</td>
<td>5</td>
<td>13</td>
<td>17</td>
<td>11</td>
<td>57</td>
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<tr>
<td>PhD theses</td>
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<td>-</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>13</td>
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<tr>
<td>Book chapters</td>
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<td>-</td>
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<td>-</td>
<td>-</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Total academic publications</td>
<td>18</td>
<td>15</td>
<td>21</td>
<td>26</td>
<td>28</td>
<td>32</td>
<td>140</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Patents*</th>
<th></th>
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<th></th>
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<tbody>
<tr>
<td></td>
<td>2</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Total research output</td>
<td>20</td>
<td>17</td>
<td>21</td>
<td>27</td>
<td>29</td>
<td>32</td>
<td>146</td>
</tr>
</tbody>
</table>

(1): numbers between brackets indicate publications obtained in cooperation with other research programmes with them as first authors as included in the first numbers.

* Two patents have passed the PCT procedure and have been awarded in major countries.

5.2. Number of PhDs (completed and in progress)

Table 5.2. PhD students

<table>
<thead>
<tr>
<th>Starting year</th>
<th>Enrolment (male/female)</th>
<th>Total (male + female)</th>
<th>Graduated after (years)</th>
<th>Total graduated</th>
<th>Not yet finished</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>≤ 4</td>
<td>4-5</td>
<td>5-6</td>
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<tr>
<td>2003</td>
<td>4</td>
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<td>2004</td>
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<td>2005</td>
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<tr>
<td>2006</td>
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<td>2012</td>
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<td>2013</td>
<td>2</td>
<td>-</td>
<td>2</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Note: The thesis defence is usually 2 months after the end of the 4-year PhD contract. PhD students generally get no extension. Graduated in 4-5 years should therefore be interpreted as: PhD work, including writing the thesis is finished in 4 years. Before the start of the thesis defence the thesis is sent to the printer, and subsequently to the committee members to read. This takes 2 months.
The average duration of the PhD students in our group is 4 years and 2 months, and no PhD student required more than 4 years and 6 months. This is achieved by the combination of a careful selection process, a well-considered work plan and intensive guidance by the supervisors. PhD students follow a training programme that consists of several courses offered by the national research school, in which they participate, as well as several courses at MSc level depending on their background and several PhD courses aimed at personal development. The latter courses are intended for example to strengthen their presentation and scientific writing skills and to provide career consulting. As a result, our PhD students easily find jobs in industry within a short time after their graduation.

6. Resources

6.1. Overview of the various sources of funding

Table 6.1. Funding at programme level

<table>
<thead>
<tr>
<th>Funding</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct funding (1)</td>
<td>45</td>
<td>8</td>
<td>54</td>
<td>12</td>
<td>91</td>
<td>23</td>
</tr>
<tr>
<td>Public grants (2)</td>
<td>166</td>
<td>31</td>
<td>180</td>
<td>40</td>
<td>298</td>
<td>51</td>
</tr>
<tr>
<td>Industry &amp; contract research (3)</td>
<td>325</td>
<td>61</td>
<td>220</td>
<td>48</td>
<td>118</td>
<td>30</td>
</tr>
<tr>
<td>Total funding</td>
<td>536</td>
<td>100</td>
<td>454</td>
<td>100</td>
<td>637</td>
<td>100</td>
</tr>
</tbody>
</table>

(1) Direct funding: PhD and post-doc projects funded directly by TU/e
(2) Public grants: NWO, STW, FOM
(3) Industry & Contract research: Industry

6.2. Earning capacity

The earning capacity of the group is shown in Table 6.2.: 

Table 6.2. External funds used/acquired in the period 2007-2012

<table>
<thead>
<tr>
<th>Sponsor</th>
<th>Most important partners</th>
<th>External funding k€ 2007-2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>NWO</td>
<td>Dept. W&amp;I, TN</td>
<td>27</td>
</tr>
<tr>
<td>STW</td>
<td>Shell, Philips, DAF, Spirotech, Océ, WUR, KEMA, RWE, Twister, Akzo, NIZO, Stork, UT</td>
<td>1470</td>
</tr>
<tr>
<td>Direct industry</td>
<td>Shell, BASF</td>
<td>1616</td>
</tr>
<tr>
<td>EU projects</td>
<td>Consortium of industrial partners</td>
<td>45</td>
</tr>
<tr>
<td>EMC</td>
<td>EMC, AMC</td>
<td>120</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>3278</td>
</tr>
</tbody>
</table>
6.3. Research facilities & investments

Experimental investigations and prototype testing take place in laboratories which are jointly operated with the Energy Technology and the Combustion Technology groups. If the facilities of the lab are not sufficient, experimental research is carried out in laboratories of external partners: Shell labs in Amsterdam and Rijswijk, BASF in Ludwigshafen Germany, BIOS in Graz Austria, NIKHEF Amsterdam, Klima Eindhoven and Spirotech Helmond. Specialties of the lab are measuring particle distributions in phase change, 3D PTV of inhomogeneous turbulence and flow though porous media.

The investments in lab facilities in the period 2007-2012 amounted to 955 k€, including equipment long-term loans from industrial partners. The most important equipment acquired is:

- Tomoflow void fraction measuring device
- Boroscope
- Cameras and post-processing software for 3D PTV
- Ultrasonic measuring device
- Several prototypes RPSs for liquid-gas separation
- Two Malvern particle sizers
- Anton-Parr Rheometer
- Pumps, flow meters
- Galai CIS-100 particle size analysis tool

Jointly with the Energy Technology and Combustion Technology groups, the group has several large computer clusters on which most of the large-scale computational research is performed. Investments in the period 2007-2012 included 3 multi-node Linux Clusters, of which the largest has 72 nodes with a fast interconnection, which enables parallel processing with good scaling properties. For larger computational work the group has access to the supercomputer facilities at SARA in Amsterdam through yearly grants from NWO. In 2009 direct numerical simulation of channel flow at high Reynolds number was performed at the powerful NEC SX9 computer in Stuttgart through a grant from DECI.

7. Academic reputation

Prof.dr.ir. J.J.H. (Bert) Brouwers, H-index WoS: 8 (Google Scholar: 15)

- Bert Brouwers spent the first 14 years of his professional career in industry (Urenco, Shell)
- From 1986 to 1998 full Professor of Thermal Engineering at the University of Twente
- Derived solutions in closed-form of the flow of a heavy gas in a centrifugal field. These showed the direction in which ultra-centrifuges had to be developed with application in today’s uranium enrichment plants of Urenco (PhD Thesis, J. Eng. Mech., Nucl. Techn.)
- Invented the Rotational Particle Separator comprising a patented method for separating micron sized particles from fluids. The technology has been implemented in various fields of application (Powder Techn., Exp. Therm. Fluid Sci., Chem. Eng. Sci.)
- Invented Condensed Rotational Separation: gas-gas separation by fast preferential condensation and separation by centrifugation. A competitive technology in statu nascendi to upgrade sour gas fields and remove greenhouse gases emitted from fossil fuel-fired power plants (Oil&Gas J., Energy, J. Petr. E&P Techn.)
• Single author of over 20 articles in SCI-ranked journals, owner of commercially applied patents, founder of the Romico Companies, advisor to the International Atomic Energy Administration IAEA in Vienna
• Receiver of the Dow Chemical Energy Award
• Advisor of over 40 PhDs and responsible for more than 200 MScs

Prof.dr. J.G.M. (Hans) Kuerten, H-index WoS: 16 (Google Scholar: 18)
• Hans Kuerten was appointed full professor Computational Multiscale Methods (0.2 fte) in the Department of Applied Mathematics of the University of Twente in April 2010
• Main field of research: development and application of numerical simulation methods to problems in multi-phase flows with emphasis on direct numerical and large-eddy simulation
• Developed a subgrid model for large-eddy simulation of particle-laden turbulent flow (Phys. Fluids) and a diffuse interface model for phase-transitional flow (Int. J. Multiphase Flow)
• Co-organiser of 2 international conferences
• Working group manager of Multiphase Flow of COST-Action P2o, LESAID and cluster manager of cluster on heat and mass transfer on solid substrates of COST-Action Smart and Green Interfaces
• Member of Scientific Committees of 4 series of international conferences
• Member of the ERCOFTAC Da Vinci Prize jury
• (Co-) author of more than 60 journal papers
• (Co-) applicant of ten projects funded by the Dutch Technology Foundation STW or directly by NWO
• (Co-) advisor of 24 PhD students and member of 8 international Ph.D. committees
• 6 invited presentations at international conferences

Prof.dr. Michael Z. Golombok (0.2 fte), H-index WoS: 10 (Google Scholar: 13)
• Mike Golombok has worked for Shell for 28 years and is currently Principal Researcher in the Materials and Physics Department in the Innovation R&D Division of Shell Projects and Technology
• Shell Thornton Academic Publication Prize
• Best presentation Award SAE (Society of Automotive Engineers)
• Experimental demonstration of centrifugal gas separation on non-isotopic systems
• First experimental study of H2S hydrates formation
• Exploration of shear induced structures on rheology of permeable flow in porous media
• Acoustic mode fingerprinting in turbulent flow pipelines – first demonstration
• Hosts high profile external international visitors to TU/e projects
• (Co-) author of 75 refereed papers
• 3-5 yearly invited presentations at international conferences
• (Co-) advisor of 9 PhDs and responsible for over 20 MScs

Dr. Cees W.M. v.d. Geld, H-index WoS: 11 (Google Scholar: 13)
• Cees van der Geld was appointed associate professor Multiphase Flow in 1990, after working for one year in industry, obtaining his PhD in 1985 and working for two years at Aerospace Engineering at TU Delft
• 1983-2000 owner of a registered consultancy agency
• Main field of research: phase transitional flows, in particular flows with boiling, condensation and steam injection
• Since 2007 involved in 12 subsidized projects, nine times as principal investigator and mostly funded by the Dutch Technology Foundation STW
• President of the Assembly of World Conferences on Experimental Heat Transfer, Fluid Mechanics and Thermodynamics (AWC)
• Chairman of the Nusselt-Reynolds prize committee in 2009-2013
• (Co-) organised international conferences (>16) and member of 6 international scientific committees
• Editor of Experimental Thermal and Fluid Science and (co-)author of 27 refereed journal papers in 2001-2009 and of 17 in 2010-2012
• (Co-) advisor of 15+6 (6 abroad) PhDs and responsible for more than 100 MScs
• 5 invited presentations at international conferences

Dr. Bart P.M. van Esch, H-index WoS: 5 (Google Scholar: 9)
• Bart van Esch became Assistant Professor at TU/e in 1998
• Since 2000 Senior Hydraulic Engineer (0.2 fte) at Bosman Watermanagement b.v. and responsible for the design of large pumping installations for polder dewatering and power stations
• Topics of research: turbo-machinery and Computational Fluid Dynamics
• Associate editor of Journal of Fluids Engineering – Trans. ASME (since 2012)
• Member of the Editorial Board of Journal of Drainage and Irrigation Machinery Engineering (since 2011)
• Member of scientific committees for 2 international conferences
• 2009 and 2010: series of invited lectures at Tsinghua University (State Key Laboratory of Hydrosience) in Beijing, China Agricultural University (College of Water Conservancy) in Beijing, Hohai University (Water Conservancy and Hydropower Engineering College) in Nanjing, Jiangsu University (National Research Center of Fluid Machinery) in Zhenjiang and Yangzhou University (Hydrodynamic Engineering Laboratory) in Yangzhou, in Shanghai University
• (Co-) author of 13 refereed journal papers and 21 refereed conference papers
• (Co-) advisor of four PhDs and responsible for 12 MScs
• 2 invited presentations at international conferences

Dr.ir. H.P. (Erik) van Kemenade, H-index WoS: 3 (Google Scholar: 7)
• After five years as project manager at LEVEL energy technology b.v. Erik van Kemenade returned to academia in 1999 as assistant professor
• Main fields of research: phase transition phenomena and heat and mass transfer equipment
• Designed a combustion heated thermionic energy converter (PhD thesis)
• Developed a laminar counterflow heat exchanger for gas turbines, recuperative and HVAC applications at LEVEL energy technology b.v.
• Developed the Rotational Particle Separator for the oil and gas industry (Chem. Eng. Techn.)
• Designed condensing heat exchangers for emission reduction in biomass systems (En. & Fuels) and gas separation processes (E. Techn.)
• Process development and equipment sizing for Condensed Rotational Separation (J. Petr. E&P Techn.)
• Acts regularly as an engineering consultant (>10) and advisor to patent lawyers or courts of law (4)
• (Co-) author of 13 refereed journal papers and 24 refereed conference papers
• (Co-) advisor of four PhDs and responsible for 20 MScs
8. Societal relevance: quality, impact and valorisation

8.1. Societal quality of the work

Almost all our research originates from problems identified by industry and is carried out in close contact and cooperation with industry and possible other users of the results. This is done both in projects directly funded by industry and in projects funded by Technology Foundation STW with financial support from industry. In the period 2007-2012 the number of projects funded directly by industry or by STW significantly increased, and this has resulted in a proportional growth of our industrial network.

For each project a user group is formed that meets frequently to discuss results, assess progress and give direction to the research. In this way we directly disseminate the results of our work to the problem owners. Staff members act regularly as consultants to industry and patent lawyers or courts. The frequent and intense interaction with industrial researchers keeps the research focused and brings our PhD and MSc students into contact with research outside the university.

8.2. Societal impact of the work

Our PhD students easily get positions in industry, where they use the knowledge acquired during their PhD research to develop improved technological solutions for society. PhD students who graduated in the period 2007-2012 found positions with companies such as DSM, ASML and Philips.

Several examples of projects carried out in our group show the societal impact of our research:

- In cooperation with staff of the International Atomic Energy Agency IAEA in Vienna, Brouwers’ solutions in closed-form of the flow of a heavy gas in a centrifugal field were transformed into a simple design formula. This enabled estimation of the potential for producing highly enriched uranium by centrifuge technology, on the basis of pictures supplemented by other data, adding to IAEA’s capability in early detection of possible misuse of nuclear material and technology.
- Research funded by the EU on biomass power plants has resulted in the identification of the size distribution of emitted particles. The realisation that particulate matter emissions from biomass combustion is bi-modal with a strong peak around 0.1 micron has changed the legislation on emission of particulate matter, the design procedure and the criteria for small-scale biomass combustion units.
- The research on endovenous laser ablation has resulted in advice given for process conditions such as wavelength and traction speed during EVLA.
- A method to size nozzles and their required inlet pressure has been developed and is now used in two industries.
- Our research has identified the main mechanism responsible for damage to fish in pumping stations, leading to a method to estimate damage rates which is now being used in the pump selection process. Our knowledge of pump operation has led to the development of a pump control method to minimise energy consumption. This method will soon be implemented in several pumping stations in the Netherlands.
8.3. Valorisation of the work

Valorisation of our research is achieved through patents, knowledge transfer to industry and products conceived and developed in our group. Examples are:

- The very efficient plastic laminar counter flow heat exchanger devised by a staff member has become standard in domestic balanced ventilation systems. Energy savings are 600 m³ natural gas equivalent per year for a Dutch reference dwelling.
- Airport Snow Sweeper — a device for compacting snow by a novel extruder to enable fast clearing of airfield strips — was conceived by a student in our group, is now going into its second phase of testing at the air force base in Eindhoven and in Finland and is financed and supported by the Netherlands Ministry of Economic Affairs and Dutch airport authorities.
- The research on the RPS has resulted in several patents. After the initial application of the technology to separation of solid particles from a gas stream, the technology of the RPS took a new direction: the oil and gas sector. Enexis is currently applying the RPS at a gas distribution station to remove condensates. Another design is being tested under supervision of Statoil, Shell, Petronas and Wintershall to remove oil droplets from water. The RPS is also central to the new technology of Condensed Rotational Separation (CRS), which enables separation of gaseous mixtures by selective condensation through combined pressure and temperature flashing. It has the potential to become a much more compact alternative to the classical 100-year-old distillation column. Applications under development include upgrading of highly sour gas fields (Saudi-Aramco, Shell, Petronas) and removal of greenhouse gases from fossil-fuel power stations (US Department of Energy). Two patents related to these applications of the RPS have passed the PCT procedure and have been awarded in major countries.
- A numerical method to simulate the penetration of micron-sized droplets on porous substrates, which was developed in our group, is presently in use at Océ to optimise the quality of inkjet-printed products.

9. Viability

The group has shown its relevance by its combination of scientific output and technological impact. Process technology will remain an important field for the Dutch economy in the coming decades. We therefore see many opportunities for continuation of our research themes, in spite of the upcoming retirement of the group leader Bert Brouwers.

Resource management: The viability of the group is demonstrated by our continuing potential to generate funding from industry and public grants and from our expanding industrial and European networks:

- Shell recently funded new research activities in our group in the area of non-traditional oil and gas exploration and production. For these activities Shell made available an amount of 2500 k€ on terms which allow us full freedom in the way the research is formulated and performed.
- In 2013 two research proposals were granted by the Dutch Technology Foundation STW. They both involve participation and financial contributions from industry. One is a combined experimental and numerical research on flow regimes with boiling; the other is a numerical research project on drying micro-droplets on porous media.
• In 2013 a research proposal was granted by FOM with financial support from Shell in the Computational Sciences for Energy Research programme. In this project the interaction between biomass particles and the surrounding gas in co-fired coal power plants is numerically studied.
• Since 2013 the group has been involved in the COST Action Smart and Green Interfaces, which aims at European funding for collaborative research projects. Group members are cluster managers in the topic of heat and mass transfer on a solid substrate in this COST Action.

Infrastructure: The research activities granted by Shell consist of:
• A new lab facility is being built to carry out subsurface geophysical flow studies, and is being used to develop innovative solutions to sub-surface water flow. Novel rheological additives are being assessed for their potential use in water short-circuits caused either by large fractures or for regions of high permeability.
• Novel rheological materials are applied to make cleaner proppant placement fluids during hydraulic fracturing of ‘tight’ (low permeability) gas reservoirs. The aim is to develop clean fracturing fluids which are applied immediately following the fracturing element.
• In the area of heavy oil we are carrying out novel work on hydrous pyrolysis exploiting near critical fluid operation. This is a real step-out project from the current technology for oil sands, and is aimed at exploring the potential of simultaneously dissolving heavy oil components and cracking them at subcritical pressure and temperature.

Innovative capacity: We have identified several challenges within our field of research which require our innovative capacity:
• The statistical description of turbulence offers the opportunity to develop well-founded turbulence models for use in CFD software, to validate them by means of dedicated experiments and detailed simulations, and to apply them to practical applications of turbulent flow in dispersion in nature and technology.
• Hydrodynamic fluid forces in rotating machinery are still not well understood. Our research aims to lead to improved methods for the design of drive-train systems for ship propellers and pumping systems.
• Combined theoretical, experimental and numerical efforts will be made to develop a multi-scale method for phase-transitional flow. The result will enable accurate simulations for engineering applications involving heat transfer and phase transition.
• The technology of condensed rotational separation will be investigated for upgrading highly sour gas fields. The current workhorse of industry for processing sour gas is amine treatment. Both energy consumption (OPEX) and size of the installation (CAPEX) are reduced dramatically by CRS, enabling economic exploitation of stranded highly sour gas fields.
• The same principle is applied to the removal of CO\textsubscript{2} from flue gases of coal-fired power plants. This research line has the interest of a number of companies and has been featured in prominent American reviews on sustainability, climate change and the associated requirements for carbon capture and sequestration.
10. SWOT analysis

Strengths (internal dimension)
- We possess a well-equipped lab with state-of-the-art facilities.
- Our research staff combine expertise on the most important topics in process technology: turbulence, phase-transitional flow and rotating flow, and cover the broad range of theory, numerical simulation and experiment. In this way we are able to develop fundamental concepts and apply them to industry-driven questions.
- Our PhD students manage to finish their projects on average in 4 years and 2 months, and easily find jobs in industry after their PhD.
- We have a good balance of funding from public grants, from the EU and from industry, and receive substantial sums of money from private sources with limited constraint of remit enabling us to follow unconventional paths towards innovative concepts.
- Our staff have experience with mechanical engineering practiced outside university. This benefits the relevance of our research.

Weaknesses (internal dimension)
- The underlying heat and mass transfer physics are considered as ‘difficult’, limiting the number of BSc and MSc students attracted to the research area and making it more difficult to find suitable PhD students. On the other hand the quality of the students enrolling is high, and they easily find jobs in industry.
- Although our financial position is good, we attract most of our funding from national sources and Dutch industry.

Opportunities (external dimension)
- The CO$_2$ problem and related global warming, limited global reserves of fossil fuel and its extraction at higher recovery factors, environmental pollution and related health threats are currently among the most important economic and environmental problems recognised worldwide. They provide ample opportunities for the successful continuation of our work.
- The group has an extended network of industrial contacts, which facilitates the generation of funding for our research projects.
- Our involvement in European collaboration networks (COST Actions) increases the possibilities for European funding of research projects.

Threats (external dimension)
- Policy on research funding changes frequently. Nevertheless, the group has been able to gain ample resources to carry out its research.
- At present, one company is responsible for a large proportion of the funding from industry. In the future the industrial network should be further extended.
- It is not easy to find a sufficient number of highly qualified PhD students for our research projects. Making better use of our existing international network and direct contacts with China and Brazil is a solution for this problem.
- The group leader will retire in 2014. Although the department intends to open a position for a new chair holder, the transition could lead to changes in the strategy of the group.
## 11. Strategy for the next period

### Table 11.1. Strategy for the next period

<table>
<thead>
<tr>
<th></th>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Opportunities</strong></td>
<td>• Exploit our expertise in the field of process technology to contribute to the solution of the currently most important economic and environmental problems of global warming, limited reserves of fossil fuel and environmental pollution.</td>
<td>• Increase visibility of fluid mechanics in the Bachelor curriculum to attract more students.</td>
</tr>
<tr>
<td><strong>Threats</strong></td>
<td>• Use our international networks to attract highly qualified PhD students.</td>
<td>• We intend to use our European network to increase the European funding and circumvent the threat due to changes in national research funding policy.</td>
</tr>
<tr>
<td></td>
<td>• Use and extend our existing industrial network to reduce dependency on one industry.</td>
<td></td>
</tr>
</tbody>
</table>
TU/e 7: Multiscale Engineering Fluid Dynamics
TU/e 7: Multiscale Engineering Fluid Dynamics

1. Objective(s) and research area

1.1. Vision, mission and objective(s) of the programme

The Multiscale Engineering Fluid Dynamics group was established in November 2009 within the framework of the 3TU Centre of Excellence for Multiscale Phenomena. The research programme of the MEFD group is based on the vision that:

In science and engineering, understanding leads to computation and computation leads to understanding

This vision reflects the fact that on the one hand science and engineering ultimately aim at quantitative predictive theories. However, the complexity of most current predictive theories is such that useful quantitative information can only be extracted from them by numerical computation. On the other hand, computational simulations provide new understanding and the development and analysis of state-of-the-art numerical techniques generate new insights into fundamental aspects of the underlying predictive theories.

Although simulation is well established as part of the trinity of modern science and engineering – Theory, Experiment and Simulation – fundamental developments are still required to harness the enormous potential of numerical simulation for complex physical problems, e.g. problems exhibiting a wide range of length and/or time scales.

The above vision leads to the following threefold mission of the MEFD group:

1. To make original and fundamental contributions to the field of computational science and engineering;

2. To apply and transfer knowledge on advanced numerical methods to relevant application areas and industrial partners;

3. To educate the next generation of engineers in the fundamental aspects of numerical simulation and foster intellectual leadership in computational science and engineering.

Within the wide scope of computational science and engineering, the research within the Multiscale Engineering Fluid Dynamics group focuses in particular on free boundaries and evolving discontinuities and interfaces, multi-field interactions such as fluid-structure interaction, and transitional molecular/continuum flows. Complementary to the above application areas, the research in the MEFD group addresses fundamental aspects of numerical models and techniques at a generic level, for example, error estimation, optimal adaptive refinement and isogeometric analysis.
1.2. Strategy

The strategy of the MEFD group to achieve its mission consists of three branches:

1. **Synergy between research themes.** The MEFD group pursues new research directions according to a roof-tile construction principle, i.e. new research directions are partly based on established expertise within the group and partly explore challenging new areas. This principle applies to both methodology and application. For example, expertise on phase-field models generated in the context of tumour-growth modelling (Veni project van der Zee) has subsequently been applied in the area of two-phase flows for inkjet applications (NanoNextNL project). A second example is the recently awarded project on hydraulic fracturing (Shell-FOM project), which builds on consolidated expertise on fracture mechanics in porous media (Veni project Verhoosel), coupled problems and fluid-structure interaction (e.g. STW-MuST project Van Brummelen), while posing new challenges in the area of fluid-permeated-crack propagation.

2. **Fundamentals and advanced applications.** The research in the MEFD group has a methodological character. MEFD aims to maintain a balanced portfolio of strategic fundamental research themes and research themes focused on advanced industrial applications. An example of the first is the development of adaptive moment-closure methods for kinetic theories (MEFD seed funding). An example of the second is the aforementioned NanoNextNL project on phase-field models for droplet formation, wetting and absorption in inkjet-printing applications (in close collaboration with Océ Technologies). It is envisaged that fundamental research themes will eventually develop into new application-oriented themes, while conversely application-oriented themes will inspire new and more fundamental research.

3. **Stimulation, training and education.** MEFD aspires to provide an environment that enables people to develop optimally. This aspiration relates not only to students at undergraduate, graduate and PhD levels, but also to staff members. The MEFD group has established a curriculum of electives to train engineering students in fundamental aspects of advanced discretization techniques, free-boundary problems and interfaces and fluid-structure interaction. From 2013 onward, MEFD will also play a central role in the numerical-methods track of the new undergraduate programme in the Mechanical Engineering department of TU/e. At the start of their PhD programme, a tailored training programme is set up for PhD students, involving both scientific and personal development courses. In addition, regular work meetings and colloquia are organised as a platform for graduate students, PhD students and staff to interact. PhD students are also encouraged to participate in advanced schools, workshops and symposia. Staff members are actively involved in strategic discussions and decisions, to prepare them for their role as future leaders.

1.3. Research area and subprogrammes

The research of the MEFD group is positioned in the field of Computational Science and Engineering (primary). Some of the research activities can be regarded to be in the adjacent field of numerical mathematics (secondary). The MEFD research programme encompasses the four subprogrammes below. Note that these subprogrammes are not separated, and that there are many complementarities and synergetic connections. MEFD staff members generally contribute to multiple subprogrammes.
Free boundaries, interfaces and discontinuities
Many problems in science and engineering are characterised by a connection between disparate subsystems at a common boundary or by a fundamental change in the behaviour of a single system across an infinitesimally thin layer. Typical examples are dynamic and thermodynamic interactions between a fluid and a solid, the interaction between two immiscible fluids, cracks and discontinuities in continua, and the intrusion of a tumour into healthy tissue. Generally, the interface between the subdomains constitutes a free boundary, i.e. it is not fixed, but its motion is interconnected with the (initial) boundary-value problems on the adjacent subdomains. In some cases, the interface can be described as an embedded manifold (sharp-interface models), while in other cases it is more appropriate to model the interface as a thin transition layer (diffuse-interface models). Interface and free-boundary problems pose fundamental challenges to numerical simulation methods, on account of the resolution requirements at the interface and/or the complicated interdependence between the boundary-value problems and their domain of definition. In the realm of free-boundary and interface problems, the research in the MEFD group focuses in particular on fluid-structure interaction, two-phase flows, fracture and tumour growth.

Goal-oriented error estimation and optimal adaptive refinement
In many engineering applications, interest is restricted to a single quantity. For example in heat-transfer applications, it is ultimately only the heat flux through a certain part of the boundary that is of interest. A crucial notion concerns the fact that the restricted interest to one particular goal functional can be exploited to reduce the complexity of numerical simulation methods. This notion is formalised by so-called goal-oriented - posteriori error estimation and optimal adaptive-refinement methodologies. By means of the solution of an appropriate dual problem, the contribution of local errors in the solution to the error in the goal functional can be established. Only the regions that have a pronounced influence on the error in the goal functional need to be refined in the numerical model. Such an approach can be used for both discretization adaptivity and model adaptivity. In the first form of adaptivity, the computational mesh or order of approximation is locally adapted to reduce the error. In the second form of adaptivity, the underlying model is locally adapted, for example by locally replacing a continuum model by a molecular model.

Isogeometric analysis
The use of advanced computer aided design (CAD) tools and numerical analysis software (e.g. finite elements) is common practice today in engineering design processes. In particular for complex systems (e.g. cars or aircraft) the necessary interactions between design and analysis tools are found to hinder the design process. The primary reason for this is that geometric design and computer analysis are not treated in a unified way. Isogeometric analysis offers a rigorous solution to the incompatibilities between the fields of design and analysis by directly using the data structures in CAD for analysis purposes. This approach has been shown to be advantageous for problems in fluid dynamics, solid mechanics, fluid-structure interactions, and many others. As well as the development of technologies that aid in the creation of a unified design and analysis framework, our research also focuses on the exploitation of the advantageous approximation properties of the spline functions underlying isogeometric analysis.

Kinetic models and transitional molecular/continuum flows
The perpetual trend towards miniaturisation in science and technology prompts the investigation of fluid flows on length scales that are no longer well separated from the molecular length scale. In this regime, conventional continuum models of fluid flows, such as the Euler and Navier-Stokes-Fourier equations, lose their validity, and kinetic models encoded by the Boltzmann
equation must be considered. In addition, the Boltzmann equation provides a prototype for kinetic models in many other applications that require a description of the collective behaviour of large ensembles of small particles, for instance, in semi-conductors, plasmas and dispersed-particle flows. However, the Boltzmann equation poses a daunting challenge for numerical approximation methods on account of its high-dimensional setting. Furthermore, boundary conditions that provide an adequate description of fluid-solid interactions on a molecular scale are still incompletely understood. The MEFD group has established a subprogramme aimed at the development of advanced finite-element methods for kinetic models of fluid flows.

2. Composition of the research staff at programme level

The composition of the Multiscale Engineering Fluid Dynamics group since its initiation in November 2009 is summarised in Table 2.1 below.

Table 2.1a. Composition of research staff at programme level (fte)

<table>
<thead>
<tr>
<th></th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
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<tr>
<td>TU/e 7: Multiscale Engineering Fluid Dynamics</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Tenured staff</td>
<td>-</td>
<td>-</td>
<td>0.07</td>
<td>0.40</td>
<td>0.40</td>
<td>0.40</td>
</tr>
<tr>
<td>Non-tenured staff</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.90</td>
<td>1.40</td>
</tr>
<tr>
<td>PhD students</td>
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<td>0.27</td>
<td>0.80</td>
<td>0.80</td>
<td>2.50</td>
</tr>
<tr>
<td>Total research staff</td>
<td>-</td>
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<td>0.34</td>
<td>1.20</td>
<td>2.10</td>
<td>4.30</td>
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<tr>
<td>Supporting staff</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Visiting fellows</td>
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<td>-</td>
<td>0.04</td>
<td>0.12</td>
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<td>0.56</td>
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<tr>
<td>Total staff</td>
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<td>-</td>
<td>0.38</td>
<td>1.32</td>
<td>2.10</td>
<td>4.86</td>
</tr>
</tbody>
</table>

Table 2.1b. Composition of research staff at programme level (numbers)

<table>
<thead>
<tr>
<th></th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
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<td>TU/e 7: Multiscale Engineering Fluid Dynamics</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tenured staff</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Non-tenured staff</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>PhD students</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Total research staff</td>
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<tr>
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</tr>
<tr>
<td>Visiting fellows</td>
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<td>1</td>
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<td>-</td>
<td>3</td>
</tr>
<tr>
<td>Total staff</td>
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<td>-</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>12</td>
</tr>
</tbody>
</table>
The chair of the Multiscale Engineering Fluid Dynamics group, prof.dr.ir. E.H. van Brummelen, was appointed as full professor in November 2009. Dr.ir. K.G. van der Zee was appointed as assistant professor in February 2011. Dr. ir. C.V. Verhoosel was appointed as assistant professor in the Numerical Methods in Engineering group of prof. R. de Borst in the Mechanical Engineering department of TU/e in November 2010. After the departure of prof. De Borst and the subsequent dissolution of the NME group, Verhoosel joined the MEFD group in June 2012. Both Van der Zee and Verhoosel received tenure in 2013.

The MEFD group has hosted the following guest researchers in the evaluation period (2009-2012): dr. W. Hoitinga (TU Delft), dr. H.M.A. Wijshoff (Océ Technologies), prof. D.H. van Campen (TU/e, emeritus).

Since its initiation, the MEFD group has hosted a steadily increasing number of PhD students, growing from 1 in 2009 and 5 in 2012 to 8 in 2013.

3. Research environment and embedding

3.1. National positioning

The Multiscale Engineering Fluid Dynamics group is unique in the Netherlands, in that it is the only pure computational-engineering group with a fluid and solid mechanics profile, as evidenced by the participation of the group in both the Engineering Mechanics graduate school for solid mechanics and the JM Burgerscentrum Research School (JMBC) for fluid mechanics. The research subprogrammes described in Section 1.3 generally represent unique and novel research themes in the Dutch context.

The MEFD group is well embedded in the relevant Dutch research environment, and maintains formal ties with the following institutions:

- **TU/e**, providing the group's local environment. The MEFD group co-operates with several other groups in its home department of Mechanical Engineering, notably with the groups Mechanics of Materials (Prof. Geers) and Structure and Rheology of Complex Fluids (Prof. Anderson). In addition, MEFD retains strong ties with several groups outside the department, in particular with the CASA group (Profs. Koren and Peletier) in the Department of Mathematics and Computer Science, in which Van Brummelen holds a 0.2 fte position. Van Brummelen is also the director of the Eindhoven Multiscale Institute (EMI), in which 7 TU/e departments participate, and MEFD is one of the prominent members of the institute.

- **EM and JMBC**, the Engineering Mechanics graduate school for solid mechanics and the JM Burgerscentrum research school for fluid mechanics. All PhD students of the MEFD group are embedded in one of these national graduate schools. MEFD also contributes to the course programme and the organization of these graduate schools.

- **WSC** (Werkgemeenschap Scientific Computing), the Dutch/Flemish platform for numerical mathematics. For example, Van Brummelen has chaired the 38th edition of the WSC’s annual Woudschoten conference on Numerical Analysis in 2013.

- **3TU Research Centre on Fluid and Solid Mechanics (FSM)** (former 3TU Centre of Excellence for Multiscale Phenomena). The 3TU FSM Research Centre’s objective is to reinforce research in fluid and solid mechanics at the 3 universities of technology in the Netherlands (TU/e, TU Delft and Twente University). The MEFD chair is one of five chairs that were initiated within the Centre of Excellence.

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1 Van der Zee has accepted a position as lecturer in the School of Mathematical Sciences of the University of Nottingham and has left the group in January 2014.
3.2. International positioning

The MEFD group acts in the relatively large international research field of Computational Science and Engineering (CSE). The research subprogrammes in Section 1.3 generally correspond to niche areas, or particular focal points are considered corresponding to intersections between themes, e.g. isogeometric methods for fracture mechanics and goal-adaptive techniques for free-boundary problems. In this manner, the group is capable of making original and fundamental contributions to the CSE field, despite its compactness.

The MEFD group collaborates with some of the leading groups and institutes in CSE, evidenced by joint publications, joint projects and/or joint organization of events:

- prof. dr. T.J.R. Hughes and prof. dr. J.T. Oden of the Institute for Computational Engineering and Sciences (Austin, TX, USA)
- prof. dr. ir. R. de Borst of the School of Engineering of the University of Glasgow (UK)
- prof. F. Auricchio and dr. A. Reali of the Center for Advanced Numerical Simulation of the Instituto Universitario di Studi Superiori (Pavia, Italy)
- prof. T. Kvamsdal of the Norwegian University of Science and Technology at Trondheim (Norway)
- dr. S. Prudhomme of the Department of Mathematical and Industrial Engineering of Polytechnique Montréal (Canada)
- prof. D. Hilhorst of the Numerical Analysis Lab of the Mathematics Department at the Université Paris-Sud (France)
- prof. dr. M. Torrilhon of the Mathematics Division of the Center for Computational Engineering Sciences at RWTH Aachen (Germany)

The MEFD group also participates in the Simulation Engineering and Entrepreneurship Development (SEED) Erasmus Mundus Joint Doctorate (EMJD) programme, together with ECN (France), IST (Portugal), IUSS (Italy), Swansea University (UK), TUM (Germany), ULB (Belgium) and UPC (Spain). The SEED programme enables bipartite research projects between these partners, resulting in a joint doctoral degree.

In addition, the MEFD group has strong connections with the European Community on Computational Methods in Applied Sciences (ECCOMAS) through the Committee for Computational and Applied Mathematics (ECCAM), chaired by Van Brummelen.

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2 Key conferences in CSE, e.g., the World Congress on Computational Mechanics, are attended by approx. 3500 participants.
4. Quality and scientific relevance

The impact potential of the research of the MEFD group is corroborated by the results of the preparatory citation analysis for the period 2002-2012 (publications that appeared in 2002-2011), conducted by the Centre for Science and Technology Studies (CWTS) of Leiden University. The following indicators characterise the citation analysis for the MEFD group:

- Average number of citations per published paper without self-citations (MCS) = 8.63
- Mean Normalised Citation Score (MNCS, crown indicator) = 2.82
- Proportion of papers that belong to the top 10% (pp top 10%) = 40%
- Proportion of papers that belong to the top 25% (pp top 25%) = 63%
- Self-citations (SC) = 14%

The MNCS indicator shows that the MEFD research programme yields significantly higher citation rates than the subfield average, exceeding the average by 182%. Note that this MNCS score represents the highest MNCS score among all groups of the mechanical engineering departments of the three universities of technology evaluated in the CWTS citation analysis.

The quality and scientific relevance of the research conducted by the MEFD group is further supported by the fact that many of the group’s publications of the group are among the top 10% and top 25% most-cited publications in the corresponding journals; see also Section 4.3.

4.1. Most significant results/highlights

Goal-adaptive methods for free-boundary problems and fluid-structure interaction

This research theme (see Figure 1) has resulted in a general paradigm for error estimation in free-boundary problems based on shape derivatives. The research has led to 6 publications in 2010-2012 in top-tier journals and has since then accumulated 35 citations. Moreover, this work has led to several invited presentations, a keynote lecture at WCCM 2010, a plenary lecture at NumDiff 2012 and 2 invitations as opponent at PhD defenses at Umeå University (Sweden) and Oslo University (Norway).

Figure 1. Goal-adaptive discretization of a fluid-structure-interaction problem.

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Phase-field modeling of crack propagation

The research of Verhoosel on phase-field models of crack propagation (see Figure 2 for an illustration) in collaboration with researchers from the Institute for Computational Sciences and Engineering (Austin, TX, USA) has resulted in 3 publications in 2011-2012. All 3 publications are in the top 10% of most-cited articles of the respective journals.

Figure 2. Dynamic crack propagation in a material containing imperfections, based on a higher-order phase-field model.

Isogeometric analysis

The research of the MEFD group into isogeometric-analysis techniques has resulted in a Veni personal career grant for Verhoosel. Recent developments relate to the combination of isogeometric analysis with goal-adaptive finite-cell techniques for modeling geometrically and topologically complex volumetric domains; see Figure 3.

Figure 3. Goal-adaptive simulation of trabecular bone deformation based on isogeometric analysis in combination with the finite-cell method.
Diffuse-interface tumour-growth models

The work of Van der Zee on phase-field models for tumour growth (see Figure 4) has led to a Veni personal career grant. The investigations have resulted in a new characterisation and estimation of errors in approximations for Cahn-Hilliard models and in the development of a new class of thermodynamically consistent models. The paper by Van der Zee and his collaborators at the Institute for Computational Engineering and Sciences on a four-species model for tumour growth is in the top 10 of most accessed papers of IJNMBE of 2012.

Figure 4. Diffuse-interface tumour-growth simulation: computational domain (l), cutplane (c) and cutplane with interface indicated (r).

4.2. Key publications


4.3. Number of articles in top 10% and top 25% of publications relevant to the discipline

In the field of Computational Science and Engineering, in which the MEFD group is active, refereed journal papers are the most important form of academic output. Of the 40 publications by members of the MEFD group over the extended period 2002-2012, 40% are among the top
10% and 63% are among the top 25%, which are the highest scores of all groups evaluated in the citation analysis. Of the 16 refereed articles published by members of the MEFD group in the period 2010-2012 since the initiation of the MEFD programme, 11 are in the top 25% of most-cited articles of the respective journals. Of these 11 articles, 5 are in the top 10% of most-cited articles of the respective journals.

4.4. Most important books or chapters of books, insofar as applicable


5. Output

5.1. Number of publications

<table>
<thead>
<tr>
<th>Publications</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>6 year total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Academic publications</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refereed articles</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3</td>
<td>9</td>
<td>4</td>
<td>16</td>
</tr>
<tr>
<td>Conference papers</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>3</td>
<td>14 (7)</td>
<td>18 (7)</td>
</tr>
<tr>
<td>PhD theses</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Book</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1 (1)</td>
<td>1 (1)</td>
</tr>
<tr>
<td>Book Chapters</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td><strong>Total academic publications</strong></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>5</td>
<td>13</td>
<td>21 (8)</td>
<td>39 (8)</td>
</tr>
<tr>
<td><strong>Patents</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total research output</strong></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>5</td>
<td>13</td>
<td>21 (8)</td>
<td>39 (8)</td>
</tr>
</tbody>
</table>

(1) numbers in parentheses indicate papers in collaboration with other groups of TU/e-ME.

4 Based on CWTS analysis, Bibliometric Study of the Faculties of Mechanical Engineering in the 3TU (2002-2011/12).
5 Source: Scopus, Reference date: 24 September 2013.
6 Of which 5 with the Mechanics of Materials group and 2 with the group Structure and Rheology of Complex Fluids.
7 The programme was initiated in 11/2009. The first PhD student from the programme has defended in 12/2013.
5.2. Number of PhDs (completed and in progress)

The MEFD programme started in November 2009. The first PhD student in the programme was appointed in September 2009 and has defended his thesis in December 2013. The programme currently accommodates 8 PhD students (3F/5M), of whom 1 shared with Delft University of Technology (prof. R.F. Hanssen) and 1 with Instituto Universitario di Studi Superiori, Italy (prof. F. Auricchio and dr. A. Reali).

### Table 5.2. PhD students

<table>
<thead>
<tr>
<th>Starting year</th>
<th>Enrolment (male/female)</th>
<th>Graduated after (years)</th>
<th>Total graduated</th>
<th>Not yet finished</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total (male + female)</td>
<td>≤ 4</td>
<td>4 - ≤ 5</td>
<td>5 - ≤ 6</td>
</tr>
<tr>
<td>M</td>
<td>F</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2010</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2011</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2012</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>-</td>
</tr>
</tbody>
</table>

Note: The thesis defense is usually 2 months after ending of the 4-year PhD contract. Students are not generally granted extension. Graduated in 4 < 5 years should therefore be interpreted as: PhD work, including writing the thesis is finished in 4 years. Accordingly, prior to the start of the defense the thesis is sent to the printer and subsequently to the committee members to read it. This takes 2 months.

6. Resources

6.1. Overview of the various sources of financing

### Table 6.1. Funding at programme level

<table>
<thead>
<tr>
<th>Funding</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>k€</td>
<td>%</td>
<td>k€</td>
<td>%</td>
<td>k€</td>
<td>%</td>
</tr>
<tr>
<td>Direct funding (1)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Research funding (2)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>16</td>
<td>100</td>
</tr>
<tr>
<td>Contract funding (3)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total funding</strong></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>16</td>
<td>100</td>
</tr>
</tbody>
</table>

The amounts in Table 6.1 are based on external funding contributions and do not include (in kind) matching. The Direct funding (1) category relates to PhD projects directly covered by TU/e and staff costs related to the matching contribution in the NanoNextNL programme. The Research funding (2) category concerns research grants from the Netherlands Organisation for Scientific Research (NWO) and the Technology Foundation (STW). The third category, Contract funding (3), relates to industrial contributions and contributions in the NanoNextNL programme.
6.2. Earning capacity

Table 6.2. External funds used/acquired in the period 2007-2012

<table>
<thead>
<tr>
<th>Project</th>
<th>Start</th>
<th>End</th>
<th>Sponsor</th>
<th>Three most important partners for the programme</th>
<th>External Funding k€ (entire funding period)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adaptive Multiscale Methods for Airbag-Deployment-Safety Simulations</td>
<td>09/2009</td>
<td>12/2013</td>
<td>STW OTP</td>
<td>TU/e only</td>
<td>248</td>
</tr>
<tr>
<td>Robust micromechanical modeling of trabecular bone using isogeometric analysis</td>
<td>05/2012</td>
<td>04/2015</td>
<td>STW Veni</td>
<td>TU/e only</td>
<td>233</td>
</tr>
<tr>
<td>Tumour growth — aggressive, benign, computable?</td>
<td>02/2011</td>
<td>01/2014</td>
<td>NWO/EW Veni</td>
<td>TU/e only</td>
<td>250</td>
</tr>
<tr>
<td>Numerical simulation of drop formation and dynamics in picoliter jetting technology</td>
<td>05/2011</td>
<td>09/2016</td>
<td>NanoNextNL Programme 10B</td>
<td>TU/e, Océ</td>
<td>618</td>
</tr>
</tbody>
</table>

6.3. Use of research facilities

The MEFD research programme is concerned with the development, analysis and application of advanced computational techniques. Accordingly, the research facilities required to support this programme are restricted to high-end computing resources and an advanced and versatile software platform.

In 2011, the MEFD group procured a 4 x 10 core 512 Gb shared memory computing cluster. The computing facilities were extended with a 2 x 6 core 48 Gb workstation for prototyping in 2012. These computing resources are exclusive to the MEFD group.

The MEFD group has developed a generic in-house Python-based software platform, NUtils, for advanced finite-element (and isogeometric) methods; Figure 3 above shows an adaptive finite-element computation obtained with the NUtils code. The selection of Python as the core programming language is motivated by its generality and its high-level. By virtue of this combination, the NUtils code on the one hand enables the development of highly advanced (e.g. adaptive) computational techniques, and on the other hand provides adequate accessibility to use the code in short-term student projects. The NUtils code has been released as open-source software in 2013 (www.nutils.org), to facilitate its application by industrial partners and to enhance dissemination of the developed methodologies.

Validation of the developed numerical techniques against experimental data is carried out in several projects in collaboration with the research labs of the involved industrial partners. For example, in the NanoNextNL project, comprehensive droplet-formation experiments are currently conducted at Océ Technologies to serve as a benchmark for numerical simulation techniques.
7. Academic reputation

The Multiscale Engineering Fluid Dynamics group consists of talented young staff members. Since its establishment in 2009, the MEFD group has gained an excellent national and international reputation. The group maintains collaborations with some of the world’s leading groups in CSE. The scientific staff members of the MEFD group stand out from their peers, as evidenced by personal grants, prizes, impact, invitations and other established forms of recognition.

Prof. dr. ir. E.H. van Brummelen (1972, H-index 11 (Scopus) / 10 (WoS) / 15 (Google))
- J.-L. Lions Award 2012 (Quadrennial award for young scientists in Computational Mathematics of the European Community on Computational Methods in Applied Sciences)
- 1 plenary lecture, 3 keynote lectures, 4 sponsored invited lectures, 1 invited lectureship
- Director of the Multiscale Simulation Techniques programme of the Dutch Technology Foundation (2012-, successor to prof. R. de Borst)
- Director of the Eindhoven Multiscale Institute (2012-)
- Chairman of the ECCOMAS Committee for Computational and Applied Mathematics (2012-)
- Editorial board member of Coupled Systems Mechanics (2011-)
- Main organiser of the first ECCOMAS Advanced School, Isogeometric Analysis: Fundamentals and Applications, (Vienna, Austria, 2012, with T.J.R. Hughes, T. Kvamsdal, A. Reali, Y. Bazilevs);
- Board member of the Engineering Mechanics graduate school (2011-)
- Co-organiser of 7 symposia at international conferences
- Member of the Committee on Fluid-Structure Interaction of the Applied Mechanics Division of ASME (2010-)

Dr ir. K.G. van der Zee (1980, H-index 6 (Scopus) / 6 (WoS) / 10 (Google))
- Veni grant of the Exact-Sciences council (2010) (Personal career grant awarded by the Netherlands Organization for Scientific Research to top young researchers (top 10% of peer group) in the Netherlands in mathematics, computer science and astronomy)
- J.T. Oden visiting-faculty fellowship (01/2011, 05/2012, 12/2012)
- Co-organiser of 5 symposia at international conferences
- Pre-congress short course organiser (USACM, 2011)
- Invited lecturer ECCAM advanced school on Isogeometric analysis (2012)

Dr. ir. C.V. Verhoosel (1982, H-index 8 (Scopus) / 9 (WoS) / 13 (Google))
- Veni grant of the Technical-Sciences council (2011) (Personal career grant awarded by the Technology Foundation STW to top young researchers (top 10% of peer group) in the Netherlands in technical sciences)
- Keynote lecture at 6th ECCOMAS Congress (2012)
- Invited lecturer at ECCAM advanced school on Isogeometric Analysis (2012)
- (Co-)organiser of mini-symposium at ECCOMAS congress (2012)
8. Societal relevance: quality, impact and valorisation

8.1. Societal quality of the work

In general, research conducted in CSE is enabling and its impact on new products, processes and services and on societal issues and debates is indirect. Contributions to society are generally achieved by dedicated collaborations with industrial partners and/or academic researchers in particular application areas.

The MEFD group considers it part of its mission (see Section 1.1) to transfer the developed expertise and technologies to application partners and assumes a proactive policy in establishing contacts with such partners. Collaboration partners of the MEFD group include:

- Océ Technologies (simulation techniques for droplet formation and absorption)
- TNO Automotive Safety Solutions (multiscale models for airbag-deployment safety simulations)
- Erasmus Medical Center (computational analysis of vulnerable plaques)
- Shell (computational modeling of hydraulic fracturing)
- Dynaflow and MSC software (isogeometric analysis techniques)
- TU/e Biomedical Engineering Department (computational methods for trabecular bone)

In addition, the group has played an active role in several research programmes specifically aimed at academic/industrial collaborations, such as the MicroNed programme, the NanoNextNL programme and, notably, the Multiscale Simulation Techniques programme, directed by Van Brummelen.

8.2. Societal impact of the work

The general societal value of the research of the MEFD group relates to the following two aspects:

- The research of the MEFD group has contributed to the research infrastructure of its industrial partners. For example at Océ Technologies and TASS numerical simulation has developed into an important research instrument, complementary to experimental investigations.
- The MEFD group has contributed to the development of human capital. Graduates of the group have without exception immediately obtained new positions in industry and academia (e.g. Cambridge University, ONERA, TU/e).

Moreover, specific societal value has been created in particular research projects, for instance:

- The STW project on Airbag deployment safety simulations has provided a new simulation methodology for crash-safety analysis.
- The Veni project of Verhoosel on robust micromechanical trabecular-bone modelling is providing a new simulation paradigm for osteoporosis research. The project moreover forms a basis for new simulation techniques for investigations of hydraulic-fracturing processes.
- The collaborative project with Erasmus MC on computational and experimental analysis of vulnerable plaques has lead to new insights in the development and treatment of cardiovascular disease.
8.3. Valorisation of the work

The Multiscale Engineering Fluid Dynamics group undertakes the following actions to achieve valorisation of its research, i.e. to make its research results available and suitable for application in products, processes and services:

• **Collaboration with advanced industrial and application partners:** The MEFD group sustains dedicated collaborations with several industrial partners and academic application partners; see Section 8.1 for an overview. These collaborations have emerged over a longer period, and are fertile in that these partners have the expertise and infrastructure to accommodate numerical-simulation results.

• **Open-source distribution of software:** An important route of valorisation of the research results of the MEFD group is the distribution of the software platform NUtils, which has been developed by the group in the context of various projects, in the form of open-source software. By virtue of this open-sourcing, methods and algorithms resulting from the research in the MEFD group will become available to the general public. Note that many research labs in industry are moving towards open-source software to avoid the restrictions of available commercial platforms.

9. Viability

The Multiscale Engineering Fluid Dynamics group is currently in the development phase. Since its initiation, MEFD has been able to attract highly talented young staff members and the number of PhD students has gradually increased. Further expansion of the group is envisaged, both with reference to staff and PhD students.

The following aspects, concerning potential/legitimacy and resources, provide a strong indication of the viability of the MEFD research programme:

• Outstanding quality of research (Section 4)
• Strong portfolio of innovative research subprogrammes in the emerging field of computational science and engineering (Section 1.3)
• Strong need for advanced computational methods in industry, notably, in applications related to multi-physics, multiscale, and interfaces and discontinuities
• Good track record in procuring funding, both in personal-grant programmes and application-oriented programmes
• Excellent output/input ratio (Sections 5 and 6)
• Low-cost research infrastructure (Section 6.3)

10. SWOT analysis

The MEFD programme was initiated in November 2009, and has not been assessed before. Reflection on the outcome and recommendations from the previous research assessment is therefore not applicable.

The lists below provide an overview of the strengths, weaknesses, opportunities and threats relating to the MEFD programme.
Strengths (internal dimension)
The main strengths of the Multiscale Engineering Fluid Dynamics group are:

- **Human capital:** The MEFD group consists of bright, talented and intrinsically motivated young researchers, with excellent expertise and international reputations.

- **High-potential research themes:** The MEFD group considers several high-potential research themes. For example, the long-standing focus on interface problems implies that the group has a strong expertise and track record in coupled multiphysics and multifield problems, which continue to gain interest in CSE research and in many application areas.

- **Synergy between fundamentals and applications:** The MEFD group targets both fundamental contributions in CSE and advanced industrial applications. Accordingly, the group has been well positioned to attract both competitive individual grants and application-oriented funding.

- **Interdisciplinary profile:** The MEFD group has an interdisciplinary profile, and the group's research themes transcend borders between engineering and applied mathematics and between fluid and solid mechanics. This interdisciplinary profile has also proven to be attractive for talented students, for example from the Fluid-and-Solid mechanics graduate programme, the EMI honors programme and graduate students pursuing bi-certification in mechanical engineering and mathematics.

- **Software:** The MEFD group has established a flexible and versatile open-source software framework, equipped with functionality for advanced finite-element computations, isogeometric analysis, (two-phase) flows, interface problems and geometric PDEs, and fracture mechanics.

Weaknesses (internal dimension)
The following aspects represent points of improvement or attention for the MEFD group:

- **Group size:** The MEFD group is presently in the development phase. Due to its current compactness, the group is vulnerable to staff mobility.

- **Limited international funding:** The main sources of research funding have been national. Only limited funding has so far been gained at the European level.

- **Visibility for graduate and undergraduate students:** As a new group, the exposure of the MEFD group for undergraduate and graduate students is still incomplete.

- **Connection with application partners:** Most collaborations with industrial partners are still emerging and need to be further consolidated.

Opportunities (external dimension)
The following items represent potential opportunities for MEFD:

- **Multiphysics challenges:** Challenges in engineering applications are increasingly concerned with the interaction of multiple physical subsystems, e.g. hydraulic fracturing and liquid absorption in porous media. The MEFD group is well positioned to address such challenges.

- **DIFFER institute:** The Dutch Institute For Fundamental Energy Research will be established on the TU/e campus in 2015. There is a strong connection between several MEFD and DIFFER research themes, e.g. between plasmas and fusion energy and advanced numerical methods for kinetic theories, and between plasma confinement and interface problems.

- **Excellence tracks in education:** The MEFD group is well positioned with respect to several educational-excellence tracks, such as the FSM graduate programme and the honours track of the Eindhoven Multiscale Institute. The FSM graduate programme has been granted by the Netherlands Organisation for Scientific Research (NWO) to the joint JMBC and EM graduate schools, and it will deliver talented new graduate students and opportunities for new PhD projects. The EMI honors track provides an opportunity to identify talented students at the undergraduate level. Extension of the track to the graduate level in the near future is envisaged.
• **SEED Erasmus Mundus programme:** The MEFD group participates in the Erasmus Mundus programme ‘Simulation in Engineering and Entrepreneurship Development’. This program will potentially result in one joint PhD position per year in 2013-2017 in collaboration with leading European partner institutes.

**Threats (external dimension)**

The following threats can be identified:

- **Increasing demands on faculty members:** There has been a significant increase in the non-research demands on faculty members. The workload is particularly severe for new and young staff members.

- **Strategic fund generation:** Many national research funds have been tapered to cover only direct project costs. As a result, it has become difficult to generate significant strategic research budgets. This difficulty is compounded by the fact that there has been a significant shift towards application-labelled and consortium funding.

- **Shortfall in qualified PhD and MSc students:** The research of the MEFD group requires students who are well trained in both engineering and applied mathematics. Due to shifts in the educational programmes, there is a risk of shortage of students with an appropriate background.

- **Outsourcing of computing expertise:** Some large companies are outsourcing their numerical simulations to engineering companies, which impedes strategic long-term collaboration.

**11. Strategy for the coming period**

Based on the SWOT analysis and MEFD’s vision and mission, the strategy of the MEFD group will target the aspects in Table 11.1 in the coming period. Clearly, maintaining high-quality scientific output will remain a core priority in the coming period.

**Table 11.1. Strategy for the coming period**

<table>
<thead>
<tr>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Opportunities</strong></td>
<td><strong>A. Consolidation and expansion of the industrial network (O1/S1-3,5)</strong>&lt;br&gt;B. Initiate collaboration with DIFFER institute (O2/S2,3)&lt;br&gt;C. Attract students and funding from FSM graduate programme (O3/S4)</td>
</tr>
<tr>
<td><strong>Threats</strong></td>
<td><strong>D. Use open-source software to strengthen collaborations with industrial partners (T4/S5)</strong>&lt;br&gt;E. Attract students from EMI honors programme (T3/S4)</td>
</tr>
</tbody>
</table>
Some of these aspects are elaborated below:

A. The industrial network of MEFD is still emerging. Existing contacts will be further consolidated, while new contacts will be surveyed and initiated. It is envisaged that a strategically positioned part-time professor is appointed in the near future. The extension and consolidation of the industrial network can on the one hand serve to enhance the transfer of knowledge to industry in accordance with the MEFD mission and on the other hand to improve the positioning relative to application-oriented research funds. Reinforcement of the industrial network can also contribute to the generation of strategic funds (T2).

C. The FSM excellence track will deliver an annual supply of approximately 10 outstanding graduate students in fluid-and-solid mechanics. These students have the opportunity to submit a proposal for a PhD fellowship, with a success rate of 50%. Due to its mixed fluid-and-solid mechanics profile, the MEFD group is in a good position to attract students from the FSM programme. The FSM programme can also ameliorate the potential shortfall in qualified PhD students (T3).

F. The participation of MEFD in the SEED EMJD programme also improves its position relative to other European funds (e.g. ITN programmes). An additional benefit of EU programmes is that the financial conditions are generally better than in current national funding programmes (T2).

H. Expansion of the group will be a primary component of the strategy in the coming period. The MEFD group has been successful in its current compact form, but is too vulnerable to staff mobility. Expansion of the group will reduce this vulnerability and will also facilitate the distribution of tasks (T3). In addition, expansion of the group will further enhance the potential for synergy between research lines and will improve the visibility to students. MEFD will immediately initiate a search for a successor to Van der Zee. Further expansion of the group by a faculty member at the assistant professor level (possibly tenure track) in 2015-2016 appears prudent.
PhD theses
Polymer Technology in the 25 years of its existence

TU/e 8: Polymer Technology
TU/e 8: Polymer Technology

1. Objective(s) and research area

1.1. Mission

The mission of the programme is to provide education and conduct research in the broad area of Polymer Technology, i.e. the industrial arts of manufacturing of polymer-based products. Special emphasis is placed on bridging the gap between science and technology in the area of polymer processing and design, through the use of experimental and computational tools in the modeling of the full thermo-mechanical history of material (elements) during their formation, processing and final design, to quantitatively predict the properties of processed objects.

1.2. Strategy

The Polymer Technology group has witnessed more than two decades of excellence in research, as evidenced by the maximum score in all three previous research assessments (in 1994, 2000 and 2008). This makes the group unique in the Dutch Mechanical Engineering landscape. Han Meijer’s Polymer Technology group and colleague Bert Meijer’s Macro-organic and Bio-Chemistry group are moreover the only ones within all the TU/e disciplines to gain the maximum score in successive assessments. This, together with other indicators of quality and success, further underlines the importance of polymer research for TU/e.

For this reason the board of the Mechanical Engineering department decided in 2011, in anticipation of the retirement of Han Meijer on 1 May 2014, to continue polymer research practically by splitting Polymer Technology into two somewhat smaller groups: the first focusing on Fluid Mechanics and Structure Development during Flow; the second on Solid Mechanics and Structure-Property relations.

1.3. Research area and sub-programmes

During the research assessment period, 2007-2011, the research area of Polymer Technology was subdivided into five sub-programmes:

1. Computational Rheology and Multi-Scale Modeling (Hulsen)
2. Applied Rheology and Process Modeling (Peters)
3. Chaotic Mixing and Two-phase Flows (Anderson)
4. Structure-Property and Constitutive Modeling (Govaert)
5. Small-scale Mechanics and Surface Engineering (Den Toonder)
From 1 January 2012 the group's associate professor dr. Patrick Anderson was appointed as full professor in the new *Structure and Rheology of Complex Fluids* section, covering the first three sub-programmes. Next, in 2013, the group's long-serving visiting professor dr. Jaap den Toonder was appointed to the new full chair of *Microsystems*. Meanwhile the fourth theme, *Structure-Property and Constitutive Modeling*, was strengthened by the appointment in 2009 of assistant professor dr. Lambert van Breemen and in 2010 of associate professor dr. Markus Hütter (ETH Zürich) through the rewarded high-potential programme of the TU/e Executive Board. Lambert’s job is to enhance computation modeling and direct the research towards the area of surface engineering, studying tribology with the emphasis on friction and wear. Markus' job is to extend the modeling of polymer mechanics into the direction of molecular detail, with the purpose of bridging the gap to the chemists who modify polymers or make new ones. A vacancy has been created to lead this *Solid Mechanics and Structure-Property Relations* group after the retirement of prof. Han Meijer; the profile description and text for the advertisement have already been written.

### 2. Composition of the research staff

*Polymer Technology* strives for a PhD/tenured staff ratio of 3, or a maximum of 4, to ensure there is sufficient time to provide guidance for individual students and to address new problems. The group as a whole has grown over recent years, as a result of strengthening the tenured staff. Apart from Lambert van Breemen and Markus Hütter, dr. Hans Wyss was also appointed in 2009 as assistant professor via ICMS, *the Institute of Complex Molecular Systems* of Bert Meijer, and more PhD students and post-docs were employed.

#### Table 2.1a. Composition of research staff at programme level (fte)

<table>
<thead>
<tr>
<th></th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TU/e 8: Polymer Technology</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tenured staff</td>
<td>2.6</td>
<td>2.5</td>
<td>3.3</td>
<td>3.5</td>
<td>3.7</td>
<td>3.7</td>
</tr>
<tr>
<td>Non-tenured staff</td>
<td>1.6</td>
<td>2.0</td>
<td>1.5</td>
<td>0.8</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>PhD students</td>
<td>8.5</td>
<td>9.4</td>
<td>9.5</td>
<td>12.3</td>
<td>14.4</td>
<td>14.3</td>
</tr>
<tr>
<td><strong>Total research staff</strong></td>
<td><strong>12.7</strong></td>
<td><strong>13.9</strong></td>
<td><strong>14.3</strong></td>
<td><strong>16.6</strong></td>
<td><strong>22.1</strong></td>
<td><strong>22.0</strong></td>
</tr>
<tr>
<td>Supporting staff</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Visiting fellows</td>
<td>0.5</td>
<td>-</td>
<td>-</td>
<td>0.8</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td><strong>Total staff</strong></td>
<td><strong>14.0</strong></td>
<td><strong>14.7</strong></td>
<td><strong>15.1</strong></td>
<td><strong>18.2</strong></td>
<td><strong>23.3</strong></td>
<td><strong>23.2</strong></td>
</tr>
<tr>
<td>External PhD students</td>
<td>0.3</td>
<td>0.8</td>
<td>0.7</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
</tr>
</tbody>
</table>

*As in 2007-2011, the 2012 data include the staff of TU/e-9 (Structure and Rheology of Complex Fluids) and TU/e-11 (Microsystems)*
In this period we had four external PhD students, not on our payroll. Two of them finished their PhDs successfully (Elena Zavinski, TU/e Mathematics and Computer Science department; and Peter Kennedy, Moldflow Australia), one stopped and went back to China (Guansheng Du), and one is only working part-time on his thesis (Timo Faber, Friesland Campina) and is expected to finish in 2014.

3. Research environment and embedding

3.1. National positioning

The Polymer Technology group is a member of, or has strong formal ties with, the following institutions:

1. **MaTe**, the Materials Technology group originating in the former Fundamental Mechanics group. It is characterised by in-house efforts to maintain synergy and cooperation in successful multidisciplinary research. MaTe houses the Computational and Experimental Mechanics (CEM) and Biomechanics and Tissue Engineering (BMTE) groups of the departments of Mechanical Engineering and Biomedical Engineering, respectively. CEM includes the chairs of Polymer Technology (Meijer), Structure and Rheology of Complex Fluids (Anderson), Microsystems (Den Toonder) and Mechanics of Materials (Geers), while BMTE comprises the chairs of Tissue Engineering (Baaijens, Bouten), Cardiovascular Mechanics (VanderVosse) and Bone Mechanics (Ito). (See www.mate.tue.nl).

2. **EPL**, Eindhoven Polymer Laboratories, the research school that coordinates polymer research within TU/e. EPL was officially (re)recognised by the KNAW in 2009 for a period of seven years. Han Meijer is the scientific director. (See www.epl.nu)

3. **PTN**, Polymer Technology in the Netherlands, coordinates research outside TU/e as well as the education programme of the PhD students. (See www.ptn.nu)
4. **DPI**, Dutch Polymer Institute, the Leading Technological Institute in polymer engineering and science, which has its centre at TU/e and provides a platform for private and public research with strong links to industry. (See www.polymers.nl)

### 3.2. International positioning

....and internationally:

5. **ETH Zürich**, the Polymer Technology and Physics Groups of the Materials Department, via a former part-time appointment of prof. Paul Smith at TU/e and a number of sabbaticals of our staff (Meijer in Smith’s Polymer Technology group, and Van Breemen in the Polymer Physics group of prof. Hans Christian Öttinger) at ETH Zürich, while Markus Hütter from HCO’s group gained a tenure at TU/e. (See www.polytech.mat.ethz.ch and www.polyphys.mat.ethz.ch).

6. **EPSRC**, the Polymer Technology Group that was part of the EPSRC-sponsored MuPP2 (Micro-Polymer Processing, project2, directed by prof. Tom McLeish) in the UK at Leeds, Sheffield, Durham, Oxford and Cambridge, with TU/e as the only non-UK university. (See www.irc.leeds.ac.uk/mupp)

7. **Stanford** University, the Complex Fluids group at the Chemical Engineering Department headed by prof. Gerald Fuller appointed Anderson as a visiting professor. At the MSc and PhD levels, students are exchanged both ways for periods of up to four months. (See: http://engineering.stanford.edu/profile/ggf).

8. **Caltech**, we have a joint basic NSF-NWO project with the Polymeric and Supramolecular Liquids (Physics and Rheology) group of prof. Julie Kornfield on flow-induced crystallisation. We do the modeling and macroscopic experiments and they experimentally change the molecular details. (See http://cheme.che.caltech.edu/faculty/kornfield_j/)

9. **NTUA**, the Computational Materials Science and Engineering group of prof. Doros Theodorou of the University of Athens starts modeling at the *ab initio* level, which is fully complementary to our more macroscopic approach. This means that intense cooperation is beneficial and natural. Lambert van Breemen did part of his sabbatical in Athens, and with a postdoc financed by the TU/e Doros Theodorou is part of the high potential programme of our Executive Board. (See http://comse.chemeng.ntua.gr/dntpage.htm).

### 4. Quality and scientific relevance

#### 4.1. Most significant results/highlights

Achievements and recognition in the period 2007-2012 include:

1. Since, as mentioned, the **Polymer Technology** group was the first group in all disciplines in the Netherlands that received the maximum score in three successive Research Assessments, in 1994, 1999 and 2008, demonstrating 20 years of excellence, this new assessment period was solidly grounded and provided a natural continuation of an excellent research attitude and research portfolio, that proved challenging and interesting for our best MSc students to enter our PhD programme.
2. The continued strong and balanced funding from both the two main sources, NWO-STW and TU/e on one hand and DPI, EU and industry on the other, provide evidence of the scientific quality and industrial relevance of our research, and provide a continuous flow of well-educated PhD students showing deep knowledge of modeling-based basic research that is broadly applicable to solve real engineering problems. Our students are very welcome in industry, see Section 8.2.

3. International recognition is evidenced by the relatively large number of invitations for plenary, keynote and invited lectures. Sabbaticals (in this period e.g. Han Meijer (twice), Patrick Anderson (twice) and Lambert van Breemen are standard policy of our department. Our PhD students (in this period e.g. dr. Pieter Janssen, dr. Rudi Steenbakkers, dr. Young Joon Choi and dr. Lambert van Breemen) prove to be welcome as postdocs in excellent groups e.g. in the USA and Europe, and our PDs (in this period e.g. dr. Wook Ryol Hwang, dr. Tai Gae Kang, dr. Young Joon Choi and dr. Lambert van Breemen) are offered tenured professor positions in Korea, Canada and the Netherlands.

4. Citation analysis, see Section 4.3 below.

4.2. Key publications


4.3. Number of articles in top 10% and top 25% of publications relevant to the discipline

The CWTS study shows that Polymer Technology was, relative to its size, one of the most productive groups and had 10% of papers in the top 10 and 28% in the top 25 journals, and an Mncs of 1.07. A high productivity automatically results in a tendency towards the average, as these numbers indeed show. However the score is still somewhat low compared with our past experience over the last 20 years. This indicates that the limitation to Polymer Solid Mechanics (after splitting off Polymer Fluid Mechanics from Polymer Technology) results in a scientific community that is apparently relatively small and relatively slow. We already know the first of these factors, and it is confirmed by the size of the DYFP meetings, at which all scientists working on Polymer Solid Mechanics meet. These tri-annual meetings typically attract 150 participants. We also know the second factor, and this is confirmed for example by the number of citations of our most important papers in Polymer Solid Mechanics, which are characterised by a long incubation time followed by a long lifetime. This is inherent in modeling work that needs to be
studied thoroughly, and digested, before other groups can use it in their work. A prime example is our basic paper: *Prediction of the mechanical behavior of nonlinear heterogeneous systems by multi-level finite element modeling* (Comp. Meth. in Appl. Mech. and Eng. Vol: 155, 1-2, 181-192), which was published in 1998 and received an averaged annual citation of almost 12, while the citations in the recent years 2010, 2011 and 2012 were 23, 24 and 23, respectively. Also the GENERIC scientific world of far-from-equilibrium thermodynamics (Hütter) is well known as accessible for experts only, and therefore limited in size, despite its long-term relevance.

### 4.4. Most important books or chapters of books


### 5. Output

#### 5.1. Number of publications

<table>
<thead>
<tr>
<th>Publications</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012*</th>
<th>6 year total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Academic publications</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refereed articles</td>
<td>19 (8)</td>
<td>35 (8)</td>
<td>40 (9)</td>
<td>39 (17)</td>
<td>41 (9)</td>
<td>26 (10)</td>
<td>200 (61)</td>
</tr>
<tr>
<td>Conference papers</td>
<td>p.m.</td>
<td>p.m.</td>
<td>p.m.</td>
<td>p.m.</td>
<td>p.m.</td>
<td>p.m.</td>
<td></td>
</tr>
<tr>
<td>PhD theses</td>
<td>1</td>
<td>6</td>
<td>5</td>
<td>1</td>
<td>2</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>Book</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Book Chapters</td>
<td>1</td>
<td>1 (1)</td>
<td>4</td>
<td>-</td>
<td>1 (1)</td>
<td>-</td>
<td>7 (2)</td>
</tr>
<tr>
<td>Total academic publications</td>
<td>21 (8)</td>
<td>42 (9)</td>
<td>49 (9)</td>
<td>40 (17)</td>
<td>44 (10)</td>
<td>31 (10)</td>
<td>227 (63)</td>
</tr>
<tr>
<td>Patents</td>
<td>-</td>
<td>-</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Total research output</td>
<td>21 (8)</td>
<td>42 (9)</td>
<td>51 (9)</td>
<td>42 (17)</td>
<td>45 (10)</td>
<td>31 (10)</td>
<td>232 (63)</td>
</tr>
</tbody>
</table>

p.m.: *pro memoria*

(#) numbers between brackets indicate publications obtained in cooperation with other research programmes with them as first authors as included in the first numbers.

* As in 2007-2011, the 2012 data include the output of TU/e-9 (Structure and Rheology of Complex Fluids) and TU/e-11 (Microsystems)
### 5.2. Number of PhDs (completed and in progress)

**Table 5.2. PhD students**

<table>
<thead>
<tr>
<th>Starting year</th>
<th>Enrolment (male/female)</th>
<th>Total (male + female)</th>
<th>Graduated after (years)</th>
<th>Total</th>
<th>Not yet finished</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>F</td>
<td>≥ 4</td>
<td>4- ≤ 5</td>
<td>5- ≤ 6</td>
</tr>
<tr>
<td>2003</td>
<td>1</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>2004</td>
<td>4</td>
<td>1</td>
<td>5</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>2005</td>
<td>3</td>
<td>-</td>
<td>3</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>2006</td>
<td>1</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>1</td>
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<tr>
<td>2007</td>
<td>5</td>
<td>-</td>
<td>5</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>2008</td>
<td>4</td>
<td>-</td>
<td>4</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>2009</td>
<td>3</td>
<td>2</td>
<td>5</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>2010</td>
<td>4</td>
<td>1</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2011</td>
<td>4</td>
<td>-</td>
<td>4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2012</td>
<td>3</td>
<td>-</td>
<td>3</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Note: The thesis defense is usually 2 months after ending of the 4-year PhD contract. Students are not generally granted extension. Graduated in 4-<5 years should therefore be interpreted as: PhD work, including writing the thesis is finished in 4 years. Accordingly, prior to the start of the defense the thesis is sent to the printer and subsequently to the committee members to read it. This takes 2 months.

### 6. Resources

#### 6.1. Overview of the various sources of financing

**Table 6.1. Funding at programme level**

<table>
<thead>
<tr>
<th>Funding</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>k€</td>
<td>%</td>
<td>k€</td>
<td>%</td>
<td>k€</td>
<td>%</td>
</tr>
<tr>
<td>Direct funding</td>
<td>165</td>
<td>15</td>
<td>100</td>
<td>10</td>
<td>275</td>
<td>25</td>
</tr>
<tr>
<td>Public grants</td>
<td>216</td>
<td>20</td>
<td>213</td>
<td>20</td>
<td>259</td>
<td>15</td>
</tr>
<tr>
<td>Industry contract research</td>
<td>633</td>
<td>65</td>
<td>629</td>
<td>70</td>
<td>719</td>
<td>60</td>
</tr>
<tr>
<td><strong>Total funding</strong></td>
<td>1014</td>
<td>100</td>
<td>942</td>
<td>100</td>
<td>1253</td>
<td>100</td>
</tr>
</tbody>
</table>

* As in 2007-2011, the 2012 data include the funding of TU/e-9 (Structure and Rheology of Complex Fluids) and TU/e-11 (Microsystems), see Table 6.2 for details.

In the period 2007-2012 for *Polymer Technology* the an average annual funding was therefore 1.4 M€.
### 6.2. Earning capacity

Table 6.2. Distribution external funds used/acquired in the period 2007-2012

<table>
<thead>
<tr>
<th>Project</th>
<th>Sponsor</th>
<th>Partners</th>
<th>Funding k€</th>
</tr>
</thead>
<tbody>
<tr>
<td>445 Janssen R.</td>
<td>DPI/PP</td>
<td>DPI Users Committees:</td>
<td>360</td>
</tr>
<tr>
<td>454 Housmans</td>
<td>DPI/PO</td>
<td>AkzoNobel, (*)</td>
<td>210</td>
</tr>
<tr>
<td>446 Janssen P. and Singh</td>
<td></td>
<td>BASF, (*)</td>
<td>425</td>
</tr>
<tr>
<td>532 Khatakar</td>
<td></td>
<td>Bayer Technology Services, *</td>
<td>135</td>
</tr>
<tr>
<td>578 Engels</td>
<td></td>
<td>Borealis,</td>
<td>260</td>
</tr>
<tr>
<td>584 v. Breemen</td>
<td></td>
<td>DSM Research,</td>
<td>220</td>
</tr>
<tr>
<td>548 Forstner</td>
<td></td>
<td>ExxonMobil, *</td>
<td>135</td>
</tr>
<tr>
<td>614 Söntjens</td>
<td></td>
<td>Friesland Campina,</td>
<td>235</td>
</tr>
<tr>
<td>616 Choi</td>
<td></td>
<td>IME Technologies, *</td>
<td>260</td>
</tr>
<tr>
<td>634 Balzano</td>
<td></td>
<td>LyondellBasell, *</td>
<td>140</td>
</tr>
<tr>
<td>689 Wang</td>
<td></td>
<td>Océ-Technologies, (*)</td>
<td>295</td>
</tr>
<tr>
<td>694 van der Walt</td>
<td></td>
<td>Philips Research, (*)</td>
<td>350</td>
</tr>
<tr>
<td>699 Liu</td>
<td></td>
<td>SABIC Europe, **</td>
<td>265</td>
</tr>
<tr>
<td>708 Cavallo</td>
<td></td>
<td>SABIC Innovative Plastics, *</td>
<td>170</td>
</tr>
<tr>
<td>714 Zhe Ma</td>
<td></td>
<td>Teijin, *</td>
<td>315</td>
</tr>
<tr>
<td>738 Zahkari</td>
<td></td>
<td></td>
<td>340</td>
</tr>
<tr>
<td>746 Jaensson</td>
<td></td>
<td></td>
<td>290</td>
</tr>
<tr>
<td>745 Saltini</td>
<td></td>
<td></td>
<td>305</td>
</tr>
<tr>
<td>Ko4a Peters</td>
<td>DPI/KW</td>
<td></td>
<td>180</td>
</tr>
<tr>
<td>K12a Hrachóvá</td>
<td></td>
<td></td>
<td>250</td>
</tr>
<tr>
<td>K11a Garofalo</td>
<td></td>
<td></td>
<td>170</td>
</tr>
<tr>
<td><strong>Total DPI</strong></td>
<td></td>
<td></td>
<td>5,310</td>
</tr>
<tr>
<td>Project</td>
<td>Sponsor</td>
<td>Partners</td>
<td>Funding k€</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>------------------------------</td>
<td>--------------------------------------------------------------------------</td>
<td>------------</td>
</tr>
<tr>
<td>07345 Wismans</td>
<td>NWO-STW</td>
<td>STW Users Committees: Borealis, DOW, DSMis, KIWA, Philips Research, SABIC Eu and SABIC IP, (*)</td>
<td>430</td>
</tr>
<tr>
<td>07730 Van Erp, Senden,</td>
<td></td>
<td></td>
<td>980</td>
</tr>
<tr>
<td>Sedighiamiri,</td>
<td></td>
<td></td>
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**Total NWO-STW and TU/e**

3,505

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**Total EU and direct industry**

2,220 (+1,800)

*, (*) after 2012 group splitting (partly) in TU/e-9 Structure and Rheology of Complex Fluids

** after 2013 group splitting in TU/e-11 Microsystems
6.3. Research facilities & investments

Within the Materials Technology group, see Section 3.1, members have access to nine joint laboratories, and in fact all laboratories are used in various research programmes. The investments in the physical laboratories (thus excluding computer infrastructure) in the period 2007-2012 by the groups of MaTe, see Section 3.1, amounted to a total of 4.4 M€.

1. Multi-scale Laboratory.
   This lab allows for quantitative in situ microscopic measurements during deformation and mechanical characterisation of a broad class of materials, structures, MEMS etc. on a wide range of length scales. It therefore constitutes the main source for all experimental research on various mechanical aspects of materials within the range of 10^{-9}-10^{-2} m. Investments 2007-2012: 1490 k€

2. Mechanical Testing Laboratory.
   The mechanical testing laboratory is equipped for testing of materials (polymers and metals in particular), evaluation of solid-state forming processes in instrumented set-ups and evaluation of the structural integrity of objects. Investments 2007-2012: 200 k€

3. Polymer Processing Laboratory.
   In this facility fundamental aspects are analysed of polymer processing such as PVT-behaviour under non-equilibrium conditions, structure development in blends and semi-crystalline polymers, and the relationship between properties and flow conditions in real and model processing flows. Full-scale multi-component injection moulding facilities are available as well as scaled-down micro-processing equipment. Investments 2007-2012: 300 k€

4. Rheology & Light Scattering Laboratory.
   The laboratory is equipped to measure rheological properties over the full range of viscosities (i.e. from water to polymer melts), both in shear and elongation, including rheo-optical measurements. In addition, the lab is equipped with a laser light scattering instrument for static and dynamic light scattering (SLS & DLS), to study the dynamics, structure and mechanics of materials. In situ X-ray combined with rheometry, film blowing or prototype injection moulding is available for Synchroton studies in Grenoble. In addition, all kind of viscoelastic fluids and many different soft tissues are characterised. Investments 2007-2012: 800 k€

5. Laser and Laser-Scattering Laboratory.
   This facility houses equipment for point- and field-wise velocity measurements, LDA and PIV, structure development during (mixing) flow and 3D flow visualisation. (No new investments in this period.)

6. MicroFab Laboratory.
   This lab enables the fabrication of structures and devices at microscopic length scales. It is a basic cleanroom equipped with facilities for photolithography, various surface treatments and coatings, and PDMS-based Soft Lithography to replicate structures from a photosensitive master. The facility is used for the fabrication of microfluidic devices and microscopically structured surfaces. Investments 2007-2012: 90 k€
7. Laboratory for Cell and Tissue Engineering.
This laboratory consists of three rooms: a cell and tissue culture facility, a preparation and biochemistry room and a large optical microscopy room, in particular confocal laser scanning and two-photon microscopy. Investments 2007-2012: **480 k€**

8. Laboratory for Biomechanics.
In this laboratory studies for cardiovascular physiology, mechanical testing of (biological) materials, medical devices, (functional) ultrasound imaging and high-resolution microCT imaging are conducted. Investments 2007-2012: **190 k€**

9. Computer Laboratory.
This virtual laboratory comprises all computational facilities of MaTe. Investments in the period 2007-2012 included a 33-node Linux Cluster, 2 Supermicro computer nodes, 2 Supermicro 2041 M-T2Rs, a Diskserver and a total of 160 desktop PCs and 42 laptops with a total value in the order of **900 k€**

### 7. Academic reputation

To avoid duplication we will only report here on the group members of the Solid Mechanics and Structure-Property relations sub-group. For the (2007-2011) group members Patrick Anderson, Gerrit Peters, Martin Hulsen and Hans Wyss, see TU/e-9 Structure and Rheology of Complex Fluids, while for Jaap den Toonder see TU/e-11 Microsystems.

1. The total number of scientific publications and citations of the Polymer Technology Group as measured on November 11, 2013 with ISI Web of Knowledge

<table>
<thead>
<tr>
<th>name</th>
<th>tot pub</th>
<th>pub. last 6 years</th>
<th>total cit.</th>
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<tr>
<td>Lambert v Breemen</td>
<td>13</td>
<td>- - 4 - 3 3</td>
<td>188</td>
<td>84 34 19</td>
</tr>
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</table>

2. Han Meijer received the DSM Performance Material Award for lifetime achievements, with a personal cheque for **50 k€**, at the Macro2010 IUPAC World Polymer Congress on July 12, 2010.

3. Members of the group are frequently invited to give plenary, keynote and invited lectures at international conferences.

Han Meijer: 8 plenary (pl), 4 keynote (kn) and 2 invited (il) lectures:
pl: Seoul Korea, Rolduc NL, Linz Austria, Banff Canada, Glasgow UK, Marrakesh Morocco, Lisbon Portugal, Pattaya Thailand.
kn: Salvador Brazil, Taipei Taiwan, Leeds UK, Palermo Italy.
il: Manchester UK, Jeju Korea.
Leon Govaert: 3 keynote (kn) and 14 invited (il) lectures:
kn: TOP Ischia Italy, Katz Arau Switzerland, Workshop DPI Eindhoven NL.
il: University of Twente NL, KIWA Apeldoorn NL, Rhodia Lyon France, DSM Geleen NL, Purac Gorichem NL, SABIC Bergen op Zoom NL, Borealis Linz Austria, Johannes Keppler University Linz Austria, Wavin Hardenberg NL, il Solvay Bruxelles Belgium, KIWA Apeldoorn NL, Solvay Atlanta USA, Exxon Houston USA.

Markus Hütter: 1 plenary (pl) and 6 invited (il):
pl: Lodz Poland.
il: Freiburg Germany, Paris France, Rolduc NL (2*), Monte Verita Switzerland, Leiden NL.

Lambert van Breemen: 1 plenary (pl), 3 invited (il):
pl: DPD Lunteren NL.
il: DSM Geleen NL, Rolduc NL, DPI Zeist NL.

Piet Schreurs: See: TU/e 11 *Mechanics of Materials*. In line with the MaTe strategy, Piet supervised 5 PhD students in this group, in return Hans van Dommelen supervised 2 PhD students in the Polymer Technology group.

3. Members of the group are asked to organise international conferences (e.g. *Polymer Processing Society, European Society of Rheology*). The scientific advisory board of DYFP asked us, as a leading group in the field, to take over from Cambridge, UK, the organisation of this three annual event on *Deformation, Yield and Fracture of Polymers*, which was successfully done in 2006 (13th), 2009 (14th) and 2012 (15th).

Co-organiser session ‘Rheology and Flow of Glass-like Materials’ at the 82nd annual meeting of the Society of Rheology, October 24-28, 2010, Santa Fe, New Mexico, USA.
Co-organiser of symposium ‘Properties after Processing’ at the annual meeting of the Polymer Processing Society (PPS-24), June 15-19, 2008, Salerno, Italy.

4. Other activities

Han Meijer is:

• Chairman Dutch Society of Rheology, NRV, International Representative European Society of Rheology, ESR, and International Committee on Rheology, from 1992
• Scientific Director Eindhoven Polymer Laboratories, EPL, from 2003
• Member of the Ext. Scientific Advisory Committee of IPC Portugal, from 2006
• Member of the Scientific Advisory Committee of Laboratoire ‘Polymères et Matériaux Avancés’, Centre de Recherches et de Technologie de Lyon, France, from 2008
• Executive Advisory Board of Macromolecular Chemistry and Physics, Macromolecular Theory and Applications, Macromolecular Materials and Engineering, Macromolecular Rapid Communications, Macromolecular Bioscience and Macromolecular Reaction Engineering

And he was:

• Member of the Visiting Committee of the Dept. of Materials, ETH, 2004-2012
• Member of the Polymer IRC Board UK, 2005-2009
• Chairman of the Organizing Committee of the 12th DYFP, 2006
• President Polymer Processing Society, PPS, 2001-2003
• Chairman of the Organizing Committee of PPS-15, 1999
• Member of the Executive Committee PPS, 1998-2005
• Chairman of the Scientific Committee of Esaform, 1998-2000
• Thrust Area Leader Dutch Polymer Institute, DPI, 1997-2001
• Editor Polymer Processing and Structure-Performance for the Encyclopedia on Materials Science, 1999.

Leon Govaert:

• Has twice been guest editor of the Journal of Polymer Science, Part B, Polymer Physics, Wiley, for special issues on Deformation, Yield and Fracture of Polymers, in 2009 and 2012.

Markus Hütter:

• Board Member of the Eindhoven Polymer Laboratories (EPL)
• Member of the Management Team of the Eindhoven Multiscale Institute (EMI).

8. Societal relevance: quality, impact and valorisation

8.1. Societal quality of the work

The Dutch Polymer Institute DPI is an LTI, Leading Technology Institute, and as such a so-called public-private funding organ based on a 1-2-1 multiplication. This means that once industry spends 100 k€, government (the Ministry of Economic Affairs) adds a further 200 k€ and the university also adds a further 100 k€. This way of organising funding ensures that university research is relevant to industry. The consequence is that each individual project is initiated by industry, and that each project has its own industrial user committee. These committees frequently meet, to discuss results and control progression and help directing the choices on how to proceed.
• Industries involved in our DPI projects include: AkzoNobel, BASF, Bayer Technology Services, Borealis, DSM Research, ExxonMobil, Friesland Campina, IME Technologies, LyondellBasell, Océ-Technologies, Philips Research, SABIC Europe, SABIC Innovative Plastics and Teijin.

• STW projects have similar user committees, and examples of companies involved in our STW projects include: DSM Research, SABIC Innovative Plastics, SABIC Europe, Teijin, AkzoNobel, Wavin, SKF, DOW and Philips Research.

Our experience with this approach with relatively frequent and intense interactions with industrial researchers is very positive, in view of the mutual benefits in progressing research, and it also helps our PhD students to later quickly find jobs, usually even before they finish their PhD.

8.2. Societal impact of the work

Our postdocs and PhD students gain positions in industry and academia, and dedicate their knowledge and energy to helping to improve society. Those working with us in the period 2007-2012 went to:

Postdocs:
- Dr. E. Sourty FEI Instruments, Eindhoven
- Dr. W.R. Hwang Gyeongsang National University, Korea
- Dr. I.F. Vega University of Madrid, Spain
- Dr. D. Hristova DPI, Dutch Polymer Institute, Eindhoven
- Dr. R. Forstner Transercenter Kunststofftechnik, Austria
- Dr. T.G. Kang Aerospace University, Korea
- Dr. S.H.M. Söntjens Symo-Chem, Eindhoven
- Dr. L. Balzano DSM Research, Geleen
- Dr. J. Hrachová SABIC Europe, Geleen
- Dr. J.M. Park Institute of Machinery and Materials, Korea
- Dr. D. Cavallo University of Genova, Italy

PhD students:
- Dr.ir. J.W. Housmans Intertek, Geleen
- Dr. A. Sarhangi Fard SABIC Europe, Geleen
- Dr. V.V. Khatavakar DSM Research, Geleen
- Dr. C. Tufano SABIC Europe, Geleen
- Dr. F. Custodio SABIC Europe, Geleen
- Dr.ir. P.J.A. Janssen SABIC Innovative Plastics, Bergen op Zoom
- Dr.ir. L. van Breemen Assistant Professor TU/e, Mechanical Engineering
- Dr. K. Singh Tata steel, India
- Dr.ir. T.A.P. Engels DSM Research, Geleen
- Dr.ir. R.J.A. Steenbakkers DOW, Terneuzen
- Dr.ir. P.E. Neerincx SABIC Innovative Plastics, Bergen op Zoom
- Dr.ir. M.G.H.M. Baltussen DSM Research, Geleen
- Dr. Y.J. Choi University of Victoria, Canada
- Dr.ir. J.G.F. Wismans SABIC Innovative Plastics, Bergen op Zoom
- Dr.ir. T.B. van Erp SABIC Innovative Plastics, Bergen op Zoom
- Dr. A. Sedighiamiri SABIC Europe, Geleen
- Dr. Z. Ma Postdoc TU/e, Mechanical Engineering
- Dr.ir. D.J.A. Senden ASML, Veldhoven
- Dr. D. Liu Postdoc TU/e, Chemical Engineering
8.3. Valorisation of the work

Apart from all transfer of knowledge in the regular contacts with industry, with colleagues at the different conferences and with the scientific and engineering community through the large number of publications and numerous conference contributions, as well as the transfer of IP through patents to industry (Tetrapak, Philips, Omlidon), we strongly support spin-off companies like IME Technologies (which develops and sells the Pirouette PVT-Tdot-Gdot apparatus developed in our group and the electro-spin cabinet), Optimal Forming Solutions (flexible mould technology for vacuum forming), PTG, Polymer Technology Group (polymer processing), and QTIS/e, now Xeltis/e (IP of our disposable bioreactor). In close cooperation with ETH Zürich, we are working to initiate a start-up to exploit the High Performance tape-making process, developed during two successive sabbaticals. The majority of the invitations that dr. Leon Govaert receives to explain mechanical performance directly to industry show that his work over the past 20 years – in not only understanding the mechanical performance but also predicting the long-term properties of polymers – is now gradually starting to be incorporated in real practice. This is good for him, good for the industry and therefore also good for society.

9. Viability

The TU/e-8 Polymer Technology programme has a proven record of excellence over the past 20 years. More than 60 PhD students have been educated and finished their PhDs, a large number of postdocs and guests have worked here with success, and the funding was strong and balanced in view of the different important sources: National Science Foundation (proving quality), Industry and European Commission (proving relevance). The university recognised the quality and relevance of Polymer Research and awarded a grant of 1 M€ for the Multi-scale analysis of the intrinsic properties of polymer systems research proposal in its high-potential program. This extra funding allowed the recruitment of new staff members dr. Markus Hütter and dr. Lambert van Breemen, both of whom are potential candidates for future positions as professor. The Mechanical Engineering department recognised the relevance of their work by recently offering both researchers tenured positions, which they have accepted, thereby strengthening the department.

In addition the department reflected in an early stage on the upcoming retirement of the group leader Han Meijer, and decided to continue the group by splitting the activities into fluid-focused and solid-focused areas. The reason for this reflection and decision was that candidates with industrial experienced and a broad background covering both research areas are scarce, because of the changing attitude of all the relevant industrial research laboratories worldwide. (Without exception they have discontinued their basic and explorative research groups, which by definition were the nuclei and incubators for new professors for successful broad, relevant research, especially in Universities of Technology. This is a strategy to which the universities had to adapt.) To ensure continuity one of the most successful staff members of the Polymer Technology group, Patrick Anderson, was selected after an open procedure with an advertisement placed broadly worldwide as the best candidate, and was already appointed on January 1, 2012 as a first successor and as full professor in the fluid-focused area. To emphasise the serious start, half of the group, or 20 people, were directly placed under his supervision, including their funding. He can continue to build on an excellent infrastructure in terms of highly up-to-date state-of-the-art laboratories, extended computer infrastructure and an extremely fruitful existing cooperation within the MaTe group. The department is at present designing the procedure to find a successor for the solid-focused group. Financing is ensured, the candidate’s profile has been defined and the advertisement is ready to be placed.
10. SWOT analysis

Strengths

• Our reference is the top of the state-of-the-art international research groups. Visiting them, directly or at international conferences, and being visible, has high priority. Sufficient funds, also for PhD students and postdocs, have been allocated and are dedicated to achieve that.
• The relatively comfortable funding position for polymer research in the Netherlands, achieved through the high potential initiative of TU/e, through STW, DPI and EU, and through direct industrial contracts, allows sufficient working power of high quality and motivation, as well as state-of-the-art laboratories and computing facilities.
• Our approach to science is based on a hybrid numerical-experimental approach in which modeling directs and defines the experiments, while complexity in experimental research is resolved by modeling. We are unique in this combined approach worldwide, as other groups and institutes usually specialise in only one of these two approaches. We strongly believe that it is the combination that is of the utmost importance to obtain valuable results in engineering environments.

Weaknesses

• Our most important weakness is that what we do is considered as not very typical, or even as ‘relatively difficult’, for undergraduate mechanical engineering students who generally prefer to do automotive, robotics and construction and design.
• Despite a lot of teaching of the basic courses we apparently fail to be sufficiently visible with our research in the undergraduate part of the study, or in demonstrating that the fundamental engineering approach we take in both fluid and solid mechanics is indeed the way to get high-standard long-term improvements in all these application areas.
• The number of undergraduate, BSc and MSc students is therefore less than we would like. However, the students who enter our graduate programme through a BSc and MSc gained in our department are sufficient in number and show above-average quality once in our PhD system. The auto-selection mechanism of students apparently works very well.

Opportunities

• Many groups, also at TU/e, claim to do multi-scale analyses, although few actually do. The multi-level finite element method (MLFEM) developed in our group has proved to be unique by simultaneously and fully coupled solving problems on two (not yet multi) different length scales.
• In MLFEM, the FEM analyses of the stress-deformation behavior on the microlevel, at every integration point of the mesh on the macrolevel, serves as a non-closed form of the constitutive equation for complex structures that change in time.
• The advantage of this analysis is that material failure could be characterised by relatively simple criteria locally at the micro-level. Predictive power results, also on how the microstructure should be organised. Guidelines for new material design and development will follow.
• An extension of the application of MLFEM to other complex problems in engineering, such as surface properties in tribology, and to be more precise friction and wear of materials and coatings, is under way and very challenging. Helping this application area away from the traditional trial-and-error approaches towards a quantitative prediction and guidelines for new polymers and polymer systems is challenging but rewarding. Lambert van Breemen has been appointed to make this possible.
• Similarly, gives our understanding based on quantitative modeling of the intrinsic materials response, the knowledge that the mechanical response of polymers, also during long-term loading under static or dynamic conditions at different temperatures, is completely determined by their thermo-mechanical history during formation (processing) and use, as a function of the kinetics of physical ageing.

• The next challenge is to couple the kinetics of ageing to the molecular structure of the polymer. This is a much more straightforward problem to solve than relating molecular structure to long-term mechanical properties directly. This is our next challenge, and to bridge the gap to the chemists who are modeling on a lower-than-continuum mechanics level is required. For this Markus Hütter has been appointed.

**Threats**

• The results of the *Polymer Technology* group are basically obtained because we were given the opportunity to work for an extended period of time with more than one student on relatively fundamental problems. Long-term and repeated financing via DPI and STW ensures continuity. The users appreciate not only the work and approach, but also the fact that very good scientists are properly educated to perform well, also in engineering disciplines.

• In relation to threats, we are concerned about the increasing development of a ‘hype culture’ in industry, government agencies and, most unfortunately, many academic institutions and scientific journals. Since we are aware that our best research results have come from prolonged efforts in the same field, such as structure-property relationships for heterogeneous polymer systems, and not necessarily from activities directed towards the fashion of the day, we regard this trend as potentially negative.

• This development makes it increasingly problematical to generate support for fundamental and basic research, leading to underrating of truly archival scientific journals and hampering the building of meaningful relationships with industry, as many of them seek to find ‘The Next Big Thing’, and preferably as quickly as possible.
## 11. Strategy for the coming period

### Table 11.1. Strategy for the coming period

<table>
<thead>
<tr>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Opportunities</strong></td>
<td><strong>Weaknesses</strong></td>
</tr>
<tr>
<td>• Continue discussion with industries and funding agencies such as DPI and STW on the importance of maintaining the funding of non-fashionable but important fundamental and basic research.</td>
<td>• Invest time to explain our research methodology and create more Demonstrators of the results to be used in the university's open days and in classroom teaching.</td>
</tr>
<tr>
<td>• Link mechanical performance, including failure, to molecular structure by MLFEM and meso-scale modeling, using the potential of easy cooperations within EPL.</td>
<td>• Reintroduce the relatively labour-intensive method of teaching undergraduates at an early stage the basic tools in the Experimental and Numerical Skills course.</td>
</tr>
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<table>
<thead>
<tr>
<th>Threats</th>
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<tbody>
<tr>
<td>• Couple analysis to synthesis by connecting to the polymer researchers in Chemical Engineering to apply the results to control microstructures.</td>
<td>• Continue investing energy in direct contacts with industry. (Our former PhD students now working in industry help here.)</td>
</tr>
<tr>
<td>• Use meso-scale modeling to design new polymers, or modify existing polymers, with better ageing kinetics. This synthesis principally allows making all polymers tough.</td>
<td>• Convince industry to help and prove the relevance of basic research to funding agencies, or finance this work directly, either individually or in a consortium.</td>
</tr>
</tbody>
</table>
TU/e 9: Structure and Rheology of Complex Fluids
1. Objective(s) and research area

1.1. Mission

The mission of the programme is to provide high-level BSc/MSc/PhD education and to conduct research in the broad area of Complex Fluids that focuses on the development and application of novel computational and experimental methods to study the flow and dynamics of complex fluids in areas where morphology and rheology are inherently coupled. The research is focused not only on understanding the fundamental properties that relate materials via processing to properties, but also to develop these methods at such a level that they can be applied to industrially relevant problems. The application areas are found in the range from polymer processing, soft condensed matter, cells and bio-polymers in lab-on-a-chip devices.

1.2. Strategy

The Structure and Rheology of Complex Fluids group was founded on 1 January 2012 after the decision by the board of the Mechanical Engineering department in 2011, anticipating the retirement of prof. Han Meijer as head of TU/e 8: Polymer Technology, to continue polymer research and split the group into two smaller groups. The polymer solid mechanics part remains within Polymer Technology and the fluids part was transferred to the new Structure and Rheology of Complex Fluids group. The two groups maintain close cooperation and continue to work on connecting molecular architecture, via processing, to resulting structure. The Structure and Rheology of Complex Fluids group combines fundamental research on complex fluids with applications in industry. By ensuring that there is a sufficient critical mass of students working in each sub-programmes there is overlap in activities, resulting in symbiosis.

1.3. Research area and sub-programmes

The group is structured around four main topics:

1. Computational Rheology and Multi-Scale Modeling (Hulsen and Peters)
3. Chaotic Mixing and Two-phase Flows (Anderson and Hulsen)
4. Soft Condensed Matter and Microfluidics (Wyss and Anderson)

The first three topics have a long history in which combined experimental and computational techniques are embraced to study, improve and design processing of polymers. The fourth topic is a relatively new direction that benefits from the established experience of the staff members and focuses on new challenges in microfluidics and soft matter.
1.3.1. Computational Rheology and Multi-Scale Modeling (Hulsen and Peters)

Rheology is the science that deals with the behaviour under flow (deformation) of fluids that cannot be described by a simple linear relation between deformation rate and resulting stress (non-Newtonian fluids). The range of applications is vast and encompasses the spectrum from polymer and food processing to flow of blood and of DNA through microdevices. Particularly important for industrial processing are polymer fluids such as melts and solutions, which are viscoelastic.

Several clear trends have emerged during the last couple of decades. First, use of computational methods such as the finite element method has become indispensable for applying (model) rheological insights to practical flow problems. Furthermore, the most successful constitutive models in simulations have proven to be those that include microstructural features. This has motivated researchers to try to bridge the gaps between length and time scales. Ideally, one would like to start at the molecular level (the very architecture of molecules) and end with a simple model that can be used to accurately predict macroscopic flows, and of course ultimately the properties of the resulting (solidified) materials obtained. This has not yet been realised.

Our focus is therefore threefold:

1. Development and implementation of numerical methods that are particularly suited for solving the flow of viscoelastic fluids.

2. Simulations at a mesoscopic level in rheometric type of flows (computational rheometry). For example, by studying suspensions of hard particles in polymer fluids by direct simulations it is possible to obtain information on the average constitutive behaviour of such systems.

3. Development of computational techniques to bridge the length-scale gaps (multi-scale modeling).

1.3.2. Applied Rheology and Process Modeling (Peters and Anderson)

Design of polymer products and shaping processes benefit from a change from experimental trial and error to quantitative predictive capability. The main objective of applied rheology is to provide knowledge and models for the prediction and understanding of structure development during processing and the resulting final properties of polymeric products. These properties are determined by intrinsic (molecular) material parameters, and to a great extent by the processing conditions. To reach this goal, applied rheology aims at bridging the gap between sophisticated rheological models and reliable and feasible predictive modeling of polymer processing.

Examples of topics in this research area are:

- Non-linear viscoelastic models
- Flow-induced crystallisation in semi-crystalline polymers
- PVT behaviour under high shear and at high cooling rates
- Developing numerical codes for specific shaping processes
- Rheology of two-phase flows

Experimental characterisation and validation are important issues. For example, data for flow-induced nucleation are not available for most polymers. For validation, specially designed flow cells that mimic processing flow conditions are used in combination with LDA, PIV, FIB and time-resolved X-ray scattering. In this way the influence of molecular parameters such as molar mass distribution and molecular architecture on flow, nucleation and crystallisation behaviour of polymer melts can be evaluated.
1.3.3. Chaotic Mixing and Two-phase Flows (Anderson and Hulsen)

Deformation, coalescence and break-up of fluid volumes, phase separation, phase inversion and interfacial deformation solely, are important physical phenomena that determine the mechanical and optical characteristics of multi-component flow and composition. If this flow results from an industrial process, the process conditions required and the product properties obtained will strongly depend on these flow and composition characteristics. In addition to relevant experimental investigation, suitable physical models, together with an appropriate implementation in a numerical code, are important to gain a better understanding of the physical phenomena mentioned above. In particular we develop mapping methods and extend diffuse interface modeling.

Applications of this work are found in chaotic mixing in micorfluidics, self-stratifying coatings (phase-separation at interfaces), inkjet design for fast, accurate printing or copying, processing of organic super-fibres that outperform steel in specific strength (and modulus) by one order of magnitude, food processing, polymer blending and processing, multi-layered structures etc.

1.3.4. Soft Condensed Matter and Microfluidics (Wyss and Anderson)

Microfluidic technology opens up the fundamental study and control of soft matter and biological materials and processes, all the way from the level of molecules to soft matter and cells. Since flow and temperature can be controlled accurately in the tiny channels and chambers of microfluidic devices, the optimal conditions for probing and analysing (biological) materials and processes can be precisely defined. The more so since (biochemical) gradients can be realised and the mechanical environment and the fluid actuation can be adapted and controlled. In addition, microfluidics devices makes it possible to read out the response in various ways, e.g. electrically by integration of electrodes, optically or magnetically. Particular examples are the study of the active mechanical control in microfluidic devices: the use of micro-actuators to control flow, probe mechanical properties of soft matter, or to control the mechanical environment in the devices. Another focus here is on manufacturing approaches that minimise the use of expensive (cleanroom) facilities, such as printing, soft lithography and polymer processing-derived methods.

2. Composition of the research staff

The Structure and Rheology of Complex Fluids group strives to a PhD/tenured staff ratio of a maximum of 4, to ensure there is sufficient time for guidance of the individual students and to address new problems. In the period 2007-2011 Anderson, Peters and Hulsen were tenured staff within the TU/e 8 programme, while dr. Hans Wyss was appointed in 2009 as assistant professor via ICMS, the Institute of Complex Molecular Systems of Bert Meijer, and was tenured in July 2012. Prof. Jaap den Toonder was a member of the group as a visiting professor from Philips Research until his appointment to the new full chair Microsystems on 1-5-2013.

Since the programme started on 1-1-2012 the existing data of the composition of the research has not been included in this table, but as a part of TU/e 8.
Table 2.1a. Composition of research staff at programme level (fte)

<table>
<thead>
<tr>
<th></th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>TU/e 9: Structure and Rheology of Complex Fluids</td>
<td>before the start of the programme the output of the members is included in TU/e 8.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tenured staff</td>
<td>1.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-tenured staff (postdocs)</td>
<td>1.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PhD students</td>
<td>8.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total research staff</td>
<td>11.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supporting staff</td>
<td>0.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visiting fellows</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total staff</td>
<td>12.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2.1b. Composition of research staff at programme level (numbers)

<table>
<thead>
<tr>
<th></th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>TU/e 9: Structure and Rheology of Complex Fluids</td>
<td>before the start of the programme the output of the members is included in TU/e 8.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tenured staff</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-tenured staff (postdocs)</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PhD students</td>
<td>14</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total research staff</td>
<td>23</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supporting staff</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visiting fellows</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total staff</td>
<td>26</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In 2012 we had two external PhD students who visited our lab but were not on our payroll: Travis Walker from Stanford University and Massimiliano Villone from Federico II, Naples, Italy.

3. Research environment and embedding

3.1. National positioning

The Structure and Rheology of Complex Fluids group is a member of, or has strong formal ties with, the following institutions:

1. **MaTe**, the Materials Technology group originated in the former Fundamental Mechanics group. It is characterised by in-house efforts to maintain synergy and cooperation in successful multidisciplinary research. MaTe houses the Computational and Experimental Mechanics (CEM) and Biomechanics and Tissue Engineering (BMTE) groups of the departments of Mechanical Engineering and Biomedical Engineering, respectively. CEM includes the chairs of Polymer Technology (Meijer), Structure and Rheology of Complex Fluids
(Anderson), Microsystems (Den Toonder) and Mechanics of Materials (Geers), while BMTE comprises the chairs of Tissue Engineering (Baaijens), Cardiovascular Mechanics (Van de Vosse) and Bone Mechanics (Ito). (See www.mate.tue.nl).

2. **EPL**, Eindhoven Polymer Laboratories, the research school that coordinates polymer research within TU/e. EPL was officially (re-)recognised by the KNAW in 2009 for a period of seven years. Patrick Anderson is a board member. (See www.epl.nu)

3. **ICMS**, Institute for Complex Molecular Systems that brings researchers from different areas together to promote cross breeding of ideas across departments and across disciplines. (See www.icms.tue.nl)

4. **PTN**, Polymer Technology in the Netherlands, coordinates research outside TU/e as well as the educational programme of the PhD students. Anderson and Peters are the two organising senior lecturers for RPK-D: Rheology on Processing of Polymers. (See www.ptn.nu)

5. **DPI**, Dutch Polymer Institute, the Leading Technological Institute in polymer engineering and science, which has its centre at TU/e and provides a platform for private and public research with strong links to industry. (See www.polymers.nl)

### 3.2. International positioning

....and internationally:

6. We have a strong collaboration with prof. Moldenaers, prof. Van Puyvelde and prof. Vermant from the Applied Rheology group at [KU Leuven](https://www.kuleuven.be) (Belgium). Both groups use the special devices (e.g. Rheo-DSC in Leuven, extended dilatometry in Eindhoven) in the other group. Moreover, combining experimental results from the Leuven group with the computational modeling of the Eindhoven group has proved to be fruitful and has resulted in 8 joint papers.

7. We have been successful in applying for synchrotron X-ray beam time (WAXD and SAXS measurements) at the European Synchrotron Radiation Facility (ESRF). This is rather important for our research on flow enhanced structure development in polymers, and we strongly support the groups with which we cooperate at the ESRF (especially the Dutch Belgian beam-line DUBBLE), by investing in special experimental devices (e.g. fast cooling device, prototype injection moulding, rheometry), suited for in situ X-ray measurement under processing conditions.

8. The work on (flow-induced) crystallisation of polymers is renown and we have a strong collaboration with the groups of prof. Titomanlio (Naples, Italy) and prof. Alfonso (Genova, Italy) which has been established by an exchange of students (undergraduates and graduates) and postdocs and sharing experimental devices. A total of 12 joint papers are the direct result of this cooperation. Companies like ExxonMobil (USA), Total (USA) and BASF (Germany) seek cooperation on this topic and support this research by financing PhD and postdoc projects.

9. There is a successful collaboration with prof. Maffettone and prof. d’ Avino from University of Naples Federico II on numerical methods for particles suspended in complex flows. This yielded more than 15 joined publications during the assessment period.
10. **Stanford** University, the Complex Fluids group headed by prof. Fuller, appointed Anderson as a visiting professor within the Chemical Engineering Department. At the level of MSc and PhD, students are exchanged both ways for periods of up to four months.

### 4. Quality and scientific relevance

#### 4.1. Most significant results/highlights

Achievements and recognition in the period 2007-2012 include:

1. The group was in the past an integral part of TU/e 8 Polymer Technology, that received the maximum score for three assessments in a row. The Executive Board of the university recognised the importance of research in the area of complex fluids and supported the start of the new Structure and Rheology of Complex Fluids group.

2. The continued strong and balanced funding from both the two main sources, NWO-STW and TU/e on one hand and DPI, EU and industry on the other, show evidence of the scientific quality and industrial relevance of our research and provide a continuous flow of well-educated PhD students who show deep knowledge of modeling-based basic research that is broadly applicable to solving real engineering problems. Our students are very welcome in industry, see Section 8.2.

3. The large number of invitations for plenary, keynote and invited lectures by the staff shows that not only a single member but all staff members are internationally well recognised. We have a selected number of academic groups with intensified collaboration and mutual visits. Our PhD students (in this period e.g. dr. Pieter Janssen, dr. Rudi Steenbakkers and dr. Young Joon Choi) have proved to be welcome as postdocs in excellent groups, e.g. in the USA and Europe and our PDs (in this period e.g. dr. Wook Ryol Hwang, dr. Tai Gae Kang, dr. Young Joon Choi, dr. Jang Min Park) are offered tenure-track professor positions in Korea and in Canada.

4. In 2013 Anderson chaired the Annual European Society of Rheology AERC2013 meeting (co-chair Van Puyvelde from KU Leuven) which attracted more than 400 participants and was financially supported by a total of 17 companies in industry, raising 57 k€.

5. A finite element formulation for the log-conformation method has been developed with Raz Kupferman that opened the route to flow and stress predictions of polymeric flows under realistic processing conditions. The paper, by Hulsen et al., has already been cited more than 100 times.

6. The CWTS citation analysis reveals that our papers are well above world average, with a value for MNCS of 1.79. In addition, the citation connection graph shows that our group has many successful collaborations with other research groups in and outside the department; ironically, most of the collaborations are with the Biomechanics and Chemical Engineering departments, which are not included in the graph in the CWTS analysis.
4.2. Key publications


4.3. Number of articles in top 10% and top 25% of publications relevant to the discipline

The CWTS citation analysis shows that the impact of the ‘Mechanics’ papers published by TU/e in this field is relatively high and above world average, with a value for MNCS of 1.55. For the TU/e 9 Structure and Rheology of Complex Fluids programme we are above this value with a MNCS of 1.79. The total number of citations is 2467, while the MCs equals 12.98 which is a clear recognition that the work gains the attention of international peers. Almost half of the publications, to be precise 46%, are in the top 25% of all publications, while 25% of the publications are in the top 10%, which is relatively high, taking into account the large number of publications.

4.4. Most important books or chapters of books


5. Output

5.1. Number of publications

Table 5.1. Number of academic publications and other research output

<table>
<thead>
<tr>
<th>Publications</th>
<th>2007-2011</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Academic publications</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refereed articles before the start of the programme the output of the members is included in TU/e 8.</td>
<td>35 (15) pm</td>
<td></td>
</tr>
<tr>
<td>Non-refereed articles</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conference papers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PhD theses</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Book</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Book chapters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total academic publications</td>
<td></td>
<td>37 (15)</td>
</tr>
<tr>
<td>Professional publications</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Patents</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total research output</td>
<td></td>
<td>37 (15)</td>
</tr>
</tbody>
</table>

p.m.: pro memoria

(#{}) numbers between brackets represent papers in collaboration with other groups

Note that all group members were part of TU/e 8 until 31-12-2011 and their number of publications before 31-12-2011 is already included in TU/e 8 Polymer Technology.

5.2. Number of PhDs (completed and in progress)

The data in the table below only includes the PhD students who graduate(d) in the Structure and Rheology of Complex Fluids group.

Table 5.2. PhD students

<table>
<thead>
<tr>
<th>Starting year</th>
<th>Male/ female</th>
<th>Total</th>
<th>≤ 4</th>
<th>4- ≤ 5</th>
<th>5- ≤ 6</th>
<th>6- ≤ 7</th>
<th>Total</th>
<th>Not yet finished</th>
<th>Discontinued</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003-2007</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td>3</td>
<td>3</td>
<td>1^</td>
<td>2^</td>
<td>-</td>
<td>-</td>
<td>3</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td>2</td>
<td>3^</td>
<td>-</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>4</td>
<td>3^</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>2</td>
<td>2^</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td>1</td>
<td>1^</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

1 Liu
2 Baltussen and Ma
3 van der Walt, Florea, Gao
4 Vivat, Fahimi, Joneidi, Gorodeskyi, Roozemond
5 Drongelen, Wang
6 Jaensson
All staff members have an excellent track record of supervising PhD students, and each of them completed their thesis and gained their PhD. Without exception all students were able to find jobs in either industry or academia, benefiting from our strong collaborations with industry and many research groups.

As well as the PhD students in the Structure and Rheology of Complex Fluids group, the staff are also actively co-advising students in other groups within Materials Technology. Currently Anderson is co-advising Rene van de Burgt, Hulsen is co-advising Anna Catharine Verkaik and Peters is co-advisor of Thomas Van Kempen, all with prof. Van de Vosse in Cardiovascular Biomechanics on developing new rheological constitutive equations. Wyss is actively involved in projects on Cell Mechanics in the Tissue Engineering group headed by prof. Baaijens.

6. Resources

6.1. Overview of the various sources of financing

Table 6.1. Funding at programme level

<table>
<thead>
<tr>
<th>Funding</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>k€</td>
<td>%</td>
<td>k€</td>
<td>%</td>
<td>k€</td>
<td>%</td>
</tr>
<tr>
<td>Direct funding</td>
<td>210</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Public grants</td>
<td>360</td>
<td>25</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Industry contract research</td>
<td>880</td>
<td>60</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total funding</strong></td>
<td><strong>1450</strong></td>
<td><strong>100</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Since the group was founded on 1-1-2012, Table 6.1 only shows our income in 2012. An average annual funding of 1.4 M€ is listed in Table 6.1 showing the TU/e 8 Polymer Technology programme.

6.2. Earning capacity

The members of the group have been successful in obtaining sufficient funding to support fundamental and industry-related research. The tables below only show the projects that were still effective as of 1-1-2012. Projects within the assessment period that ended before that date are included in TU/e 8 Polymer Technology.
### Table 6.2. Distribution external funds used/acquired in the period 2007-2012

<table>
<thead>
<tr>
<th>Project</th>
<th>Start</th>
<th>End</th>
<th>Sponsor</th>
<th>Partners</th>
<th>Funding k€</th>
</tr>
</thead>
<tbody>
<tr>
<td>TU/e-ME Gorodetskyi</td>
<td>02/2009</td>
<td>02/2013</td>
<td>TU/e</td>
<td>Energy Technology</td>
<td>200</td>
</tr>
<tr>
<td>CvB high-potential project</td>
<td>01/2009</td>
<td>01/2013</td>
<td></td>
<td>Chemistry and Physics TU/e</td>
<td>320</td>
</tr>
<tr>
<td>CvB high-potential project</td>
<td>01/2009</td>
<td>01/2013</td>
<td></td>
<td>Chemistry and Biomedical Eng. TU/e</td>
<td>320</td>
</tr>
<tr>
<td><strong>Total Direct Funding TU/e</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>840</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Project</th>
<th>Start</th>
<th>End</th>
<th>Sponsor</th>
<th>Partners</th>
<th>Funding k€</th>
</tr>
</thead>
<tbody>
<tr>
<td>07730 Van Erp, Senden, Van Drongelen (0.5)</td>
<td>04/2007</td>
<td>04/2013</td>
<td>NWO-STW</td>
<td>STW Users Committees: Borealis, DOW, DSM Research, Philips Research, SABIC EU and SABIC IP, SKF, Teijin</td>
<td>980</td>
</tr>
<tr>
<td>08083 Roozemond</td>
<td>01/2008</td>
<td>06/2014</td>
<td></td>
<td></td>
<td>225</td>
</tr>
<tr>
<td>10458 Gao</td>
<td>03/2009</td>
<td>10/2013</td>
<td></td>
<td></td>
<td>230</td>
</tr>
<tr>
<td><strong>Total Public grants NWO-STW</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>1,535</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Project</th>
<th>Start</th>
<th>End</th>
<th>Sponsor</th>
<th>Partners</th>
<th>Funding k€</th>
</tr>
</thead>
<tbody>
<tr>
<td>694 van der Walt</td>
<td>01/2009</td>
<td>01/2013</td>
<td>DPI/PP</td>
<td>DPI Users Committees: AkzoNobel, BASF, Bayer Technology Services, Borealis, DSM Research, ExxonMobil, FrieslandCampina, IME Technologies, LyondellBasell, Océ-Technologies, Philips Research, SABIC Europe, SABIC Innovative Plastics, Teijin</td>
<td>295</td>
</tr>
<tr>
<td>699 Liu</td>
<td>03/2009</td>
<td>03/2013</td>
<td>DPI/PO</td>
<td></td>
<td>350</td>
</tr>
<tr>
<td>708 Cavallo</td>
<td>04/2009</td>
<td>04/2013</td>
<td></td>
<td></td>
<td>265</td>
</tr>
<tr>
<td>714 Zhe Ma</td>
<td>07/2009</td>
<td>07/2013</td>
<td></td>
<td></td>
<td>170</td>
</tr>
<tr>
<td>689 Wang</td>
<td>08/2011</td>
<td>08/2015</td>
<td></td>
<td></td>
<td>315</td>
</tr>
<tr>
<td>746 Jaenssson</td>
<td>04/2012</td>
<td>04/2016</td>
<td></td>
<td></td>
<td>290</td>
</tr>
<tr>
<td>738 Aangenendt</td>
<td>06/2013</td>
<td>06/2017</td>
<td></td>
<td></td>
<td>335</td>
</tr>
<tr>
<td>787 Troisi</td>
<td>04/2013</td>
<td>04/2018</td>
<td></td>
<td></td>
<td>510</td>
</tr>
<tr>
<td>788 Smit</td>
<td>01/2014</td>
<td>01/2018</td>
<td></td>
<td></td>
<td>405</td>
</tr>
<tr>
<td>K11a Garofalo</td>
<td>03/2010</td>
<td>06/2013</td>
<td></td>
<td></td>
<td>170</td>
</tr>
<tr>
<td><strong>Total DPI Industry contract research</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>3,105</strong></td>
</tr>
</tbody>
</table>
6.3. Research facilities & investments

Within the Materials Technology group, see Section 3.1, members have access to nine joint laboratories, and in fact all laboratories are used in various research programmes. The investments in the physical laboratories (thus excluding computer infrastructure) in the period 2007-2012 by the groups of MaTe, see Section 3.1, amounted to a total of 4.4 M€.

1. Multi-scale Laboratory.
   This lab allows for quantitative in situ microscopic measurements during deformation and mechanical characterisation of a broad class of materials, structures, MEMS etc. on a wide range of length scales. It therefore constitutes the main source for all experimental research on various mechanical aspects of materials within the range 10^{-9}-10^{-2} m. Investments 2007-2012: 1490 k€.

2. Mechanical Testing Laboratory.
   The mechanical testing laboratory is equipped for testing of materials (polymers and metals in particular), evaluation of solid-state forming processes in instrumented set-ups and evaluation of the structural integrity of objects. Investments 2007-2012: 200 k€.

3. Polymer Processing Laboratory.
   In this facility fundamental aspects of polymer processing are analysed such as PVT behaviour under non-equilibrium conditions, structure development in blends and semi-crystalline polymers, and the relationship between properties and flow conditions in real and model processing flows. Full-scale multi-component injection moulding facilities are available as well as scaled down micro processing equipment. Investments 2007-2012: 300 k€.

4. Rheology & Light Scattering Laboratory.
   The laboratory is equipped to measure rheological properties over the full range of viscosities (i.e. from water to polymer melts), both in shear and elongation, including rheo-optical measurements. In addition, the lab is equipped with a laser light scattering instrument for static and dynamic light scattering (SLS & DLS) with which the dynamics, structure and mechanics of materials can be studied. As well as all kinds of viscoelastic fluids, many different soft-tissues are also characterised. Investments 2007-2012 (dependence bij DUBBLE: 150 Keuro): 800 k€.
5. **Laser and Laser-Scattering Laboratory.**
This facility houses equipment for point- and field-wise velocity measurements, LDA and PIV, structure development during (mixing) flow and 3D flow visualisation. (No new investments in this period.)

6. **MicroFab Laboratory.**
This lab enables the fabrication of structures and devices at microscopic length scales. It is a basic cleanroom equipped with facilities for photolithography, various surface treatments and coatings, and PDMS-based Soft Lithography to replicate structures from a photoresist master. The facility is used for the fabrication of microfluidic devices and microscopically structured surfaces. Investments 2007-2012: **90 k€**.

7. **Laboratory for Cell and Tissue Engineering.**
This laboratory consists of three rooms: a cell and tissue culture facility, a preparation and biochemistry room and a large optical microscopy room, in particular confocal laser scanning and two-photon microscopy. Investments 2007-2012: **480 k€**.

8. **Laboratory for Biomechanics.**
In this laboratory studies for cardiovascular physiology, mechanical testing of (biological) materials, medical devices, (functional) ultrasound imaging and high-resolution microCT imaging are conducted. Investments 2007-2012: **190 k€**.

9. **Computer Laboratory.**
This virtual laboratory comprises all computational facilities of MaTe. Investments in the period 2007-2012 included a 33 node Linux Cluster, 2 Supermicro compute nodes, 2 Supermicro 2041 M-T2R, a Diskserver and in total 160 desktop PCs and 42 laptops with a total value of the order of **900 k€**.

7. **Academic reputation**

Below we report on the academic details of the tenured staff group members for the full period of the assessment. For prof. Jaap den Toonder, who was a part-time professor in the Structure and Rheology of Complex Fluids group until 1 May 2013, see TU/e 11 Microsystems.

<table>
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<td>Gerrit Peters</td>
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<td></td>
<td>761</td>
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</table>
1. Patrick Anderson was awarded the Morand Lambla Award in 2008. This international award is given by the Polymer Processing Society to honor outstanding researchers, below the age of 40, in the field of polymer processing.

2. Members of the group are frequently invited to give plenary, keynote and invited lectures in international conferences.

   **Patrick Anderson:** 4 plenary, 10 keynote and 1 Invited lectures:
   - plenary: Novi Sad (Serbia), Kish Island (Iran), Salerno (Italy), Niagara Falls (Canada), keynote: Snowbird (USA), Niagara Falls (Canada), San Sebastian (Spain), Marrakech (Morocco), Istanbul (Turkey), Banff (Canada), Montreal (Canada), Dresden (Germany), Columbus (USA), Cardiff (Wales), invited Ludwigshafen (Germany)

   **Gerrit Peters:** 1 plenary, 5 keynote, and 1 invited lectures:
   - plenary: Kish Island (Iran), keynote: Marrakech (Morocco), Banff (Canada), Genova (Italy), Goa (India), Salvador (Brasil), invited: Shizuoka (Japan)

   **Hans Wyss:** 1 plenary and 5 invited lectures:
   - plenary: Heraklion (Greece)
   - invited: Leiden (Netherlands), Lausanne (Swiss), Regensburg (Germany), Denver (USA), Rotterdam (Netherlands)

   **Martien Hulsen:** 1 keynote, and 3 Invited lectures:
   - keynote: Seoul (Korea)
   - invited: Ventura (USA), Eindhoven (The Netherlands), San Diego (USA)

3. Members of the group are asked to organise international conferences (e.g. Polymer Processing Society, European Society of Rheology) under the auspices of the societal organisations.

   **Patrick Anderson**
   - Chair 8th European Rheology conference AERC2013, Leuven, 2013 (co-chair: Peter Van Puyvelde, KU Leuven)
     - ‘Process Modeling and Simulations’ at PPS 27, Marrakech, Morocco, 2011
     - ‘Injection Molding and Molds’ at PPS, Banff, Canada, July 2010
     - ‘Morphology and Structure Development’ at PPS 25 Goa, India, March 2009
   - Other selected meetings:
     - ‘Computational Rheology’, FEF 2011, Munich, March 2011
   - Member Scientific Steering Committee of ISMIP, International Symposium on Mixing in Industrial Processes, 2008-2013
Gerrit Peters
Session organiser ‘Morphology and structure development’ sessions at PPS international meetings:
24th - Salerno Italy, 2008, 25th - Goa, India, 2009
26th - Banff, Canada, 2010, 27th - Marrakesh, Morocco, 2011
PPS Euro-Africa region meetings:
Gothenburg, Sweden, 2007 & Kish Island, Iran, 2011

Hans Wyss
Session organiser ‘Relaxation and flow in soft materials’, APS March meeting, 2007
Session chair ‘Microrheology and microfluidics’ AERC2013, Leuven, 2013

Martien Hulsen
‘Modelling, simulation and computational rheology’, AERC2010, Göteborg, 2010

4. Other academic activities

Patrick Anderson is:
• Chairman Dutch Society of Rheology NRV from September 2012.
• Board Member of Eindhoven Polymer Laboratories, EPL, from 2012
• Member of the International Scientific Committee of European Symposium of Polymer Blends
• Member International Advisory Board of Macromolecular Materials & Engineering
• Member International Advisory Board of Progress in Polymer Processing
• Editor for special issue ‘Rheology, Mixing, and Flow of Polymeric Materials’ in Macromolecular Materials & Engineering, appeared 2011
• Editor for special issue ‘Dynamics of Complex Liquid-Liquid Interfaces’ in European Physics Journal, appeared 2013

Gerrit Peters is:
• International representative for the Netherlands in the Polymer Processing Society Executive Committee
• Member of the editorial Board of Rheologica Acta

Martien Hulsen is a member of the editorial board of the Journal of Non-Newtonian Fluid Mechanics

8. Societal relevance: quality, impact and valorisation

8.1. Societal quality of the work

The societal quality of our research is ensured through a variety of platforms. The first platform is the public-private funding structure of the Dutch Polymer Institute DPI, which is a Dutch government initiated Leading Technology Institute and is based on a 1-2-1 funding multiplication. This means that once industry spends 1, government – in other words the Ministry of Economic Affairs – adds 2 and the university also adds 1. This structure of organising funding ensures that university research is relevant to industry. A second and third platform is via our National Science Foundation projects and our European projects. In these projects industrial partners are part of the user committee:
• Industries involved in our DPI projects include: AkzoNobel, BASF, Bayer Technology Services, Borealis, DSM Research, ExxonMobil, FrieslandCampina, IME Technologies, Océ-Technologies, Philips Research, SABIC Europe, SABIC Innovative Plastics, Teijin.

• Companies involved in our NWO-STW projects include: DSM Research, SABIC Innovative Plastics, SABIC Europe, Teijin, AkzoNobel, DOW, Philips Research.

• Our EU-FP6 and EU-FP7 projects generally have meetings at least four times a year with participating companies: BASF, Bayer Technology Services, Philips Research, WIKKI, Evonik, Solvay-Rhodia, Arkema, Proctor & Gamble, AstraZeneca.

Our experience with these frequent and intense interactions with industrial researchers is positive, given the mutual benefits in progressing research, and in addition helps our PhD students to later quickly find jobs, often before they finish their PhD theses.

8.2. Societal impact of the work

Society is brought into contact with our research through our postdocs and PhD students who gain positions in industry and academia. Since there are close links in many of our projects with industrial partners, our postdocs and PhD students often gain positions with the industrial partners who are already involved in their project. In addition, different societal groups are reached by the dissemination process as defined in our European projects. In most of our EU projects, specific work packages are defined to ensure outreach through workshops, folders and the Chambers of Commerce.

The postdocs and PhD students who worked with the current staff of TU/e 9 in the period 2007-2012 went to:

Postdocs:
Dr. W.R. Hwang Gyeongsang National University, Korea
Dr. J.F. Vega University of Madrid, Spain
Dr. D. Hristova DPI, Dutch Polymer Institute, Eindhoven
Dr. R. Forstner Transfercer Kunstofftechnik, Austria
Dr. T.G. Kang Aerospace University, Korea
Dr. L. Balzano DSM Research, Geleen
Dr. J.M. Park Institute of Machinery and Materials, Korea
Dr. D. Cavallo University of Genua, Italy

PhD students:
Dr. J.W. Housmans Intertek, Geleen
Dr. A. Sarhangi Fard SABIC Europe, Geleen
Dr. V.V. Khatavkar DSM Research, Geleen
Dr. C. Tufano SABIC Europe, Geleen
Dr. F. Custodio SABIC Europe, Geleen
Dr. Ir. P.J.A. Janssen SABIC Innovative Plastics, Bergen op Zoom
Dr. M.K. Singh Tata steel, India
Dr. Ir. R.J.A. Steenbakkers DOW, Terneuzen
Dr. Ir. M.G.H.M. Baltussen DSM Research, Geleen
Dr. Y.J. Choi University of Victoria, Canada
Dr. Z. Ma Postdoc TU/e

We are proud that all our PhD students successfully defended their theses and their knowledge is passed on to society in this way.
8.3. Valorisation of the work

We strongly support the transfer of knowledge to society and of intellectual property to industry. Valorisation of this work is achieved via:

- The transfer of IP to industry
- Consultancy of staff members in industry
- Support of spin-off companies such as IME Technologies (which develops and sells the Pirouette PVT apparatus developed in our group and the electro-spin cabinet)
- PTG, Polymer Technology Group at Chemical Engineering that answers questions on polymer processing for the society and often consults us
- Through our adjunct professorship of prof. Den Toonder with his main position at Philips until 1-5-2012
- Through dr. Engels from DSM Ahead who has been appointed on a 0.2 fte basis as a part-time assistant professor in our group
- Through dr. Poortinga from FrieslandCampina who is a 0.2 fte visiting guest. The procedure for a formal appointment as a part-time associate professor has now been started.

9. Viability

The TU/e 9 programme Structure and Rheology of Complex Fluids is a young group that started on 1 January 2012. However the members of the group have a proven track record of excellence over the last 20 years while being a part of the Polymer Technology group. At the start of the new group more than 20 people were transferred, providing a smooth start.

On the viability we can comment:

- The funding of the group is healthy, see Section 6, with a yearly funding of $1.4\,\text{M}\,\text{€}$.
- The research output is solid, see Section 5.1, and the work is considered relevant, see the citation analysis in Section 4.
- The department has open vacancies for two full-time assistant professor positions as well as part-time professor positions

The part-time positions of dr. Engels (DSM) and dr. Poortinga (FrieslandCampina) create strong links with industry. The group currently has a vacancy for an assistant professorship on Processing with Polymers that combines the development of experimental methods and design with polymers. In addition, a second assistant professorship has been awarded by the department, and it is expected that dr. Cardinaels, who received her PhD in Leuven in 2010 working on experimental rheological methods for viscoelastic fluids, will join the group. The two new positions together with the industrial part-time positions complement the expertise and experience of the current group.

The Structure and Rheology of Complex Fluids group is integrated within the MaTe group with its excellent infrastructure in terms of highly up-to-date state-of-the-art laboratories, extended computer infrastructure and fruitful existing collaborative work. Anderson, Peters, Hulsen and Wyss together supervised more than 50 PhD students, and also after the start of the new group the members have succeeded in gaining continued funds from the National Science Foundation (which is a recognition of quality), bilateral industry and the European Union through the FP7 programme (relevance & society).
10. SWOT analysis

**Strengths**

- The group has strong ties with two communities: rheology and polymer processing.
- The group is well known for its numerical methods for complex fluids of polymers and multi-phase flows. Through multi-scale modeling, we fully couple – both macro > micro and micro > macro – processing with microstructural properties. Examples are flow-induced crystallisation and polymer blends modeling.
- We strive to invest in competing and collaborating with the best groups worldwide. Our students are welcome for internships and staff members, are invited for plenary and keynote lectures at national and international conferences, all of which contributes to maintaining a strong reputation.
- The funding possibilities for polymer research are fruitful in the Netherlands, not only through the DPI but also through NWO and bilateral contracts. We are able to gain sufficient funding to continue working on the problems that we find important, challenging and societally relevant.
- For a number of research lines, including distributive mixing and applied rheology, we have developed a framework through which fundamental research is now directly connected to applied research, which generates funding from industry to support more fundamental work.

**Weaknesses**

- The staff of the group are active in the BSc educational programme and responsible for three courses, with two basic courses in the first semester, first year. Although we come in contact with most students, the undergraduate mechanical engineering students prefer more practical engineering tracks in automotive and robotics. This results in an undesirable imbalance in the department.
- When we have the option in the educational programme to attract students to enrol in our MSc track they have often already chosen another track. Some are discouraged by the required fundamental skills in our track. However, the students who do choose our programme have above average grades; they are highly motivated and good ambassadors for the group when we send them on internships.

**Opportunities**

- In our group we have developed a framework to connect rheology with processing which brings many challenges and opportunities, not only in the field of polymer processing but also in growing research areas such as energy, new functional and structured materials, biomechanics and food. With the part-time position of dr. Poortinga we are applying our expertise in structure development with polymers to industrially relevant food processes.
- Our modeling approach is powerful and enables is to react quickly to new developments in the field. For example together with our collaborators in Leuven and Stanford we are setting up projects on interfacial rheology in which a combined experimental-computational approach is needed to develop constitutive equations on interfaces, with applications in, for example, thin films, bio films, and protein transport on interfaces. These new activities also enhance our connections with the ICMS group headed by prof. Bert Meijer.
**Threats**

- Our new group can be seen as the fluid-subset of the Polymer Technology group, and we have to ensure a continuing close connection with the solids part. Fortunately, with the part-time appointment of dr. Engels from DSM, we have further strengthened our activities and continued our work on relating processing of polymers with their final (mechanical, optical, conductive) properties.

- Funding possibilities have been quite strong for polymer research. The funding possibilities in the future are not clear, due to the influence of the political arena in the Netherlands and Europe. In addition, within project proposals the expected outcomes of research have to be described in advance with such a level of detail that it could jeopardise the freedom in defining the research programme. ‘Out-of-the-box’ thinking is often needed to make big steps forward.

### 11. Strategy for the coming period

**Table 11.1. Strategy for the coming period**

<table>
<thead>
<tr>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Opportunities</strong></td>
<td>• Increase our role in EPL.</td>
</tr>
<tr>
<td></td>
<td>• Reach out to funding agencies by combining fundamental and applied research.</td>
</tr>
<tr>
<td></td>
<td>• Shift our Processing BSc course to an earlier stage in the curriculum, when students have not yet chosen a track.</td>
</tr>
<tr>
<td></td>
<td>• Scout for potential MSc students, not only within TU/e but also at Strategic Partner Universities.</td>
</tr>
<tr>
<td><strong>Threats</strong></td>
<td>• Strengthen collaborations within Eindhoven Polymer Laboratories.</td>
</tr>
<tr>
<td></td>
<td>• This will provide guidelines on how to choose other materials or more appropriate process conditions to obtain the desired properties.</td>
</tr>
<tr>
<td></td>
<td>• Continue to be active in larger European projects and combine fundamental and applied research.</td>
</tr>
<tr>
<td></td>
<td>• Embrace the option of applying our knowledge of structure and processing of polymers to other types of materials such as gels and food.</td>
</tr>
</tbody>
</table>
1. Objective(s) and research area

1.1. Vision, mission and objective(s) of the programme

The mission of the Mechanics of Materials group is to understand, predict and optimise the mechanical response of high-tech materials and products as a function of their underlying microstructure, processing and evolution, through focused and co-ordinated experimental, theoretical and computational efforts.

High-tech materials are key in developing novel products with revolutionary functionality. Our vision is that by carrying out dedicated world-class research across a range of length scales, we will be able to contribute to the growing demands in society and industry. Our research programme therefore establishes a strong link between application, experiment, theory and computation.

The objective of the Mechanics of Materials programme is to be a leading international research group in our discipline, aiming for the highest scientific level, and thereby addressing the most challenging industrial questions to the benefit of society and the young engineers and scientists that we educate.

1.2. Strategy

The Mechanics of Materials group pursues a generic research strategy that is systematically aligned with industrial needs, from which fundamental and scientifically challenging research questions are distilled. To reach a high scientific level, we focus on specific key problems in mechanics of materials, aligned with our research subprogrammes.

The strategy for generating a healthy project portfolio therefore connects to different funding sources, i.e. STW, NWO, FOM, AgentschapNL, the EC, industry and the Materials innovation institute (M2i). Maintaining a balanced financial situation is also an important strategic objective.

A third important element of our strategy is the training we provide to all our students at BSc, MSc and PhD levels. Our PhD educational programme is embedded in the Engineering Mechanics graduate school, through which we provide trainings and courses covering both professional skills and technical in-depth high-level subjects.
1.3. Research area and subprogrammes

The scientific research activities in the Mechanics of Materials group concentrate on the experimental analysis, theoretical understanding and predictive modelling of a range of phenomena in engineering materials at different length scales, which emerge from the physics and mechanics of the underlying multi-phase microstructure. The main challenge within this programme is the accurate prediction of the mechanical properties of materials with complex microstructures. This focus is closely related to intrinsic material properties (multi-scale plasticity in advanced steels, interfacial properties in laminates, thermo-mechanical fatigue in cylinder heads etc.), the application of materials in microsystems (i.e. multi-phase functional materials, MEMS, stretchable electronics etc.) and various systems and processes involving mechanically complex interfaces (e.g. in Systems-in-Package, flexible displays, electronic textiles). The programme aims for a substantial increase of the predictive power of state-of-the-art models, thereby enabling the optimisation of critical, high-tech products and manufacturing processes in direct relation to the complex loading history of the underlying materials and joining interfaces. A systematic and integrated numerical-experimental approach is generally adopted for this purpose.

The research activities are organised in three subprogrammes (see also TU/e 10, Appendix 1):

1. **Multi-scale mechanics and structure-property modelling**. Upscaling from microstructure towards engineering properties requires advanced methods to extract relevant information from small scales and reveal the emergent behaviour at larger scales. The subprogramme targets this goal through the development of advanced homogenisation and multi-scale approaches, with a challenging application perspective.

2. **Computational and experimental micromechanics**. The ultimate performance of materials and high-tech micro-systems originates from the mechanics at underlying characteristic length scales, where microstructures play an intrinsic role. To achieve a comprehensive understanding of these phenomena, this subprogramme focuses on the development of advanced physical models, computational tools and state-of-the-art experimental techniques to study them at the micro-scale.

3. **Damage, fracture and reliability**. The lifetime and reliability of engineering components and devices at all length scales are governed by damage and fracture of their constituting materials and interfaces. This subprogramme develops the in-depth understanding of all the related failure phenomena and provides powerful models and computational solution strategies, along with dedicated integrated numerical-experimental identification methods.

2. Composition of the research staff at programme level

At present, the group consists of 8 scientific faculty members (2.5 fte research capacity):

- **Full professors**: Dr. Marc Geers (49), Dr. Vikram Deshpande (41; part-time; also full professor at the University of Cambridge).
- **Associate professors**: Dr. Ron Peerlings (42), Dr. Hans van Dommelen (38).
- **Assistant professors**: Dr. Joris Remmers (39), Dr. Varvara Kouznetsova (37), Dr. Johan Hoefnagels (37) and Dr. Olaf van der Sluis (43; part-time; also senior scientist at Philips Research).
Table 2.1a. Composition of research staff at programme level (fte)

<table>
<thead>
<tr>
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<th>2007</th>
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<tr>
<td>Tenured staff</td>
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<td>2.8</td>
<td>2.5</td>
<td>2.5</td>
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<tr>
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<td>Total staff</td>
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<td>14.8</td>
<td>17.3</td>
<td>18.7</td>
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Table 2.1b. Composition of research staff at programme level (numbers)

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<td>Non-tenured staff</td>
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<td>PhD students</td>
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<td>Total research staff</td>
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<td>28</td>
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</tr>
</tbody>
</table>

Supporting staff: technical and administrative staff with 0.4 fte for each supporting staff member.
Visiting fellows: all research guests or fellows who are not funded through the research programme, with a minimal participation of 1 year.

The group supervises on average 15 PhD or post-doc researchers and 20-30 Master’s students.

The supporting staff is limited to one technician (Marc van Maris) and one secretary (Ms. Alice van Litsenburg). The technician takes care of all technical challenges in the multi-scale lab in direct support of the experimental research projects. The system manager for the Computational Laboratory (Leo Wouters) is formally part of the Polymer Technology group, but also works for the Mechanics of Materials group. The group is completed by Dr. Sebastiaan Boers who contributes to our group from within his spin-off company OptiMal Forming Solutions.

Changes in the evaluation period

- Dr. Vikram Deshpande (part-time full professor) joined the group in 2009.
- Dr. Marcel Brekelmans (associate professor) retired in 2010.
- Dr. Olaf van der Sluis (part-time assistant professor) joined the group in 2010.
- Dr. Joris Remmers (assistant professor) joined the group in 2012.
3. Research environment and embedding

3.1. National positioning

- The Mechanics of Materials group is one of the groups in MaTe, the Materials Technology cluster. It is characterised by efforts to maintain in-house synergy and cooperation in successful multidisciplinary research. MaTe comprises the Computational and Experimental Mechanics (CEM) and Biomechanics and Tissue Engineering (BMTE) chairs of the departments of Mechanical Engineering and Biomedical Engineering, respectively. CEM includes the chairs of Polymer Technology (Meijer), Structure and Rheology of Complex Fluids (Anderson), Microsystems (Den Toonder) and Mechanics of Materials (Geers), while BMTE comprises the chairs of Soft Tissue Biomechanics & Engineering (Baaijens, Bouten), Cardiovascular Mechanics (Van de Vosse) and Orthopaedic Biomechanics (Ito) (see www.mate.tue.nl and TU/e 10 Appendix 4).

- The Mechanics of Materials group plays a central role in the national Graduate School Engineering Mechanics, which provides national research co-ordination in the field of solid mechanics at the three universities of technology and in an educational programme for the PhD students (www.em.tue.nl). The group provides the scientific director (Geers) and the daily management (Van Dommelen).

- The group is one of the constituting groups of the 3TU Centre of Excellence for Multi-scale Phenomena, which is now the 3TU Research Centre on Fluid and Solid Mechanics. The 3TU research centres aim to strengthen the research activities across the three universities of technology in the Netherlands (Delft, Eindhoven, Twente), which enables them to carry out internationally outstanding and societally relevant research (http://www.3tu.nl/en/research/).

- Mechanics of Materials is one of the core groups of the Materials innovation institute (M2i). M2i is an industrially oriented institute for fundamental and applied research in the fields of structural and functional materials. M2i works in close collaboration with top-level academic and industrial partners, focusing on new materials to promote economic growth in the Dutch High-Tech Materials industry and to contribute to a more sustainable society. The Mechanics of Materials group coordinates the cluster on Multi-scale fundamentals of materials (see http://www.m2i.nl/).

- The group has a clear impact on the national research agenda in mechanics in the Netherlands: Its members participate in and contribute to the Graduate Programme Fluid & Solid Mechanics supported by NWO, the Foundation for Fundamental Research on Matter (FOM), various committees and roadmaps and national research programmes (MicroNed) etc.

- The embedding of the research programme in the Dutch industrial network is essential. This is further detailed in section 8.

3.2. International positioning

The international position of the Mechanics of Materials group is strongly related to its core disciplines in the field of Materials, Computational Mechanics and Solid Mechanics. Significant contributions are made to international organisations and societies: the European Mechanics Society (EMMC conferences; Euromech, www.euromech.org), IUTAM (IUTAM symposia; ICTAM conference), courses or summer schools at CISM (International Centre for Mechanical Sciences, Italy) and elsewhere.
Since 2012, the group has participated in the Erasmus Mundus Joint Doctorate Programme SEED (Simulation Engineering and Entrepreneurship Development). Within this programme several joint research projects (with joint PhD degrees) are carried out with the following partners: Ecole Centrale de Nantes (France), Instituto Superior Técnico (Portugal), Instituto Universitario di Studi Superiore (Italy), Swansea University (UK), Technische Universität München (Germany), Université Libre de Bruxelles (Belgium), Universitat Politècnica de Catalunya (Spain).

Several guests have been hosted in the group since 2006, among whom Marie Curie Fellows and guest researchers from other universities who worked with us for a period of at least one year: Dr. McShane, Cambridge; Dr. Duchêne, ULg Liège; Dr. Zeman, CTU Prague; Dr. Salvadori, Brescia; several knowledge workers from industry.

The Mechanics of Materials group has participated in several EU projects/networks, e.g. APROSYS, MAAXIMUS, NANOTHERM.

The group maintains sustained scientific collaborations with several recognised research teams (which have resulted in joint publications): University of Cambridge (Fleck/Deshpande); MPIE, Düsseldorf (Roters, Raabe); University of Glasgow (de Borst, Scardia); Université Libre de Bruxelles (Massart, Bouillard); MIT (Boyce, Parks); Harvard (Vlassak, Suo, Bertoldi); RWTH Aachen (Svendsen); Czech Tech. Univ. Prague (Zeman); UCL Louvain-la-Neuve (Pardoen, Delannay); ULg Liège (Duchêne, Habraken); National University of Singapore (Poh).

The Mechanics of Materials group has contributed on a regular basis to several Interuniversity Attraction Poles of the Belgian Science Policy Office, providing support for teams of excellence. The presently running IAP is INTEMATE (2012-2017) on Multiscale mechanics of interface dominated materials. Partners in this IAP are: UCL (Louvain-la-Neuve), ULg (Liège), ULB (Brussels), RUG (Ghent), KUL (Leuven), TU/e (Eindhoven), CEIT (San Sebastian, Spain), Paul Scherrer Institute (Villigen, Switzerland) and the University of Grenoble (France).

Most faculty members of the group have spent shorter and longer research periods abroad, collaborating with other research groups: Ecole des Mines de Paris (Geers); National Univ. of Singapore (Peerlings); Harvard Univ. (Hoefnagels); Cambridge Univ. (Peerlings, Van Dommelen).

### 4. Quality and scientific relevance

The citation analysis performed by CWTS for the period 2002-2012 reports a citation score (MNCS) for the Mechanics of Materials group of **2.11**, based on a representative number of papers (168). This score is among the highest given in the CWTS-report. All other indicators for our group given in Table 4 of the CWTS-report support the high quality of our publications.

A second indicator of the quality and scientific relevance of our publications is the Hirsch index of each faculty member (according to Web of Science, October 2013): Marc Geers (**30**); Ron Peerlings (**21**); Hans van Dommelen (**14**); Joris Remmers (**11**); Varvara Kouznetsova (**10**); Johan Hoefnagels (**12**).
4.1. Most significant results/highlights

Our most significant results are summarised below, spanning the three subprogrammes:

**Bridging scales in mechanics of materials**

In the past period, we have pushed the frontiers in multi-scale mechanics on the basis of novel methods to new applications. The main results in this regard are: (1) the development of a multi-scale method that enables the gradual evolution from damage to fracture in engineering materials; (2) the development of a computational multi-scale method for fibrous materials based on the quasicontinuum method; (3) The development of a multiscale model for traumatic brain injury, from which a novel anisotropic criterion resulted. This work was supported by NWO, STW and the Materials innovation institute, in the interest of Tata Steel, DAF Trucks, Royal Schelde, Philips, Polymer Vision and Océ. The group's papers on multiscale mechanics have been cited 1214 times (Web of Science, period 2002-2012, October 2013).

**Advanced plasticity models**

Considerable emphasis has been given to state-of-the-art micro-mechanically based models for plasticity in metals at small length scales. Most important achievements are the physically based models for dislocation interactions, which have shown their merits in advanced plasticity models for different length scales. These results have been adopted in microstructural analyses for the metals industry (e.g. Tata Steel) and time-dependent deformation of metallic RF-MEMS (EPCOS). The group's papers on advanced plasticity models have been cited 1314 times (Web of Science, period 2002-2012, October 2013).

**Interfacial characterisation**

The mechanics of interfaces of various types has been a key element in the group's research portfolio in the past decade. The research activities focused on delaminating interfaces (cohesive) and constraining interfaces (grain/phase boundaries). The main achievements are: (1) the development of novel large deformation cohesive zone models and an advanced miniaturised mixed-mode bending device to characterise them; (2) the development of advanced phase and grain boundary models; (3) the development of partition of unity based models for the simulation of: (i) multiple, interacting cracks, (ii) dynamic crack growth, (iii) fracture in porous materials including hydraulic fracturing, (iv) delamination growth in composite materials, (v) multiscale analysis of crack growth in heterogeneous materials. The interface models that have been developed are currently in use in industry (Philips, Tata) to predict delamination in microelectronic components and multi-phase microstructures. The group's papers published on interface mechanics have been cited 1257 times (Web of Science, period 2002-2012, October 2013).

**Ductile damage**

The group has a long tradition and vast expertise in the field of damage mechanics. The main computational achievements are the development of large deformation ductile damage models coupled to propagating cracks in 3D ductile solids. From an experimental perspective, an in-depth comparison of six theoretically equivalent ductile damage quantification methodologies has been performed, revealing serious limitations of methods proposed in the literature. This work mainly served our industrial partners DAF, Royal Schelde, Tata Steel and Philips. The group's papers on advances in ductile damage mechanics have been cited 1194 times (Web of Science, period 2002-2012, October 2013).
4.2. Key publications


4.3. Number of articles in top 10% and top 25% of publications relevant to the discipline

The citation analysis by CWTS reports that 50% of our published papers belong to the top 25% of our field. Moreover, 27% of our papers even reach the top 10%.

4.4. Most important books or chapters of books


## 5. Output

### 5.1. Number of publications

**Table 5.1. Number of publications and other research output**

<table>
<thead>
<tr>
<th>Publications</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>6 year total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Academic publications</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refereed articles</td>
<td>20 (1)</td>
<td>28 (4)</td>
<td>26 (6)</td>
<td>26 (12)</td>
<td>21 (4)</td>
<td>22 (8)</td>
<td>143 (35)</td>
</tr>
<tr>
<td>Conference papers</td>
<td>13</td>
<td>21</td>
<td>17 (6)</td>
<td>20 (4)</td>
<td>10 (3)</td>
<td>8 (4)</td>
<td>89 (17)</td>
</tr>
<tr>
<td>PhD theses</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>6</td>
<td>3</td>
<td>17</td>
</tr>
<tr>
<td>Books</td>
<td>-</td>
<td>-</td>
<td>1 (1)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1 (1)</td>
</tr>
<tr>
<td>Book Chapters</td>
<td>1</td>
<td>4 (2)</td>
<td>2 (1)</td>
<td>6 (3)</td>
<td>1</td>
<td>2 (1)</td>
<td>16 (7)</td>
</tr>
<tr>
<td>Total academic publications</td>
<td>37 (1)</td>
<td>54 (6)</td>
<td>48 (14)</td>
<td>54 (19)</td>
<td>38 (7)</td>
<td>35 (13)</td>
<td>266 (60)</td>
</tr>
<tr>
<td>Patents</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>4</td>
</tr>
<tr>
<td>Total research output*</td>
<td>38 (1)</td>
<td>55 (6)</td>
<td>49 (14)</td>
<td>55 (19)</td>
<td>38 (7)</td>
<td>35 (13)</td>
<td>270 (60)</td>
</tr>
</tbody>
</table>

Note: output numbers given in parenthesis are publications in collaboration with other research groups.

* A complete overview of all research output is provided in the Appendices (TU/e 10, Appendix 3).

### 5.2. Number of PhDs (completed and in progress)

**Table 5.2. PhD students**

<table>
<thead>
<tr>
<th>Starting year</th>
<th>Enrolment (male/female)</th>
<th>Total (male + female)</th>
<th>Graduated after (years)</th>
<th>Total</th>
<th>Not yet finished</th>
<th>Discontinued</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>s 4</td>
<td>4- s 5</td>
<td>5- s 6</td>
<td>6- s 7</td>
<td>Total graduated</td>
<td></td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>F</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2003</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2004</td>
<td>1</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2005</td>
<td>4</td>
<td>-</td>
<td>4</td>
<td>-</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>2006</td>
<td>3</td>
<td>-</td>
<td>3</td>
<td>-</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>2007</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>-</td>
<td>1 (c)</td>
<td>-</td>
</tr>
<tr>
<td>2008</td>
<td>1</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>2009</td>
<td>4</td>
<td>-</td>
<td>4</td>
<td>-</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>2010</td>
<td>4</td>
<td>-</td>
<td>4</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2011</td>
<td>3</td>
<td>2</td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2012</td>
<td>3</td>
<td>-</td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Note that the thesis defense is usually 3 months after the PhD thesis has been finalized. Graduated in 4 - 5 years therefore should be interpreted as: PhD work, writing the thesis, evaluation and approval by the committee, printing the final thesis. The special cases indicated in Table 5.2 are respectively:

(a) This PhD student suffered from a serious delay due to an accumulation of reasons: he was called for military service in his country of origin during his PhD; he has been exempted for several months due to medical reasons, and as a consequence thereof he had to finish his PhD while he was working in industry.

(b) This PhD student did not reach a PhD worthy level and was therefore forced to discontinue. Maintaining quality thresholds implies that incidentally students may fail.

(c) This PhD student has a special medical history (incurable progressive disease already at the start of the PhD), which required more time to finish the PhD project than usual.

In this period, we also successfully supervised 2 external PhD students, one working at NLR (Netherlands National Aerospace Laboratory) and one working at Corus. These students did not formally enrol, since they combined their PhDs with full-time employment elsewhere. They graduated in 2009 and 2010 respectively.

6. Resources

6.1. Overview of the various sources of financing

Table 6.1. Funding at programme level

<table>
<thead>
<tr>
<th>Funding</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>k€</td>
<td>%</td>
<td>k€</td>
<td>%</td>
<td>k€</td>
<td>%</td>
</tr>
<tr>
<td>Direct funding (1)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Public grants (2)</td>
<td>173</td>
<td>19</td>
<td>258</td>
<td>29</td>
<td>314</td>
<td>26</td>
</tr>
<tr>
<td>Industry &amp; contract research</td>
<td>746</td>
<td>81</td>
<td>626</td>
<td>71</td>
<td>879</td>
<td>74</td>
</tr>
<tr>
<td>research (3)</td>
<td>919</td>
<td>100</td>
<td>884</td>
<td>100</td>
<td>1193</td>
<td>100</td>
</tr>
<tr>
<td>Total funding</td>
<td>919</td>
<td>100</td>
<td>884</td>
<td>100</td>
<td>1193</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>1255</td>
<td>100</td>
<td>1131</td>
<td>100</td>
<td>1200</td>
<td>100</td>
</tr>
</tbody>
</table>

(1) Direct funding: PhD and post-doc projects funded directly by TU/e
(2) Public grants: NWO, STW, FOM, ERC
(3) Industry & contract research: Industry, Senter, M2i, DPI, ...

In the period 2007-2012, the average annual funding of Mechanics of Materials was 1.1 M€.
6.2. Earning capacity

To illustrate our portfolio of acquired projects and programmes through competitive funds, public and private, national and international, the group’s acquired funds are grouped in Table 6.2. A complete list of individual projects can be found in the Appendices.

Table 6.2. External funds used/acquired in the period 2007-2012

<table>
<thead>
<tr>
<th>Funding scheme</th>
<th>Sponsor</th>
<th>Most important industrial partners involved</th>
<th>External Funding k€ (entire funding period)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NWO grants</td>
<td>NWO</td>
<td>Philips, IMEC, Ford, Arai Helmet, TNO, NTCP, Holst Centre, Thales</td>
<td>518</td>
</tr>
<tr>
<td>STW projects &amp; grants</td>
<td>STW + industry</td>
<td>Philips, Tata Steel, Polymer Vision, QTIS/e, Smurfit Kappa, Océ, EPCOS, Hauzer, DAF, TNO, MSc Software, Holst Centre, In Summa Innovation, Dassault Systems Simulia, DSM Research</td>
<td>2111</td>
</tr>
<tr>
<td>FOM projects</td>
<td>FOM</td>
<td>EPCOS, NXP</td>
<td>464</td>
</tr>
<tr>
<td>M2i programme</td>
<td>M2i + industry</td>
<td>Tata Steel, Océ, NLR, TNO, Philips (Research &amp; other divisions), DAF Trucks, Royal Schelde, INPRO, Holst Centre, NXP</td>
<td>5113</td>
</tr>
<tr>
<td>NL Agency</td>
<td>Economic Affairs</td>
<td>MicroNed partners, TU Delft, EPCOS, NXP</td>
<td>405</td>
</tr>
<tr>
<td>EU projects</td>
<td>EU</td>
<td>Consortium of EU &amp; industrial partners, TNO</td>
<td>1006</td>
</tr>
<tr>
<td>Direct industrial funds</td>
<td>Industry</td>
<td>Gouda VV, Tata Steel, KCPK, DAF, EPCOS, Kappa packaging</td>
<td>998</td>
</tr>
<tr>
<td>Other (KAUST, IAP, ...)</td>
<td>Various</td>
<td>KAUST, IAP partners</td>
<td>310</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>10925</strong></td>
</tr>
</tbody>
</table>

Note: The projects shown ended or started in the period 2007-2012, and also include projects active during the full period.

An important part of the funding has been acquired through the M2i programme (46%) in collaboration with various industrial partners. This formula has been attractive for many of our industrial partners, since they realise a multiplier on their investments by funding research projects through the M2i programme. The second substantial part originates from the Science and Technology foundations (NWO, STW, FOM) for about 28%. The other funds, including direct industrial funding and EU projects, represent the remaining 26%.
6.3. Research facilities & investments

Within the Materials Technology group, see Section 3.1, members have access to nine joint laboratories. The investments in the physical laboratories (i.e. excluding computer infrastructure) in the period 2007-2012 by the groups of MaTe, amounted in total to $4.4 \text{ M}\,\text{€}$. The Mechanics of Materials group makes use of facilities within the MaTe labs (see TU/e 10 Appendix 1.2) and operates/directs the Multi-Scale Laboratory in particular. Extensive use is also made of the Computer Laboratory.

1. **Multi-Scale Laboratory**: This lab takes a rather unique position as it bridges the gap between traditional materials science and mechanical characterisation, by integrating mechanical testing with (real-time and *in situ*) microscopic observation. With a focus on developing novel (miniature) testing devices and strategies, the lab allows for quantitative *in situ* microscopic measurements during deformation and mechanical characterisation of a broad class of materials, structures, MEMS etc. on a wide range of length scales from nanometres to centimetres. The lab perfectly fits in the research group's mission, and enables a symbiosis between computational modelling and advanced experimentation across the scales. Investments 2007-2012: $1490 \text{ k}\,\text{€}$.

2. **Computer Laboratory**: This virtual laboratory comprises all the computational facilities of MaTe. Investments in the period 2007-2012 included a powerful 33 node Linux Cluster, 4 Supermicro computing nodes, 2 Supermicro 2041 systems, a disk server and in total 160 desktop PCs and 42 laptops with a total value of the order of $900 \text{ k}\,\text{€}$.

3. **Other MaTe labs**: Mechanical Testing Laboratory; Polymer Processing Laboratory; Rheology & Light Scattering Laboratory; Laser and Laser-Scattering Laboratory; MicroFab Laboratory; Laboratory for Cell and Tissue Engineering; Laboratory for Biomechanics. Detailed information on these labs is given in the Appendices (TU/e 10).

7. Academic reputation

This section highlights the main elements of academic reputation and recognition of the faculty members in Mechanics of Materials. Short CVs are provided in Appendix 2, TU/e 10.

1. **Major academic awards/recognition:**
   - Marc Geers received an ERC Advanced Grant from the European Research Council (submitted in 2012; granted in 2013).
   - Marc Geers was elected Fellow of the European Mechanics Society in 2012. “In appreciation of his outstanding contributions to the fields of solid and computational mechanics including in particular micromechanics, multiscale methods and homogenization, and damage mechanics”.
   - Johan Hoefnagels received 3 prestigious grants under the Innovational Research Incentives Scheme of the Netherlands Organisation for Scientific Research (NWO): Rubicon (2005), VENI (2007) and recently a VIDI (2013).
   - Hans van Dommelen received a prestigious VENI grant (2006) under the Innovational Research Incentives Scheme of the Netherlands Organisation for Scientific Research (NWO).
2. Members of the group actively contribute to international conferences through the scientific advisory boards, plenary, keynote and invited lectures. Invited seminars at other universities and industry are also frequently given. In the period 2007-2012:

- **Plenary lectures** (at larger conferences with parallel sessions): Marc Geers (9, among which 2 conferences with ~2000 participants: ECCM-2010, ECCOMAS-2012); Ron Peerlings (1).
- **Keynote lectures**: Marc Geers (9); Hans van Dommelen (1); Varvara Kouznetsova (1); Johan Hoefnagels (1).
- **Invited lectures** in single-session conferences: Marc Geers (12); Ron Peerlings (3); Hans van Dommelen (2); Varvara Kouznetsova (8); Johan Hoefnagels (4); Joris Remmers (3).
- **Invited lectures in mini-symposia** and workshops: Marc Geers (3); Ron Peerlings (8); Hans van Dommelen (3); Johan Hoefnagels (5); Varvara Kouznetsova (9).
- **Invited seminars** (at universities or industry): Marc Geers (21); Ron Peerlings (9); Hans van Dommelen (4); Varvara Kouznetsova (4); Johan Hoefnagels (3); Joris Remmers (4).

3. The Mechanics of Materials group largely contributes to the editorial and review processes in the scientific community. For the period 2007-2012, we highlight:

- **Editorial boards**: Marc Geers (8); Hans van Dommelen (2); Johan Hoefnagels (1); Varvara Kouznetsova (1).

4. The Mechanics of Materials group contributed significantly to the organisation of international conferences and symposia. In the period 2007-2012:

- Marc Geers: Chairman of the EUROMECH Mechanics of Materials EMMCC committee; Chairman and organisation of the IUTAM Symposium Multiscale plasticity of crystalline materials, Eindhoven, 2007; Co-chair of EUROMECH colloquium 537 on Multiscale computational homogenisation of heterogeneous structures and materials (Université Paris-Est, Marne-la-Vallée, March, 2012).
- (Co-)organisation of minisymposia at international conferences and workshops: Marc Geers (12); Ron Peerlings (3); Hans van Dommelen (1); Varvara Kouznetsova (4); Johan Hoefnagels (2); Joris Remmers (4).
- Membership of Scientific Committees or Advisory Boards:
  - Marc Geers: EMMC (chair), CFRAC, GIENS, NUMIFORM, ICMM, MMM, CMM, SPPM, NUMIFORM ECCM, ECF, THERMEC, CSMA, CMM, ICHMM, ECCOMAS.
  - Ron Peerlings: CFRAC, ICMM.
  - Hans van Dommelen: ICMM, THERMEC.
  - Joris Remmers: Composites (ECCOMAS thematic conference series).
  - Johan Hoefnagels: ICEM.

5. Members of the Mechanics of Materials group are frequently invited as a member of external PhD committees or Habilitation committees. In the period 2007-2012: Marc Geers (> 50); Ron Peerlings (7); Varvara Kouznetsova (1).
6. The Mechanics of Materials group contributes to various research assessments and scientific evaluation panels. Research assessment committees: DTU, Mech. Engng., Denmark, 2010; TNO-EPT, the Netherlands, 2012; ONERA-DMSM, France, 2013. Scientific evaluation panels for NWO, STW, FOM, Senter (The Netherlands), IWT, FWO (Belgium), CNRS, ANR (France), FCT (Portugal), ISF (Israel), DFG (Germany), FWF (Austria), ERC (EU) and several professor or tenure track committees (in the Netherlands and abroad).

7. In addition to its extensive contributions to the Graduate School Engineering Mechanics, the Mechanics of Materials group also contributes significantly to international courses at the PhD level:
   - Geers: 3 courses at the International Centre for Mechanical Sciences (CISM, Udine; 2010, 2011, 2013); summer schools at the universities of Hannover, Glasgow; GrasMech courses in Belgium.
   - Peerlings: GrasMech course, Belgium; JM Burgers Centre course, Eindhoven.
   - Kouznetsova: GrasMech course, Belgium, 2007; Summer school, Zakopane, Poland, 2009.

8. Other awards and signs of reputation/recognition:
   **Awards:**
   - *Czestochowa University of Technology Medal for excellent lectures*, 2009, Zakopane, Poland, Varvara Kouznetsova.
   - Finalist ‘Ei van Columbus’ award for innovation and sustainability, S. Boers, 2010.
   - *Perkins Prize*, best paper in Medical Engineering and Physics 2010, Van Dommelen et al.
   - *Unilever Research Prize* 2011, Jeroen van Beeck.
   - *Best paper award within the MEMS division of the SEM2011 conference*, Uncasville, CT, USA, June 13-15, 2011, Jan Neggers.
   - Multiple poster and presentation awards at conferences and symposia.

**Other relevant positions:**
- **Marc Geers**: Member of the Koninklijke Hollandsche Maatschappij der Wetenschappen; Scientific Director of the Engineering Mechanics Graduate School accredited by the KNAW; Member of the Board of Governors of the Foundation for Fundamental Research on Matter (FOM); Member of the GAMM research committee on Multiscale Material Modelling; Member of the Comité de Recrutement en Mécanique, Ecole Polytechnique, Paris (France); Programme leader of the FOM-M2i research programme on Size Dependent Material Properties; Cluster coordinator of the cluster Multiscale fundamentals of materials of the Dutch Materials innovation institute (M2i).
- **Ron Peerlings**: Member of the High-Tech Systems and Materials Printing Roadmap Team.
- **Hans van Dommelen**: General manager of the Engineering Mechanics Graduate School.
- **Johan Hoefnagels**: Dutch representative of the European Structural Integrity Society.
Finally, it is worth emphasising that also the part-time faculty members also contribute significantly to the reputation and recognition of the group:

- **Prof. Vikram Deshpande** is part-time professor (20%) in the Mechanics of Materials group. He is a full Professor at the University of Cambridge with about 160 journal publications and h-index of 35 with about 4110 citations (Web of Science). He is winner of the Philip Leverhulme Prize and Fellow of the Institute of Physics, UK. He has been an associate editor of a number of Journals including ASME Jnl. of Appl. Mech., European Jnl. of Mech. A. He is currently on the editorial boards of Jnl. Mech. Phys. Solids, Mod. Sim. Mat. Sc. Engng., Int. Jnl. Mech. Sciences and Molecular and Cellular Biomechanics. He has also guest edited a number of issues of the ASME Jnl. of Applied Mechanics, Int. Jnl. of Impact Engng. and Jnl of the Mech. of Mat. and Struc. He is regularly invited to give keynote lectures and plenary lectures at conferences: most recently he was the plenary speaker at the Dec. 2012 Asia Pacific Conference on Engineering Plasticity.

- **Dr. Olaf van der Sluis** also works part-time (20%) in the Mechanics of Materials group. His main affiliation is Philips Research, where he focuses on the mechanics of microelectronics. He actively contributes through invited and keynote lectures to a number of conferences, is a member of conference scientific committees (2) and external PhD committees (3), and performs many review duties for international journals. He was also the scientific co-ordinator of a FP7-NMP project (5.2 M€, 10 partners) and is at present an invited expert reviewer for EU Horizon NMP 2020 calls.

### 8. Societal relevance: quality, impact and valorisation

#### 8.1. Societal quality of the work

The societal quality of the work in the Mechanics of Materials group is strongly linked to its close interactions with industry. Almost all research projects originate from an industrial problem, through which at least one industrial partner is involved in the execution of the project. The resulting research topics are therefore driven by a range of societal needs, e.g. healthcare, mobility, energy and the environment. This industrial and societal backbone has been further developed in recent years through: (1) our leading role in the Materials innovation institute (M2i), in which industry collaborates with academia in research, see section 3.1; (2) a systematic participation in STW technology programmes; (3) direct research to the benefit of industry. The M2i programme originates from one of the Leading Technology Institutes in the Netherlands and is considered very successful by all its industrial partners.

The policy in relation to the economic quality, impact and valorisation of our work is rooted in the **industrial network** that has been built up over the years. Important companies and technological institutes with which the group collaborates are: Philips (microelectronic devices, System-in-Package, Solid State Lighting components, Stretchable Electronics), Tata Steel (Advanced High Strength Steels), NXP (MEMS), Océ (Paper mechanics), DAF (Thermo-mechanical fatigue), EPCOS (Metallic MEMS), NLR (Lightweight materials and structures), TNO (Thermo-shock, interconnects), HOLST (Flexible electronics). These industrial partners collaborate with us in one-to-one projects (2 projects fully funded by industry in the period under review), M2i projects (with substantial industrial co-funding) and STW projects (with partial co-funding). For all projects, industry participates actively in the regular progress meetings (M2i) or user committee meetings (STW).
Part of the success formula of our partnership with industry is the active involvement of MSc students in the various research projects. They typically translate the novel scientific developments in a particular PhD project into solutions for specific problems or challenges put forward by the industrial partners. This enables us to serve multiple industrial partners based on the results from a single PhD project.

8.2. Societal impact of the work

The research work in the Mechanics of Materials group impacts society in a number of ways:

- Since 80% of our projects are carried out in close collaboration with industry, most of our research projects clearly address particular **research questions** that are of **economic value** for the industrial partners involved.
- Our research work has led to **strategic partnerships with industry**, sometimes supported by part-time appointments in our group. The most prominent example is Philips, for which we have carried out sustained research activities over the years.
- A societal indicator for the manner in which our research programme impacts society is the **strong demand for PhD students and post-docs** who have graduated in our group. Most of them obtained positions/jobs in Dutch industry even before they defended their PhD theses. Typical companies in which our former researchers work are: Philips (Lighting, Research), Code Product Solutions, TNO, ASML, Segula Technologies, Ocê, NRG, McDermott International, W.L. Gore & Associates, Volkswagen AG, DAF Trucks.
- Several talented researchers have successfully started a **career in academia**, which spreads our impact in society further. Among our former PhD students and post-docs, 11 are now faculty members at: Université Libre de Bruxelles (Belgium), Max Planck Institute (Düsseldorf, Germany), University of Glasgow (UK), Cardiff University (UK), University of Twente (NL), Atılım University (Ankara, Turkey), National University of Singapore (Singapore), IFMA (Clermont-Ferrand, France), ENSTA ParisTech (Paris, France), Navrachana University (Vadodara, India), Loughborough University (UK).

Much of the **societal impact** is made in the **individual projects**, for which a few examples are given below:

- The Traumatic Brain Injury project contributed to the future use of numerical head models for assessment of traffic safety.
- Our research in the MAAAXIMUS programme contributed to the development of numerical techniques to design ‘first-time-right’ efficient, lighter and environmentally friendly aircraft.
- The porous fracture model is now used to analyse the fracking process to minimise the risk of environmental damage in shale gas recovery.
- Our contributions to the development of the new generation of advanced high-strength steels (Tata Steel) are mainly driven by the automotive industry, in which weight reductions are required without compromising passenger safety. This work is embedded in the roadmap towards a future clean environment, for which CO₂ emissions and fossil fuel consumption have to be reduced drastically.
- ABAQUS is the first commercial finite element code that contains an implementation of the partition of unity method. This implementation is partly based on papers from Joris Remmers.
- Several articles on the potential impact of our research on stretchable electronics have been published in a handful of Dutch newspapers/magazines.
8.3. Valorisation of the work

Societal impact is strongly related to the valorisation of our work. Our valorisation strategy focuses on:

- **Valorisation through direct knowledge transfer** to industry: project meetings, cluster meetings, symposia, workshops, industrial contacts, publication approval procedures and joint publications (e.g. with Philips) are key.
- **Valorisation through software**: our more theoretically and numerically oriented work generally leads to software that has been implemented in an industrial environment.
- **Valorisation through hardware**: several PhD projects involved the design, construction and testing of advanced testing equipment for particular industrial problems of interest.
- **Valorisation through people**: after graduating, students generally start to work for companies, bringing with them valuable knowledge, experience and capabilities.

To illustrate our valorisation efforts, we highlight the following examples:

- Implementation and application of computational methods and models to electronic textiles (Philips), paper (Océ), flexible displays (Polymer Vision), OLEDs (Philips).
- Use of micromechanical model for semicrystalline polymers by Borealis and Holst Centre.
- Transferred and implemented ductile damage and fracture codes (Tata Steel, Philips, TNO).
- Transferred cohesive zone models to Philips and Tata Steel.
- Transferred the computational homogenisation approach to Philips and TNO.
- Transferred an advanced energy-based solution control technique to Philips.
- Set-up of a dedicated bending stage for flexible foils (flexible electronics and systems-in-foil).
- Set-up for measuring interface delamination used by industry (Philips, NXP).
- Set-up of a nano-tensile tester of on-chip testing of metallic MEMS.
- Key knowledge leading to specific design guidelines for the development of future engines by DAF trucks, based on novel insights on thermo-mechanical fatigue of cast iron.

Within the framework of the M2i-programme, several dedicated valorisation projects have also been carried out. In one of these valorisation projects, we implemented an *in situ* experimental-numerical approach at Philips for characterisation and prediction of interface delamination, as recently developed in our group.

We do not have a strong policy in acquiring patents ourselves, since we believe this is the prime interest of the industrial partners with which we collaborate. Nevertheless, a series of patents resulted from the PhD thesis of Sebastiaan Boers, based on which a **spin-off company** (Optimal Forming Solutions) was set up around the start of this evaluation period. The FlexiMould technology developed was awarded an STW valorisation grant of 200 k€ and the Herman Wijffels Innovation Award (2010). A proof-of-principle Fleximould system (450 k€) was delivered to DuPont at the end of 2012 to fabricate 3D double curved Corian® Panels.

Finally, an important part or our valorisation activities consists in consulting activities for various industrial partners. Our well-equipped Multi-Scale lab is a unique facility to support our industrial partners in solving their problems.
9. Viability

The Mechanics of Materials group started in 2000 and has grown to a senior group of experts with complementary knowledge and skills. The future looks bright and at this point we have no real concerns about securing the viability of our research programme.

Resource management
In terms of resources, the recently received ERC Advanced Grant (2.5 M€) and the NWO-VIDI grant (800 k€ + 200 k€ support from Philips) give our research programme a major financial injection for the next 5 years. In parallel with these grants, we will successfully continue our M2i role, through the High-Tech Materials calls at STW and FOM. Clearly, we will continue to collaborate with our industrial partners in addressing their future research challenges.

Infrastructure
The strategy adopted in acquiring facilities and building novel instruments and set-ups in the Multi-Scale lab has proved to be very versatile. We will continue to invest in the renewal of our equipment and strengthening of the integrated approach combining microscopy with mechanical testing. We are now at the point of gaining the full benefit of the recently developed IDIC (integrated digital image correlation) method, which will make the symbiosis between the computational part and the experimental part of our work more fruitful and productive than ever before.

Innovative capacity
Within our discipline, we are facing major challenges which will keep our innovative capacities sharp. At present we are working on novel models for complex interfaces, novel methods to unravel and design mechanical metamaterials, novel methods to bridge scales combined with reduced-order approaches, and multi-physics problems. The present team of experts is optimally positioned to address these challenges.

10. SWOT analysis

Strengths (internal dimension)
• A strong team of experts operating at state-of-the-art level in the international community and with an excellent academic reputation.
• A high-tech, well-equipped lab relying on a symbiosis between microscopy with mechanical testing, integrating advanced numerical methods with full-field experimental analyses.
• A continuous focus on high-quality publications and high-impact presentations.
• A strong industrial network which is most supportive in defining scientific challenges that are at the same time industrially driven.

Weaknesses (internal dimension)
• In our group, typically MSc students graduate each year, among whom only the best qualify as PhD students. This is insufficient and we therefore still have to recruit a substantial number of talented students from elsewhere, which is a difficult task.
• Despite our healthy financial position, our financial resources are 90% national. We thereby focus mainly on the Dutch industry, even though the scientific arena in which we work is international.
Opportunities (external dimension)

- There are plenty of challenging opportunities in our research programme through which we can further increase our scientific impact. These include interfacial mechanics, IDIC-based methods, mechanics of metamaterials, damage and fracture across the length scales, rigorous scale bridging methods etc.
- In parallel with these, we see great opportunities to address the main societal needs with our research: energy (battery failure mechanics; plasma-wall interaction in fusion; high-performance composites in wind energy etc.), healthcare and high-tech systems (next-generation flexible/stretchable electronics; MEMS; NEMS), mobility (advanced high-strength and dissipative materials).
- Our research portfolio is ideally positioned to support the coming decade's developments in miniaturisation. Our combined and integrated focus on materials, mechanics, size-effects and structure-property relationships is strongly required to pursue the downscaling trend in micro-systems and microelectronics.
- We have established strong collaborations with the Fluid Mechanics community and other Graduate Schools in the Netherlands. Mutual benefits will emerge from these collaborations.

Threats (external dimension)

- Financing the acquisition and maintenance of high-tech equipment is increasingly difficult nowadays through the limitations in existing funding schemes.
- The political landscape in the Netherlands related to research funding is changing constantly. Despite this, we are reassured that our industrial network is strong enough to accommodate the unpredictable changes in national funding routes.
- Despite the ample amount of funding received in 2013, we also need to maintain the focus on other opportunities.
- Finding sufficient numbers of highly qualified PhD students for all research projects remains a challenge, which takes up significant time.

11. Strategy for the coming period

Our strategy for the coming period is driven by: new challenges; scientific quality; industrial and societal impact; international reputation; the strengths of our discipline-oriented research expertise; focus on excellent MSc and PhD students; balanced financial resources.

Among the new challenges, we are initiating new research on:

- The mechanics of materials in extreme conditions (e.g. the plasma-wall interaction in fusion)
- Advanced multi-scale methods for identifying emergent behaviour (ERC advanced grant)
- Analysis and design of metamaterials (e.g. for acoustic shielding)
- Mechanics of the next generation electronics (rollable, stretchable, printable)
- Mechanics for energy harvesting and storage (e.g. Li-ion batteries)
- Mechanics of miniaturization (applications in systems-in-package, lab-on-a-chip devices etc.)
- Damage-resistant materials and damage engineering (e.g. in photovoltaic cells)
- Advanced composites for light-weight applications
- Full symbiosis between experiments and simulations by advancing the Integrated Digital Image Correlation method (IDIC)
- Integration of mechanical testing with multiple microscopic visualization techniques
An analysis of our strategy in terms of the SWOT analysis is given below.

**Table 11.1. Strategy for the coming period**

<table>
<thead>
<tr>
<th></th>
<th><strong>Strengths</strong></th>
<th><strong>Weaknesses</strong></th>
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<tbody>
<tr>
<td><strong>Opportunities</strong></td>
<td>• Further increase our scientific impact at an international level by focusing on our scientific strengths and novel challenging research questions</td>
<td>• To attract more MSc and PhD students, new research initiatives have been taken that appeal to many students. This includes our recently initiated work on energy and fusion applications, lightweight composites and challenging metamaterials.</td>
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<td>• Exploit our strengths to the benefit of societal needs, with a particular emphasis on breakthroughs in high-tech systems and materials and energy challenges.</td>
<td>• In the new BSc curriculum, we are currently implementing an elective course package that is expected to have a significant impact on the popularity of our discipline.</td>
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<tr>
<td><strong>Threats</strong></td>
<td>• Use international reputation to recruit excellent students/postdocs from abroad.</td>
<td>• To alleviate the threat due to unpredictable changes in the national funding landscape, we aim to increase our funding from European resources from 10% to 25% in the period 2013-2018.</td>
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<td></td>
<td>• Capitalise on the industrial applications of our work and our industrial network to increase our attractiveness towards MSc and PhD students.</td>
<td>• To ensure the continuous financing of high-tech equipment in the Multi-Scale lab, we will focus on dedicated funding schemes that provide more options in this regard.</td>
</tr>
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TU/e 11: Microsystems
Microsystems is a new group that was formed in May 2013 around the recently appointed full professor Jaap den Toonder, formerly of Philips Research and part-time chair of Microfluidics Technology in the Polymer Technology and Structure and Rheology of Complex Fluids groups (see TU/e 8 and TU/e 9), dr. Yves Bellouard, formerly associate professor in the Micro- and Nano-Scale Engineering group (MNSE) directed by professor Andreas Dietzel who stepped down as a full professor in 2007 to join the Holst Centre, and dr. Regina Luttge from the MESA+ Institute at the University of Twente. Assistant professor Erik Homburg, formerly in the group MNSE, completes the scientific team. Although the group did not officially exist in its present form during the assessment period, we would like to take the opportunity of this Research Assessment to share our ambitions and views with the Committee, and ask for constructive feedback.

1. Objective(s) and research area

1.1. Vision, mission and objective(s) of the programme

Trends in microsystems science and technology are the ongoing miniaturisation, increased function integration, adaptivity to environmental conditions, interaction and merging with biological materials and low-cost manufacturing approaches. The mission of the Microsystems group is to carry out excellent scientific and technology-driven research that contributes to these developments. The concrete objectives are the investigation and development of novel microsystems design approaches and rapid, flexible out-of-cleanroom micro-manufacturing technologies. These are applied to achieve active mechanical control in micro-fluidics, to create and study cells and organs on chips, to investigate integrated microsystems that combine optics, fluidics and mechanics, and to develop advanced microsystems applications with industrial partners.

1.2. Strategy

The common theme of all the research carried out in the group is microsystems design and technology using rapid, flexible out-of-cleanroom micro-fabrication. In particular the unique combination of monolithic laser micro-fabrication with active microfluidic technology distinguishes the group from other (national and international) research groups. The main applications targeted are microfluidic systems and biomedical applications – the demands for which are expected to grow rapidly in the coming years. To develop these applications, we will collaborate with biomedical, clinical and industrial partners. An important element of the group’s strategy is to create a state-of-the-art micro-fabrication laboratory that will act as the cross-departmental micro-manufacturing centre for the TU/e as a whole. In this way, the group will fill in a gap within the TU/e Mechanical Engineering department in which a broader micro-fabrication program has not yet been prominent.
1.3. Research area and subprogrammes

Four subprogrammes have been defined with microsystems design and technology based on out-of-cleanroom fabrication as a common theme, driven by the proven expertise of the new group members.

1. Micro-manufacturing, with a focus on technologies such as laser processing and micro-manufacturing, soft lithography, on-foil processing and printing (PIs Yves Bellouard, Regina Luttge).

2. Active control in microfluidics, in which we develop and apply micro-actuators, responsive surfaces and magnetic bead actuation systems, to realize functions in microfluidic systems (PI Jaap den Toonder).

3. Cells and organs on chips, in which, in collaboration with biological, biomedical and clinical groups, we apply our microsystems to study and understand the behaviour of cells, tissues and organs. This work is aimed at learning about health and disease, with the ultimate aim of developing novel therapies and medicines. We focus on two areas: cancer and brain (PIs Regina Luttge and Jaap den Toonder).

4. Microsystems design and applications, in which we work with industrial partners to develop relevant technologies for their specific applications in medical devices, high-precision metrology, flexible electronics and advanced sensors and actuators (PIs Jaap den Toonder, Yves Bellouard and Erik Homburg).

2. Composition of the research staff at programme level

The staff members, with different backgrounds and coming from different groups, joined in May 2013 to enthusiastically start building the new Microsystems group. The group is headed by full professor Jaap den Toonder, and further consists of 2 associate professors Yves Bellouard and Regina Luttge, 1 assistant professor Erik Homburg, and 1 visiting assistant professor Rajesh Mandamparambil. Completing the team of the Microsystems group are 11 PhD students and 3 postdocs, 1 technical staff member (Willie ter Elst) and 1 administrative staff member (Liesbeth van Ballegooij). For more background about the scientific staff members, see Section 7. Table 2.1 only shows the present 2013 data (May-December 2013).

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* The group Microsystems started in May 2013, and did not yet exist in the period 2007-2013.
Table 2.1b. Composition of research staff at programme level (numbers)

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* The group Microsystems started in May 2013, and did not yet exist in the period 2007-2013.

3. Research environment and embedding

3.1. National positioning

The Microsystems group is either a member of or has strong formal ties with the following national institutions:

- **MaTe**, the Materials Technology group, aims at creating synergy and cooperation in successful multidisciplinary research, as well as shared investments and use of experimental facilities. MaTe houses the Computational and Experimental Mechanics (CEM) and Biomechanics and Tissue Engineering (BMTE) groups of the departments of Mechanical Engineering and Biomedical Engineering, respectively. CEM includes the chairs of Polymer Technology (Meijer), Structure and Rheology of Complex Fluids (Anderson), Microsystems (Den Toonder) and Mechanics of Materials (Geers), while BMTE comprises the chairs of Tissue Engineering (Baaijens), Cardiovascular Mechanics (Van de Vosse) and Bone Mechanics (Ito). (See www.mate.tue.nl).

- **ICMS**, the Institute for Complex Molecular Systems, is a young interdisciplinary initiative at the Eindhoven University of Technology (TU/e), led by prof. Bert Meijer. It brings together excellent researchers from different areas to promote both interdisciplinary and interdepartmental cross-fertilisation of ideas. The scientific agenda of ICMS consists of two lines of research: functional molecular systems and bio-inspired engineering. (See http://www.tue.nl/icms).

- **EPL**, the local research school Eindhoven Polymer Laboratories, which establish fruitful cooperation with very similar research groups at the TU/e. As well the colleagues in MaTe, EPL in particular involves professors Dick Broer (Chemical Engineering & Chemistry), Menno Prins (Applied Physics) and Carlijn Bouten (Biomedical Engineering). (See www.epl.nu).

- **JMBC**, the J.M. Burgers Centre is the Dutch research school for fluid mechanics, in which about 50 professors participate with their groups. With the combined knowledge, skills and facilities of these research groups, the JMBC offers a very stimulating, multidisciplinary environment for advanced research in fluid mechanics and for the education of talented graduate and postgraduate students (see http://www.jmburgerscentrum.nl). The centre has a special long-term cooperation with the physics group of prof. Patrick Onck (first Delft University of Technology and later University of Groningen).
• **EM**, the Graduate School on Engineering Mechanics, embraces all important research groups that are active in the field of solid mechanics at the three universities of technology in The Netherlands. The primary aims of the EM Graduate School are to provide additional education and training for PhD students of the participating institutions and to promote scientific contacts and collaboration at an early career stage of the participating researchers (see www.em.tue.nl).

• **Organs on Chips** is a novel initiative that aims at establishing a KNAW (Royal Netherlands Academy of Sciences) Institute. The initiative brings together groups from engineering, materials science and technology, physics, biology, stem cell research and medical sciences. Jaap den Toonder plays an active role in the core team of the initiative. (See http://www.organonochips.nl/en/).

• **University of Twente (UT) MESA+ Institute for Nanotechnology** is one of the world's largest nanotechnology research institutes and is the largest research institute in this field in the Netherlands. A total of 525 researchers work together on leading-edge research at the highest level. Amongst other co-financed national project activities specifically our research into organs-on-chips has a base in the MESA+ Institute funded by Regina Luttge's ERC starting grant, which has a focus on brain-on-a-chip. In this activity she co-supervises two PhD students with prof. Han Gardeniers (Mesoscale Chemical Systems, UT) and prof. Michel van Putten (Clinical Neurophysiology, UT).

• **VU University Medical Center Amsterdam (VUmc)** is a leading academic medical centre carrying out research that is dedicated to five focal areas: cancer & immunology, neurosciences, cardiovascular disease, public health, primary care & long-term care and movement sciences. Regina Luttge currently works closely together with the ERC Advanced Grant winner 2013 prof. Yvette van Kooyk (Molecular Cell Biology and Immunology) on the development of novel vaccination strategies based on microneedle array technology.

### 3.2. International positioning

The Microsystems group collaborates internationally with the following partners (we present the main connections of each senior scientist constituting the new group).

**Jaap den Toonder**

- **Wyss Institute at Harvard University**: Jaap den Toonder was visiting scientist at the institute and gave an invited Wyss Institute lecture (August 2010). Since then this cooperation has continued through common research themes that include organs on chips, responsive surfaces and microfluidic technology.

- **Zhejiang University at Hangzhou, China**: Through an exchange of PhD and MSc students leading to joint publications, we collaborate with prof. Xun Fang on microfluidics for cell diagnostics. This collaboration was initiated in 2006 within the ‘Brainbridge’ research programme defined between Zhejiang University, TU/e and Philips Research.

**Yves Bellouard**

- As part of the research on femtosecond laser processing, Yves Bellouard has strong links with the **University of Southampton** (ORC, Peter Kazansky's group) in the UK, **Colorado School of Mines** in the USA (Jeff Squier's group), **Ecole Polytechnique Fédérale de Lausanne** (EPFL, prof. M.-O. Hongler), **University of Tokushima** (prof S. Matsuo) and **Tokyo Institute of Technology** (prof. T. Yano) both in Japan – and recently, **Swinburne Institute of Technology** (prof. S. Juodkazis) in Australia. These collaborations have led to numerous joint publications, shared projects and students exchanges.
• Yves Bellouard was visiting scientist at the University of Tokushima in Japan (2013) and Ecole Polytechnique Fédérale de Lausanne (EPFL) in 2011. Two guest researchers from Japan, prof. S. Matsuo (Univ. of Tokushima) and dr. T. Kishi (Tokyo Inst. Of Technology) visited our group in 2012 for sabbaticals of two and three months respectively to work on laser processing. One guest researcher, dr. Zdenek Hurak from the Czech University of Technology (CTU), spent five months with us on a sabbatical working on microrobotics topic.

Regina Luttge
• University of the Witwatersrand, Johannesburg: The Wits Advanced Drug Delivery Platform (WADDP), under the directorship of prof. Viness Pillay, entered into the collaboration with MyLife Technologies B.V. and the University of Twente in February 2012, facilitated through the National Medical Devices Innovation Platform, an initiative of the South African Medical Research Council Innovation Center and the Dutch Ministry of Economic Affairs. The nature of the collaboration entails the co-development of a safe, minimally invasive, and cost-effective Micro-Needle Electro-Active Device as a new treatment modality for managing chronic pain.
• National Institute of Standards and Technology (NIST, Gaithersburg, USA): Regina Luttge has ongoing contacts with dr. J. Alexander Liddle (Group Leader Nanofabrication Research Group, Center for Nanoscale Science and Technology) at NIST. Based on securing travel funding for an internship NIST will be able to host suitable candidates (either working towards their PhD or postdocs) to allow them to acquire additional insight into research and development of microsystems technology and design including state-of-the are quality assessment techniques.
• Imperial College at University of London: Regina Luttge received her PhD in Microsystems Technology from the Electronics and Electrical Engineering Department in the Optical and Semiconductor Devices group under supervisor of prof. Andrew Holmes. This contact continues to be a first entry point to explore opportunities for collaborative European research funding in our shared areas of interest dedicated to microsystems technology as well as nanofabrication for bio-electronic devices.

4. Quality and scientific relevance

The quality and scientific relevance of the research carried out by the group's members is evidenced by the excellent citation scores they receive, even though their ‘scientific age’ is relatively young. Jaap den Toonder’s h-index is 22 (WoS), with the top publication cited over 150 times. Yves Bellouard’s h-index is 15, with the top publication cited 153 times. Regina Luttge has an h-index of 15, with the top publication cited over 100 times. Both Yves Bellouard and Regina Luttge received an ERC Starting Grant in 2012 and 2011 respectively, which is a clear recognition of their personal scientific quality and ideas. The group's members have been pioneering a number of scientific and technological developments, as described below.

4.1. Most significant results/highlights

(We present one highlight of each senior scientist constituting the new group).

Jaap den Toonder
The pioneering and crucial contributions to the development of the field of “artificial cilia”: this field was initiated by Jaap den Toonder in 2007, and since then the topic has been picked up by many groups worldwide. Artificial cilia are innovative polymer-based microactuators that are
inspired by biological cilia. The artificial cilia, integrated in microfluidic systems, can be actuated magnetically, electrostatically or by light, and can create fluid flows, transport particles, or act as sensors. Jaap den Toonder has published a number of serial papers on this topic, initiated and directed a European project on artificial cilia, and he has summarised the state-of-the-art in an edited book. ‘Artificial cilia’ forms an ongoing research topic in the group, within the ‘Active control in microfluidics’ subprogramme.

**Yves Bellouard**
Innovative laser microfabrication, in particular using non-linear laser-matter interaction to tailor material properties to introduce system functionalities selectively and locally, is driven by Yves Bellouard. Controlled laser modification of dielectrics and in particular fused silica, combined with HF etching, makes it possible to create, in a single fabrication step and in a monolithic material, combinations of photonic, mechanical, and fluidic functionalities. Yves Bellouard directed a European project on this unique topic, entitled “Femtoprint”, which received the EuronanoForum 2013 Best Project Finalist Award. The topic continues to be one of the central subjects in the group’s ‘Micro-manufacturing technologies’ subprogramme.

**Regina Luttge**
Regina Luttge’s research activities on organs on chips combine the principles of microfluidics, tissue engineering and neuroelectrophysiology into one brain-on-a-chip platform technology to answer clinical questions of neurodynamic diseases such as epilepsy. In this research, micro-total analysis systems technology combined with microchip capillary electrophoresis, potentially coupled to mass spectrometry, is developed in order to correlate electrophysiology with neurochemistry. This subject is an important topic in the group within the ‘Cells and Organs on a Chip’ Subprogramme.

### 4.2. Key publications


4.3. Number of articles in top 10% and top 25% of publications relevant to the discipline

For the Microsystems programme, the CWTS citation analysis is based on the analysis of the publications by the scientists forming the group in May 2013 (Jaap den Toonder, Yves Bellouard, Erik Homburg). The analysis shows that the impact of the ‘Mechanics’ papers published by TU/e in this field is quite high, above world average, with a value for MNCS of 1.55 (Average normalized number of citations of the publications, self-citations not included). For the TU/e 11 Microsystems programme we are above this value with a MNCS of 1.62. The total number of citations is 729, while the MCS (average number of citations of the publications, self-citations not included) equals 11.57 which is a clear recognition that the work is picked up by the international peer group. More than half of all publications – to be precise 54% – are in the top 25% of all publications, while 18% of the publications are in the top 10%. The percentage of inter-institutional collaborative publications is quite high at 76%, indicating the multidisciplinary nature of the work and showing its impact in other fields.

4.4. Most important books or chapters of books, insofar as applicable


5. Output

5.1. Number of publications

We summarise the publications by the senior scientists Jaap den Toonder, Yves Bellouard, Regina Luttge, and Erik Homburg, produced in their own environment in the period 2007-2012. The list below shows the past performance of the individual scientists who since May 2013 constitute the new group. The detailed lists of publications can be found in the Appendix.
Table 5.1. Number of academic publications and other research output

<table>
<thead>
<tr>
<th>Publications</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>6 year total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Academic publications</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refereed articles</td>
<td>14 (12)</td>
<td>10 (6)</td>
<td>7 (6)</td>
<td>11 (6)</td>
<td>15 (12)</td>
<td>19 (12)</td>
<td>76 (54)*</td>
</tr>
<tr>
<td>Conference papers</td>
<td>pm</td>
<td>pm</td>
<td>pm</td>
<td>pm</td>
<td>pm</td>
<td>pm</td>
<td>pm</td>
</tr>
<tr>
<td>PhD theses</td>
<td>-</td>
<td>1 (1)</td>
<td>2 (2)</td>
<td>-</td>
<td>1 (1)</td>
<td>2 (2)</td>
<td>6 (6)*</td>
</tr>
<tr>
<td>Book</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>1 (1)</td>
<td>-</td>
<td>2 (1)*</td>
</tr>
<tr>
<td>Book Chapters</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>1</td>
<td>3*</td>
</tr>
<tr>
<td>Total academic</td>
<td>14 (12)</td>
<td>12 (7)</td>
<td>9 (8)</td>
<td>14 (6)</td>
<td>17 (14)</td>
<td>21 (14)</td>
<td>87 (61)*</td>
</tr>
<tr>
<td>publications</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Patents</td>
<td>8</td>
<td>5</td>
<td>5</td>
<td>3</td>
<td>-</td>
<td>1</td>
<td>22**</td>
</tr>
<tr>
<td>Total research output</td>
<td>22 (12)</td>
<td>17 (7)</td>
<td>14 (8)</td>
<td>17 (6)</td>
<td>17 (14)</td>
<td>22 (14)</td>
<td>109 (61)</td>
</tr>
</tbody>
</table>

pm: pro memoria

* All publications listed have been published by the senior scientists in their previous working environment.
** 16 of the 22 patents have been published by Jaap den Toonder in his previous Philips Research affiliation.
(#) numbers between brackets represent papers in collaboration with other groups.

5.2. Number of PhDs (completed and in progress)

Not applicable since this group is new. For results and performance of Jaap den Toonder in his previous part-time professorship, see TU/e 8 and TU/e 9.

6. Resources

6.1. Overview of the various sources of funding

Not applicable since this group is new. For results and past performance of the senior scientists forming the new group, see the next section.

6.2. Earning capacity

The senior scientists in the Microsystems group have an excellent track record in acquiring projects and programmes through competitive funds obtained in their previous working environments. Jaap den Toonder, in his role as (20%) part-time professor in the TU/e 8: Polymer Technology group (see the corresponding chapter), has (since 2004, as a main applicant) been responsible for obtaining 5.9 M€ of funding from the European Union and national funding sources (STW, DPI, CTMM, NWO, KNAW), with the participation and financial support of industry (Philips, DSM, Holst Centre, SolarExcel, Micronit, TNO, LiquidsResearch). This is an average yearly funding of 593 k€. Yves Bellouard initiated and coordinated two European projects (GOLEM FP6, 2.85 M€ and Femtoprint FP7, 2.45 M€). Femtoprint has been labelled as a ‘success story’ by the European Commission. Since 2006, the funding obtained by Yves Bellouard as main applicant from the European Union (including an ERC Starting Grant), TU/e and industry amounts to 7.1 M€. This is an average yearly funding of 1 M€. Regina Luttge has been responsible as
a main applicant (since 2007) for obtaining 2.2 M€ of funding from the European Union and national funding sources (STW, NWO). This is an average yearly funding of 320 k€.

The following table summarises the funding for projects running in the period 2007-2012 of each of the senior scientists as obtained in their own environment. This shows the past performance of the individual scientists, who since May 2013 constitute the new group.

**Table 6.2. External funds used/acquired in the period 2007-2012**

<table>
<thead>
<tr>
<th>Project name</th>
<th>Main Applicant/Co-Applicant</th>
<th>Start</th>
<th>End</th>
<th>Sponsor</th>
<th>Total project funding (k€)</th>
<th>Funding for PI (k€)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Jaap den Toonder</strong> (obtained in the groups Polymer Technology, and Structure and Rheology of Complex Fluids, see TU/e 8 and TU/e 9)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Microindentation</td>
<td>MA</td>
<td>01/2004</td>
<td>01/2008</td>
<td>NWO/CW</td>
<td>205</td>
<td>205</td>
</tr>
<tr>
<td>MuWear</td>
<td>CA</td>
<td>06/2005</td>
<td>06/2009</td>
<td>DPI</td>
<td>220</td>
<td>220</td>
</tr>
<tr>
<td>PolyMEMS</td>
<td>MA</td>
<td>12/2005</td>
<td>12/2009</td>
<td>DPI</td>
<td>1200</td>
<td>396</td>
</tr>
<tr>
<td>Brainbridge</td>
<td>MA</td>
<td>10/2008</td>
<td>10/2009</td>
<td>Industry</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Circulating Cells</td>
<td>CA</td>
<td>09/2009</td>
<td>09/2013</td>
<td>CTMM</td>
<td>470</td>
<td>470</td>
</tr>
<tr>
<td>Artflag</td>
<td>MA</td>
<td>03/2009</td>
<td>03/2013</td>
<td>DPI</td>
<td>492</td>
<td>265</td>
</tr>
<tr>
<td>Magneto-active mixing</td>
<td>CA</td>
<td>10/2009</td>
<td>10/2013</td>
<td>STW</td>
<td>633</td>
<td>228</td>
</tr>
<tr>
<td>Hairy</td>
<td>MA</td>
<td>08/2011</td>
<td>08/2015</td>
<td>DPI</td>
<td>240</td>
<td>240</td>
</tr>
<tr>
<td>Organs on Chips</td>
<td>MA</td>
<td>09/2012</td>
<td>09/2013</td>
<td>KNAW</td>
<td>34</td>
<td>34</td>
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<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7255</td>
<td>3537</td>
</tr>
<tr>
<td><strong>Total, as Main Applicant</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5932</td>
<td>2620</td>
</tr>
<tr>
<td><strong>Yves Bellouard</strong> (obtained in the group Nano- and MicroScale Engineering, MNSE)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GOLEM</td>
<td>MA</td>
<td>09/2006</td>
<td>09/2009</td>
<td>FP6/NMP/EC</td>
<td>2850</td>
<td>456</td>
</tr>
<tr>
<td>FEMTODRILL</td>
<td>MA</td>
<td>01/2010</td>
<td>12/2013</td>
<td>Industry</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>FEMTOPRINT</td>
<td>MA</td>
<td>05/2010</td>
<td>05/2013</td>
<td>FP7/NMP/EC</td>
<td>2450</td>
<td>490</td>
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<tr>
<td>Excellentie Fund</td>
<td>MA</td>
<td>12/2010</td>
<td>12/2014</td>
<td>TU/e</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>NANOFILTERS</td>
<td>MA</td>
<td>01/2012</td>
<td>12/2013</td>
<td>Industry</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>GALATEA</td>
<td>MA</td>
<td>12/2012</td>
<td>12/2017</td>
<td>EU/ERC</td>
<td>1730</td>
<td>1730</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7115</td>
<td>2761</td>
</tr>
<tr>
<td><strong>Total, as Main Applicant</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7115</td>
<td>2761</td>
</tr>
</tbody>
</table>
6.3. Research facilities & investments

As part of the Materials Technology group MaTe (see Section 3.1), the group has access to the nine joint laboratories of MaTe. The investments by the groups of MaTe in the physical laboratories in the period 2007-2012 amounted to 4.4 M€. To avoid duplication: a description of these facilities is given in Section 6.3 of the Chapter TU/e 8: Polymer Technology.

As stated in Section 1.2, the strategy of the group is to establish a state-of-the-art microfab lab that will be part of the MaTe infrastructure, but that will also act as the cross-departmental micro-manufacturing centre for the TU/e as a whole. The plans for the lab are currently in a final stage (December 2013). The lab will encompass a controlled-environment laboratory for micro-fabrication, a laser micro-manufacturing lab, a microfluidics testing lab, and a basic cell bio-lab. This facility will not only be central to the group’s research, it will also meet the need for rapid and flexible manufacturing of microsystems prototypes for other research carried out at TU/e, and is complementary to the existing advanced cleanroom facility Nanolab@TU/e. Groups from the departments of Mechanical Engineering, Biomechanical Engineering, Applied Physics and Chemical Engineering and Chemistry are therefore actively supporting this initiative. ICMS (see Section 3.1) has agreed to contribute by funding a new lab technician for three years.

7. Academic reputation

Jaap den Toonder (1968) was appointed full professor in May 2013. Before that he had a position as Chief Technologist at Philips Research, which he combined since 2004 with a parttime (20%) professorship in the Polymer Technology group of Han Meijer at TU/e (see the description in the Section TU/e 9: Polymer Technology). He has given 23 invited and keynote lectures at international conferences worldwide in the period 2007-2012. He is a member of the Editorial Board of Lab on a Chip, and is a reviewer for numerous journals. He has organised and co-chaired two international conferences (Circulating Tumor Cells and Organs on Chips), and has participated in the program committee of three other international conference series (microTAS, ISPS-ASME, EuroSimE). He has co-authored over 80 peer-reviewed scientific papers (h-index 22, WoS, December 2013), and over 40 patent applications.
Yves Bellouard (1971) is associate professor of micro- and nano-scale engineering. He specialises in system design at the micro-scale and non-linear laser-matter interaction, in particular to tailor material properties to introduce system functionalities selectively and locally. He received an ERC Starting Grant in 2012 for this work. In addition, he received the Omega Scientific Prize (2001) and a JSPS fellowship (2013). He is or has been coordinator of several European projects, one of which received the EuroNanoForum Best Project Finalist Award (2013) and was labelled as ‘success story’ by the European Commission. He has published over 35 peer-reviewed scientific papers (h-index 15, WoS, December 2013), one monograph, 5 book chapters, and 5 patents (three of them transferred and licensed to industry). He has been Editor-in-Chief of the International Journal of Optomechatronics (Taylor & Francis) since 2011. He has organised and co-chaired one conference (Workshop on Ultrafast Laser modifications of Materials in Cargèse 2013), was technical programme committee chair of two editions of the ISOT Conference (Paris 2012, Hong-Kong 2011). He is currently sub-committee programme chair for the Conference on Laser and Electro-Optics (CLEO, Optical Society of America), one of the key reference conferences in the field of lasers and electro-optics. He has given 10 invited lectures at major conferences in the field of ultrafast lasers, in particular for the CLEO conference series.

Regina Luttge (1968) is associate professor of micro & nanoengineering, with a focus on nanoengineering for medicine and biology. In 2011 she received an ERC Starting Grant for her work on ‘brain on a chip’. Earlier, she gained personal grants and valorisation grants that resulted in a spin-off company. She has given 14 invited and keynote lectures at international conferences. She has been involved in the organisation or scientific committees of 4 international conferences (8th World Micromachining Summit, 1st Lab-in-a-Cell Workshop, International Conference on Micro- and Nano Engineering, ICMNT) and participates in the programme committee of two long-term international conferences in her field of expertise (Micro- and Nano-Engineering (MNE), and Electron, Ion, Photon Beam Technology and Nanofabrication (EIPBN)). She has published 40 peer-reviewed scientific papers (h-index 15, WoS, December 2013) and 1 patent.

Erik Homburg (1955) has been assistant professor in the department of Mechanical Engineering since 2000, and has broad industrial experience in the design and realisation of miniaturised systems from a working history at Philips. His focus is on educational tasks, and in this role he forms the important link between the scientific research carried out in the group, and the educational programme of the department of Mechanical Engineering.

Rajesh Mandamparambil (1977) has been visiting assistant professor (20%) in the department of Mechanical Engineering since 2012. His main position is at TNO/Holst Centre, and through this position he forms the important bridge between the group and industry. His expertise is in the area of laser manufacturing and optofluidics.

8. Societal relevance: quality, impact and valorisation

8.1. Societal quality of the work

Our scientific and technological work is driven by present and future needs in (industrial) manufacturing, and therefore starts from an application perspective from which we derive scientific and technological challenges to be tackled. This means that we are and will remain in a constant dialogue with industry to define and carry out our research programme, thereby ensuring that it stays relevant to industrial (and consequently societal) development. We will
therefore continue, and strengthen, our links with industrial partners such as Philips, TNO-Holst Centre, DSM, Xpress and others. Direct relationships are in place: Jaap den Toonder is part-time (10%) scientific advisor to Philips Research on both scientific and strategic matters. Regina Luttge spends 10% of her time on the activities of the University of Twente spin-off MyLife Technologies. Rajesh Mandapparambil is employed by TNO/Holst Centre, and through this has an extensive network across different industries.

8.2. Societal impact of the work

The group’s natural contribution to society is through our postdocs and PhD students, who get positions in industry and academia. Our work in subprogram (3) Cells and organs on a chip (see Section 1.3), aims at learning about health and disease, and ultimately at developing novel therapies and medicines, which has a potentially large and direct societal impact. We have medical groups (Erasmus Medical Center, Leiden University Medical Center) as partners to provide technological solutions to current grand challenges in healthcare (caused by demographic and societal changes over the past decades). This may contribute to revolutionising healthcare protocols and regulations. The close collaboration with medical and clinical groups ensures that (1) we work on relevant topics, and (2) there is a direct path to implementation. As part of the activities related to laser processing for integrated microsystems, we investigate the use of this technology for developing labs-on-a-chip capable of rapid monitoring of water quality, in particular by assessing the algal load.

8.3. Valorisation of the work

Valorisation of the work is achieved:

• by transfer of knowledge and IP (via patents) in the joint projects and regular contacts with industry;
• directly through the scientific advisorship of Jaap den Toonder to Philips Research;
• by publications in journals and conferences, directed both towards the scientific community and the general public. Jaap den Toonder frequently gives lectures to the general public. One good example is the recent Public Lecture of the Royal Society of Chemistry (London, September 2013).
• by the implementation of technological solutions in clinical settings, through our biomedical and clinical partners (see Section 8.2) – as an example a microfluidic chip for studying brain metastasis has been transferred to Erasmus Medical Center for clinical studies;
• through spin-offs: the company Xpress is an example of a direct spin-off from former activities at TU/e, while MyLife Technologies is a spin-off from Luttge’s previous research activities at the University of Twente. She still contributes directly to the scientific and technological developments of the company as Chief Scientific Officer and shareholder.
• through participation in the Innovation Trade-Show opened to the public and sponsored and organised by the European Commission (Brussels Innovation Conference 2010, Vilnius 2013) to promote the Femtoprint project.
9. Viability

The basis of the new Microsystems group is the people, who have proven excellence in the different backgrounds required to reach the defined goals. The mix of experience and expertise provides a strong point of departure to implement the plans and strategy laid out in Section 1: scientific experience (Yves Bellouard, Regina Luttge, Jaap den Toonder) together with an industrial research background (Jaap den Toonder, Erik Homburg, Rajesh Mandamparambil), and complementary expertise (by proven track records) in micro-manufacturing and microsystems design (Yves Bellouard, Regina Luttge), microfluidic technology (Jaap den Toonder), biomedical applications (Regina Luttge, Jaap den Toonder) and microsystems applications (Jaap den Toonder, Erik Homburg, Rajesh Mandamparambil), all combine in naturally mapping on the subprogrammes described in Section 1.3.

‘Micro-manufacturing’ strongly complements existing programmes in the department of Mechanical Engineering at TU/e. These programmes are usually more oriented towards (numerical and experimental) analysis and understanding rather than to synthesis and manufacturing. This also meets the need for rapid and flexible manufacturing of microsystems prototypes for other research carried out at TU/e.

The currently available infrastructure, apart from the laser micro-fabrication facilities, will be extended to carry out the research programme described. As described in Section 6.3, a state-of-the-art microfabrication laboratory will be established as part of the strategy of the group. Financial resources for this investment are available within the department of Mechanical Engineering and TU/e. An additional lab technician will be appointed next to lab manager Willie van der Elst, to support the activities in the laboratory.

Finally, the choices made with respect to the focus of the research (microsystems design and technology based on out-of-cleanroom manufacturing), as well as the choice of applications (microfluidics and biomedical applications) are strongly aligned with the needs of industry, as well as other scientific areas. This is reflected for example in the descriptions of national and international funding themes such as the Dutch Topsectors and the European Horizon 2020 programme. The outlook for gaining continued and increasing funding for the group’s research is therefore positive.

10. SWOT-analysis

Strengths
- The combination of expertise in micro-fabrication on the one hand, and the knowledge of and network in bio(medical) applications on the other, gives the group a unique position with the ability to develop technology for relevant biomedical applications.
- Our focus on out-of-cleanroom, rapid, and flexible fabrication, with a recognised position in monolithic laser micro-fabrication and in active microfluidics (see Section 4.1), distinguishes the group from other (national and international) research groups.
- Our links with industry and application partners such as clinical groups are a vital success factor.
- Most important, however, is the specialisation and knowledge, and particularly the enthusiasm of all participants in this new group, to set new goals in this challenging research area and work towards achieving them.
Weaknesses
- The currently available infrastructure, apart from the laser micro-fabrication facilities, should be extended to carry out the research programme described. Establishing a state-of-the-art micro-fabrication laboratory therefore has high priority.

Opportunities
- Developments in microsystems are driven by ongoing miniaturisation, increased function integration, adaptivity to environmental conditions, interaction and merging with biological materials, and low-cost manufacturing approaches.
- Economical, demographic, and societal developments in the past decades, both regional and local, demand new approaches to healthcare (diagnostics, treatments and therapy and drug development). In particular our subprogramme (3) Cells and organs on a chip, is driven by these needs. This offers opportunities to carry out relevant scientific work and to team up with biomedical and clinical groups.
- The group fills a gap within the department of Mechanical Engineering, as well as within the TU/e as a whole, in which there is a need for scientific and technological research into the manufacturing of microsystems prototypes.
- Collaboration with other groups in Mechanical Engineering but also with groups from different disciplines at other departments and universities, will make it possible to extend our activities and reach the set goals.

Threats
- Establishing and maintaining a scientific research group requires long-term, consistent and well-balanced efforts. These are made possible only by long-term and repeated funding for a number of "PhD periods" in a row. We are aware of the increasingly shorter-term horizons in industry, which make it more difficult to receive long term (funding) commitments from industry. This negative trend is further strengthened by the political trend to shift responsibility for science funding to industry. To mitigate this threat, we will continue investing in direct contacts and dialogues with industry, to reach long-term agreements and secure long-term funding.
- It is increasingly difficult to find good PhD students for the projects we get funded. Our new programme that combines scientific depth with practical and societal relevance is aimed at attracting top-level candidates.

11. Strategy for the coming period

The general strategy, in other words the set of actions to lead to the achievement of the group's mission, has already been described in Section 1.2. Particular strategic actions that follow from the SWOT analysis of in Section 10 are listed in Table 11.1.
### Table 11.1. Strategy for the coming period

<table>
<thead>
<tr>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Opportunities</strong></td>
<td></td>
</tr>
<tr>
<td>• Building on the scientific quality of the group members, the group will focus on microsystems design and fabrication based on novel out-of-cleanroom micro-fabrication approaches.</td>
<td>• Investments to establish a state-of-the-art micro-fabrication laboratory.</td>
</tr>
<tr>
<td>• In collaboration with biomedical and clinical groups, we will develop technology that enables new approaches to medical challenges.</td>
<td></td>
</tr>
<tr>
<td><strong>Threats</strong></td>
<td></td>
</tr>
<tr>
<td>• Our new programme that combines scientific depth with practical and societal relevance is aimed at attracting top level PhD students.</td>
<td>• Continued investment in direct contacts and dialogues with industry to reach long-term agreements and secure long-term funding.</td>
</tr>
</tbody>
</table>
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