Theme: Durable & Sustainable Structural Materials[1]

Initial themes within this research area as defined by the Working Group were:

1) Hybrid materials (durable, light weight, recyclable)
2) Protective coatings
3) Adhesion improvement at interfaces of hybrid materials
4) Recyclable thermosets
5) High-performing structural materials with multifunctionality
6) Sustainable processes for manufacturing of materials and products

As some of these themes overlap or are synergetic it was decided to **cluster** as follows:

2.1 Hybrid structural materials
2.2 High performance structural materials with multi-functionality
2.3 Sustainable processes (for manufacturing, processing and recycling of structural materials)

The 2011 workgroup review confirmed the importance and relevance of these 3 clusters for organisations in Flanders, while no additional clusters were added. It was clear from the discussions that durable and sustainable structural materials still needs a lot of further R&D and additional program and project ideas are easily found within these science themes and clusters. This was also confirmed by the feedback from the attendants to the SIM colloquium on 23 May 2011 where the conclusions from the SIM workgroups were presented.

The proposed scientific themes within this research area match the interest and specialisation of material related industry and research organisations in Flanders and allow Flanders to specialise within strategic important themes for the future.
Flanders has top-level capabilities related to structural materials:

- **K.U.Leuven**, **Ghent University** and **V.U.Brussels** have extensive experience in metals, polymers, composites, adhesion systems, fibre reinforcement, nano-particles, modelling.
- **University of Antwerp** and the **University of Hasselt** have significant characterization and modelling knowhow.
- **VITO** is active in the field of surface technology and recycling
- **SIRRIS, FLAMAC,** a.o. specialize in composites, manufacturing and surface treatment techniques
- **Flanders Drive** has a strong expertise in testing material components for automotive applications

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[1] Durable & Sustainable Structural Materials is one of the 3 present SIM Research areas:
- Tailored Nanomaterials
- Materials for Energy and Light
- Durable & Sustainable structural materials

The 2011 revision discussion on these SIM Research areas indicated a possible additional SIM Emerging Research Area:
- Renewable Materials

However for the time being, the topics on renewable materials within Durable & Sustainable structural materials have been retained in this update revision of the original document.

- **Flanders' Plasticvision** is the "competence cluster" supporting the Flanders-based plastics/rubber converting industry , towards more & better Innovation.
- **BIL** is specialized in welding technology for metals
- Industrial R&D centres in Flanders like **CRM Ghent, OCAS, Bekaert Technology Center,** etc. have significant expertise and resources in the area of structural materials (both surface and bulk)
- LMS is delivering mission critical software and advanced engineering services to the advanced high-tech mechanical and mechatronic industries.
- Etc.

Achieving significant progress and breakthroughs in **durability and sustainability of high-performance structural materials** is clearly of high relevance for:

- ***Transport*** (automotive, rail, ship, but also aerospace)
- ***Construction*** (residential, infrastructure)
- ***Energy and Power Systems*** (wind energy a.o.)
- ***Consumer Products***
- ***Machine Building***
- ***...***

The need for hybrid structural materials and the research themes proposed in this document is also confirmed as one of the key elements in the European multiannual roadmaps for the 3 PPP's (Public Private Partnerships): Green Cars, Energy Efficient Buildings and Factories of the future. The proposed research area therefore fits perfectly within this European strategic vision. For example the multi-annual roadmap on Energy efficient buildings states:

Europe is facing an increasing scarcity of raw material supply in various fields. In order to reduce the energy and carbon burden linked to building materials and components, Europe will see an increasing pressure on their sustainable performance, i.e. longer service life, multi-functionality as a primary step to create added-value of material use, more efficient use of primary raw materials, an increase in recycling as well as an increasing use of renewables. In addition, the application of lightweight materials and systems will be inevitable to reduce the environmental impact of the construction process. Particularly with respect to the last two issues, the scarcity of resources will be a restraining factor. As energy demand for the operational phase of the building life cycle is decreasing and/ or for a larger part covered by renewable energy, the embodied energy of building materials and components will become an increasingly important aspect to take into account. The present ratio between embodied energy and energy during the use phase of a building is about 20/80.

Also the European Green Cars Initiative Multi-annual Roadmap[2] is clear on this:

A lightweight truck have many advantages like increased payload capacity (increasing energy efficiency) i.e. less fuel consumption (especially for start-stop situations), reduced road wear (per ton transported goods). However, this is a challenge that needs to find an optimum balance between many demands and requirements – safety is not to be neglected; production cost, too. As a HGV is most likely to have a life of several 100 thousands of km, durability is a key element.
For a truck cab, new light weight designs and materials have many possibilities; improving aerodynamics for the hood, if present, roof and air deflectors. The weight reduced cab will also be optimised with regard to manufacturability, structural integration, durability and safety. Lessons

[2] http://www.green-cars-initiative.eu/public/documents/EGCI%20Roadmap.pdf/view

and synergies from the passenger car industry are increasing and transferred not only to trucks, but also to busses and other heavy equipment. Similar approaches will be adopted for the chassis and trailer structures.
Being a place of work, the importance of the interior design of the vehicle must not be overlooked. New solutions for thermal, acoustic and vibration comfort must be sought by improving in the design of the cab interior and its sub-systems including the seat, controls and HVAC system, and through the development of multifunctional materials. The use of advanced materials and innovative technologies could also lead to weight reduction in addition to improving the real and perceived comfort which will also lead to improved safety through enhanced driver performance.
In this context, the development of materials as an enabler must not be underestimated. The development of nanotechnologies will have a significant impact on future manufacturing and designing of components – the nano era will make possible to tailor material properties for specific applications; high stiffness and high damping in the same material, for example. Nano reinforced (thermo-) plastic matrices will also make it possible for more rational manufacturing processes. When considering novel materials, one must maintain a rational view on the benefit, from a Life Cycle Assessment perspective, or cradle-to-cradle analysis. This means that the introduction of new materials, for instance compared to steel, the life of the product must be analysed – from manufacturing, via usage, to recycling and "rebirth". Key here is to find the most effective solution for increased transport efficiency and lowered energy consumption, both laden and empty.

Also the Horizon2020 (FP8) draft document – Smart, Green and Integrated Transport indicates the importance of research and innovation on low weight materials and structures tp contribute to the European transport polivy target of achieving 60% reduction in CO2 by 2050. Solutions should reduce dependence on fossil fuels, drastically lower the emissions that are harmful to the environment such as CO_2, NO_x, SO_x, etc., reduce the perceived noise, vibration, and impact on biodiversity, and preserve natural resources. The activities will also address lean and ecological manufacturing processes where recyclability is already integrated in the design phase.*The nano technology will also here be of importance.*

Large industrial companies with facilities in Flanders, active in this field are e.g.:

- SIM members: Arcelor-Mittal, Bekaert, Recticel, LMS
- Other: Aleris, Solvay, Owens corning, Huntsman, Samsonite, Hansen transmissions, Atlas Copco, Extex group, Denys, Group Monument, Bosal, automotive assembly, Van Hool, Jonckheere, Picanol, Vandewiele, LVD ....
- SME's: many machine builders, coating companies, parts manufacturers, engineering companies, composite manufacturers, natural fiber companies, architects, ...

Valorisation of several topics (e.g. lightweight) can be facilitated by SLC.

2.1 Hybrid structural materials

0. Definition of Hybrid Structural Materials

Hybrid structural materials[3] can be defined in different ways. Here the following well focused, but not too narrow definition is proposed:

- hybrid materials are hybridized ***because of improved structural performance***,
- hybrid materials are composed of ***materials which exist also by themselves*** and are combined as such (in contrast to e.g. metallic alloys and polymer blends, which phase-separate during cooling),
- hybrid materials ***can have different reinforcement dimensionalities***: 0D (particles), 1D (fibres, wires), 2D (sheets, laminates), 3D (skeletons, scaffolds).

Because the term 'composite materials' is often (implicitly) understood as 'fibre reinforced polymers', it is proposed to use the term 'hybrid materials', as we explicitly want to include in this subtheme all kinds of structural hybrid materials.

1. Short Subtheme Description and State-of-the-Art

It is generally recognized that most homogeneous structural materials are coming to a mature state of development. In contrast hybrids, combining materials with drastically different properties, have realized over the past decades important breakthroughs. Metal-polymer multi-layered laminates might be an underestimated innovation, but fibre reinforced polymers (FRP's) are generally considered as one of the most important breakthroughs in structural materials for light-weight structures and products.

FRP's now have a proven record of superior specific stiffness and strength, but their durability is threatened by the intrinsic brittleness of the fibres, and the poor resistance against delamination (the latter also being a problem in metallic laminates).

Although both FRP's and metallic laminates contribute, by their improved specific properties, to lighter and hence more sustainable products, further improvements are needed in both the beginning and end-of-life (using renewable-based materials ànd improving recyclability). Ultralight hybrids can further reduce the structural weight significantly, leading to reduced energy consumption and increased sustainability of products.

New science themes within hybrid structural materials have emerged or received increasing attention: Biopolymers, Renewable materials, Amorphous metals, CNT, Self-healing material systems, Material recovery techniques and Nano-modification of coatings.

Also durability management is becoming more and more an important research topic. Material damage monitoring will be key to decide on replacement or repair. Also the monitoring of repaired materials becomes important such as lay-ups in airplane materials. Durability can also be increased by improving adhesion between the different constituents of such materials, while intelligent coating functionalization can improve recyclability at the end of lifetime. Hybrid structural materials should therefore be designed with damage monitoring, repairability and recyclability in mind.

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[3] Structural Materials are materials which have as a primary function to bear a certain load (by providing strength, stiffness, support in a product or structure) in a variety of demanding environmental conditions.

2. Identification of Subtheme Targets

- ***Durability of hybrid structural materials***

  Durability of hybrid structural materials is mainly threatened by early damage initiation and development (matrix and fibre cracks in fibrous composites, delamination in layered hybrids). This can be counteracted in different ways, and it is proposed to concentrate on innovative approaches like more complex fibre architectures and multi-scale reinforcements, the latter not only in fibrous hybrids but also in bonding layers of (metal) laminates. In order to realize such improvements in a rational way, better damage monitoring techniques and more powerful, integrated multi-scale modelling of damage are absolutely necessary. Today materials are still taken out when their predicted usage time has passed, rather than taking this decision based on real damage monitoring techniques and conclusions. Materials need to be designed with damage monitoring and repairability in mind: testing at very early stages, study material degradation, corrosion aspects, etc. Regarding repairability many scientific challenges exist especially on joining and adhesion level. Also damage monitoring of repaired materials (such as patches and lay-ups) is an important research topic. It also seems interesting to look at the combination of materials: how do they behave in terms of corrosion, even on nano-materials level. The question rises whether or not there exist over time inherent corrosion and degeneration problems of nanoparticles used in hybrid materials.

  This durability target is most relevant for all applications of FRP's and metal laminates in primary structures in applications where weight reduction is crucial, like in all transportation applications (automotive, truck&bus, train, aerospace…). More and more however it is also getting very important for structural materials for energy generation (wind-turbines, ….) and for materials used in building and construction.

- ***Sustainability of hybrid structural materials***

  Sustainability in hybrid structural materials is already partially realized by the very nature of these materials, as the goal of hybridization is most often weight reduction, which in itself leads to reduced energy consumption when these hybrids are used in transportation applications (this again applies both for fibrous as well as for laminated hybrids). Further weight reduction can be achieved by breakthrough improvements on the mechanical properties of ultra-light structural materials (like foams, honeycombs). The ecological impact could be further reduced by recycling "from hybrid to hybrid" without losing too much of the initial performance of the material. A second, even more drastic improvement could be realized by the use of renewables based hybrids.

  Important challenges exist in making hybrid structural materials "renewable materials" rather than just recyclable materials. The ultimate goal is to make products that are completely reusable. (No waste, complete recycle).

- **Multi-functionality of hybrid structural materials**

  The use of advanced materials and the introduction of lightweight design strategies cannot be done at the expense of current design performance. Indeed, recent studies show that consumers are ready to pay more for eco-friendly products but not if this is at the cost of the product performance. According to 3M who worked closely with manufacturers on some of the world's most successful hybrid programmes, including Toyota's Prius and Auris and the Honda CRZ, "the early-adopters buying these cars expect hybrids to provide an efficient, premium driving experience with superior refinement. Balancing the weight and performance of the car's acoustic package is a fine art and requires lightweight materials optimized to manage the higher range of frequencies."

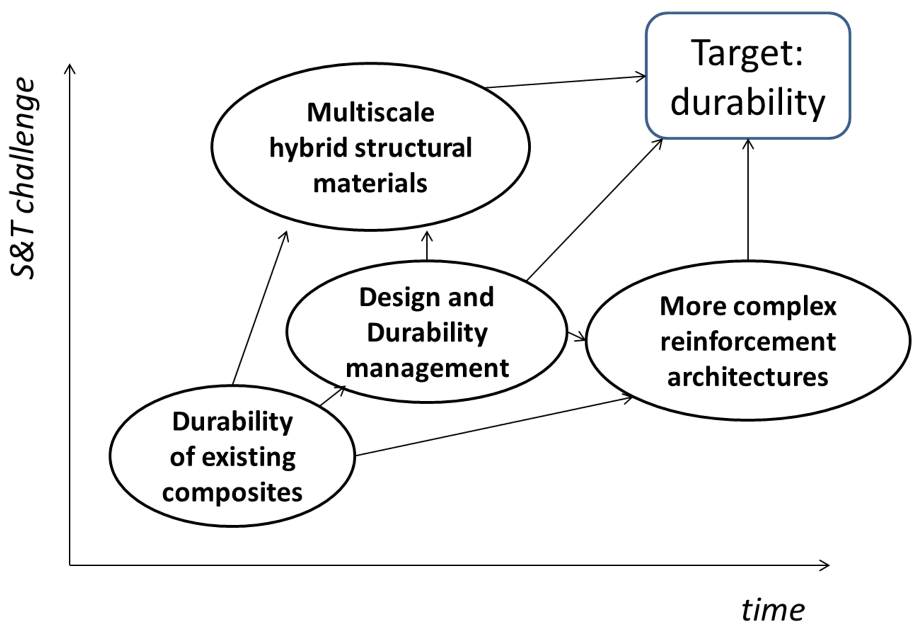
  The same applies to other systems such as green espresso machines, dishwashers, lawn mower, elevators, etcetera. However, unfortunately the application of lightweight structures typically

results in higher vibration and noise levels and these can results in not only a lower buying incentive but also more environmental noise pollution and regulation and homologation issues.
Next to noise and vibration, also thermal and electrical conductivity and crash behaviour (safety, energy absorption, integrity vs brittleness etc). are important research areas.

3. Roadmap

The challenges related to ***durability of hybrid structural materials*** will mainly have to be tackled gradually over time. Breakthroughs in understanding and improving the durability of existing short and long fibre composites will by itself lead in an implicit way towards new insights and improvements in more complex reinforcement architectures and multiscale hybrid structural materials.

Figure 15a: The durability challenge in hybrid structural materials



The identified challenges related to ***sustainability of hybrid structural materials*** are of major importance in each phase of the lifespan of a product, but can be tackled in parallel research projects or packages.

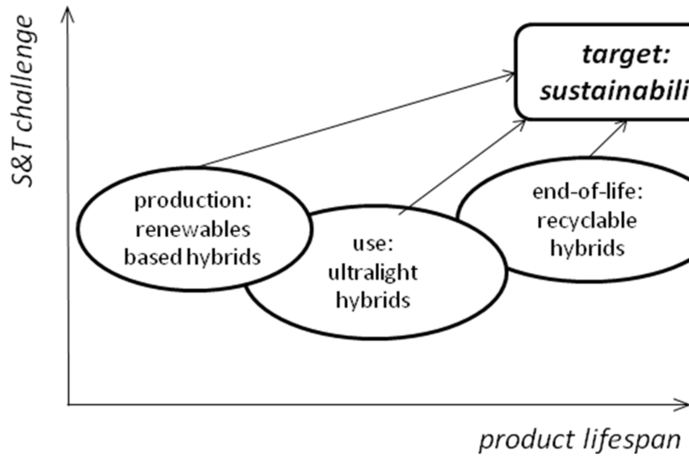


Figure 15b: The sustainability challenge in hybrid structural materials

It is estimated that in a framework of a medium to long term ***Strategic Initiative***, each of the identified challenges should and will evidently consist of an ***SBO-type*** research phase, followed by ***IBO-type*** projects.

4. Science and Technology Challenges

For both subtheme targets, durability and sustainability, the following ***science and technology challenges*** are identified as being of strategic importance.

- ***for durability of structural hybrid materials:***
    - improvement of the ***durability of existing short & long fibre composites***: durability of FRP's is most relevant under fatigue and impact loading conditions. First, a more fundamental understanding is needed of the damage initiation and propagation mechanisms during fatigue and impact. On-going advanced modelling work at Flemish universities should be further extended, and will provide rational pathways to material innovations necessary for realizing more durable FRP's.

    - development of ***more complex reinforcement architectures*** for increased durability. More complex reinforcement architectures, like 3D-weaves and braids, or stitched multilayers, will delay damage initiation and reduce damage development, without giving in on stiffness. Also improved joining and assembly methods are needed, in order to decrease the effect of stress concentrations and fibre discontinuities or distortions around the connections points. Next to the currently frequently used materials (carbon, glass, steel, ...) in-depth study of the potential with new components including bio-based materials, amorphous metals, CNT, graphene, a.o. in hybrid structural materials.

    - development of ***multi-scale hybrid structural materials*** with nano-reinforcements in the matrix. Most hybrid structural materials have only one *(metal laminates) or two* reinforcement scales (*FRP's have fibres on the micro-scale and a layered or textile structure on the meso-scale).* An additional reinforcement scale *(nano-scale)* can be introduced by adding nanoparticles in short-fibre reinforced thermoplastics, carbon nanotubes in long fibre reinforced thermosets, nano-cellulose in natural fibre composites and nanoparticles in adhesive layers in laminates. Preliminary results show that these additional nano-reinforcements offer a great potential for increased durability.

- Knowledge build and expertise development for **durability management of hybrid structural materials including management after repair.** Research should build on the knowledge on failure mechanisms to create powerful, integrated multi-scale modelling of damage and focus on a fundamental understanding of damage initiation to allow for damage monitoring with resulting conclusions on the existence and progress of damage and the need for replacement or repair. Repair techniques for hybrid materials need to be developed and studied. Also design knowledge should be built to improve the lifetime (eg adhesion and alternative joining/bonding techniques for minimum stress concentration) and to improve the recyclability (eg intelligent coating functionalization). This topic has a link with self-healing materials discussed in the second science theme and with material recovery techniques. Additional research is also needed at the level of combination of materials: how do they behave in terms of corrosion, even on nano-materials level. The question should be addressed whether or not there exist over time inherent corrosion and degeneration problems of nanoparticles used in hybrid materials. Understanding the durability and degradation of nano-sized particles is necessary. This may lead to specifically designed nanoparticles for specific material usage purposes.

- ***for sustainability of hybrid structural materials:***
  - breakthrough development of innovative hybrid solutions for better ***ultra-light structural materials*** like foams, honeycombs, scaffolds/skeletons. Actual foams and honeycombs seem to have reached their limits in structural efficiency (mechanical performance per weight). In addition, they exhibit poor noise and vibration damping characteristics, such that their intrinsic weight benefit is annihilated to a large extent in many applications by the mandatory addition of damping material treatment to achieve reasonable noise and vibration characteristics. Novel concepts are needed to come up with the next generation ultra-light structural materials, in order to further reduce the product weight, and to minimize their ecological footprint when used in mechanical applications..

  - possibilities for ***recycling hybrid materials to hybrid materials***. If the constituents of a hybrid material cannot be separated efficiently (which is often the case), the hybrid as such has to be recycled into new hybrid materials, with no or limited down-grading.

  - use of ***renewables based structural hybrid materials***, such as improved wood and/or wood-based laminates and natural fibre and/or bio-based polymer composites. Also disassembling and debonding techniques for hybrid materials need to be studied.

- ***for modelling multi-functionality of structural hybrid materials***
  - ***Acoustics**:* In the past decades modal superposition has been used extensively to reduce model sizes in computational dynamic analysis. This has become the default approach for dynamic analysis over a certain frequency range. Modal superposition was also used to couple models together.
    Most advanced materials show a frequency dependent behavior (like some epoxy based composites for instance) which prohibits the use of modal superposition.
    Additionally, modal superposition also fails to provide an accurate representation when damping is local (e.g. visco-elastic patches). Furthermore, note that many composite components nowadays are assembled through bounding techniques (gluing) whose properties are both frequency and position dependent.
    The modal superposition approach therefore cannot be used and alternatives have to be developed.

    Additionally, lightweight panels typically strongly couple to acoustics in many applications. This vibro-acoustic coupling is inversely proportional to the surface mass of the panel (i.e. the lighter the structure, the more coupling to its acoustic environment).

    This strong coupling, together with the fact that modal superposition cannot be used for frequency dependent systems, adds additional complexity to the simulation. Not only does it result in larger models due the two physical domains that need to be addressed simultaneously, but discrepancies of the discretisations at the interfaces need to be handled in some way as modal projections are not applicable anymore.

5. Science and Technology Challenges – Needed Competences

For each of these science and technology challenges the most **relevant competence(s)** that is (are) needed, is (are) indicated. It is immediately recognized that in all cases, modelling and characterization skills and capabilities are major competences that need significant further development and/or radically new ways of doing.

- ***for durability of structural hybrid materials:***
  - improvement of the ***durability of existing short & long fibre composites***
    - *developing damage monitoring and test methodologies,*
    - *developing material models which allow adequate simulation of damage onset and growth*

  - development of ***more complex reinforcement architectures***
    - *understanding the relationship between reinforcement architecture and required properties*
    - *capabilities for making, tailoring and dispersing nanoparticles in polymers*
    - *make, assemble and test hybrid structural materials based on emerging components*

- development of ***multi-scale hybrid structural materials***
  - *understanding multi-scale interactions by developing integrated (nano/micro/meso-scale) models for their mechanical performance*
  - *develop new nano/micro/meso-scale reinforcement concepts, and develop processing routes to realise them*

- **durability management**
  - *powerful, integrated multi-scale modelling of damage and decision algorithms*
  - *Repair techniques and monitoring of repaired materials*
  - *Design strategies for improved durability and recyclability*

- ***for sustainability of hybrid structural materials:***
  - better ***ultralight structural materials***
    - *developing adequate structure-property models,*
    - *developing efficient fabrication techniques*

  - ***recycling hybrid materials to hybrid materials***
    - *developing realistic processing routes*

  - ***renewables based structural hybrid materials***,
    - *understanding and being able of controlling structural properties and structural response of renewables based hybrids*
    - *Disassembling and debonding techniques*

- ***for modelling multi-functionality of structural hybrid materials:***
  - *Functional performance in dynamic load environments:*
    Conventional material performance indicators are typically based on static testing and for some types of materials on impact testing on material samples. However, for the application of materials in dynamic load environments, such as in machine design and transport applications, such static and impact characterization is no longer sufficient and a need has risen for dynamic performance indicators. A good knowledge and understanding of the dynamic Noise, Vibration and Harshness properties of materials is of crucial importance for good, efficient, durable and economic product design and harmony with other attributes such as crashworthiness has to be strived for in multi-attribute optimization.

  - *Furthermore, since it is well known that the environment in which a material is used is of crucial importance for the performance indicators of this system, especially for dynamics, i.e. a vehicle roof panel will exhibit a very different behavior when considered as individual panel component or as assembled in a full car, it is important that materials are investigated with respect to their functional performance attributes. As such, material* *characterization should not only be done on material samples, but also on components in their end-application environment or in test benches which can simulate this environment.*

- *Better modeling and integration of advanced materials and lightweight structures into the vibro-acoustic simulation process, which requires fast and accurate prediction tools.*

6. Interference/interaction with other themes

With respect to ***renewable based structural hybrid materials*** there is a clear interaction with the ***Renewable Materials*** embryonic theme.

The ***Hybrid Structural Materials*** will without any doubt

- need input from the **Tailored nanoparticles in their environment** theme; this is particularly needed for the development of multi-scale hybrid structural materials, and for the ultra-light structural materials. Also a link exists with nanofacturing techniques.
- be supporting to the ***Materials for Energy*** theme, where components and/or structural elements may for example have to take high static and/ or repeated dynamic (thermo-)mechanical loads, or may have to be self-supporting.

Overview of cross-cutting themes

- LCA models for new materials and processes
- Durability management: Material damage monitoring and modelling, including repairability and up-front design of materials in view of durability management
- Characterisation and modelling techniques
- Nanoparticles, e.g. that result in a triggering function
- High throughput screening techniques.

7. Capabilities in Flanders

*Referring to Report C, it is obvious that strong research groups on "classical" composite materials are present at **K.U.Leuven**, **Ghent University** and at **V.U.Brussels**. Less explicit background is available on (metallic) laminated materials, but this could be compensated by good understanding of laminated composites in the aforementioned universities, and of general behaviour of metallic structures on the other hand. Additionally, the **University of Antwerp** and the **University of Hasselt** can provide significant characterization and modelling knowhow.*

8. Relevant Application Areas

Achieving significant achievements and breakthroughs in ***durability and sustainability*** of (hybrid) structural materials is clearly of high relevance for ***Aerospace***, ***Transport*** (including automotive, rail, ship), ***Construction***, ***Consumer Products***, ***Energy and Power Systems*** and ***Machine Building***.

Durable and ultra-light (hybrid) structural materials are equally relevant for ***Medical*** applications.

The identified science and technology challenges related to ***sustainability*** are further of high importance for ***Materials Processing***.

2.2 High performance structural materials with multi-functionality

1. Problem description

Structural materials seldom need to fulfil only their primary function which is to bear a certain load. Most often they are operating in demanding environmental conditions which require them to have a secondary or even a multitude of additional functionalities.
These supplementary features should be designed, tailored and implemented to meet the challenges which today's, but even more important, tomorrow's industry will be facing and therefore, very often, will require breakthrough innovations and radical improvements to be made to them.

Generally speaking, these additional, non-structural features can be either surface and/or bulk related. Examples of surface related functionalities are environmental protection, bonding, friction, self-healing, light and heat reflectivity etc. and of bulk related properties: conductivity (temperature and electric), abrasion, damping, formability, machinability, weldability etc.

Surface related multifunctionality:
Playing a major role, protective surface layers are contributing to increase the durability and wheatherability of materials. Layers can be added to increase specific functionalities such as the need for resistance to very high or low temperatures or also as surface treatments for acoustic absorption'. Thermal insulation and energy storage are of specific interest in many applications such as energy efficient buildings and Transport. Quite often pure organic layers are not performing enough and new approaches to render them multifunctional are desirable e.g. grafting via covalent bonding of inorganic (nano)particles on the organic parts or a multilayer approach to get laminates (alternating of layers of inorganic and organic materials). For metallic layers alternatives have to be developed under pressure of the environmental legislation which will ban some mineral products such as chromates e.g. use of inorganic (nano) particles acting as redox systems with similar anti-corrosion performances.

Moreover there is a strong push from customers to get multifunctional materials whose surface could offer properties changing with external conditions such as pH, T°, humidity, offering simultaneously self-repairing properties (self-healing) together with haptic (soft feel) and/or bacteriostatic/bactericidal (hygienic) and/or anti-friction ones at an affordable cost/performance ratio.

The trends towards light weight components and construction, the use of multifunctional and hybrid materials as well as the legislation driven obligation for environmental friendly production processes evoke the need to develop new joining techniques and innovative bonding technologies, e.g. welding of dissimilar materials, adhesive bonding in multi-layered materials and products etc.

While some solutions exist in high end markets (such as aerospace), direct translation of these concepts into the commodity market (e.g. cooling applications) is way too expensive. Cost and performance of materials are the main issue here. For renewable energy a lot of concepts are only viable at high temperatures with combined heat and power. For this one runs into problems with the traditional materials. Hybrids can be a solution. A further example is in railway where the power electronics are increasing spectacularly. Heat evacuation while not adding weight is very important. A last example is in thin television screens where lots of heat need to be dissipated while one must be able to still touch the material: remain cool enough for the electronics inside and for people to touch. Thin layered structures with surface related functionality are to be examined here.

Bulk related multifunctionality:
Although improvements in terms of life cycle energy efficiency might spontaneously spark ideas related to lightweight design, there is also still room for significant progress in fields such as energy dissipation due to friction, thermal or electrical conductivity, light and heat reflectivity, for vibration damping and acoustic insulation etc.

As indicated in the European multiannual roadmap for energy efficient buildings; development of new multifunctional materials is also needed for energy efficient buildings, having a low embedded energy and higher thermal and acoustic properties (embodied energy is often proportional to mass), overcoming scarcity of renewable materials.
Horizon2020 (FP8) draft document – Smart, Green and Integrated Transport also proposes that research and innovation in low weight materials and structures will substantially contribute to the European transport policy target of achieving 60% reduction in CO2 by 2050 for aircraft, vehicles and vessels.
It is becoming more apparent that the next technological frontiers will be opened not through a better understanding and application of a particular material, but rather by understanding and optimising material combinations and their synergistic function, hence blurring the distinction between a material and a functional device comprised of distinct materials. Future research will be strongly focused on the final performance properties and less on the individual material performance. New technology routes to integrate waste in the production cycle (recycling) of materials are needed.

Next generation structural materials should also answer to our Health and Safety needs. As strength goes up and weight is reduced, alternative ways of dampening noise and vibrations or increasing stiffness should for instance be pursued. Explosion, bullet-, or stab-proof materials should protect us in case of attack, while light, strong and bio-compatible prostheses should help us to recover more rapidly.

2. S&T challenges

Breakthroughs in the following topics are strongly encouraged.

Surface related multifunctionality:

- Protection against environment: thin layers; multilayer solutions or treatments as alternative.
- Breakthrough protective surface layers to increase durability of materials (e.g. grafting via covalent bonding of inorganic (nano)particles on the organic parts or a multilayer approach to get laminate coatings)
- Multifunctional coatings to face external conditions such as pH, T°, humidity, offering simultaneously self-repairing properties (self-healing), or bacteriostatic/bactericidal (hygienic), or anti-friction properties
- New joining techniques and innovative bonding technologies, e.g. welding of dissimilar materials, adhesive bonding in multilayered materials and products etc
- Friction improvement.
- Heat and light reflectivity.
- Alternative metallic layers, as an answer to mineral scarcity or environmental legislation
- Study interaction material with environment to extend lifetime of products
- New generation of coatings driven by environmental issues or material security
- Ceramic protection layers
- Surface treatments to reduce vibrations and for acoustic absorption
- New bonding techniques can also be exploited to reduce vibration by adding local damping.

In this field technological opportunities consist of e.g.: new routine analysis techniques for surface characterization, better knowledge of the colloidal stability and film formation of water based systems, new accelerated weathering tests, optimization of the physico-chemistry of surfaces etc. New enabling technologies such as (cold) atmospheric plasma can contribute to total solutions for sustainable and solvent-free surface engineering. Dedicated chemical functionalization of any substrate (plastic, glass, metal) can lead to improved adhesion and/or lamination properties. Adding pre-cursors to various thin (nm range) intermediate layers or protective layers can be applied e.g. anti-corrosion, gas barrier, antibacterial, low friction, etc. properties. Inspiration to modify surface layers might also be looked for in biological phenomena such as e.g. the ability of a lizard to walk on the ceiling.

Bulk related multifunctionality:

Superior mechanical properties combined with additional properties like minimal energy dissipation due to friction, energy absorption during impact, thermal or electrical conductivity, light and heat reflectivity, minimal dampening noise and vibrations. explosion, bullet-, or stab-proof. Also for building related application interests were available in (thermal) energy storage through bio-based phase change materials covering aspects of isolation, thermal conductivity, bio-based polymers and leading to new composite materials, polymers and metals. Other mentioned challenges included photo-catalysis, incorporation of biocides, bio-mimetics, bio-induced processes.

An apparent paradox which future structural materials will need to solve is to reconcile weight reduction and durability. New materials will need to last longer (resistance to abrasion, corrosion, fatigue, creep, …), require less maintenance (self-healing, self-cleaning, …) and should be easy to assemble and dis-assemble (machining, welding, clinching, separation, …).

Alternative hybrid material concepts such as multilayer materials, fibre-reinforcements, foams etc., could be interesting candidates to answer to the challenges in terms of weight reduction in combination with damping, stiffness, safety, formability, energy absorption, etc. requirements.

- conductivity optimization (temperature and electric),
- fatigue and creep improvement,
- abrasion improvement,
- damping absorption,
- improved formability, energy absorption, machinability, weldability etc.
- bulk treatment for vibration damping and acoustic insulation

Embedding nano-particles into the bulk or surface of the component might offer opportunities to change properties in the needed direction, for instance in friction properties, heat transfer, bonding, environmental protection, self-cleaning or self-healing but also to bulk properties as electrical and heat transfer, abrasion resistance etc.

3. Roadmap and timing

Recent strategic reports indicate as main drivers for structural materials:

- Environment
- Cost
- Creation of value added (multifunctionality, composites,..)
- Governmental legislation (environment and safety)

(see e.g. http://www.matuk.co.uk/docs/structuralreport1a.pdf). We also refer to the roadmap vision documents for the 3 PPP's: Energy Efficient Building and Green Cars where the urgent need for new hybrid structural multifunctional materials is indicated (see introduction to this document section).

Therefore the topic of multifunctionality is one of the most important directions for the future R&D work on durable and sustainable structural materials in Flanders. As such, the multifunctionality creates a significant added value in our increasingly competitive economic environment, which is a strong driver for the fast industrial implementation and valorisation of the R&D efforts.

Due to their high priority, two sub-themes are expected to receive attention first in the SIM Programme, namely:

- Developing sustainable and durable environmental protection (organic and metallic layers, eco-friendly pre-treatments, etc.), related to the surface multifunctionality;
- Increasing the durability and maintenance improvement (abrasion, fatigue, creep, etc.), related to bulk multifunctionality

All the other sub-themes can be developed in parallel, without a particular preference in timing.

4. Overview of needed competences in Flanders

Research Area	Science Themes	Challenges in S&T (starting from capabilities in Flanders)	Competences/ Technological domains	Horizon to applications	Relevant Business Areas
*Durable & Sustainable **Structural Materials***	*High Performance **Structural Materials with Multi-functionality***	***Surface related***	*Developing sustainable and durable environmental protection (organic and metallic layers, eco-friendly pre-treatments)*	*ST/MT*	** Transport * Construction * Consumer products*
			Creating innovative solutions related to changing properties triggered by external conditions (self cleaning, anti-bacterial, …)	*MT/LT*	** Aerospace * Construction * Consumer products * Materials processing * Medical*
			Developing Innovative joining and bonding techniques	*ST/MT*	** Aerospace * Transport * Construction * Consumer products * Materials processing * Machine building (Engineering materials)*
			Improving life cycle energy efficiency (modified friction coefficient, light & heat reflectivity, …)	*MT, LT*	** Aerospace * Transport * Construction * Consumer products * Machine building (Engineering materials)*
		Bulk related	*Increasing the durability and maintenance improvement(abrasion, fatigue, creep,…)*	*ST,MT*	** Aerospace * Transport * Construction * Energy and power systems * Medical*
			Generating solutions related to health & safety (sound insulation and vibration damping, energy absorption, formability)	*MT,LT*	** Aerospace * Transport * Construction * Consumer products * Energy and power systems * Medical*
			Improvement of life cycle energy efficiency (temperature and electrical conductivity, machining, joining, separation…), etc.	*ST/MT*	** Aerospace * Transport * Energy and power systems*

5. Capability in Flanders

Referring to report C, strong research groups on structural materials exist at K.U. Leuven, Gent University and V.U. Brussels. Additionally to the mentioned Universities, the University of Antwerp and Hasselt can provide significant characterization and modelling know-how. VITO is active in the field of surface technology, joining and materials analysis and testing. Sirris specialises in surface treatment techniques for the optimization of multifunctional material surfaces. OCAS has a strong expertise in surface protection (coatings, pre-treatments etc), welding technology, modelling and materials characterization.

6. Overview of cross-cutting themes

- LCA models taking into account the multi-functionality
- Characterisation and modelling techniques
- Nanoparticles that result in surface or bulk multifunctionality improvement, e.g. in friction properties, heat transfer, abrasion resistance etc.

2.3 Sustainable processes (for manufacturing, processing and recycling of structural materials)

1. Problem description

Structural materials are used in about every part of our daily life (transport, construction, consumer products, power infrastructure, machine building, health and safety products,…). Important areas towards a sustainable world in 2050, to be concluded from the world business council for sustainable development in 2010, were zero waste, solutions for low energy buildings and transport, value chain innovation, "more for less", cradle to cradle and 4-10 fold efficiency.

Fabricating structural materials and their derived products is a major economic activity, involving extensive manufacturing processes. Mineral scarcity will add to this complexity leading to full recyclability and research on finding alternatives for scarce minerals. Main concerns for structural materials in this is on Coating and Alloying elements:

- Reduce (extend lifetime, less waste, efficient processes,...)
- Re-use (repair, self-healing, second lifetime, C2C,...)
- Recycle (max. material and energy recovery,..)
- Substitute (alternative renewable materials, alternative low energy solutions,..)

Technology developments on structural materials themselves have come to focus especially on the durability and sustainability of these materials, so we should also ensure that the manufacturing processes to make and further process these materials can be called sustainable. It would clearly make no sense at all to promote a durable material if it was made or used in a way that is not sustainable.

When we think of sustainable manufacturing processes we think of processes that require:

- low amounts of energy
- low amounts of materials and other natural resources

- minimal impact on health and safety on the work floor
- minimal impact in terms of waste (effluents, exhaust, solid waste) for the environment

The technical challenges are very diverse and often complex, but the impact can be enormous.
The needs are both at the level of finding breakthrough solutions for making and processing existing structural materials as at the level of alternative structural material solutions that clearly provide an advantage in terms of sustainable processing.

The PPP roadmap for factories of the future confirms that new materials pose new challenges for cost efficient manufacturing to shape, handle and assemble complex structures that can involve macro/micro/nano-scale, multiple material combinations such as sandwich structures and composites, and smart materials involving integration of sensing and actuation technologies within a material (e.g. smart textiles). A topic of research is also how to integrate such smart materials in numerical simulations especially in view of design, optimization and validation of controllers making use of such smart materials as actuators. In other cases, there is a need to work with bio-inspired materials to integrate them more effectively with conventional and new materials, to meet the needs of new bio-industries and environmental targets. Recycled materials are also relevant in this domain, due to their large potential both for cost and environmental reasons.

One important research topic is the cost of processing for hybrid structural materials. Layered approaches are easy to delaminate, while machining cost is high for traditional materials. From energy point of view it is very interesting to ensure new materials get a good process. Hybridisation allows for easier processing than existing materials. Frugal innovation, a specific kind of innovation which takes great care to minimize costs of innovation and cost of final product ('fit for use') is of ever growing importance.

A specific interesting research theme for Flanders is Additive Manufacturing: Computer Assisted very efficient production and scrap avoidance. Intelligent production with computers, near netshape manufacture with minimal number of production steps and minimal labour. Flanders should indeed stress more on localised, small scale, custom made production like additives manufacturing. Quite a lot of scientific challenges are seen in such material developments: materials optimal for specific processes, semi-finished products, …. Illustrative today is that one loses ±30% of the (precious) material when going to the final product. Working with nearly finished products results in much less waste (5-10%). A reference is the "buy to fly ratio", which is the mass of material that is required to machine a part compared to the mass of material in the finished part.

Net-shape manufacturing technologies have gained industrial significance to produce structural parts made of a wide range of materials, namely metals, ceramics and polymers. Transferring traditional low-cost net shape manufacturing processes to novel material classes, such as structurally reinforced composites (e.g. metal-ceramic or polymer nano-composite materials) will lead to completely new possibilities in the design of components and to significant savings in materials and processing costs.

Also, new recycling or reusing routes will have to be developed for end-of-life structural materials. In this respect, the focus should be on material-to-material recycling. While there is an evident need to have a solution for any new material being developed, there is at least one major challenge left among our existing materials: thermosets. As opposed to thermoplasts, today's thermosets can't be recycled by reshaping upon heating. Different techniques exist by which thermoset (composite) materials can be end-processed, such as mechanical recycling, chemical processing, thermo-chemical processing or energy recovery. Although practiced to some extent, these methods do not provide an adequate answer for the future. Due to the continuous evolution in both regulatory and environmental directives, increasing landfill costs and decreasing landfill space, the theme of recycling thermosets is becoming a major topic.

2. Roadmap and timing

The European commission summarized the challenges of the manufacturing industry in its vision document 'Manufuture, a vision for 2020'.
http://www.manufuture.org/documents/manufuture_vision_en[1].pdf

Principal drivers for change in the whole European economic environment are:

- Increasingly competitive global economic climate.
- Rapid advances in science and technology,
- Environmental challenges and sustainability requirements.
  The manufacturing sector will also have to comply with stricter environmental regulation in the future, which should further stimulate the adoption of energy- and resource-saving technologies
- Socio-demographic aspects.
- The regulatory environment, standards and IPR.
  Stricter environmental and safety regulation will no doubt lead to changes in manufacturing. The intellectual property rights (IPR) system might have to respond to changes in an innovation process that is increasingly based on knowledge sharing and networking. The adoption of new technologies in manufacturing will also depend on the availability of industrial standards and testing procedures
- Values and public acceptance of new technology.

Similarly, and more specifically for structural materials, recent strategic reports indicate as main drivers:

- Environment
- Cost
- Creation of value added (multifunctionality, composites,..)
- Governmental legislation (environment and safety)

(see e.g. http://www.matuk.co.uk/docs/structuralreport1a.pdf)

The "Factories of the Future" (FoF) initiative is a € 1.2 billion programme (2010 – 2013) in which the European Commission and industry will support the development of new enabling technologies for EU manufacturing which have cross-sectorial benefits and contribute to greener production. In this Strategic Multi-annual Roadmap for the FoF PPP, four major priority areas have been identified:

- Sustainable manufacturing
- ICT-enabled intelligent manufacturing
- High performance manufacturing
- Exploiting new materials through manufacturing.

Development of sustainable competitive processes, both for existing and new materials is of very high importance.

The PPP multi-annual roadmap for Factories of the future states that production using environment-neutral materials is a key research element for sustainable manufacturing: Growing use of alternative materials in the production environment (e.g. use of renewable materials, bioprocesses, heavy metals control, fossil resources control), adequate management of hazardous materials (measurement methods, treatment standards) and increased use of bio-renewable materials. Development of new technologies for processing, recycling and recovery of materials and energy from waste, producing secondary materials with a high degree of purity and re-workability at lowest energy consumption

There is thus little doubt that the topic of sustainable processes for manufacturing should be on the top of the R&D agenda for structural materials.

As a minimum we can expect a progress as dictated by governmental legislation (Kyoto, REACH, Vlaams Benchmarkconvenant,...).
In many areas however, we are convinced that much more can and will be achieved:

- many solutions for sustainable processes fortunately also create cost saving opportunities, an important driver for industry in the ever competitive environment (and in the light of a longer term trend of increasing energy and raw material costs)
- Social responsibility and company image vis-à-vis an increasingly eco-conscious public are a second important driver

Industry is increasingly looking at improving sustainability in the full life cycle of its products. The general belief is that a company's impact may be many times larger by clever design for the full life cycle rather than an internal optimization of its own manufacturing.

These strong drivers are the best guarantee that R&D results will be taken up by industry swiftly, leading to a fast valorisation of the R&D effort.

3. S&T challenges

Creative solutions for sustainable manufacturing should be found at the level of e.g.:

- Alternatives to substances being used during the manufacturing of structural materials which may well become restricted for environmental reasons (e.g. alternative to Lead for efficient high temperature heat transfer, alternative to many chemicals,..)
- Structural materials which require less energy to make final parts (by e.g. strengthening in the last process step)
- Methods to make parts for structural purposes in completely different sustainable ways (e.g. in situ shaping starting from raw material)
- Additive manufacturing and the use of semi-finished products or near netshaping
- Analysis of the microstructural behaviour of materials and its interaction with the production process
- Structural materials which include additional properties avoiding the need for a number of subsequent process steps
- Cost and Energy-efficient alternative forming techniques to shape structural materials
- Cost and Energy-efficient alternative heating techniques to tune the properties of structural materials
- Plasma treatments on polymer waste materials to improve their upcyclability
- Composite materials for high volume production (manufacturing optimisation)
- Etcetera.

When thinking of material-to-material recycling concepts, possible research tracks are e.g.:

- Intelligent separation and disassembling techniques that provide the possibility to take apart the products and recuperate basic materials that can be reused to make new products
- Incorporating elements into the thermoset matrix that can be activated with an external trigger and lead to the downsizing of the material (eventually to the macromolecular level) to recuperate basic materials to make new products or applications
- New depolymerisation techniques that allow obtaining primary raw materials of high quality that can be reused without purification
- New synthesis manufacturing techniques that produce zero waste during the manufacturing or even over the lifecycle of the product. Working towards a "Cradle-to-Cradle" concept during the design of the materials or products is in this case advisable or even necessary.

With the practical application in mind, it should be stressed that the materials resulting from these recycling processes should by all means be of a quality level that make them useful in other material combinations or products without extra processing steps (purification, …).

Any proposal for sustainable processes should take into account the knowledge of the TLC-data of the basic material(s), the manufacturing process up to the final application. A minimal to zero impact in terms of waste should be strived for.

4. Overview of needed competences in Flanders

Research Area	**Science Themes**	**Challenges in S&T (starting from capabilities in Flanders)**	**Competences/ Technological domains**	**Horizon to applications**	**Relevant Business Areas**
*Durable & Sustainable **Structural Materials***	*Sustainable processes (for manufacturing, processing and recycling of structural materials*	*Manufacturing and processing of **structural materials***	*Environmental friendly consumables in manufacturing*	*ST/MT*	** Transport * Construction * Consumer products * Materials processing*
			Alternative material strengthening techniques	*MT/LT*	** Aerospace * Transport * Consumer products * Materials processing * Machine building (Engineering materials)*
			Alternative shaping techniques (incl. additive manufacturing, near netshaping, …)	*MT*	** Aerospace * Transport * Consumer products * Energy and power systems * IT/computing * Medical * Machine building (Engineering materials)*
			Breakthrough alternative processing routes	*MT*	** Transport * Consumer products * Materials processing * IT/computing*

			Energy-efficient breakthrough manufacturing techniques	*ST/MT/LT*	** Transport * Construction * Consumer products * Materials processing * IT/computing * Machine building (Engineering materials)*
		*Material to material Recycling of **structural materials***	*Breakthrough separation and disassembling techniques*	*MT*	** Transport * Construction * Consumer products * IT/computing*
			Controlled downsizing and degradation techniques	*LT*	** Transport (Automotive, Rail, Ship) * Construction * Consumer products * Materials processing * IT/computing * Machine building (Engineering materials)*
			CTC and TLC optimization techniques	*ST/MT*	** Transport * Construction * Consumer products * Materials processing * Machine building (Engineering materials)*

5. Overview of cross-cutting themes

- o LCA models for new materials and processes
- o Characterisation and modelling techniques
- o Nanoparticles, e.g. that result in a triggering function
- o High throughput screening techniques.

2.4 SIM Programs and projects

From the 2011 workgroup discussions and the feedback from the subsequent colloquium attendants it was clear that many additional programs and projects can be defined within the above mentioned science themes, important for Flanders. Today 2 programs are running in this research area:

- Nanoforce (Light weight hybrid structural materials
- SHE (Self-healing materials)

Within these programs there is plenty potential for additional SBO and IBO projects as illustrated below for Nanoforce:

- Leverage towards joining/bonding/adhesion
- From polymer to biopolymer
- Search or develop ideal nanoparticles

- Sustainable process, recyclability, Cradle-to-cradle
- Model joining/bonding/adhesion
- Model biopolymers
- Model and understand ‘ideal nanoparticle’
- Model multifunctionality
- Roll to roll CNT
- Sustainable process
- Obtain multifunctionality in CNT bundles
- Damage monitoring and durability management

Next to these running programs also ideas on additional programs were mentioned during the 2011 Workgroup discussions:

- Program ‘new generation coatings for structural materials’
  - Coatings based on renewable materials and/or nano-particles, which extend lifetime, increase multifunctionality,.. of structural materials (e.g. Based on bio-polymers, ‘elements of hope’, self-healing or other protective properties,...), aiming primarily towards <u>durability</u> and <u>multifunctionality</u>
- Program ‘durable windmill materials’
  - Material challenges: marine environment, durability, recyclability, damage monitoring and modelling, corrosion and fatigue prediction, ...
- Program ‘nano structured metals for superior performance’
  - Create nano-crystalline, nano-structured or amorphous metal alloys which outperform present alloys without use of scarce elements. (Which elements? How to make them? Model? Stability? Recyclability? Performance? Fitness for use at low material cost?...)
- Program ‘fully renewable structural materials’
  - Create a set of fully renewable and sustainable structural materials which provide a broad range of properties (biopolymers, natural fibers,..).
- Sustainable production techniques
  - E.g. Make additive manufacturing a fully recyclable process: raw material development, end of life processing,..
- Use of lightweight, high performance composites in machine parts preserving the intrinsic ecological benefits of lightweight, high performance materials when used in dynamic load environments such as industrial machinery and transportation

As many further projects and programs are possible, a clear indication exists for a long-term commitment and possible roadmap to the above mentioned themes .

2.5 Conclusion

- Structural materials are crucial in many large application domains
- Science themes with many challenges and opportunities have been identified
- Flemish institutes and industry have expertise and are important stakeholders for these indicated challenges and science themes
- Within the existing programs there is a clear track for continued scientific projects
- Several concrete ideas for new programs are suggested

Appendices:

Recent visionary studies (with relevance for structural materials):

- Vision 2050. World Business Council for Sustainable Development, 2010. www.wbcsd.org/web/vision2050.htm
- Scarcity of Minerals and Materials. M2i study, 2009. www.m2i.nl/images/.../m2i%20material_scarcity%20report.pdf
- Factories of the Future. PPP strategic multi-annual roadmap. EUR 24282 EN, 2010. www.manufuture.org/.../wp.../Technology_Roadmap-Full_Version.pdf
- Manufacturing the Future. Federal Priorities for Manufacturing R&D, 2008. www.manufacturing.gov/.../NSTCIWGMFGRD_March2008_Report.pdf
- Technologies Clés 2015. http://www.industrie.gouv.fr/enjeux/innovation/sommaire.php
- Structural materials. Issue date 2009 www.matuk.co.uk
- Bouwen aan een duurzame economie. Investeren in de toekomst. EWI, 2008.
- HighTech Systems and Materials. M2i, 2010
- Trends in Technologie. Agoria en Sirris.
- ...

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