European Cooperation in Science and Technology -

COST Action FP1105

UNDERSTANDING WOOD CELL WALL STRUCTURE, BIOPOLYMER INTERACTION AND COMPOSITION: IMPLICATIONS FOR CURRENT PRODUCTS AND NEW MATERIAL INNOVATION

Draft strategy document

Introduction

This document should be seen as a draft strategy, designed to stimulate further ideas for the newly formed COST Action (FP1105).

Key objectives:

- To build knowledge and understanding of fundamental processes that drive cell wall structure and chemical composition.
- To explore how new knowledge of biopolymer structure and composition of the cell wall can be used in the short to medium term to support improvement in existing forest products processes including biorefinery.
- Development of a new platform for the development of new biopolymer based materials based upon natural self-assembly processes.
- Use new knowledge to support improvement in tree breeding and biotechnology programs.
- Creating a critical and focused mass of research capacity in the field of the action.
- The development of new research proposals to cover research activities related to the objectives of the Action.

It should be stressed that the COST Action provides funding for networking and to facilitate the development of collaborative research proposals but not for the research activity itself.

Background to the Action

The Forest Based Sector is under increasing pressure to add value, not only to the primary product of manufacture but also to utilize the residuals in higher value applications. This has led to the evolution of a bio-refinery concept, which requires an “in depth” characterization of a complex package of

biopolymers and to understand the processes required to extract different components. Interest in the development of wood as a bio refinery feedstock has led to significant advances in our understanding of cell wall ultra-structure and biopolymer composition.

As our knowledge improves there is an increasing awareness that there is much still to learn. Further complexity is added by a poor understanding of how primary industrial processes influence and change cell wall ultra-structure and overall composition, these processes may alter the assembly of the biopolymers in unintentional ways that lead to suboptimal extraction and utilization of the residual material in whole tree utilization processes.

A hypothesis has been proposed that the fractal structure of the tree and the cell itself, along with the majority of biological and inorganic materials that are allowed to self assemble (in what is traditionally seen as a thermodynamically driven process of diffusion limited aggregation), is driven by the underlying fractal structure of space in a way that we are still trying to understand. The physics underlying this work is already providing new, fundamental insights into the nature and structure of matter.

Within the field of biochemistry and genetics there is a growing understanding of some of the factors under genetic control but in other instances, it is clear that there is still a poor understanding of the incredibly complex phenotype (at the cell wall level). Without this understanding, it is impossible to determine the relative contribution of genes, environment and the underlying physical processes in determining the structure, and composition of the cell wall.

There is a growing interest in the mimicking of biological systems in the development of new materials. One of the challenges has been to identify the processes by which some of these structures are formed, as biological processes can be very complex. However, if we can confirm that the processes that define plant wall structure are physical rather than genetically driven then it opens up opportunities for us to model and mimic these processes more easily from first principles.

Conversely, if we know that fundamental physical processes drive some processes, then we need to understand the role of the genome in influencing these structures and the overall biopolymer composition of the plant cell wall. I.e. it is important to understand how manipulation of genes is capable of changing and modifying the cell wall. This has implications for current biotechnology initiatives in plant sciences and the Forest Based Sector.

The work identified is primarily medium to long term and multidisciplinary in nature. A successful outcome requires the development of new networks between different scientific fields including physics, genetics, plant physiology, plant science, materials science, mathematical modeling, wood science and industrial processing of biopolymers. One of the key outcomes will be the development of a new European wide platform of competencies and capacities with a common goal that can be harnessed to compile and integrate existing knowledge and to develop new multidisciplinary research proposals into the future. COST offers an ideal mechanism to facilitate this

objective.

COST Action structure:

The COST Action is divided into three working groups illustrated below (Figure 1) and described in more detail below. In addition to a brief description of each working group we aim to develop a list of proposed research areas that will require focus over the next 4 years of the Action and beyond.

The Working Groups will be responsible for:

1. Organizing training schools, STSM's and any more focused workshops that might be require during the course of the Action.
2. Populating the proposed research database, which will include ongoing projects and project proposals plus current PhD students working in the field of the Action.
3. Populating a research funding opportunities database
4. Populating a Wikipedia site with technical details on the Action for sharing with Action participants and the broader community.

1. Short-term scientific missions (STSM's) and training schools. Coordinator (Claudia Crestini):

Within the more detailed actions contained in each working group there is a target for this activity. We would like to request that Action participants make suggestions/proposals for these activities. This could be a volunteer to host an activity or it could be a suggestion/request for one of these activities at another institution. Alternatively, it could be a more generic idea for sharing with the broader Action to stimulate proposals from others. We have a deadline for the first round of requests for STSM's of November 15th and these will be considered at the management committee meeting on the 3rd and 4th of December in Stockholm. Could you please submit your requests to the relevant working group leader.

Tomas Larsson from Innventia has volunteered to host an STSM on cellulose/solid state carbon-13 NMR. Any one interested in this please contact Tomas or Claudia Crestini in the first instance.

2. Ongoing research proposals and PhD students:

We would like to ask participants to identify any current research proposals or approved funding related to the activities of the COST Action. This will assist in establishing a foundation upon which new ideas can be developed. Information provided to date is recorded in Annexure 1. A new section will be created on the COST Action website to log this information.

An important aim of the above activities is to support the development of PhD students. The minimum target for PhD students for each working group is highlighted in the working group section. As part of this process it is important that we record these students in a database. As a starting point we would like to include a list of current PhD students involved in research activities that support the goals of the Action and to continue to update this list as new students begin their studies. We have added a spreadsheet to the FP1105 COST website (http://www.napier.ac.uk/forestproducts/cost-action/Pages/Documents-publications.aspx) under the name of "current research activities" which participants can download this information from and send it back. It will then be displayed on the Action website to create awareness of current activity.

3. Research funding opportunities:

One of the key outcomes of the Action is the development of a new network of researchers that will lead to the development of both focused and multidisciplinary research. Within the original MoU a number of proposals were envisaged and included in the list of expected outcomes. These are discussed within the more detailed content for each working group. We would like to encourage individuals to suggest or propose general areas of focus for research or more specific research proposal ideas that could be included in this document for discussion.

In order to facilitate this outcome it was agreed that we would identify and list Research funding opportunities. The most obvious European sources include Marie Curie research fellowships, Era net, FP7, and Horizon 2020. There are also some regional European funding opportunities. In addition to this there are a number of National Research Councils in different countries that support more fundamental research, which may view research proposals more favorably if they are part of a broader international consortium. We would like to request that participants send information on any additional funding sources that they are aware of that could be included in the document. We have added a spreadsheet to the FP1105 COST website (http://www.napier.ac.uk/forestproducts/cost-action/Pages/Documents-publications.aspx) under the name of "European funding opportunities. Participants can download the form to complete from the website and send it back with the relevant information. It will then be displayed on the Action website to create awareness of current opportunities and activity.

4. A Wikipedia site with technical details on the Action for sharing with Action participants and the broader community.

The aim is to bridge the gaps in scale and interest by introducing a glossary of terms, techniques and tools used by the participants of the Action to facilitate understanding and communication between company managers, industrialists and scientist from different fields. On the same theme, it is also proposed to introduce a "measurement" document, highlighting which measurements are

used to obtain which data. How are they related to the different scales (e.g. molecular level, cell-wall level, single fibre level, large scale processing level, or end-product level). By highlighting these issues, gaps can be identified early in the Action.

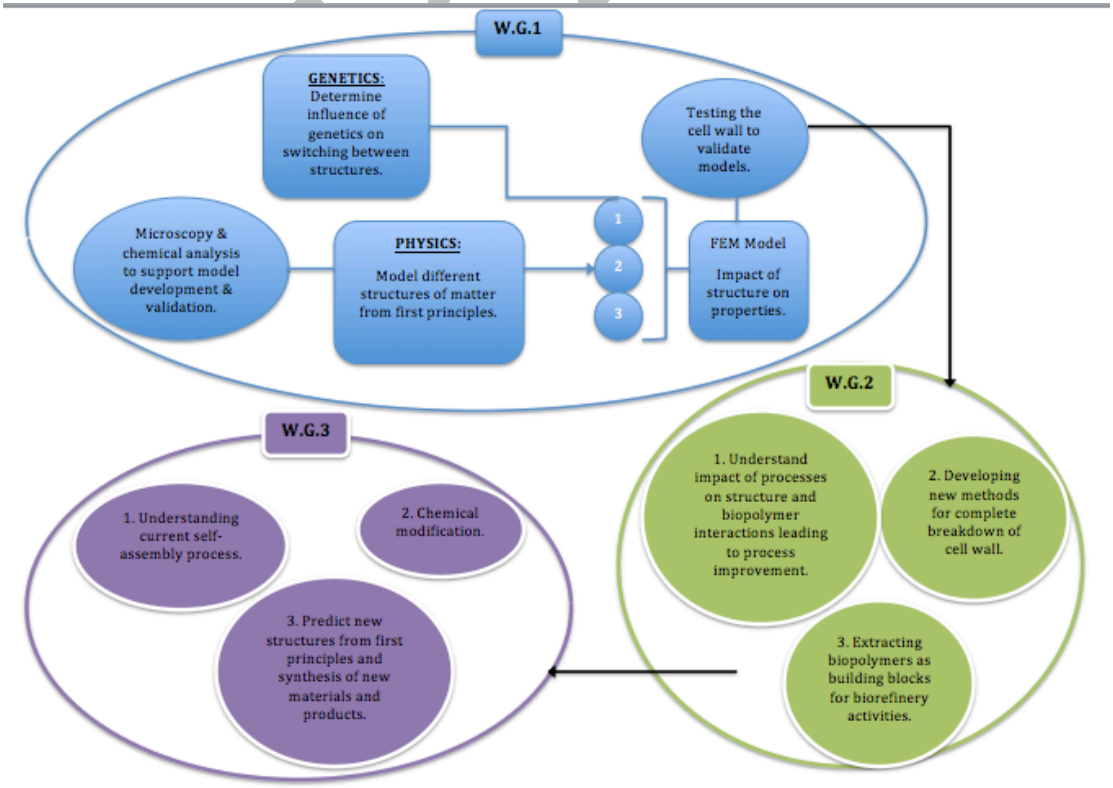
It has been proposed by the core group that these documents should take the form of a COST Action Wikipedia site to which participants can freely add information as required. Further information on this will be communicated via email and the COST Action website.

Key outputs of the working groups

The Working Groups are planned to run in parallel over four years. A summary of each WG's outputs will be published in an annual report. Detailed work will be either published or presented in the Action's Workshops and Conferences. Workshops or conferences will be held at least twice a year during the Action's lifetime. We aim to organize regular cross working group workshops to maximize communication and synergies within the Action. Subject to available funding it may also be possible to arrange more focused workshops for a particular area of interest (e.g. biochemistry, physics etc.).

The working groups and their activities

Figure 1. An outline of the three working groups and the key work activities to be included in the Action.



Working group 1:

Understanding of the structure, biopolymer composition and polymer interactions within the cell wall, what determines these variables and their impact on cell wall properties.

It is anticipated that there will be broad based, multidisciplinary collaboration between physics, biochemistry, genetics, analytical chemistry, microscopy and experts in characterization of cell wall properties to develop a better understanding what controls cell wall formation. The collaboration is expected to evolve into a number of complementary, parallel strands of activity including:

- **The physics of self assembly**
  Development of a collective understanding of the role of fundamental physical processes in defining cell wall structure, composition and biopolymer interaction. This will include established approaches, combined with more complexed self assembly hypotheses such as that described by Nottale and Auffray (2008) who have used a modified Schrödinger equation to model biological functions (morphogenesis, duplication, multiscale hierarchy of organization etc.) and fractal structures found in biological systems. Traditionally, scientists have viewed growth as a process of "diffusion limited aggregation" while Nottale and Auffray suggest that growth processes are based upon the laws of quantum mechanics. It should be emphasized that quantum mechanics and diffusion process are opposite processes. Diffusion laws describe disorganization and entropy increase. Conversely quantum-type laws are an archetype for laws of self-organization and local entropy decrease. We need to test this hypothesis.

- **Genetics vs. physics**
  We need to test the hypothesis that the role of genes is to "switch" between different "physical processes" rather than driving the underlying structures we observe in biological systems (A principle first proposed by Erwin Schrodinger in 1943).

  We need to unwrap the different components of the system that we are trying to understand.

  It is anticipated that knowledge from the action will provide support for genetic improvement/modification programs through improved phenotype characterization at the cell wall level. It is anticipated that there will also be a focus on better understanding of the biological mechanisms of cell wall formation and how to control biopolymer composition and interactions within the cell wall. This will include a natural link to Working Group 2, creating knew knowledge of how to improve the processability of the cell wall and increase the proportion and quality of high value components for different end use applications.

- **Cell wall characterization**

  A number of advanced techniques have proved successful over recent years, but the greatest gains in knowledge will emerge from synergies between these new techniques. Examples include:

  - Synchrotron radiation provides the X-ray beam brilliance needed to reveal the detail of packing in cellulose Nano fibrils, e.g. through calculation of diffractograms from first principles, or through precise measurement of diffraction angles.
  - Solid-state C^{13} NMR provides information about the molecular conformations of biopolymers, and can therefore be used to distinguish between cellulose chains enclosed in the core of a Nano fibril and those exposed on surfaces. This information can be used to characterize the role of water in cell-wall architecture, interactions between non- cellulosic biopolymers and cellulose Nano fibrils or interactions between Nano fibrils during wood processing and product aging.
  - One component of the work will involve determining the viscoelastic characteristics of fibers Using Dynamic Vapor Sorption (DVS) and thermal testing using differential scanning calorimetry (DSC) and dynamic mechanical thermal analysis (DMTA) to determine the influence of cell wall organization and the composition of lignin, cellulose and hemicellulose on the macroscopic cell wall properties.
  - Electron microscopy and AFM techniques have developed extensively over the last 5 years. There is now a range of approaches that can be applied to obtain a more accurate characterization of the cell wall.
  - Hydro mechanical peeling of fibres surface layers as a method for characterization of the cell walls. Using hydro mechanical peeling it is possible to separate the surface material of the pulp fibres (mainly P-S1 layers) for further analysis. The method can also be applied to obtain fibres with open and "clean" secondary wall S2 structure. Another alternative is to use the peeling with different shape of the mixer blades to obtain micro- and nano-whiskers.

  - Literature indicates that there has been a lot of attention on understanding the self-assembly processes that operate in the cell wall with the polysaccharide components dominating. The forces operating within lignin are less understood with significant potential advances that need be made. Advanced techniques using surface Plasmon resonance spectroscopy, light scattering, NMR, AFM coupled with modeling are needed.

  - With regard to ultra structural investigations two relatively new approaches include:

    Electron tomography. This approach is challenging but can produce good high-resolution information. Interpretation of data can be difficult and would benefit from more groups

trying it.

Confocal fluorescence spectroscopy where lignin autofluorescence is used as a built in probe for cell wall modification. Lignin fluorescence will change in response to almost any chemical modification of the cell wall.

Mechanical modeling

Development of improved models of nano-scale and cell wall structures from first principles and from state of the art microscopy and analytical tools that could lead to improved prediction of the characteristics wood, pulp and paper, and other wood based materials properties. Structural studies will focus on different approaches to modeling, including fractal structures observed at the micro fibril level (i.e. the cellulose skeleton of the cell wall). Attempts will also be made to model interactions between structural cellulose, lignin and amorphous polysaccharides. This will be supported by ongoing work to study wood structure and composition and its relationship to the mechanical properties of the cell. As an example, recent insights into cellulose structure offers new knowledge to support the development of improved models to predict wood, pulp and paper and other wood based materials properties. It appears that the existing model of a highly oriented S2 layer and its impact on issues such as wood strength, stability and creep needs a re-think. We need to better understand the role of the micro fibril and the different cell layers on structural performance of the cell. This understanding is important if we are to manufacture different potential end products (of the best quality) in the most efficient and effective manner. Specific areas of work proposed include:

- Development of Finite Element Models of micro-fibrils and whole cell structures.
- Modeling fibre interactions in pulp from first principles to improve understanding of factors that determine the structural role of the cell in products such as pulp and paper. This will form a natural link with working group 2.
- Sharing macro, micro and nano-scale testing techniques for micro-fibrils and cells to validate models. Recently finished cost action E54 (Characterization of the Fine Structure and Properties of Papermaking Fibres Using New Technologies) and an ongoing COST Action (FP0802; Experimental and Computational Micro-characterization Techniques in Wood Mechanics) has played an important role in creating an established network of competencies that this new Action will build on.

Materials testing

Over the last 5 years there has been significant progress in the development of new micro and nano- scale testing technologies that can be used to characterize the mechanical properties of individual wood/plant cells and crystalline micro fibrils. These tools form an

important part of the Armory available to validate mechanical models of the structure of cells and micro fibrils, which will be supported by the cell wall characterization studies.

It would be very useful for the "experimentalists", i.e. groups developing new tools and technologies to have a "wish list" of the parameters that the modeling groups would need to be measured. The groups working e.g. on mechanical models of nano-scale and cell wall structures could give examples of parameters that would be necessary or useful to be experimentally measured.

Selection of common sample materials

Wherever possible, common sample materials for characterization, testing and modeling will be selected for comparison purposes, and made available across the Working Groups, preferably throughout the entire action. Model compounds isolated from different species will constitute a suitable set of starting materials.

It is recognized that working group 1 has a large remit. It is possible that this working group could be subdivided into two or more smaller, working groups if the participants think that this is appropriate. An alternative approach could be to organize in depth, focused workshops over the course of the Action, which cover one or two components of the Working Group.

Key outputs proposed in the Memorandum of Understanding (MoU) over the duration of the Action for WG1:

The physics of self-assembly

- Publications on improved understanding of the role of fundamental physics on cell and micro fibril structure.
- Joint research proposals to develop modeling of cell structures from first principles.
- Proposals to include applications for at least 2 Marie Curie proposals and 3 PhD students.

Genetics vs. physics

- A proposal to better understand the role of genetics and biological processes vs. physics in defining cell wall structure and composition. To include at least 2 Marie Curie proposal at 18 and 36 months and 2 PhD students at 12 at 24 months.
- 1 STM per year
- A review paper on state of the art understanding on Genetics vs.

physics at 24 months with proposals for ongoing research.

Cell wall characterization

- **Analytical techniques**
  - Joint proposals to develop/refine analytical techniques to include at least 1 Marie Curie fellowship and 1 PhD student.
  - 1 STM/year
  - Summer Schools in year 2, 3 and 4
- **Microscopy techniques**
  - Produce a review document on state of the art to characterize the structure of micro-fibrils and the cellulose skeleton of the cell wall (End of year 1) Review to include current limitations and future potential
  - Preparation of Joint research proposals to develop/refine microscopy techniques (18 months)
  - Summer school in year 2,3 and 4
  - 1 Marie Curie proposal at 18 months

Materials testing

- Share best practice on testing of nano-fibrils, cells and hand sheets to validate theoretical models
- Report on state of the art at 18 months
- 1 STM per year
- 1 Marie Curie proposal at 18 months

Working group 2: Fibre Processing

The second working group will use the combined knowledge developed in working group 1 to support ongoing improvement in three key areas of interest. These include:

- **Understand impact of processes on cell wall structure and biopolymer interactions**
  Improving our understanding of how different processes impact on cell wall structure and biopolymer composition and how they can be modified to improve quality and performance of the end products. There will also be a focus on how processes such as pulping could be improved to facilitate the better utilization of secondary products such as hemicelluloses and lignin.

- **Cell wall breakdown mechanisms**
  Develop new or improved chemical, enzymatic and mechanical processes to break down the wood cell wall into individual biopolymers and monomers that can be used as biorefinery feedstock.

This approach is expected to include mechanical, chemical and enzymatic approaches to fibre wall disintegration. It could include for example new cellulose solvents. This objective is partially addressed under COST Action FP0602 **"Biotechnology** for lignocellulose Biorefineries" and close links will be developed with this action as well as bringing together alternate mechanical and chemical processes. An essential component of research in this Working Group will be to understand the influence of cell wall composition on these activities. This highlights the requirement for analytical and microscopic techniques in Working Group 1 to overlap with the research activity in Working Group 2.

- **Fractionation and separation technologies**
  Investigation and ongoing development of fractionation technologies to look at separating and refining biopolymers into chemical building blocks that could be used for a range of downstream bio-refinery activities.

  The work on separation could also include fractionating pulp fibres used for specific processes such as dissolution or enzymatic breakdown.

  The work in this section feeds directly into the activities of Working Group 3 looking at polymer and monomer functionalisation and the subsequent development of new materials. Well-separated, high purity chemicals are an important part of the development process.

  It should be noted that this work is not necessarily limited to lignins and cellulose/hemicellulose but could also include terpenes, fatty acid esters, steroids etc.

Key outputs proposed in the MoU over the duration of the Action for WG2:

Understand impact of processes on cell wall structure and biopolymer interactions

- Share knowledge of impact of current processes including pulping, bleaching, recycling on cell wall composition and impacts on downstream products
- Workshop and report at 12 months to specifically identify opportunities to improve current processes and develop a more detailed research strategy
- Joint research proposals to explore potential to improve existing processes and products (18 months)
- Marie Curie proposals at 24 and 36 months

Cell wall breakdown mechanisms

- Share best practice on cell wall disintegration and separation/fractionation technologies
- Annual progress report
- Joint proposal development at 12 months
- 1 STM per year
- Marie Curie Proposals at 12 and 24 months

Working group 3: Self-assembly to develop new biopolymer based materials.

This working group will look at developing self-assembly processes that could lead to the development of a platform of new biopolymer based materials and products. Results exist on self-assembly of hemicellulose onto cellulose nano-particles (Larsson et al. 1999), which could serve as a starting point for e.g. computational studies. Work will include:

- **State of the art review**
  Reviewing and sharing state of the art self-assembly processes. This knowledge will be used as a starting point for the development of new self-assembly processes.

- **Modification of biopolymers**
  Functionalisation of biopolymers, which can be used as building blocks in the development of new materials. There are two important aspects to such modification.

    - The synthesis of molecules with interesting properties (product / property driven synthesis)

    - An efficient, optimized process in terms of cost, processing times, waste minimization etc. (process driven development) is another.

  It is likely that self- assembly processes will be heavily influenced by the molecular structure. Having the ability to tweak the structures, producing small changes, using chemical synthesis is probably an important thing to be able to do when it comes to gathering experimental data on the properties of the polysaccharides.

- **Prediction of new materials from first principles**
  Using new knowledge of the underlying physics driving self-assembly processes found in biological and inorganic materials as a theoretical

platform for the development of new self-assembly processes at molecular, nano-meter and macro scales.

There are huge challenges in understanding self-assembly and the underlying thermodynamics (and other fundamental processes), which might drive this. It is anticipated that in the first instance, the Action will focus on learning about and understanding self-assembly processes rather than making materials. However, we hope that as new understanding emerges it will stimulate and support new research into new materials development.

It is important to show how fundamental work can eventually translate into more applied research and strategic development. A big challenge of the Action is to stimulate new thinking and new approaches. It is anticipated that the real gains in new materials development and certainly commercialization will fall outside the timescale of the Action. If at the end of 4 years we can point to 1 or two likely new approaches then we will be seen to have been successful.

- **Characterization of new products and materials**
  Within this area, extensive characterization of the anticipated self-assembled biopolymers will be required. Work will include evaluating the molecular weight and polydispersity of the lignin and carbohydrate based fractions isolated from fibers to understand the effects of heterogeneity of cell wall biopolymers on end product quality. The mechanics of anticipated polymers should also be investigated through dynamic mechanical analysis. Other tests should be related to final material properties, such as rheology and strength properties.

Key outputs proposed in the MoU over the duration of the Action for WG3:

- Share state of the art knowledge on self-assembly processes
- Documented review of state of the art in self-assembly processes across a broad range of disciplines at 18 months, 36 months and in COST Action book.
- Development of a research strategy for investigation and development of self-assembly processes (work shop at 18 months)
- Joint research proposals to national research councils at 24 and 36 months
- Marie Curie proposals at 12 and 24 months
- 1 STM per year 2 PhD students at 12 and 24 months

Generic inputs required from participants

The development of young researchers forms a cornerstone of the Action. The main mechanisms for doing this include the following:

We want suggestions that can integrate studies across the Action. An example here could be to identify one or more common pulp fibres that could be evaluated. This sort of approach could allow us to build an integrated knowledge base covering everything from analysis, microscopy, models for self-assembly, FEM for mechanical properties and validation using physical characterization of fibres and hand sheets. We could also include studies of processes on biopolymer accessibility and interactions and impact on products and downstream processing of residual biopolymers. This work could also extend to investigations into full breakdown and separation of these polymers to individual components.

How will the objectives of the Action be achieved?

The objectives of this Action will be achieved through collaborative exchange of ideas and knowledge in basic and applied research from both academia and industry. The means to reach the objectives will be:

Coordinating research activities, ensuring best practical use of resources, i.e. minimizing duplication creating a common development program. This will start with the development of a database of current and past research proposals and activities to be populated by the Action participants.

Joint collaboration among the different institutions and research activities, including the development of joint research proposals, exchange of personnel and the provision of access to specialist equipment. This will encourage greater synergy between institutions. Networking between scientists from different disciplines is essential to address the proposed approach to the challenges identified.

Identification and supply of a set of common sample materials.

This COST Action is ambitious. Many topics are addressed to increase not only the knowledge on the cellulose fibre ultra-structure but also potential benefits in large scale processes. This holistic approach might fail if everyone is only focused on his or her own field. The proposed mapping of competencies and measurement capabilities by topics and geographical areas within the network will facilitate future project establishment, as it will be possible to look up possible missing partners. It is proposed that the mapping of competencies is a two-tier system. The first will involve a summary of individuals and competencies on the Action website. This will be hyperlinked to more detailed individual competency profiles, posted on LinkedIn. Using LinkedIn will allow individuals to constantly update their profiles and publication records as required. It is hoped that all participants in the Action

will register on the COST Action FP1105 LinkedIn group. This will facilitate easy access to information on the full range of Action participants.

The mapping of competencies can become a significant output and evaluation criteria of the Action representing our network.

Organization

A key role of the Action will be to collate, assess and share existing expertise from ongoing research initiatives including international, national and institution specific activities. It is planned that this will include presentations from representatives of all interconnected current cost actions so that we can build on existing European networks and research activities. The first workshop will focus on presenting and collating this information and the production of a web based document summarizing past, current and ongoing research activities amongst the participants within the COST Action.

A number of STM's have been proposed. However, the total number will be dependent upon the amount of funding available. A key milestone common to all working groups will be annual report on progress, which will be collated into an annual report on the Action. Across the Action a summer school will be held during year 2,3 and 4. At the end of year 1 a coordinated research road map will be published that identifies:

- New research areas
- Shows how the activities of the different working groups can most effectively integrate and support one another
- Further research opportunities where research proposals can be integrated to form larger multidisciplinary proposals.

Gender balance and involvement of early-stage researchers

The Action will provide focused support for the development of early-stage researchers by facilitating the development of both specific and multidisciplinary proposals at international, (Research Council), European (FP7, Era net and Marie Curie) and National level. The Action will also actively seek funding for PhD and Post Doctoral research projects outside of these funding sources. The over arching goal of the Action is to build new capacity through the integration of existing capabilities and infrastructure. The Action offers the opportunity to attract a new cohort of young scientists. In all activities, it will be committed to supporting gender balance.

References

Nottale L and Auffrey C (2008): Scale relativity theory and integrative systems biology: Macroscopic quantum type mechanics. Progress in Biophysics and Molecular Biology 97, 115-157.

Turner P, Kowalkczyk M and Reynolds A (2011): New insights into the micro-fibril architecture of the wood cell wall. COST Action E54 Book. Fine Structure of Papermaking Fibres. ISBN: 978-91-576-9007-4

Annexure 1

Current research projects

*1. Wallenberg Wood Science Center,WWSC duration 2009 to maximum 2018 (*http://wwsc.se/)

2. Grant from Swedish research council (Project no: 2010-30547-78318-67, *Innventia co-applicant) in project "*Energy production from lignocellulosic materials - development of robust bioprocessing steps for industrial conditions*", duration 2011-2014*

Pasi Kallio

PowerBonds: "Enhancement of Fiber and Bond Strength Properties for Creating Added Value in Paper Products". This is an ERA-NET WoodWisdom project with 15 partners. 1.1.2012-31.12.2014.
http://www.wwnet-powerbonds.eu/

FIBAM: Autonomous Microrobotic System for Manipulation, Stimulation and Characterization of Fibrous Materials. This research funded by the Academy of Finland. Duration of the project: 1.9.2011 – 31.8.2014
http://www.tut.fi/en/units/departments/automation-science-and-engineering/research/projects/fibam/index.htm

Annexure 2
Current PhD students

To be included on the Action Website.

PhD student	Name of the lead researcher	Country	Institution	Topic	Abstract
Pooya Saketi	Prof. Pasi Kallio	Finland	Tampere University of Technology	Microrobotics for individual paper fiber and bond characterization (hardware)	
Juha Hirvonen	Prof. Pasi Kallio	Finland	Tampere University of Technology	Microrobotics for individual paper fiber and bond characterization (computer vision)	
Mathias von Essen	Prof. Pasi Kallio	Finland	Tampere University of Technology	Microrobotics for individual paper fiber and bond characterization (software)	
Mariaana Savia	Prof. Pasi Kallio	Finland	Tampere University of Technology	Modeling of interaction forces between micro- and nanoscale objects	
Michael Kowzwalski	P Turner	UK	FPRI	Biophysics	
Inese Sable	Arnis Treimanis	Latvia	Latvia University	Impact of poplar and pine cell wall structure on properties of fibrous products	
Laura Vikele	Arnis Treimanis	Latvia	Latvia University	Production and application of cellulose and chitosan nanoparticles in	

papermaking