# SIXTH FRAMEWORK PROGRAMME
# PRIORITY FP6-2003-NEST-PATH
# TACKLING COMPLEXITY IN SCIENCE

**Contract for:**

## SPECIFIC TARGETED RESEARCH OR INNOVATION PROJECT

## *Annex I - "Description of Work"*

Project acronym: **MMCOMNET**
Project full title: **Measuring and Modelling Complex Networks Across Domains**
Proposal/Contract no.: **12999**
Related to other Contract no.: **N/A**

Date of preparation of Annex I: 18 December 2004

Operative commencement date of contract: **01 February 2005**

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# 1. Project Summary

**Measuring and Modelling Complex Networks Across Domains**

**MMCOMNET**

Activity code addressed: *NEST-2003-Path-1 for "Tackling complexity in science"*

Proposal abstract

The overall aim of this Specific Targeted Research Project is to develop a unified and cross-disciplinary understanding of the dynamic behaviour and functional properties of complex networks in different domains of application within the biological, social, and engineering sciences. Three domains have been selected on the basis of their abilities to be subject to the collection of systematic data that may be analyzed to reveal the structure, function and dynamics of the system. Further, each domain must be a promising candidate for a generalised modelling approach that could be applied beyond the originating domain. All the systems under consideration can be characterized as consisting of interacting networks of autonomous and adaptive agents (or components) that allocate global resources with high efficiency on the basis of incomplete and noisy information, typically without the need for a central control mechanism. The project partners will develop techniques and tools to measure and analyse the properties of the agents and the dynamic structure of their network. Modelling such networks will help address questions such as the nature of the implicit trade-offs between the different functional properties of the system, and the degree to which these properties can be realised jointly. The general problem of characterising efficiently and effectively the macroscopic properties of a network from the microscopic behaviour of its agents will be addressed, in order to realise the third objective of identifying possible methods of altering the network structure and dynamics and/or agent behaviour in order to enable real world target networks to achieve the desirable properties of robustness and persistence despite incomplete and noisy information. The most significant outcome from the proposed combination of empirical research and modelling work is to formulate and develop general principles that can inform the design and management of complex networks in a variety of real-world scenarios.

# 2. Project Objectives

The MMCOMNET project aims to develop unified tools for the empirical characterisation and modelling of complex network structures in different application domains and disciplines. The focus of the research is on the functional and dynamic properties of networks, and how they relate to the observed network structure and the characteristics of the agents which are linked in the network. The application domains under consideration span the biological, engineering and social sciences, and the particular systems that the research focuses on are fungal networks, supply networks, transport networks and innovation networks.

The identification of the project objectives is driven by three generic and domain independent research questions, which involve the interplay of network structure, function and design:

1. Although the structural properties of networks are reasonably well understood, research on the dynamic processes that determine functional network properties are much less well developed. Hence a key question is to establish the constitutive properties of dynamic,

agent-based networks (biological and socio-economic) that lead to properties of robustness, persistence, flexibility, responsiveness and efficiency.

2. While there may be many constructions of agent and network dynamics that could account for the observed behaviour of a biological or social network, what are the criteria for selecting the particular constructions that are likely to lead to the desired behaviour in the designed networks? The criteria might be based on physical plausibility or efficiency of information or energy transfer, for example, and are likely to depend on the nature of the designed network.
3. To what extent is it possible to transfer properties from socio-economic, biological and other extant and persistent networks to designed networks, e.g. enterprise networks, socio-technical work systems, and distributed and virtual enterprises?

The four project objectives identified below should provide solutions to these research questions.

### 1. *The development of novel statistical metrics for complex and dynamic networks*

There are many ways to measure and characterise empirically observed network structures and their dynamic properties. Existing measurement techniques include Q analysis, entropic measures of complexity, queuing models, and the use of summary statistics such as the diameter and clustering coefficients. However, even the properties of these standard statistical measures are only poorly understood to date, and traditionally different measures have been deployed in different disciplines, thus complicating the comparative analysis of networks in different domains. The first project objective for MMCOMNET is to develop novel statistical measures that can be deployed in different application domains, thus enabling a meaningful comparison of the functional and dynamic properties of biological, social and engineered networks. This project objective will develop a common language and a shared toolset for interdisciplinary research on complex and dynamic networks. The statistical measures developed will be tested on real data sets, in particular the Stockholm data with regard to social and socio-economic networks, and the laboratory data on growth for fungal mycelia, and can also guide the work on network models which is addressed in the second project objective. The key milestones for achieving the first objective are:

- Initial development of statistical measures and summary statistics, including trial software code (month 12, WP6).
- Testing statistical tools against Stockholm and fungal mycelia data (month 24, WP6).
- Statistics of public transport networks in Polish cities (month 24, WP5).
- Delivery of software package incorporating statistical tools (month 36, WP6).

### 2. *Developing and connecting micro and macro approaches to models of complex and dynamic networks*

The behaviour of networks may be modelled using a highly granular representation in which the non-homogeneous properties of individual agents can be specified, as is typically the case in agent-based models. However, the dynamic properties of many networks can also be modelled by relying on continuum descriptions which relate the macroscopic state variables of the system using partial differential equations. The fruitfulness of each approach is not only determined by the properties of the system under consideration, but also a determination of which network properties are considered important, and the relevant length scale. This project objective seeks to advance both approaches to modelling in parallel with respect to the real-world network systems which serve as paradigms in the different application domains (i.e. fungal networks, supply networks, transport networks, innovation networks). The novel statistical measures developed as part of the first project objective can help establish goodness of fit between different models and empirical measurements. The key challenge of this objective is to explore and integrate the differences between the traditional top-down, partial differential equation (PDE) -based approach, and the bottom-up, agent-based approach, and to explore how hybrid models might be constructed and validated. Participating researchers from the collaborating organisations will contribute their existing expertise on the assessment of the complexity of the performance of individual nodes, the structure of the network and the global behaviour of the network. The key milestones for achieving this second objective are:

- Test agent-based models and PDE models against the experimental results for fungal mycelia (month 12, WP1).
- Develop PDE models of the supply network (month 12, WP3).
- Develop models of diffusion on innovation networks (month 18, WP4)
- Directly compare agent-based and PDE models of fungal mycelia to determine the feasibility of a hybrid model approach (month 24, WP1).
- Models of critical properties of networks (month 36, WP5).

3. ***The Reverse Problem: Deducing agent properties and network dynamics from the global behaviour of network systems.***

The development and empirical validation of novel statistical measures and summary statistics under the first project objective, and the development of PDE and agent-based models for specific systems under the second project objective, will provide a foundation for developing frameworks and techniques which allow potential models to be inferred systematically from empirical data sets, such as those obtained in the different MMCOMNET application domains (e.g. fungal networks, supply networks, transport networks, innovation networks). These models will be tested through simulation, although it must of course be recognised this is an under-constrained problem and that there are likely to be many possible candidate models for any empirically observed network system. Hence cross-disciplinary collaboration will be required to develop general methodologies and criteria for identifying plausible or mechanism-based explanations of observed behaviour, and new methods for choosing the most efficient models and descriptions. The measures of local, structural and global behaviour derived in the context of the first two project objectives will influence how this objective is pursued, and similarly the findings reached as part of the third project objective will redefine how the first two project objectives are approached. For instance, the development of a framework for inferring network and agent properties from the available empirical data sets of different network systems may necessitate the development of additional statistical measures. The main deliverables relating to this project objective will centre on techniques for suggesting constructions of agents and networks that can account for the observed global network behaviour, testing the behaviour of candidate models by simulations, and developing a robust methodology and criteria for selecting between different configurations of networks and agents. The key milestones for achieving this third objective are:

- Models of the decision-making behaviour of agents in supply networks (month 18, WP2).
- Simulations of supply networks that display some aspects of observed behaviour, including software documentation. (month 36, WP2).
- Develop an experimentally supported multi-scale model of fungal growth and nutrient transport (month 36, WP1).
- Generative model for innovation networks in high-tech clusters (month 36, WP4).

4. ***The Forward Problem: The design of networks with desirable properties***

The previous project objectives enable the development of techniques which allow existing networks in different application domains to be characterised and modelled. As part of the fourth project objective this logic is now reversed, and in the forward problem we consider how strategies which allow specific networks in certain application domains to perform well against certain performance metrics (i.e. robustness, responsiveness, etc.) can be transferred to other contexts so that the desirable properties are preserved in the designed network. The successful identification of such design principles would make it possible to construct complex network systems which exhibit the desired characteristics of improved robustness, persistence, efficiency etc. Some potential application domains for this approach include engineered and IT networks, organisational networks, socio-economic networks such as high-tech innovation clusters, and socio-technical systems such as transport networks and supply chains. This approach, based on the transfer of specific functional network characteristics from one application domain to another, offers the prospect of designing networks with characteristics that cannot simply be reduced to a narrow conception of "optimality." By adjusting the local decision-making behaviour of agents or introducing new types of agents, for example, we may be able to achieve stability in supply networks, resistance to attack or node/link failure in computer networks, or more effective dissemination of innovation in business networks. The deliverables of this objective will be based on the simulation of networks with characteristics that are considered desirable, and the validation of these simulations against real world networks, with pilot application of these techniques to real world networks. Since this objective is contingent on success in all three previous project objectives, the corresponding deliverables at the end of the project lifetime will necessarily be more speculative and preliminary.

- Presentation of potential design principles for supply networks at Industrial Workshop (month 36, WP2 and WP3).

Presentation of preliminary policy suggestions for improving the performance of high-tech innovation clusters at Workshop (month 36, WP4).

## 3. List of Participants

| **Partic.Role*** | **Partic. no.** | **Participant name** | **Participant short name** | **Country** | **Date enter project**** | **Date exit project**** |
|---|---|---|---|---|---|---|
| CO | 1 | University of Oxford | UOXF | United Kingdom | Month 1 | Month 36 |
| CR | 2 | Technische Universität Dresden | TUD | Germany | Month 1 | Month 36 |
| CR | 3 | Politechnika Warszawska | WUT | Poland | Month 1 | Month 36 |
| CR | 4 | INSEAD Business School | INSEAD | France | Month 1 | Month 36 |
| CR | 5 | Swiss Federal Institute of Technology Zurich | ETHZ | Switzerland | Month 1 | Month 36 |
| CR | 6 | Stockholm University | SU | Sweden | Month 1 | Month 36 |

*CO = Coordinator
CR = Contractor

** Normally insert "month 1 (start of project)" and "month n (end of project)"
These columns are needed for possible later contract revisions caused by joining/leaving participants

## 4. Relevance to the objectives of the specific programme and/or thematic priority

The objectives of the NEST Pathfinder Initiative “Tackling Complexity in Science” are to promote the development of techniques for the successful tackling of specific but important real-world problems, to encourage the transfer of such techniques between different areas of science, and to develop a research community working jointly on such problems. These objectives are addressed by the MMCOMNET project as follows.

The overall aim of the project is to develop a unified and cross-disciplinary understanding of the dynamic behaviour and functional properties of complex networks in different domains of application within the biological, social, and engineering sciences. Although network theory is rapidly changing our understanding of complex systems, the relevance of topological features for the dynamic behaviour and functional properties of metabolic networks, food webs, production systems, information networks, or cascade failures of power grids is only poorly understood. Topological features seem to play an important role in determining relevant properties of socio-economic networks and the robustness of the World Wide Web. They are also conjectured to be responsible for the beating of a leech's heart, pumping effects in some slime moulds, strong variations in ecosystems, or glycolytic oscillations in yeast cells. A key challenge is to gain an improved understanding of what mechanisms and structural and dynamic features enable such networks to be, *inter alia*, autonomous, dynamically configurable, robust, capable of recovery from critical conditions, flexible and able to meet distributed demand in real time.

In each application domain the focus will be on carefully chosen paradigmatic examples of complex networks. The systems to be studied have in all cases been selected on the basis of two overriding criteria. First, each system must be amenable to the systematic and consistent collection and verification of empirical data corresponding to system behaviour and performance, in order to facilitate the rigorous validation of the models that will be developed. To this end, it will be necessary to develop new techniques that will allow the properties of agents and their network structures to be measured under circumstances where the available information is often noisy and incomplete, or when the network is inherently random. Suitable statistical measures and metrics will need to be developed for model validation, and also in order to make meaningful cross-domain comparisons. Second, the modelling approaches that will be chosen must be promising candidates for a generalised approach that extends beyond the original domain of application. The different application domains contained in this proposal will thus be strongly linked through shared models and modelling techniques. All the systems under consideration can be characterized as consisting of interacting networks of autonomous and adaptive agents (or components) that allocate global resources with high efficiency on the basis of incomplete and noisy information, typically without the need for a central control mechanism. Modelling such networks will help address questions such as the nature of the implicit trade-offs between the different functional properties of the system, and the degree to which these properties can be realised jointly. The most significant outcome from the proposed combination of empirical research and modelling work is to formulate and develop general principles that can inform the design and management of complex networks in a variety of real-world scenarios.

Advances beyond the current state of the art will be achieved by addressing three scientific objectives related to the common themes of network structure, function and design:

1. To integrate and develop metrics of complex networks that measure the structural and dynamic properties of agents and networks, to derive suitable summary statistics and their properties, to test these on real and simulated data, and to develop supporting software tools.

2. Using data from existing networks (e.g. biological, socio-economic and socio-technical networks), to construct and simulate combinations of agents and network dynamics that could account for desired behaviour, such as robustness, persistence, flexibility, responsiveness and efficiency, and to develop criteria for selecting between them.

3. To develop design principles and tools to transfer desirable properties to networks of computers, businesses and enterprises, by testing on simulated networks, prior to pilot testing on real world networks (e.g. rail networks, business and enterprise networks).

## 5. Potential Impact

The strategic impact of this project could be very significant for the well-being and effective organisation of every member state and every citizen in the EU and EAA. Despite sustained improvements in technology and productivity, and persistent economic growth as reflected by rising GDPs, it remains the case that infrastructural problems related to instabilities and disruptions in transport and traffic flows, and manufacturing and distribution problems related to unreliable supply networks pose significant problems. These problems impinge on the overall quality of life, particularly amongst the socially disadvantaged, and also can have a negative impact on competitive advantage in manufacturing and services. Competitive advantage in the domain of science and technology led innovation, which is expected to play an increasingly important role in the knowledge-based economy, depends crucially on the appropriateness and responsiveness of the network structures that underpin successful high-tech innovation clusters. A better understanding of such innovation networks should lead to a higher success rate in establishing internationally competitive high-tech clusters, with corresponding economic benefits. This project seeks to address these problems through a deeper understanding of the nature of complex networks and by identifying ways in which man-made networks can be designed so that they function reliably and efficiently. The potential long-term benefits of this project are of such strategic significance that they could improve the quality of life of almost every member of the EU.

By conducting this research at the European level, the project will benefit from the skills of the participating partners and from the datasets that will be available. The two significant data sets to which we will have access are social data on employment, income and education for residents of the Greater Stockholm area, as well as data on the structure and performance of the companies in the area. Social data on companies in Poland will also be supplied to the project, enabling a unique opportunity to compare the findings from the two contrasting data sets. The project partners bring together a strong set of skills on statistical and other measures of the networks, from a number of perspectives, ranging from the macroscopic approach using differential equations to model the gross behaviour of a system, to the microscopic approach that focuses on the behaviour of individual agents.

Members of the project consortium are already well connected to other projects and networks on related topics, with many involved in projects in the USA and elsewhere in Europe. Prof N Johnson is a visiting professor at the Universidad de Los Andes (Bogotá), where he is collaborating on a project to develop an agent-based model of the spread of corruption. Prof Schweitzer is a member of the EXYSTENCE consortium. Prof. Schweitzer and Prof. Kogut attended a workshop on agent-based networks at the University of Oxford in October 2003, which was attended by researchers on agent-based systems from over 10 countries including Europe and beyond. An article covering the workshop appeared in the *Economist* magazine of 6 May 2004, thus disseminating the results to a wider public. Relationships between consortium members and journalists (in the print media, radio and television) will be cultivated to ensure that significant research results obtained as part of the MMCOMNET project will be disseminated to the public as widely as possible. The workshops listed in the individual work packages will also be used for public dissemination.

## 5.1 Contributions to standards

Work packages 2 and 3 may contribute to the extension of industry standards for the exchange of data in supply chains and networks.

## 5.2 Contribution to policy developments

Work package 4 may lead to recommendations which could be incorporated in policy initiatives to encourage the successful development of high-tech clusters.

## 5.3 Risk assessment and related communication strategy

There is no potential risk to society/citizens associated with the MMCOMNET project.

# 6. Project management and exploitation/dissemination plans

## 6.1 Project management

The project management will be undertaken at the University of Oxford, with the assistance of a part-time project manager. A **management committee** consisting of one representative elected from each of the six institutions will meet every 6 months in the context of an MMCOMNET workshop, to which the European Commission's Project Officer will be invited. These meetings will provide an opportunity to review milestones and outputs, to revise the project plan to meet changes in circumstances if necessary, to respond to new initiatives and identify emerging projects and proposals. Before the start of the project, each work-package will be reviewed at a meeting of all the investigators who will be contributing to that work-package. They will be asked to prepare a detailed project plan (including milestones and deliverables) for their Research Assistants (RA) and Research Students (RS). This will form the reference document against which to monitor the progress of the project. The progress of each RA and RS will be the responsibility of their home organisation. A **steering committee** will be formed that will meet annually to review progress and suggest further collaborations, sources of funding and potential applications. This committee will consist of senior academics, industrialists and the representatives of regional and national public bodies, from within the participating organisations and beyond. This steering committee may also be called for guidance, should particular difficulties arise.

The mechanisms that will be in place to maintain and support the cross-disciplinary work and international collaboration are:

- Research students will be encouraged to arrange and hold their own project workshops.
- Every member of the team will publish in journals outside their core discipline.
- Web cams will be used to link investigators in different departments and institutions quickly for short meetings, to avoid delays caused by scheduling, and to augment regular face-to-face meetings.

- Video-conferencing facilities will be used to enable review meetings and larger project presentations.

All project participants will be encouraged to participate in and attend the dissemination activities in order to maintain awareness of the project's progress.

## 6.2 Plan for using and disseminating knowledge

The research results will be disseminated to Business, Industry and the Public Services through:

- articles in the media and professional publications, building on existing relationships with journalists.
- attendance and presentations at EU conferences, seminars and workshops.
- a professionally managed web site (see http://sbs-xnet.sbs.ox.ac.uk/complexity/).
- a series of workbooks and case study reports.
- a set of one day workshops aimed specifically at SMEs and representatives of regional and national government agencies.

In addition to the above, the results of the research will be further disseminated to Academia through:

- a new book series "Complex Systems and Interdisciplinary science", published by World Scientific.
- about 20 academic papers and articles and one or more books, with at least 50% of authors publishing articles in journals outside their normal discipline.
- the web site, containing articles, simulation tools, demonstrations, videos and course material.

It is expected that the novelty and industrial focus of this research will generate a substantial portfolio of Intellectual Property, which the Partner Institutions will wish to exploit through spinout companies, licences and royalties. Prior to signing the final project contract with the European Commission, all Partner Institutions will be asked to accede to a standard Consortium Agreement which will be drawn up and circulated by the Coordinator.

## 6.3 Raising public participation and awareness

The members of the consortium will raise awareness of their own project but will also actively participate in activities that will raise the profile of the NEST-PATHFINDER "Tackling Complexity in Science" initiative in general.

The contractors will ensure that the project works with and interacts with the other projects supported by this initiative. They will seeks to collaborate and cooperate amongst each other, and participate in any "clustering" activities which may be organised in the future, e.g. workshops or joint review meetings.

In addition to the planned activities at project level, the partners of the consortium will contribute to common dissemination activities of the initiative (as e.g. organising press conferences, inviting journalists to major project events with industrial participation as part of conferences, seminars or brokerage events, etc.).

The members of the consortium will ensure that appropriate resources from the project are devoted to the efforts outlined above. Decisions on how to spend the money put aside for the specified activities on clustering and dissemination will be made by the consortium in consultation with the Commission.

# 7. Workplan– for whole duration of the project

## 7.1 Introduction - general description and milestones

The MMCOMNET project will address three overall research objectives pertinent to complex network structures encountered in different application domains. First, to develop novel characterisations and models of empirically observed and measured networks. Second, to develop techniques which allow the properties of agents or components of networks to be inferred from the dynamic properties of networks as a whole. Third, to develop design principles for the construction of networks with desirable properties. The three application domains that form the focus of this project are: biological networks, supply networks, and innovation networks. Since each domain roughly corresponds to a traditionally defined area of research, four of the Work Packages (WPs 1-4) correspond to sets of research problems within these application domains. However, it is important to note that the key focus of the MMCOMNET project is on models and techniques which can act as bridges between application domains, as well as explaining phenomena, encountered in each domain. Hence, Work Package 5 and 6 provides the organisational and methodological link that unites the different application domains.

The key milestones for the project are as follows. In WP1 the decision in month 24 whether to develop a hybrid model, combining multi-agent and PDE approaches, for fungal growth. In WP2 the decision in month 12 whether the empirical data is sufficient and appropriate for modelling. In WP3 the meeting in month 18 to compare results with WP2. In WP4 the comparison of data sets for different innovation clusters in month 18, and the development and validation of a generative network model in month 36. In WP5 the generation of an empirical data set for public transport networks in Polish cities in month 24. In WP6 the application in month 24 of new statistical tools to two databases (Stockholm data and fungal networks) and the successful development of a software package of statistical tools by month 36.

The project risk is evaluated independently for each work package, both in terms of perceived a priori risk (low, medium, high) and in terms of the ability to recover (low, medium, high) from specific failures.

| **Work Package** | **Perceived Risk** | **Ability to Recover** |
|---|---|---|
| WP 1 | medium | high |
| WP 2 | medium | medium-high |
| WP 3 | low | high |
| WP 4 | medium | high |
| WP 5 | low | high |
| WP 6 | low | high |

**WP1** Existing work shows the viability of both the multi-agent and PDE approaches to biological networks such as the fungal network, so the initial phase of this work package will be low in risk. A key decision point occurs at month 24, with regard to whether to pursue hybrid models or not. The main risk point of this project concerns the development of an experimentally supported multi-scale model of fungal growth by month 36. However, the failure of any particular approach or technique can be overcome since a number of different techniques are being pursued in parallel.

**WP2** The main risk of this work package concerns access to relevant supply chain data, and issues around the comparability of data sets from different organisations and countries. At month 12 it will be possible to review whether this constitutes a problem. However, a number of steps have been taken to ameliorate the potential risk. Some data sets have already been collected, or partially collected. Agreements are in place with manufacturing organisations for the collection of data, and the relevant consortium members have existing relationships with these organisations.

**WP3** This work package is based on the extension of a methodology which has already been established by one of the project partners, so the perceived risk is low.

**WP4** The main risk relates to access to relevant data, and to the successful exploitation of the Stockholm data base, as well as the development of generative models for innovation networks. The risk of not having access to data is not serious since the project makes substantial use of existing data sets. The format of the Stockholm data base is well known to one of the project partners, and the risk of the data not supporting the construction of relevant socio-economic networks can be overcome by the construction of suitable proxies. The development of a full generative model of innovation networks by month 36 is challenging, and as a fallback position it might only be possible to construct a partial model.

**WP5** Based on an extension of successful existing research and hence perceived as low risk.

**WP6** Based on an extension of successful existing research and hence perceived as low risk.

A more detailed description of the scientific content of the work packages, and the planned deliverables, follow.

## WORK PACKAGE 1. Biological networks

### *Description*

This Work Package corresponds to the application domain of biological networks, with a particular emphasis on fungal networks. Fungal networks represent one of the simplest biological systems that forms a true adaptive network. This provides an ideal opportunity to abstract the critical features that enable self-organisation of a network with decentralised control, and may act as a future paradigm for robust network design. Inherent in this approach is the assumption that solutions adopted by biological networks will exemplify useful generic theoretical principles, such as persistence, robustness, error-handling or appropriate redundancy, as they have been honed by many cycles of evolutionary selection.

Fungal mycelia can form extensive interconnected hyphal networks that scavenge for scarce resources extremely efficiently in a highly heterogeneous environment using a variety of foraging strategies that differ over time or between species. The architecture of the network is not static, but is continuously reconfigured in response to local nutritional or environmental cues, damage or predation, through a combination of growth, branching, fusion or regression. Embedded within the physical structure is an equally complex set of physiological processes that contribute to uptake, storage and redistribution of nutrients throughout the network in a well co-ordinated manner. Local sensory perception and responses are coupled over different range scales leading to optimisation of long-term behaviour. The overall success of each foraging strategy arises from the iterative interaction between environmental sensing, physiological adaptation and developmental re-organisation.

Unlike almost every other type of complex biological network, fungal mycelia have the major advantage that almost the entire physical system is visible and accessible. In many cases development is naturally restricted to a 2-D plane, greatly facilitating non-invasive imaging approaches to map and analyse changes in network architecture. To complement morphological mapping, comparable imaging techniques have been developed to track the dynamics of nutrient uptake and distribution. Although at an early stage, these studies have already revealed a number of novel phenomena, including abrupt switching between different pre-existing transport routes, a marked pulsatile component superimposed on the rapid underlying flux, and organization of the network into well demarcated domains differing in phase or frequency of the oscillations.

A number of modelling approaches have already been successfully applied to fungal development based on PDEs (partial differential equations) to describe distribution of mass and substrate levels over time and space. These provide a useful solution for isotropic systems, but are less suited to anisotropic situations in heterogeneous environments. They also have limited utility in understanding the behaviour of the underlying network as this feature is only loosely encapsulated in the equations used. Alternative agent-based models are better suited to handle heterogeneity across a range of scales and intrinsically capture the decentralised behaviour characteristic of mycelial systems. One promising approach that is still at a very early stage utilises a regular lattice geometry of agents that deal with fluxes of resources according to rules compatible with the anticipated physiological behaviour, to simulate the functional capabilities of the network. In this system, the network architecture becomes an emergent property of their collective behaviour. Initial indications from this agent-based system already predict canalisation of fluxes, and a shift from isotropic to anisotropic growth dependent on local nutrient supply and storage capacity.

To exploit the potential insights to be gained from using a biological system as a basis for model development demands a tight iterative cycle between abstraction of appropriate rules from the biological system and their implementation and evaluation in the simulation environment. One of the most significant reasons we have for adopting the mycelial network as a paradigm, is the possibility to close this developmental cycle by subsequent experimental testing of predictions arising from the simulation models. Thus, for example, network responses to extreme perturbation can be explored *in silico* to define conditions where the system becomes unstable. Comparable stimuli can then be applied *in vivo* to see whether the real network collapses in a similar manner or has additional properties that can handle rare, extreme events. The tight linkage possible between model and biology opens up the almost unique opportunity to develop new techniques to extract and refine appropriate rules directly from the data itself.

Although the focus of this package is on fungal networks, connections to models of other biological networks will also be pursued. One area in which one of the project partners has considerable expertise is related to hybrid models of tumour growth, in which network growth and branching is modelled with cellular automata, and transport properties are modelled with PDEs. Similarly, metabolic networks provide another type of biological network where good qualitative, albeit not necessarily quantitative, data are available. Understanding metabolic control mechanisms will have a large impact not only on devising new therapies and drugs, but also on constructing robust and efficient chemical reaction networks. Typically, in a simplified metabolic network model such as for *Escherischia coli*, chemical agents are linked if they occur in the same reaction; the type of reaction might be limited to say, carbon atom transport. It is much discussed which type of architecture would best describe such networks; here, also evolutionary relationships have to be taken into account. This type of network enables us to gain knowledge not only about modelling but also about suitable test for assessing the fit of a suggested model.

***Work Plan***

(1) Test separately the multi-agent models and PDE models against experiment results (months 1 - 12).
(2) Compare and test the output of multi-agent and PDE models against each other, in order to gain an improved understanding of the cross-over from discrete (multi-agent) models to continuous (PDE) descriptions. Investigate whether hybrid models can be constructed. (months 13 – 24).
(3) Development of an experimentally supported multi-scale model of fungal growth and nutrient transport (months 25 – 36).
(4) Abstraction and generalization of concepts, techniques and approaches developed in the context of modelling and measuring fungal networks, with a view to transferring them to other application domains (months 25 – 36).

***Deliverables***

(i) Initial results for agent-based and PDE models - publications (month 12).
(ii) Delivery of initial version of hybrid model – publications (month 24).
(iii) Workshop on transferring biological network concepts and models to other application domains, such as supply networks and innovation networks (month 24).
(iv) Delivery of full multi-scale fungal model – publications and software (month 36).

**Lead contractor: UOXF**
**Other Participants: TUD**
**Person-months: 99**
**Start month: 1**
**End month: 36**

**WORK PACKAGE 2. Supply chain and network characteristics**

Supply chains consist of many manufacturing and distribution organisations, interconnected by the flow of information, money and goods. The organisations each have a number of functions, specialising in the flow of typically more than one kind of product, but paying attention to the flow of others. Hence supply networks typically are multi-scale and consist of several kinds of networks, layered on top of each other, but with connections between each layer.

Supply networks function smoothly when the flows of information, material and money are synchronised, predictable and independent for each value chain, where a value chain refers to the flow within the network of the components contributing to a single product.. Thus, a retail organisation receives regular deliveries of the requested goods in the same quantity each day, and this flow pulls deliveries along the whole network. Each organisation therefore delivers its components in the same quantity in a co-ordinated way at regular intervals. This simple behaviour can however easily become complex for a number of reasons, such as:

- An organisation schedules its manufacturing independently of its customers, thereby cross-linking with the flows to other customers and entangling the value chains.
- The customer requests different quantities for each delivery of different products.
- A supplier fails to deliver the quantity requested.
- Total demand on the network varies.
- Faulty goods have to be returned.

In most real world scenarios, supply networks must therefore re-configure themselves dynamically to cope with these changes and to anticipate them. This involves using forecasting and frequent exchanges of information along the network to help organisations to be prepared for disruptions. Stocks of material may be held at various locations in order to cope with changes rapidly, but these are costly and may become obsolete or damaged. Alternative sources of supply of material or information may need to be identified and maintained for use in an emergency. The key question is how, despite local disruptions and loss of functionality, supply networks can be designed to retain their integrity and remain resilient and robust. In particular, to what extent is the behaviour of the system determined by the network structure, and to what extent does it depend on the behavioural characteristics of the organisations contained in the network? Empirical data on supply networks is available which can characterise both the structure and the behaviour of the nodes in the network. Information-theoretic measures of complexity have been developed for measuring the complexity of network nodes in value chains.

The research goal of this Work Package, which is closely linked to Work Package 3, is to develop models and simulations of different supply networks, based on data and tools available within the consortium, in order to develop a deeper understanding of the performance of these networks and to develop policies on how the structure and dynamic behaviour of real-world networks may be modified. In order to achieve this goal, data on the structure and dynamic behaviour of supply networks in the EU will be gathered and analysed using the tools available and to be developed within the project. This will constitute the first set of deliverables of this Work package at M12, and will also contribute to Work Package 6, which integrates the tools and techniques of the whole project.

The next eight months of the project will be concerned with understanding the behaviour of the decision-making agents within the network. Although all the networks are within the broad range of supply networks, it is likely that the behaviour of the agents will differ significantly due to cultural, technical and other reasons. Interviews with agents may need to be carried out in order to obtain models of decision-making behaviour. This phase of the project will model the behaviour of the agents and begin to understand the constraints that apply to the agents that produce the observed behaviour. These constraints may be due to the availability of good quality information, time constraints that apply to making decisions (i.e. bounded rationality) and the perceived and actual consequences of making poor quality, local decisions.

The network structure and dynamics obtained from the first phase of the project will be integrated with the models of agent behaviour obtained in the second phase to produce some models and simulations of the networks. These simulations will be compared with the macroscopic network performance observed in the real world. The simulations will be used to test the combinations of network structure, dynamics and agent behaviour in order to see which combinations achieve the effective performance with respect to robustness, efficiency and effectiveness, under different conditions of information quality, agent heterogeneity and network size. Characteristics of agent behaviour seen in the other work package domains will be compared with the findings from this work package, and the transference of agent and network characteristics will be explored as a means of achieving better network performance. The comparisons and findings from this phase will be analysed with respect to their potential to influence policy on supply network structure and local decision-making.

Small and Medium sized Enterprises (SMEs) are essential to the success of this project, since we need to understand the dynamics of information exchange across the entire supply network. This means both the exchange between large companies, between small and large companies, and between small companies. The routes to identifying SMEs are:

1. Many organisations exist to support and encourage small businesses, such as those supported in the UK by government (e.g. Regional Development Agencies, the Department of Trade and Industry), as well as local networks, e.g. Venturefest, The Oxford Trust.

Similar networks will be identified for all project partners. This approach has the advantage of identifying groups that are located within a geographical area, in order to monitor the pattern of data exchange within physically co-located supply networks.

2. We will also target communities of companies that are engaged in particular business sectors, e.g. electronics, automotive, food. This will enable identification of patterns of communication that may be appropriate for separate sectors, regardless of geographical area. These companies will be identified through trade associations, articles in newsletters and contacts through government organisations.
3. Special interest groups have already grown up to discuss and gather views on the implementation of data exchange formats. These groups will also be contacted to identify organisations that are contributing to the development of the formats, so that they may also be encouraged to participate in the gathering of data on the live exchange of data between organisations. Presentations will be made at regional meetings of these groups and project outlines submitted to their newsletters as a means of raising awareness of the project within the potential user community in general.
4. Project participants have a substantial network of personal contacts at all levels of industry and commerce. These personal contacts will also be invited to participate. We will encourage each participating company to suggest three or four of their regular suppliers and customers who may also be encouraged to participate in the scheme in order to establish the pattern of communication along longer reaches of supply chains.

Using these methods, we will be in a position to identify and establish a network of companies across Europe, spanning a range of company sizes, business sectors, and geographical location throughout Europe.

This Work Package will result in at least eight journal articles, with the intention of each article involving personnel from more than one partner organisation. Software tools will be developed and documented, and integrated with tools developed elsewhere within the consortium. The real-world applicability of this work is likely to be of interest to the popular media, so articles in the press, radio and television will be prepared in order to disseminate as widely as possible the findings and potential of this work.

**Lead contractor: UOXF**
**Other Participants: TUD, ETHZ**
**Person-months: 69**
**Start month: 0**
**End month: 36**
**Deliverables:**

WP2-D1. Datasets on supply networks, analysed and compared. Month 12

WP2-D2. Three journal articles on characteristics of supply networks. Month 12.

WP2-D3. Models of the decision-making behaviour of agents in supply networks. Month 18

WP2-D4. One day interim industrial workshop for SMEs and government agencies. Month 18.

WP2-D5. Two journal articles on agent behaviour. Month 18

WP2-D6. Simulations of supply networks that display some aspects of the observed behaviour, including software documentation. Month 36

WP2-D7. Three journal articles and two theses. Month 36

WP2-D8. One day final industrial workshop for SMEs and government agencies. Month 36.

**WORK PACKAGE 3. Dynamic flows in supply chains and networks**

This Work Package is closely linked, by virtue of focussing on the same application domain, to Work Package 2, but the methodological approach is predominantly based on the use of macroscopic state variables and system descriptions in terms of partial differential equations, rather than agent-based models and simulations. For this reason the close interaction between Work Packages 2 and 3 will play a key role in addressing Project Objectives 1 and 2. In addition, the dynamic behaviour investigated in the context of this Work Package is expected to be highly relevant to the biological systems which are the focus of Work Package 1.

Although network theory is rapidly changing our understanding of complex systems, the relevance of topological features for the dynamic behaviour of metabolic networks, food webs, production systems, information networks, or cascade failures of power grids is only poorly understood. Topological features determine relevant properties of socio-economic networks and the robustness of the world wide web. They are also conjectured to be responsible for the beating of a leech's heart, pumping effects in some slime moulds, strong variations in ecosystems, or glycolytic oscillations in yeast cells.

Models of supply networks have recently offered an interpretation of the strange instabilities and oscillations observed in these biological, ecological, economic and engineering systems. It is surprising that supply networks display damped oscillations, even when their units---and linear chains of these units---behave in an overdamped (i.e. non-oscillatory) way. Moreover, networks of damped oscillators tend to produce growing oscillations.

Supply network models offer a versatile, flexible, general and integrated approach to many problems of cross-disciplinary nature. They suggest that the network of material flows can itself be a source of instability, and cyclical variations are an inherent feature of decentralized adjustments. This offers a new interpretation of business cycles and of oscillating or pulsating processes in natural and man-made systems. The quantitative nature of this approach offers new control and optimisation potentials, which will allow one to improve production networks, traffic control, logistic processes, and supply networks. The project is expected to have impact on bioengineering and disaster management. It will particularly develop strategies to resolve the problem that industries often suffer from over-reactions in production and that disaster management struggles with a temporary clustering of forces and materials at some places, while they are missing at others. Moreover, it will offer new ways to fight ``booms'' and ``recessions''.

The expertise of one of the consortium partners in pedestrian crowd dynamics will be utilized to investigate the links of this Work Package to related problems in the fields of traffic and transportation.

**Lead contractor: TUD**
**Other Participants: UOXF, ETHZ**
**Person-months: 66**
**Start month: 0**
**End month: 36**
**Deliverables:**

WP3-D1 Initial publications on supply network models. Month 12

WP3-D2 One day workshop for SMEs and national and regional government agencies. Month 18

WP3-D3. Milestone meeting to compare interim results with Work Package 2. Month 18

WP3-D4. Publications integrating Work Packages 2 and 3. Month 24.

WP3-D5. Final one day industrial workshop for SMEs and government agencies (in coordination with Work Package 2). Month 36.

## WORK PACKAGE 4. High-tech innovation networks

### *Description*

This Work Package focuses on a particular class of socio-economic networks that link firms, individuals, and technologies. There is considerable empirical evidence that economic activity is more intense with higher value added in certain regional industrial agglomerations, such as high-tech clusters. In addition, the presence of dense industry networks (e.g. in the biotech sector) seems to be positively correlated with measures of innovation such as patenting rates. This has driven a desire at the policy level to successfully replicate such innovation network structures in new geographical areas. However, existing cross-sectional observations of different innovation networks (i.e. Route 128 vs. Silicon Valley), based either on a comparison of formal network structures or the organisational ecology populating a network, can only provide very limited guidance in understanding the fundamental processes of technological innovation and wealth creation. Instead, a dynamic model of innovation network growth and development is required, which gives equal weight to the topology of social networks and the behavioural characteristics of the organisational nodes. Ultimately, the aim is to develop generative rules for innovation networks that can be implemented in agent-based models, and validated against empirical time-series data.

Networks linking firms with each other and other organisations, such as public research organisations, can be formal and exclusive (e.g. strategic alliances) or informal and diffuse (e.g. shared communities of practice). In common with many biological network structures, organisational networks are commonly multiple, overlapping, and multi-scale. Thus, there will be institutionalised legal links between organisations, as well as informal social ties which can link research personnel through mechanisms such as co-publication or joint membership of scientific advisory boards. Standard social network analysis can only characterise such structures very inadequately, by choosing units of analysis at what *a priori* is assumed to be the relevant scale, and hence missing the potentially important interactions between different scales. For this reason one aim of this Work Package is to develop new statistical network measures, which go beyond network centrality and cohesiveness, and which are relevant to the functional behaviour of complex multi-scale and multiple network structures. These novel formal measures can be used to analyse large empirical data sets (see below), and can also serve as a starting point for understanding the nature of dynamic processes on innovation networks.

Inter-organisational networks fulfil an analogous role to the biological networks of Work Package 1, by regulating the flow of information and resources among organisations. Hence, some of the same questions about the allocation of scarce resources and the effective processing and use of information arise. However, whereas some information about technological innovations and their commercial exploitation is easily transmitted (e.g. publications, patents), other information such as tacit knowledge or know-how is inherently sticky, and requires different types of diffusion mechanisms. Moreover, even easily transmitted knowledge may be public or private and thus either more or less prone to spill-over effects. Models of knowledge transfer in innovation networks must be able to account for different transmission mechanisms for different types of knowledge. Similar considerations apply to the transmission of organisational practices. A key example in the context of this Work Package is venture capital, which can be regarded as the institutionalisation of certain types of property rights. In understanding the growth of successful high-tech clusters, it is crucial to understand how an instrument like venture capital diffuses across industries and geographies. It is notable that the aggregate properties of such dynamic processes exhibit power scaling laws, and seem to conform closely to dynamic processes in the domains exemplified by work packages 1 and

2. This also suggests that it should be possible to identify critical points by which inter-organisational networks expand robustly to new regions, creating in turn new pockets of economic activity.

Models which only consider dynamic processes and flows on fixed innovation network structures are fundamentally unsatisfactory because they cannot account for the generation and sustainability of new networks, or the evolution of network structures and possible phase transitions in terms of functional properties. Methodologically it is also preferable to pursue a modelling approach where characteristics (or decision-making processes) of heterogeneous network nodes (i.e. organizations) interact with the social and institutional network structure, with the ultimate aim of constructing generative models in which the network structure emerges from the application of plausible local rules. These generative models, and the validity of the posited local rules, can then also be validated against empirical data sets for high-tech clusters and networks, partly based on the statistical measures developed in the initial phase of the work package.

At present the participants of this Work Package have access, through collaborators, to empirical data sets which provide a coarse-grained picture over time of biotech clusters in the US and Europe (sources: Bruce Kogut (INSEAD), Lee Fleming (Harvard Business School), Fiona Murray (MIT), Walter Powell (Stanford)). The main new empirical resource which will be developed as part of WP3 is an extensive and very rich longitudinal data set of the population and businesses in Stockholm over a 10 year period which has only become available very recently is being made available by Prof Peter Hedstrom (Nuffield College, Oxford). The data is sufficiently detailed to provide longitudinal network data on different scales for high-technology firms in the Stockholm area, including ownership structures, profitability, employee movements, etc.

***Work Plan***

1. Development of new statistical measures for the characterisation of irregular, multi-scale and complex networks. This activity is also relevant to work packages 1, 2 and 6 (months 1 – 12).
2. Exploratory analysis of Stockholm census data to develop robust methodology for extracting and constructing network links (months 1 – 12).
3. Analysis and comparison of existing data sets on biotech clusters (months 1 – 18).
4. Development of models of diffusion on innovation networks (months 1 – 18).
5. Development of full generative models of innovation networks (months 18 – 36).
6. In depth analysis of Stockholm census data in order to construct empirical time-series of innovation network evolution. (months 18 – 36).

***Deliverables***

1. Models of diffusion on innovation networks – journal publications and workshop (month 18).
2. Initial extraction of relevant network data from Stockholm data – journal publications and openly available network data set (month 24).
3. Generative network models for innovation and validation – journal publications and workshop (month 36).

**Lead contractor: UOXF**
**Other participants: ETHZ, INSEAD, SU.**
**Person-months: 94**
**Start month: 0**
**End month: 36**

## WORK PACKAGE 5. Functional and Dynamic Network Characteristics

### *Description*

The function of this Work Package, together with Work Package 6, is to integrate the domain specific Work Packages (i.e. WP1, WP2, WP3 and WP4), by generating transferable techniques and methods which can be used to tackle complex problems across domains whenever appropriate. The involvement of most project partners in this Work Package also maximises the potential for the cross-disciplinary exchange of ideas and information. The overall aim is to generate modelling approaches which are genuinely and non-trivially universal and hence can be applied in a variety of different application domains.

Although there are many papers concerning the structure of evolving networks in the sense of their geometrical properties, the dynamics and critical properties of these systems are almost unknown. Current research shows notable effects even for a simple system such as the Ising spin model mapped onto the Barabasi-Albert network. The critical temperature in this system diverges in the thermodynamic limit, and this behaviour is probably caused by the existence of highly clustered subgroups of nodes in the network, in which the coordination number is very large and magnetic order can be maintained even at high temperature. It is important to stress that a network entering into the critical region exhibits large-scale fluctuations and is very sensitive to the presence of external fields. It follows that the stability of such a network changes dramatically, which is crucial for the existence of biological networks or for the efficiency of economical or innovation networks. Questions to be addressed in this context include how the presence of cycles and structural correlations (assortative and disassortative ) influences the percolation phase transition in random networks, and whether the existence of a self-similar hierarchy in the structure of a network influences the spontaneous order.

Many of the systems addresses in the Work Packages 1, 2, 3 and 4 consist of a number of coupled networks, rather than a single network, and the analytic and computational tools to deal with multiple and overlapping networks are presently underdeveloped. For instance, fungal networks often must coexist in the same habitat, supply networks generally consist of several types of loosely connected networks corresponding to different commodities, and socio-economic networks almost invariably are multiple and multi-scale. Within the project a theoretical and numerical description of multi-network systems will be created. Internal variables will be localized at networks nodes to describe dynamics of corresponding agents. Cases of cooperation and competition between different networks will be considered, and conditions for the dominance of one network by another will be studied. Structural and ordering phase transitions which appear as the result of network-network interactions in multi-network systems will also be investigated. To compliment numerical and analytical investigations the structure of public transport networks in Poland will be studied in detail from the point of view of their degree and distance distributions.

### *Deliverables*

1. Theoretical and numerical models of multi-network systems. Journal publications (month 12).
2. Statistics of public transport networks in Polish cities, journal publication and data set (month 24).
3. Models of critical properties of networks. Journal publication (month 36)

**Lead contractor: WUT**
**Other participants: UOXF, TUD, ETHZ, INSEAD.**
**Person-months: 78**
**Start month: 0**
**End month: 36**

## WORK PACKAGE 6. Statistical Network Metrics

***Description***

The function of this Work Package, together with Work Package 5, is to integrate the domain specific Work Packages (i.e. WP1, WP2, WP3 and WP4), thus enabling the transfer of techniques and methods for tackling complex problems from one area of science to another in those circumstances where it is appropriate. Hence the different research issues raised below are relevant to all previous work packages.

As network data are often noisy either due to sampling or because they are intrinsically random, a number of statistical issues arise:

1. How can we best summarize network data? Often the amount of data is overwhelming, so data-reducing summary statistics are much needed. These summaries will depend on the type of question asked about the network. For parametric models for networks, a rigorous statistical derivation of such summary statistics is envisaged; for general network models, summaries of the adjacency matrix for the networks such as eigenvalues and eigenvectors will be very useful.
2. How can we make meaningful comparisons between networks? Networks generated by the same underlying mechanism will differ from each other by chance; this needs to be disentangled from networks that are generated by a different mechanism. Here the development of metrics for networks will play a crucial role.
3. How can we classify networks? Networks generated by different mechanisms may still fall in the same category depending on which question is asked. Take for example scale-free networks, which can be generated in various ways. In practical applications, the property of scale-freeness may not always be useful; instead one could for example look for basic building blocks of networks, so-called network motifs. In biological networks a number of such motifs have already been identified. These motifs are associated with network properties such as short paths between randomly chosen vertices and robustness. Hence a rigorous study of such motifs will not only lead to classification of networks but also to guidelines on how to construct networks depending on which properties are desired.
4. How can we test hypotheses about the network? Relevant hypotheses may not only be the type of network the data come from, but also functional properties of the network, as well as the effect of parameter changes in the network.

To date the statistical properties of complex networks are poorly understood. When summarizing irregular networks, the main statistical measures used so far are the mean or median of the following: the shortest distance between two randomly chosen points, the clustering coefficient, and the vertex degrees; recently other network motifs such as cycles of some given length have also been suggested. Bayesian approaches which take prior information on well-understood networks into account when analyzing new network data have shown to be fruitful in the study of genetic networks, and this technology will be pushed further, with applications to fungal networks and to social networks in mind. As soon as one leaves the realm of Bernoulli random graphs, little is known about the statistical properties of these measures and their interplay. Hence until now network comparisons are mainly based on visual inspection. Part of our toolbox would therefore be a solid statistical foundation for these summaries, allowing for hypothesis testing on networks and the development of supporting software tools. This is strongly connected to Work Package 4.

Networks will be compared on the basis of such summary statistics, but sometimes more details on their topological structure are important. Large networks may not be sensitive to adding or removing a link between agents, but hierarchical networks may be very sensitive to the removal of an agent. When links are given weights, if the weights are not too different, then related networks may be judged not too different. Techniques and metrics used in the context of phylogenetic trees will be adapted to this more complex situation in networks.

Underlying the analysis will be a suitable class of probabilistic models for networks, such as small-world network models. Developing manageable yet informative classes of such models will be a main goal of this Work Package. Such classes will help to standardize the to date sometimes haphazard approaches to statistical network analysis.

A statistical analysis of networks will also lead to quantifiable improvements in network design. As an illustration, consider the effects of random shortcuts in an otherwise deterministic network. For small-world networks it has been shown that even a small number of shortcuts reduce the shortest path between two randomly chosen vertices dramatically, often from linear dependence on network size to only logarithmic dependence on network size. The shortest path can be viewed as the time to transmit information, or an infective virus, from one agent to another. Whereas for the spread of diseases short communication times are not desirable, for other networks a short communication time will be advantageous. This also illustrates how interventions to the network will change its properties.

Dynamics on networks not only pose an additional challenge, but they can also be used to obtain information on the structure of the network. Large networks such as the world-wide web can hardly be studied in their completeness; rather one might explore the network by running random walks on it; starting with a vertex at random and then moving to an adjacent vertex, also at random, from that vertex to another adjacent vertex, and so on. Observations from sufficiently many such random walks reveal the underlying network structure. For example, if many walks include the same small set of edges, then this indicates a bottleneck; if a random walk re-visits many edges a large number of times, this indicates high connectivity. This dynamic approach links most strongly into Work Package 5, but also touches all other Work Packages.

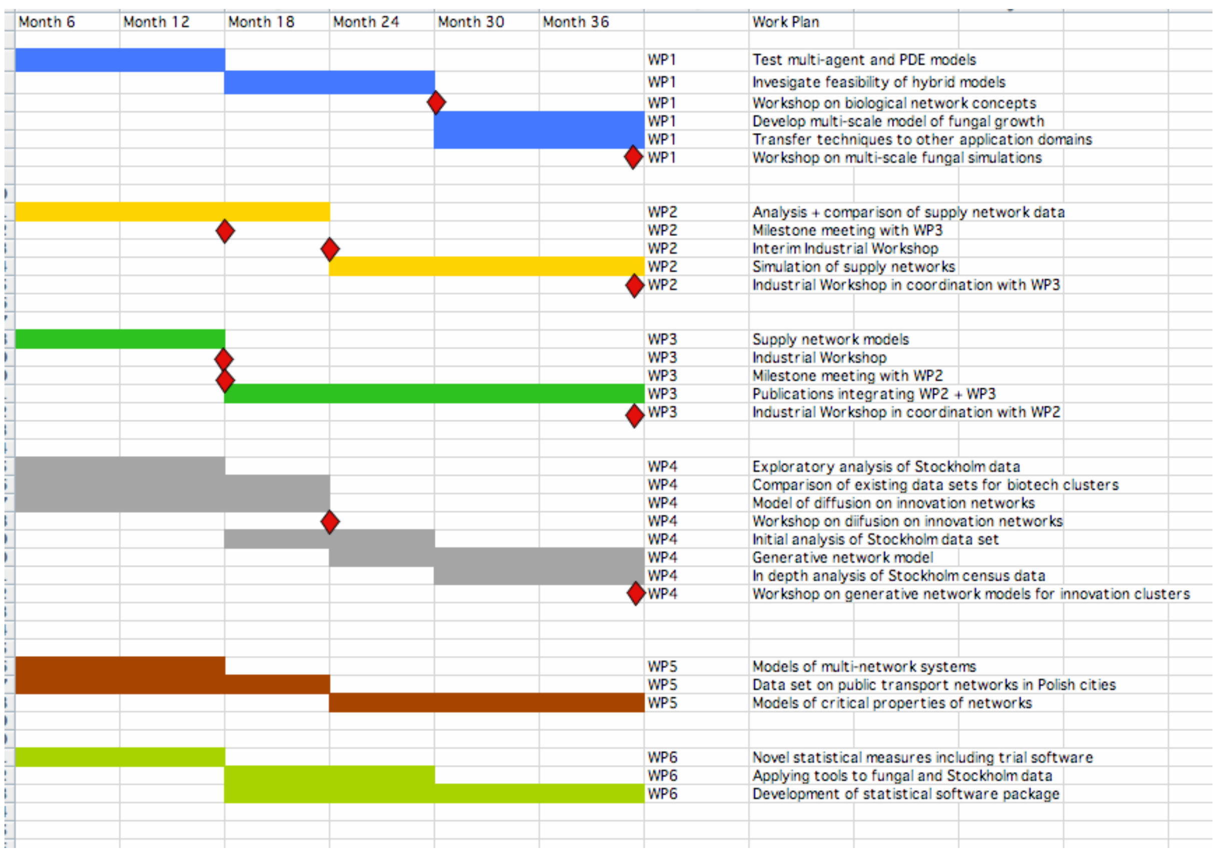
***Deliverables***

1. Novel statistical measures and summary statistics for networks – journal publications and trial software code (month 12).
2. Application of statistical tools to fungal network (WP1) and Stockholm data (WP4) (month 24).
3. Software package incorporating statistical tools (month 36).

**Lead contractor: UOXF**
**Other participants: WUT, TUD, ETHZ, INSEAD, SU.**
**Person-months: 15**
**Start month: 0**
**End month: 36**

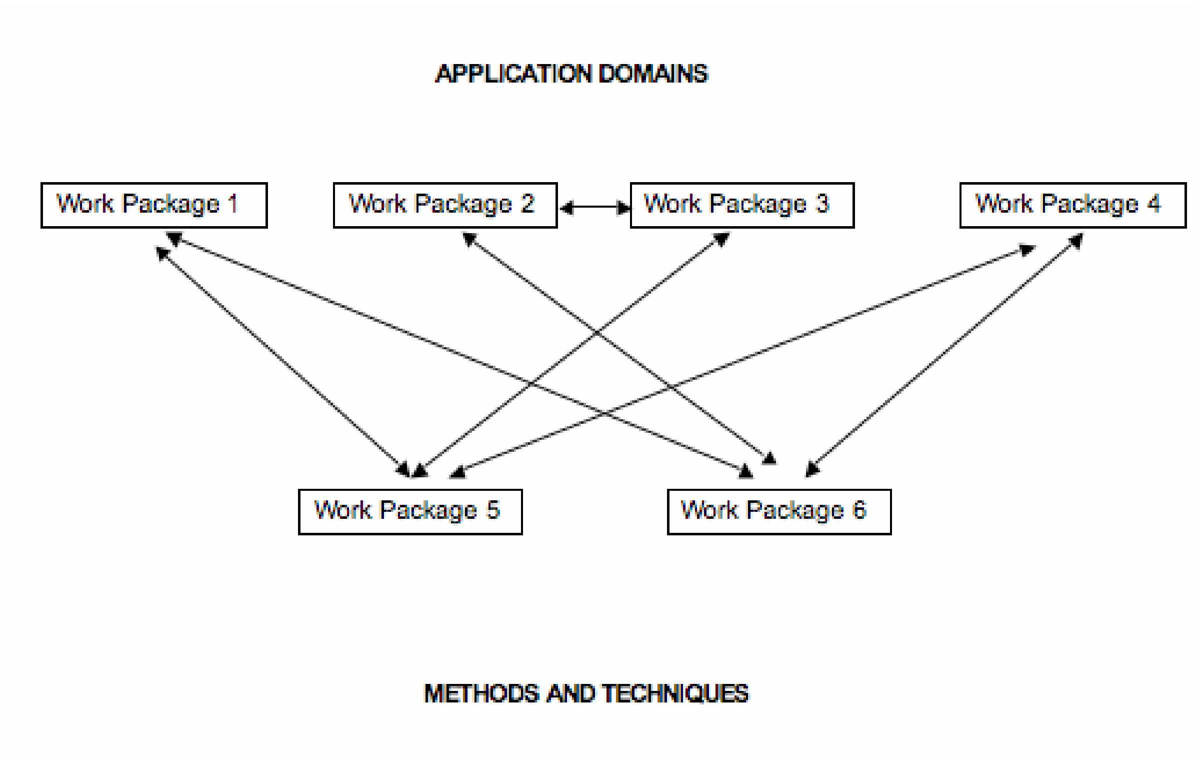
## 7.2 Planning and timetable

Details of the timing of the different phases of each work package are provided in the work package descriptions. The Gantt chart shown below gives a global overview of all activities which form part of the MMCOMNET project.



## 7.3 Graphical presentation of work packages

The graph below shows the interactions between the different work packages. The work packages can be associated with two broadly defines categories: application domains and methods and techniques. Except for Work Packages 2 and 3, which are closely related, work packages for application domains interact via the work packages (5 and 6) for methods and techniques.



## 7.4 Work package list /overview

### Work Package list (full duration of project)

| Work-package No[1] | Work Package title | Lead contractor No[2] | Person-months[3] | Start month[4] | End month[5] | Deliv-erable No[6] |
|---|---|---|---|---|---|---|
| 1 | Biological networks | 1 | 99 | 1 | 36 | WP1-1 – WP1-4 |
| 2 | Supply chain and network characteristics | 1 | 69 | 1 | 36 | WP2-1 – WP2-8 |
| 3 | Dynamic flows in supply chains and networks | 2 | 66 | 1 | 36 | WP3-1 – WP3-5 |
| 4 | High-tech innovation networks | 1 | 94 | 1 | 36 | WP4-1 – WP4-3 |
| 5 | Functional and Dynamic Network Characteristics | 3 | 78 | 1 | 36 | Wp5-1 - WP5-2 |
| 6 | Statistical Network Metrics | 1 | 15 | 1 | 36 | Wp6-1 - WP6-3 |
| | TOTAL | | 421 | | | |

1 Workpackage number: WP 1 – WP n.
2 Number of the contractor leading the work in this workpackage.
3 The total number of person-months allocated to each workpackage.
4 Relative start date for the work in the specific workpackages, month 0 marking the start of the project, and all other start dates being relative to this start date.
5 Relative end date, month 0 marking the start of the project, and all ends dates being relative to this start date.
6 Deliverable number: Number for the deliverable(s)/result(s) mentioned in the workpackage: D1 - Dn.

## 7.5 Deliverables list

### Deliverables list (full duration of project)

| Work Package No. | Deliverable No | Deliverable name | Lead Participant | Estimated person months | Delivery date | Nature | Dissemination level |
|---|---|---|---|---|---|---|---|
| WP1 | D1 | Initial results for agent-based and PDE models, including publications | UOXF | 30 | M12 | R | PU |
| WP1 | D2 | Initial version of hybrid model, including publications | UOXF | 30 | M24 | R,D | PU |
| WP1 | D3 | Workshop on transferring biological network concepts and models to other application domains, such as supply networks and innovation networks | UOXF | 5 | M24 | O | PU |
| WP1 | D4 | Delivery of full multi-scale fungal model – publication and software | UOXF | 34 | M36 | R | PU |
| WP2 | D1 | Datasets of supply networks, analysed and compared | UOXF | 20 | M12 | R | PP |
| WP2 | D2 | Three journal articles on characteristics of supply networks | UOXF | 3 | M12 | R | PU |
| WP2 | D3 | Models of the decision-making behaviour of agents in supply networks | UOXF | 18 | M18 | R | PU |
| WP2 | D4 | One day interim industrial workshop for SMEs and government agencies | UOXF | 1 | M18 | O | PU |
| WP2 | D5 | Two journal articles on agent behaviour | UOXF | 2 | M18 | R | PU |
| WP2 | D6 | Simulations of supply networks that display some of the observed behaviour, including software documentation | UOXF | 20 | M36 | R,D | PU |
| WP2 | D7 | Three journal articles and two theses | UOXF | 4 | M36 | R | PU |
| WP2 | D8 | One day final industrial workshop for SMEs and government agencies | UOFX | 1 | M36 | O | PU |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| WP3 | D1 | Initial publication on supply network models | TUD | 25 | M12 | R | PU |
| WP3 | D2 | One day workshop for SMEs and national and regional government agencies | TUD | 1 | M18 | O | PU |
| WP3 | D3 | Milestone meeting to compare interim results with Work Package 2 | TUD | 3 | M18 | O,R | PU |
| WP3 | D4 | Publications integrating Work Packages 2 & 3 | TUD | 36 | M36 | R | PU |
| WP3 | D5 | Final one-day workshop for SMEs and government agencies (in co-ordination with Work Package 2) | TUD | 1 | M36 | O | PU |
| WP4 | D1 | Models of diffusion on innovation networks – journal publications and workshop (month 18). | UOXF | 30 | M18 | R | PU |
| WP4 | D2 | Initial extraction of relevant network data from Stockholm data – journal publications and openly available network data set. | UOXF | 32 | M24 | R | PU |
| WP4 | D3 | Generative network models for innovation and validation – journal publications and workshop (month 36). | UOXF | 32 | M36 | R,O | PU |
| WP5 | D1 | Theoretical numerical models of multi-network systems. Journal publication | WUT | 25 | M12 | R | PU |
| WP5 | D2 | Statistics of public transport networks in Polish cities, journal publication and data set | WUT | 28 | M24 | R | PU |
| WP5 | D3 | Models of critical properties of networks. Journal publication | WUT | 25 | M36 | R | PU |
| WP6 | D1 | Novel statistical measures and summary statistics for networks – journal publications and trial software code | UOXF | 5 | M12 | R | PU |
| WP6 | D2 | Application of statistical tools to fungal network (WP1) and Stockholm data (WP4) | UOXF | 5 | M24 | R | PU |
| WP6 | D3 | Software package incorporating statistical tools | UOXF | 5 | M36 | R,D | PU |

## 7.6 Work package descriptions

### Work Package description (full duration of project)

| **Work Package number** | 1 | **Start date or starting event:** | | | | **Month 0** | |
|---|---|---|---|---|---|---|---|
| **Participant id** | OXFU | TUD | WUT | INSEAD | ETHZ | SU | **TOTAL** |
| **Person-months per participant** | 44 | 55 | 0 | 0 | 0 | 0 | 99 |

**Objectives**

1. Test separately the multi-agent models and PDE models against experimental results (months 1-12).

2. Compare and test the output of multi-agent and PDE models against each other. Investigate construction of hybrid models.

3. Develop an experimentally supported multi-scale model of fungal growth and nutrient transport.

4. Abstraction and generalization of concepts, techniques and approaches developed in the context of modelling and measuring fungal networks with a view to transferring them to other application domains.

**Description of work**

Develop models and abstractions of the structure and dynamics of fungal networks based on experiments and simulations. Compare agent-based simulations with descriptions based on PDEs

**Deliverables**

D1. Initial results for agent-based and PDE models, including publications.

D2 Delivery of initial version of hybrid model, including publications.

D3 Workshop on transferring biological network concepts and models to other application domains, such as supply networks and innovation networks.

D4 Abstraction and generalization of concepts, techniques and approaches from fungal networks with a view to transferring them to other application domains.

**Milestones and expected result**

M12 Delivery of initial results

M24 Delivery of initial version of hybrid model. Either develop hybrid model or develop purely agent-based model.

M36 Workshop, delivery and demonstration of multi-scale fungal simulations, or agent-based model.

# Work Package description (full duration of project)

| **Work Package number** | 2 | | **Start date or starting event:** | | Month 0 | | |
|---|---|---|---|---|---|---|---|
| **Participant id** | OXFU | TUD | WUT | INSEAD | ETHZ | SU | **TOTAL** |
| **Person-months per participant** | 41 | 3 | 0 | 0 | 25 | 0 | 69 |

**Objectives**

1. To gather data on the flow of goods, information and material through supply networks from Germany, the UK, Switzerland and Poland.

2. To apply measures of agent behaviour and network structure to the data to identify differences

3. To propose network and agent behaviour that could account for the observed behaviour and simulate networks with the proposed characteristics.

4. Measure the network characteristics under varying conditions and compare with the observed behaviour

**Description of work**

Development and application of tools developed with other project participants to the data sets on supply networks and traffic flows. Document software developed and write up findings as reports, articles and items in the popular media. Develop simulations, in collaboration with project partners, to test and compare performance of supply networks. Conduct interviews with agents in real-world networks to understand decision-making behaviour and information characteristics. Identify desirable characteristics of networks and propose means of adjusting simulations to display new behaviour. In collaboration with partners, develop links between micro- and macro-behaviour of the networks and propose methods for selecting between candidate solutions.

**Deliverables**

1. Datasets on supply networks, analysed and compared. Three journal articles.

2. Models of the decision-making behaviour of agents in supply networks. Two journal articles

3. Simulations of supply networks that display some aspects of the observed behaviour. Software documentation. Three journal articles and two theses.

**Milestones and expected result**

M12 Data acquired and analysed. Software documented. Differences between supply networks identified. Structure and dynamic characteristics of networks modelled.

M20 Interviews with decision-making agents completed. Analysis of decision-making strategies

M36 Simulations completed, using combinations of network structure and agents' decision-making. Differences in observed behaviour at least partially accounted for.

# Work Package description (full duration of project)

| **Work Package number** | 3 | **Start date or starting event:0** | | | | | |
|---|---|---|---|---|---|---|---|
| **Participant id** | OXFU | TUD | WUT | INSEAD | ETHZ | SU | **TOTAL** |
| **Person-months per participant** | 4 | 20 | 0 | 0 | 42 | 0 | 66 |

**Objectives**

Conduct time series analysis of material flows in production systems to investigate the onset of instabilities.

Develop models of material flows in supply chains in which the generation of instabilities is endogenous.

Investigate the extent to which such models can be applied to the biological networks investigated in Work Package 1.

To investigate the application of the findings to public policy and SMEs to encourage the diffusion of innovation.

Validate the new statistical measures and models developed elsewhere in the Work Packages of the consortium.

**Description of work**

Develop models of supply chains which exhibit endogenous instabilities, and compare with empirical time series data. Compare PDE based approaches used in the Work Package to agent-based results from Work Package 2. Extend and translate models for applications to the biological systems investigated in Work Package 1.

**Deliverables**

1. Initital publications on supply network models (month 12)
2. One day workshop for SMEs and national and regional government agencies (month 18)
3. Publications integrating Work Packages 2 & 3

**Milestones and expected result**

Month 18 Milestone meeting to compare interim results with Work Package 2.

Month 36 Final one day industrial workshop for SMEs and government agencies (in co-ordination with Work Package 2)

## Work Package description (full duration of project)

| **Work Package number** | 4 | **Start date or starting event:0** | | | | | |
|---|---|---|---|---|---|---|---|
| **Participant id** | OXFU | TUD | WUT | INSEAD | ETHZ | SU | **TOTAL** |
| **Person-months per participant** | 50 | 0 | 0 | 41 | 1 | 2 | 94 |

**Objectives**

1. Develop new statistical measures of networks.
2. Analyse Stockholm census data to identify network links
3. Compare with biotech clusters
4. Develop models of diffusion on innovation networks
5. Develop full generative models of innovation networks
6. In depth analysis of Stockholm census data to construct empirical time series of innovation networks evolution.

**Description of work**

Conduct statistical and time series analysis of census data using new established measures of network structure.

Carry out similar analysis on biotech networks and compare findings with Stockholm data.

Develop models that explain this behaviour and that may provide explanatory power for other systems.

To investigate the application of the findings to public policy to encourage the diffusion of innovation.

Validate the new statistical measures developed elsewhere in the Work Packages of the consortium.

**Deliverables**

4. Models of diffusion on innovation networks – journal publications and workshop (month 18).
5. Initial extraction of relevant network data from Stockholm data – journal publications and openly available network data set.
6. Generative network models for innovation and validation – journal publications and workshop (month 36).

**Milestones and expected result**

Month 18 Workshop on diffusion networks, including publications and demonstrations of findings.

Month 36 Generative network models. Presented at end of project workshop.

# Work Package description (full duration of project)

| **Work Package number** | 5 | **Start date or starting event:0** | | | | | |
|---|---|---|---|---|---|---|---|
| **Participant id** | OXFU | TUD | WUT | INSEAD | ETHZ | SU | **TOTAL** |
| **Person-months per participant** | 1 | 1 | 74 | 1 | 1 | 0 | 78 |

**Objectives**

1. To generate models and a theoretical framework which capture the critical properties of networks.

2. Generate theoretical and numerical descriptions of multi-network systems

**Description of work**

To develop measures that identify the transition of a network from one qualitative condition to another, and that can predict the onset of new behaviour.

To simulate and analyse the behaviour of multi-network systems.

**Deliverables**

1. Theoretical and numerical models of multi-network systems. Journal publication

2. Statistics of public transport networks in Polish cities, journal publication and data set.

3. Models of critical properties of networks. Journal publication.

**Milestones and expected result**

No milestones

# Work Package description (full duration of project)

| **Work Package number** | 6 | | **Start date or starting event:0** | | | | |
|---|---|---|---|---|---|---|---|
| **Participant id** | OXFU | TUD | WUT | INSEAD | ETHZ | SU | **TOTAL** |
| **Person-months per participant** | 10 | 1 | 1 | 1 | 1 | 1 | 15 |

**Objectives**

1. Integration of domain-specific techniques and methods for measuring complex systems

2. Generate robust and generalisable techniques for characterising real world dynamic networks

**Description of work**

Develop novel statistical measures and develop software tools that allow the application of these measures to data sets generated in different application domains; in particular to

1. Establish summary statistics and metrics for network data analysis
2. Suggest suitable classes of network models, and tools to discriminate between networks and to classify networks
3. Establish statistical tests for hypotheses on networks.

**Deliverables**

D1. Novel statistical measures and summary statistics for networks – journal publications and trial software code.

D2. Application of statistical tools to fungal network (WP1) and Stockholm data (WP4)

D3. Software packages incorporating statistical tools

**Milestones and expected result**

M12 Tutorial paper on available statistical tools for network analysis; trial software code

M24 Research papers on suitable metrics for networks and the interplay between summary statistics; application to fungal networks and Stockholm data

M36 Software package and comprehensive overview on the newly developed techniques.

# 8. Project resources and budget overview

## 8.1 Efforts for the project
## (STREP/STIP Efforts Form in Appendix 1)

### STREP/STIP Effort Form - Full duration of project

Project number (acronym): MMCOMNET

| *STREP/STIP Activity type* | | | | | | | |
|---|---|---|---|---|---|---|---|
| | UOXF MQ | TUD | WUD | INSEAD | ETHZ | SU | TOTAL ACTIVITIES |
| RTD/Innovation activities | | | | | | | |
| Biological Networks | 44 | 55 | 0 | 0 | 0 | 0 | 99 |
| Supply Chains and Network Characteristics | 41 | 3 | 0 | 0 | 25 | 0 | 69 |
| Dynamic Flows in supply chains and networks | 4 | 20 | 0 | 0 | 42 | 0 | 66 |
| High-tech Innovation Networks | 50 | 0 | 0 | 41 | 1 | 2 | 94 |
| Functional and Dynamic network characteristics | 1 | 1 | 74 | 1 | 1 | 0 | 78 |
| Statistical Network metrics | 10 | 1 | 1 | 1 | 1 | 1 | 15 |
| Total research | 150 | 80 | 75 | 43 | 70 | 3 | 421 |
| Demonstration activities | | | | | | | |
| Total demonstration | | | | | | | |
| Consortium management activities | | | | | | | |
| Total consort. management | 7.2 | | | | | | |
| TOTAL per Participant | 157.2 | 80 | 75 | 43 | 70 | 3 | |
| Overall TOTAL EFFORTS | | | | | | | 428.2 |

## 8.2 Overall budget for the project (Forms A3.1 & A3.2 from CPFs)

## Form A3.1

| Participant no. | Organisation short name | Cost Model used | Estimated eligible costs and requested EC contribution (whole duration of project) | | RTD or innovation related activities | Demonstration activities | Consortium Management Activities | Total |
|---|---|---|---|---|---|---|---|---|
| 1 | UOXF | AC | | Direct Costs | 422,904 | | 33,445 | 456,349 |
| | | | | of which subcontracting | | | 4,000 | 4,000 |
| | | | Eligible | Indirect costs | 84,581 | | | 84,581 |
| | | | Costs | Total eligible costs | 507,485 | | 33,445 | 540,930 |
| | | | Requested EC Contribution | | 507,485 | | 33,445 | 540,930 |
| 2 | TUD | AC | | Direct Costs | 204,987 | | 2,000 | 206,987 |
| | | | | of which subcontracting | | | 2,000 | 2,000 |
| | | | Eligible | Indirect costs | 40,997 | | | 40,997 |
| | | | Costs | Total eligible costs | 245,984 | | 2,000 | 247,984 |
| | | | Requested EC Contribution | | 245,984 | | 2,000 | 247,984 |
| 3 | WUT | AC | | Direct Costs | 205,820 | | 3,000 | 208,820 |
| | | | | of which subcontracting | | | 3,000 | 3,000 |
| | | | Eligible | Indirect costs | 41,164 | | | 41,164 |
| | | | Costs | Total eligible costs | 246,984 | | 3,000 | 249,984 |
| | | | Requested EC Contribution | | 246,984 | | 3,000 | 249,984 |
| 4 | INSEAD | FC | | Direct Costs | 287,387 | | 3,600 | 290,987 |
| | | | | of which subcontracting | | | 3,600 | 3,600 |
| | | | Eligible | Indirect costs | 114,955 | | | 114,955 |
| | | | Costs | Total eligible costs | 402,342 | | 3,600 | 405,942 |
| | | | Requested EC Contribution | | 189,216 | | 3,600 | 192,816 |
| 5 | ETHZ | AC | | Direct Costs | 205,820 | | 5,000 | 210,820 |
| | | | | of which subcontracting | | | 5,000 | 5,000 |
| | | | Eligible | Indirect costs | 41,164 | | | 41,164 |
| | | | Costs | Total eligible costs | 246,984 | | 5,000 | 251,984 |
| | | | Requested EC Contribution | | 246,984 | | 5,000 | 251,984 |
| 6 | SU | AC | | Direct Costs | 10,440 | | 3,000 | 13,440 |
| | | | | of which subcontracting | | | | 0 |
| | | | Eligible | Indirect costs | 2,088 | | | 2,088 |
| | | | Costs | Total eligible costs | 12,528 | | 3,000 | 15,528 |
| | | | Requested EC Contribution | | 12,528 | | 3,000 | 15,528 |
| **TOTAL** | | | **Eligible Costs** | | **1,662,307** | **0** | **50,045** | **1,712,352** |
| | | | **Requested EC Contribution** | | **1,449,181** | **0** | **50,045** | **1,499,226** |

## Form A3.2

**CONTRACT PREPARATION FORM (STREP/STIP) A3.2**

| Start Month | End Month | Total | In which the first six months |
|---|---|---|---|
| 1 | 18 | 778412 | |
| 19 | 36 | 720814 | 350000 |
| | | | |
| | | 1499226 | |

## 8.3 Management level description of resources and budget.

The resources for the project will be located at the six partner organizations in the EU and EAA. The project will fund salaries and expenses for one part-time post-doctoral research assistant and ten research students or early stage researchers. In addition, the time of twelve experienced research post-holders will also be contributed to this project. The allocation of researchers at the participating organizations is shown in Table 1 below.

| **Research organisation** | **Pre-existing post-holding researchers** | **Researchers to be appointed** |
|---|---|---|
| University of Oxford, UK | Dr M Fricker,<br>Prof P Hedstrom<br>Prof N Johnson<br>Dr F Reed-Tsochas<br>Prof G Reinert<br>Dr J Efstathiou<br>Prof P Maini | 1 part-time Research Assistant (supervised by Prof P Hedstrom, with the involvement of Prof G Reinert and Dr F Reed-Tsochas);<br>3 Doctoral research students or Early Stage Researchers (supervised by Dr J Efstathiou, Dr F Reed-Tsochas and Prof N Johnson) |
| Dresden University of Technology | Prof D Helbing | 2 Doctoral Research Students<br>or 40 person months Research Assistant |
| Politechnika Warszawska (Warsaw University of Technology) | Prof J Holyst | 2 Doctoral research students or Early Stage Researchers (4 years of research experience) |
| INSEAD Business School | Prof B Kogut | 1 Research Assistant |
| Swiss Federal Institute of Technology Zurich | Prof F Schweitzer | 2 Doctoral Research Students or Early Stage Researchers. |
| University of Stockholm | Prof Edling | No research students or research assistants |

**Table 1.** Human resources participating in the project

The data analysis task at Oxford University requires the greater experience of a post-doctoral researcher, and so one of the posts at Oxford University is funded as a half-time three-year post-doctoral appointment. Similarly, at INSEAD a Research Assistant will be appointed. Four of the six participating organizations have two or three research students or early stage researchers, providing a good cohort of young researchers who can communicate and exchange ideas and results.

The material resources that will be deployed on this project are data on networks (e.g. biological, supply networks, innovation networks) and computer resources for analysing and simulating network configuration. Prof Peter Hedstrom (Nuffield College, University of Oxford) will supply a rich, deep and extensive longitudinal data set on the networks of connections between companies in the Greater Stockholm area. This will be a valuable contribution to the project, especially for Work-package WP4 High-tech innovation networks.

The travel budget is to cover travel to meetings within the EU to visit research collaborators and industrial colleagues, and to attend EU conferences on relevant topics. It is estimated that this travel budget will be enough to pay for one EU conference visit each year and two or three short visits or one longer visit each year to other researchers in the network. We estimate that this level of support is necessary and sufficient to provide the level of communication and integration that this project requires.

Prof. Dr. Dr. Frank Schweitzer has recently moved from the Fraunhofer Institute for Autonomous Intelligent Systems to the Swiss Federal Institute for Technology (ETH). Despite his move from a Member State to an Associated State, he remains a member of the project consortium. His contribution to the project is vital, because of his very extensive experience in modelling agent-based systems. He is already closely integrated with a large network of EU institutions and researchers, and will be able to make unique contributions to the project.

## 9. Ethical issues

The proposed research does not involve the use of human beings, human biological samples (including stem cells), genetic information or animals of any species. See Table 4.

Personal data on the inhabitants of the Greater Stockholm area will be made available to this project, but under strictly controlled conditions of anonymity, as set by the Swedish authorities. The data also has an expiration date, so that it will be impossible to retain the data after the end of the project. The use of the data will conform to the applicable national and international regulations and codes of conduct, including the Data Protection Act of the UK. The data will be social data, such as employment, salary and education. Genetic data is not included in this databank.

Of the eleven established researchers on this project, two are female (Dr Gesine Reinert and Dr Janet Efstathiou). Both will be playing significant roles in the management and research direction of this project. Where it does not contravene local legislation, Research Assistant and Research Student posts will be advertised so as to encourage applications from female researchers who have the equivalent qualifications as male applicants. All project participants, male and female, will be encouraged to take advantage of training and courses available within their environments to acquire additional career skills.

The outcomes of this research will be disseminated widely (see B5 Project Management above) to industry, business and the public services. Courses, workbooks, articles and seminars will be organized at national and international levels, in order to encourage exchange of experience an ideas by industrial collaborators at all levels, from large international corporations to Small and Medium-sized enterprises. Articles on television and radio will also be created through our network of contacts in the print and electronic media.

Professional development courses, and undergraduate and graduate university courses will also be created and tested as part of the outreach of this course.

The potential benefits of this project to improving the performance, efficiency and reliability of public services could be significant, and could benefit many millions of members of the public in the EU and EAA states.

| **Does you proposed research involve** | **Yes** | **No** |
|---|---|---|
| **Human beings** | | ✔ |
| Persons not able to consent | | ✔ |
| Children | | ✔ |
| Adult healthy volunteers | | ✔ |
| **Human biological samples** | | ✔ |
| Human embryonic stem cells in culture | | ✔ |
| Human foetal tissue/human fetuses | | ✔ |
| **Personal data (whether identified by name or not)** | ✔ | |
| **Genetic information** | | ✔ |
| **Animals (any species)** | | ✔ |
| Transgenic animals | | ✔ |
| Non-human primates | | ✔ |
| Dogs, pigs, cats | | ✔ |

# Appendix A – Consortium Description

## A.1 Participants and Consortium

### Participating Organisations

**<u>Oxford University, UK</u>**

The University of Oxford is globally renowned for the quality and diversity of its research, with over 3000 academic staff and 3000 postgraduate students working on research. Oxford has a total staff of over 16,000, including about 4,860 research-active personnel. Amongst its 16,500 students, a quarter are of European and international origins, covering 130 nationalities. The University consists of over 70 main departments structured into five Divisions and housing a variety of subdepartments, schools, institutes and research centres of international standing. The latest Research Assessment Exercise shows Oxford having more academics working in world-class research departments (ranked 5 or 5*) than any other UK university. The University's position as a centre of academic excellence is consolidated by its ongoing development of inter-disciplinary research centres and groups cutting across traditional subject boundaries, many of which collaborate with international academic and industrial partners.

In 2002, Oxford University claimed first place in the annual *Times Good University Guide,* which ranks universities according to the quality of teaching and research, as well as indicators including staffing levels, facilities spending and graduate destinations. Oxford, Stanford and Yale Universities have recently become partners in a joint 'distance learning' venture, the Alliance for Lifelong Learning, which will provide on-line courses in the arts and sciences initially to their combined 500,000 alumni. Isis Innovation, the University's technology transfer company, files on average one new patent application a week and spins out a new company from University research every two months. Oxford has spun out more companies than any other UK university. Our spin-out companies are collectively worth around £2 billion, and have helped produce some 30 multi-millionaires.

The University of Oxford has a long-term, successful relationship with the European Union's research programmes. On average, Oxford has approximately 240 ongoing contracts with the Commission at any given time, producing ca. 8 million Euro per annum in research income (out of ca. £163 million annual external research income plus £65 million in government research grants ~ 342 million Euro in total). Over the last couple of years (FP4-FP5) Oxford has had an average of 65 new EU contracts per year with a total worth of 11 million Euro.

Oxford also has links with many European universities through: SOCRATES (ERASMUS) exchange programmes; membership of the Coimbra Group of European universities; membership of the Europaeum, a group of leading universities promoting staff and student exchange, joint research, and conferences and summer schools in European Studies. All European research projects are supported by administrative staff and experienced personnel drawn from across the University of Oxford, in particular from Research Services for management, contractual and legal issues, Research Accounts for financial reporting, Departmental Administrators for the day-to-day project management and ISIS Innovation Ltd., the University of Oxford's knowledge and technology transfer company, for the protection and exploitation of knowledge-related issues.

The CABDyN Research Cluster (see http://sbs-xnet.sbs.ox.ac.uk/complexity/) was established in Oxford in July 2003 with start-up funding from the EPSRC. Since inception CABDyN has been conceived as a highly interdisciplinary research cluster with a focus on the functional and dynamic properties of complex systems and networks in a broad cross-disciplinary range of application domains, which traverse the social, physical, mathematical, life and engineering sciences. As a result more than ten University Departments are currently participating in CABDyN's activities, and international collaborations are being developed both with Europe and the United States.

**Dresden University of Technology, GERMANY**

*Dresden University of Technology* was founded in 1828 and educates 30,000 students each year. According to national rankings, it is one of the leading German full universities with a focus on technological and related subjects. It is involved in more than 50 SOKRATES networks and 20 EU projects, and coordinates several of them. Moreover, it maintains a complete *Faculty of Traffic and Transportation Sciences,* whose complexity and completeness is unique in Europe. The concept of this faculty is a multi-disciplinary one, covering traffic engineering and transportation economics. Its scope reaches from individual over public traffic up to freight transport, from road over rail traffic up to air traffic, from transportation infrastructure up to spatial and macro-economics, from transportation telematics and automation up to information technology, from traffic psychology over transportation policy up to ecological mobility, from logistics over tourism up to communication economics.

The institution more directly involved in the present project will be the Center of Excellence for Transport and Communication. The *Center of Excellence for Transport and Communication (CoETC)* is being established as an international institute at Dresden University of Technology with yearly changing focus programs in the area of complex systems. Between 20 to 40 leading scientists, PhD students and postdocs will be invited each year for periods up to 10 months to contribute to an interdisciplinary effort in emerging research areas with promising applications. The focus areas will be *communication processes* (self-organized communication networks, data routing, ad-hoc and sensor networks, ubiquitous computing, learning and self-healing information systems, data compression and safety, attack tolerance, encryption), *transport processes* (emergent phenomena in traffic and pedestrian flows, driver information and traffic assistance systems, intervehicle communication, adaptive traffic control in street networks), *logistics and production* (simulation and on-line scheduling of production and supply networks, stability of material flows under variable and unreliable conditions, business cycles, optimization of good flows and distribution networks), *urban and regional systems* (non-linear interactions of traffic, urban, and economic evolution considering demographic effects, migration and tourism, implications of EU enlargement, scaling laws of energy, supply and traffic systems), *socio-economic networks and decision processes* (flexible and robust infrastructures, decentralized control, optimal use of scarce resources, emergent "macroscopic" socio-economic dynamics based on "microscopic" interactions), *catastrophe dynamics and disaster management* (cascade failures and large-scale blackouts, robustness of critical infrastructures, redundant and adaptive supply networks, optimization of communication structures and information flows), *transport and communication in biological and medical systems* (cellular transport processes and transport of drugs in the body, spatio-temporal spreading of diseases and epidemics, functioning of the immune system, genetic regulation and protein networks, information flows in neural networks).

**Warsaw University of Technology, POLAND**

The origins of Warsaw University of Technology date back to 1826 when engineering education was begun in Warsaw Institute of Technology. Warsaw University of Technology is the largest academic school of technology in Poland, employing 2.000 professors. The number of students is 30.000, most of them study full-time. There are 17 faculties covering almost all fields of science and technology.

The Faculty of Physics was established in 1999, however the tradition of physics at the Warsaw University of Technology (WUT) is 100-years old. The first formal Chair of Physics was created in 1919 and the independent Chairs existed up to 1965 when the Institute of Physics was founded. Ten years later this Institute and the Institute of Mathematics formed together the Faculty of Applied Physics and Mathematics, which existed up to 1999. Currently the Faculty of Physics employs 81 academic teachers, among them 27 associate professors and professors, in this 11 full professors. Within the Faculty of Physics the Research Group in "Nonlinear Dynamics in Complex Systems", led by Prof. Holyst, conducts research in working areas which include the dynamics of complex systems, evolving networks, the dynamics of thin liquid layers, deterministic chaos, and the implementation of physics in economics and sociology.

## INSEAD, FRANCE

INSEAD (www.insead.edu) is widely recognised among the world's top-tier business schools as one of the most innovative and influential. It is the only business school with full-fledged campuses in Asia (Singapore) and Europe (Fontainebleau). Currently, 147 faculty members teach more than 800 MBA students, 6,500 executives and 73 PhD students from over 90 countries. The INSEAD Executive MBA was launched in autumn 2003. INSEAD's unique global perspective and multicultural diversity are reflected in all aspects of its research and teaching. The INSEAD-Wharton Alliance, announced in May 2001, combines INSEAD's resources with those of Wharton's campuses in Philadelphia and San Francisco, to deliver business education and research across a Global Learning Network.

Begun in 1989, the four-year PhD programme in management prepares students for an international academic career. In 2003 13 candidates were admitted, bringing the total number of students enrolled to 73 from 24 countries. They are specialising in Decision Sciences, Finance, Production & Operations Management, Strategy, Marketing and Organisational Behaviour. In the programme 47 courses are offered and 75 faculty members are involved. Comprised of graduates placed at leading institutions around the world, the number of INSEAD PhD alumni currently stands at 49. Business schools to which INSEAD graduates have been appointed include Boston, Carnegie Mellon, Chicago, Emory, Harvard, IESE, IMD, LBS, Northwestern, Stanford, Wharton and Yale. Through INSEAD Fellowships, the school is able to provide full financial assistance for a period of four years for all candidates currently enrolled on its PhD programme. Additional financial support is also given to students who have obtained some outside financial support.

There are 147 resident faculty at INSEAD representing 33 nationalities. In addition to the teaching in the MBA, PhD and executive education programmes, INSEAD faculty research represents a major contribution to the academic study of international business and economics. The faculty drive INSEAD's research activities and course development, with support from the school's PhD students and research associates. In 2003, INSEAD faculty published 19 books, 123 case studies and 93 articles in academic journals. During the year, 327 research projects were in progress. The school's aim to produce leading-edge, relevant course materials and research is underpinned by close collaboration between faculty and business leaders worldwide, in all spheres of industry and commerce.

## ETH, SWITZERLAND

The Swiss Federal Institute of Technology Zurich (ETH Zurich) is an institution of the Swiss Confederation dedicated to higher learning and research. Together with the ETH Lausanne and four research institutes, it forms the federally directed, and to a major degree financed, ETH domain. The institutions of the ETH domain uphold their autonomy and identity on the basis of the ETH

Federal Law and in the full awareness of their social, economic and cultural responsibility to the nation and its citizens.
In education, research, and services the ETH Zurich measures itself against the highest recognised international standards. It promotes science and scientific activity for their own sakes, as well as for their importance to the near and distant context: the city and canton of Zurich, Switzerland, Europe, the world. The ETH Zurich consciously directs its activities to the needs of human beings, nature and society. It is aware that knowledge and skills must be grounded in a fundamentally open and dynamic attitude if they are to be truly useful in practical life and capable of growth. With its focus on the conservation of the Earth's ecosystem for future generations, the ETH Zurich endeavours to apply its knowledge and skills to its utmost, aware that voluntary economies can also be creative.

Solutions to mankind's most urgent problems -- poverty, hunger, disease, the threat to our very existence due to the spread of human civilisation -- demand that we find new approaches to knowledge and skills. It believes that a network of knowledge and skills acquired in an interdisciplinary environment best respond to the natural and cultural interdependencies of life. By integrating the natural sciences, technology, the humanities and social sciences, we can devise innovative concepts of education and research which will allow us to tackle the enormous challenges facing mankind, and help lay a path for a meaningful and sustainable development of present and future civilisations.

The ETH Zurich imparts to its students the highest state of knowledge and practical skills. It seeks to enable young people to find their orientation in a complex and rapidly changing world, and to stimulate an understanding of ethical and cultural values so that, upon completing their studies, they will be not only highly qualified professional people but also responsible members of society.

The ETH Zurich is not content with mere participation in solving already known problems. In the context of global civilisation, it must respond to changing conditions, it must identify new problems as a kind of early warning system, and assume a leading role in seeking solutions. In doing so, it depends on the spirit of discovery, innovative force, and flexibility in its members.

As a technical university in a small country, the ETH Zurich can only compete with the world's best by establishing international links, by recruiting its academic and research staff worldwide, and by remaining attractive to students from abroad. The multicultural tradition of Switzerland, its cultural heritage acquired over many generations, provide in our view a strong base for this purpose.

The basis of education at the ETH Zurich is formed by the core areas of engineering, natural sciences, architecture and mathematics. In addition, courses in physical education and military sciences are offered. The goal of instruction is to enable the students to acquire solid technical knowledge, practical skills, and the ability to take part in interdisciplinary activities. Relying on an atmosphere of a mutual trust among teachers and students, and a reciprocal awareness of social and ethical concerns, the ETH Zurich encourages in its students both individual creativity and the ability to reflect on and evaluate their own actions, with the aim of achieving a comprehensive outlook and a responsible mode of behaviour. Considering the need for a new approach to knowledge and technology and a better understanding of the nature of man, the ETH Zurich treats the humanities and social sciences as integral parts of its educational profile.

At the ETH Zurich teaching and research are closely linked. Equal standing is assigned to knowledge-oriented basic research and to problem-solving research. Both areas are dedicated to fulfilling the highest standards, and are long-term oriented. The ETH Zurich is specially committed to the continuous development of that innovative potential within society and industry. As an institute of higher learning and research, the ETH Zurich cultivates an international standing. It is aware that its scientific contribution has to be confirmed by the international research community.

Thus the ETH Zurich strongly supports international co-operation in all fields of research and education. As a long-term strategy, it also devotes special attention to structurally and economically underdeveloped countries. The ETH Zurich encourages partnerships and interdisciplinary co-operation among members of its community, with other educational and research institutions, with industry, and with the public administration, and it believes in keeping the public informed regarding these activities. The sustainable development of human society depends on our efforts both to create and support a strong and innovative economy.

**University of Stockholm, SWEDEN**

Stockholm University is a centre for higher education and research, organised into four faculties: natural sciences, humanities, social sciences and law. its 34,000 students and 3,570 permanent employees make Stockholm University one of Sweden's largest educational establishments as well as one of the largest employers in the Stockholm area. Undergraduate education is pursued alongside postgraduate studies and research at the four faculties. With about 80 departments offering approximately 1050 courses and 45 study programmes each year, the university is able to provide a wide variety of choices to meet the needs of its students.

Research is focused at basic research but also at more applied research and it is carried out in subjects ranging from Oriental Languages, High-Energy Physics, and the Legal Dimension of European Integration to Medieval History, Philosophy, Immigration Issues, Ecological Economics and the Conservation of Natural Resources. In the Social Sciences, well-established areas of expertise include Criminology, Democracy and Bureaucracy, Demography, International Migration and Ethnic Relations, International Studies, Labour Markets, Longitudinal Studies in the Social Sciences, Medical Sociology, Public Sector Administration and Policy, Public Health and Health Care, Social Research on Alcohol and Drugs.

**Participant CVs**

**Oxford University, UK**

**EFSTATHIOU, Janet.** Department of Engineering Science, University of Oxford

Janet Efstathiou (http://www.robots.ox.ac.uk/~manufsys/janet.htm) is a Reader in the Department of Engineering Science at the University of Oxford, where she runs the Manufacturing Systems Group. Janet took at BA in Physics at Oxford University and PhD in Computing at the University of Durham. The main recent funded research projects are on Complexity in the Supply Chain and Mass Customisation. Details of the projects may be found on the group's website at: http://www.robots.ox.ac.uk/~manufsys. The MSG's research approach is a combination of theoretical modelling, computer simulation and case studies of industrial organizations. The two research projects mentioned above are both supported by a consortium of organizations actively involved in projects at any one time. The research interests are complexity of mass customizing systems, mass customizing supply chains, manufacturing system complexity and the complexity of scheduling. Janet is author of over 100 publications in the areas of Artificial Intelligence and Manufacturing Systems complexity.

**FRICKER, Mark.** Department of Plant Sciences, University of Oxford.

Mark Fricker (http://dps.plants.ox.ac.uk/external/) is a Lecturer in the Department of Plant Sciences. His main area of research is imaging signaling and transport in intact plant and fungal systems operating in their correct tissue context. The interest in complexity has arisen in two areas - first, in trying to understand the network of interactions that underpin stomatal responses, one of the archetypal plant signaling system, and second, in mapping the fluxes of nutrients and control over their distribution in the physical network of foraging fungal mycelia. The fungal mycelium provides a unique opportunity to study network architecture and how it develops in response to varying stimuli as the entire system is visible. The new imaging and analysis techniques developed provide an opportunity to assess the functional transport capabilities of the network rather than just its topology. Already results suggest resources and information flows are concentrated in a sub-set of the total available morphological network. The close convergence of physical and functional simulations with experimental data suggest that this system may be ideally suited as a model system to extract critical features that underpin robust biological networks.

**HEDSTROM, Peter.** Nuffield College, University of Oxford.

Prof Peter Hedstrom (http://www.nuff.ox.ac.uk/Sociology/Group/Hedstrom.htm) is an Official Fellow in Sociology at Nuffield College, Oxford. His research interests include analytical sociology, action-based theorising, network analysis, micro-macro links, and quantitative methods appropriate for analysing such processes. Current research projects focus on social interactions and labour market processes; the diffusion of social movements, and principles of analytical theorising. He has co-authored (with Richard Swedberg) ‘Social Mechanisms: An Analytic Approach to Social Theory’ (Cambridge University Press, 1998), and he is the author of numerous articles in leading journals. He is a fellow of the European Academy of Sociology, he has been President of the Swedish Sociological Association, and he has been the editor of *Acta Sociologica* and associate editor of *American Journal of Sociology* and *Rationality and Society*. He received his BA from Stockholm University and PhD from Harvard University.

**JOHNSON, Neil**. Clarendon Laboratory, University of Oxford.

Neil Johnson (http://www.lincoln.ox.ac.uk/fellows/johnson/) is Professor of Physics at the Physics Department, Oxford University where he leads the Complex Systems Theory Group in the Clarendon Laboratory. He took his BA at Cambridge University (St John's College) and PhD at Harvard University as a Kennedy Scholar. He was then made a Research Fellow at St John's College, Cambridge University, and a Professor in Physics at the Universidad de Los Andes (Bogotá). His group's research focuses on complex systems, both in the classical and quantum regimes. This work incorporates a wide range of topics, from quantum information processing in nanostructures, through to descriptions of the fluctuations in financial markets. He has more than 120 publications in various aspects of complex system behaviour, from the quantum properties of many-particle nanostructure systems through to the classical properties of many-agent competitive populations. He is also a director of Oxford University's computational centre for the study of financial markets as complex systems OCCF (see http://www.occf.ox.ac.uk and also 'Financial Market Complexity' (Oxford University Press, 2003)).

**MAINI, Philip.** Centre for Mathematical Biology, University of Oxford

Philip Maini (http://www.maths.ox.ac.uk/~maini/) is Professor of Mathematical Biology in the Mathematical Institute, Oxford. His main interests are in deterministic modelling of embryological pattern formation and in cancer modelling. Both these areas involve processes interacting on multiple length and time scales, as cells respond to and modify external signalling cues depending on their internal dynamics, which themselves are determined by the environment. Examples of current research projects include; investigating the spatiotemporal dynamics involved in somitogenesis; determining bacterial colony behaviour from studying single cell responses to chemoattractants; analysing the effects of domain growth on the spatial patterning behaviour of a model pattern generator; studying how the nutrient heterogeneity induced by vascular networks affect tumour growth; modelling the cell cycle.

**REED-TSOCHAS**, **Felix**. Saïd Business School, University of Oxford.

Felix Reed-Tsochas (http://www.sbs.ox.ac.uk/html/faculty_profile.asp?ID=4456) is a Senior Research Fellow in Complex Systems at the Said Business School and Keble College in the University of Oxford, and a University Fellow of the James Martin Institute. He is a Co-Director of the Oxford based CABDyN (Complex Agent-Based Dynamic Networks) Research Cluster (http:/ sbs-xnet.sbs.ox.ac.uk/complexity/), and also runs the Complex Adaptive Systems Group Seminars at the Said Business School. His original background is in theoretical condensed matter physics and the physics of disordered systems. His current research uses agent-based models as a tool that can provide a better understanding of how organisational behaviour in populations or networks can evolve, especially when the competitive environment has the characteristics of a complex system. At present he is particularly interested in modelling some of the dynamic processes that drive changes in populations of organisational strategies, and the emergence of innovation networks in high-technology clusters. He is a joint Series Editor (with Neil Johnson) of World Scientific's new book series dedicated to *Complex Systems and Interdisciplinary Science.*

**REINERT, Gesine.** Department of Statistics, University of Oxford

Gesine Reinert (http://www.stats.ox.ac.uk/people/reinert/) is a Professor of Statistics in the Department of Statistics, University of Oxford (since 2000). Having obtained her Ph.D. in Zurich, Switzerland, she subsequently held positions at USC (Los Angeles), UCLA, and King's College, Cambridge. Her research is centred on assessing the quality of approximations; she is a world expert on the so-called Stein's method, a prime tool for such problems. Applications in her work include statistical issues in computational biology, and in the spread of epidemics. Over the last three years, together with co-workers she established the first rigorous results on the statistical distribution of the shortest path length, and on the number of cycles of given length, in small-world networks. The main examples to date are given by metabolic networks, and by the spread of epidemics.

**<u>Dresden University of Technology, GERMANY</u>**

**HELBING, Dirk.** Institute of Economics and Traffic, Technische Universität, Dresden.

Professor Dr. Dirk Helbing (http://www.helbing.org/) is Managing Director of the Institute of Economics and Traffic at the Technische Universität Dresden, where he holds the chair for Traffic Modelling and Econometrics. Professor Helbing's training is in physics, and he holds a PhD and Habilitation in theoretical physics. Professor Helbing has published around 150 publications including about eighty articles in journals such as *Nature, Science*, *Physical Review Letters, Europhysics Letters*, etc. He has acted as referee for the German Research Foundation, the National Science Foundation as well for numerous journals. He is editor in chief of *TrafficForum* and the Internet journal *Co-oper@tive Tr@nsport@tion Dyn@mics*. Professor Helbing's work has been widely reported in newspapers, radio and TV. His research interests include multi-agent simulation of socio-economic systems, business and cycles and dynamics of supply networks, and the optimisation of traffic and production processes.

**Warsaw University of Technology, POLAND**

**HOLYST, Janusz.** Physics Faculty, Warsaw University of Technology.

Janusz Holyst (www.if.pw.edu.pl/~jholyst) is Professor at the Physics Faculty of Warsaw University of Technology (since 1998) where he leads the Research Group Nonlinear Dynamics of Complex Systems. His current research field includes the simulation of evolving networks, collective opinion formation, self-organized criticality, analysis of chaotic economical data, and stochastic resonance. He is one of the pioneers in applying physical methods to economical and social systems. His total list of publication includes 80 papers and he organized or co-organized eight international workshops or conferences. He was a scientific advisor of 5 Ph.D. thesis and conducted several research projects for the Polish Research Committee. Holyst maintains a close collaboration to many Institutes in Germany, France, and Italy, where he spent over five years as Guest Scientist, Visiting Professor or a fellow of Humboldt Foundation. He is a Director of Center of Excellence for Complex Systems Research at Warsaw University of Technology, member of Complex Systems Network of Excellence (EXYSTENCE), member of ESF Programme Stochastic Dynamics: Fundamentals and Applications (STOCHDYN) and Vice-Chairman of the COST P10 Programme Physics of Risk.

**INSEAD, FRANCE**

**KOGUT, Bruce.** INSEAD, Fontainebleau.

Bruce Kogut (http://www.insead.edu/facultyresearch/strategy/kogut/index.htm) is currently Professor of Strategy and Management at INSEAD, France. Until December 2002, he was the Dr. Felix Zandman Professor at the Wharton School, University of Pennsylvania where he headed the Reginald H. Jones Center for Management Policy, Strategy, and Organization. He has been a visitor at the Ecole Polytechnique, the Stockholm School of Economics, the Wissenschaftszentrum and Humboldt University in Berlin, and the Santa Fe Institute. The research areas he works in include strategic networks and alliances, technology transfer and diffusion, technology policy, organizational learning, and knowledge management, as well as international direct investment, development economics, and privatisation. He is a past or current member of the board of editors for *Management Science*, *Administrative Science Quarterly*, *Organization Science*, *Journal of International Business Studies*, *Strategic Management Journal*, and *Strategic Organization*. He recently finished a report for the World Bank reviewing their privatisation policies in East and Central Europe. In June 2003, Peter Cornelius (now senior economist Shell Corporation) and Bruce Kogut published an edited book on Corporate Governance and International Capital Flows, Oxford University Press, which was presented at the 2003 meetings of the World Economic Forum.

**ETH, SWITZERLAND**

**Schweitzer, Frank.** Eidgenössische Technische Hochschule, Zurich.

Professor Dr. Dr. Frank Schweitzer has a long-standing affiliation with the Fraunhofer Institute for Autonomous Intelligent Systems in Germany, but is now based at the Swiss Federal Institute for Technology (ETH) in Zurich. He has published seven books in the areas of complex systems and self-organisation in economics and social systems. He has published over one hundred papers and articles since 1982. His current research interests are active particles and agent models of complex systems with application to biology, socio-economic systems, urban systems and evolutionary organisation. He has worked on the application of information theory and entropy to financial systems and has published widely on the kinetics of nucleation and cluster growth. Professor Schweitzer is on the Steering Committee of the EU network of excellence on complex systems

(EXYSTENCE). He is on the editorial boards of *Advances in Complex Systems* and *Selbstorganisation.*

**University of Stockholm, SWEDEN**

**EDLING, Christofer.** Department of Sociology, University of Stockholm.

Christofer Edling (www.sociology.su.se/edling) is Associate Professor of Sociology at Stockholm University and Fellow at the Swedish Collegium for Advanced Studies in the Social Sciences at Uppsala. He received his PhD from Stockholm University in 1999 and has been a visiting scholar at Harvard University, Stanford University and the European University Institute. His main research interests concern social networks and processes of contagion. In his dissertation, *Essays on Social Dynamics* (1998), he developed formal models to understand the spread of organizational and societal ideas. He is currently directing a large project on the dynamics of inter-firm networks in Swedish big business, and involved in applying social network analysis to epidemiology. He has published many papers in edited books and scholarly journals, including *Annual Review of Sociology*, *European Sociological Review*, and *Nature*.

## A.2 Sub-contracting

All project partners will rely on professional services firms for the 18 month audits, since the option of internal audits is not available to any of the participating organisations.