Framework for structuring information for environmental management of industrial systems

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Why did brains evolve to start with?
The answer lies in the value of information,
which brains have been designed to process.

Pinker S., *How the mind works*

For by the fruit the tree is known.

The New Testament, Matthew 12:33

Framework for structuring information for environmental management of industrial systems

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This thesis addresses information structuring for reducing cost, facilitate understandability, increase relevance and improve quality of environmental information. The research is based in experience, practical results and syntheses from three different but related research and development projects conducted between 1994 and 2004. The projects have involved different industrial and academic partners in Sweden and other EU countries, and have also had active interactions with the international standardisation effort within ISO (International Organization for Standardization).

To actively take environmental responsibility for designing, producing or purchasing a product it is necessary to have information about consequences from the decisions. Environmental impacts from industrial products, activities and systems may be gradual, diffuse, long term and complex. They originate not only from extraction of natural resources, emissions and waste generation, but also from transportation, storage, use and end of life phases. The complexity makes it difficult to foresee the total environmental impact from industrial systems. There are methods and tools available to environmentally assess environmental performance of the life cycle of products and services, but it is still difficult to acquire the information needed to perform the assessment. It is also difficult to present the results from the assessments in a clear and logic way. Hence, it is difficult for consumers or professional decision makers to take into regard environmental consequences from their decisions. Due to the increasing global population and accelerating economies of the developing worlds, it is probable that the needs for more effective and efficient information handling for different global responsibility issues will increase.

The material presented concerns solving problems of environmental management of different industrial systems, using techniques for information structuring. The techniques include a combination of linguistic analysis, relational database modelling, system architecture design, and general description of data aggregation and data quality.

Significant and immediately useful results from the research work are 1) the outline of a methodological framework for building environmental information structures, 2) the importance of environmental indicators to build functioning environmental information systems and 3) the different practically useful and partially integrated prototype information systems for LCA and DfE resulting from the three research projects.

The doctoral studies are financed by the Swedish competence centre CPM (Center for environmental assessment of Product and Material systems), which is a joint research forum including Swedish industry and Chalmers university of technology, supported by the Swedish government through VINNOVA (Swedish Governmental Agency for Innovation Systems).

Keywords: industrial environmental information systems, information structuring, sustainable development, database, data format, Life cycle assessment (LCA), Design for Environment (DfE), characterisation, weighting, indicator

Publications

The thesis is based on the following published articles:

I. Carlson R., Löfgren G., Steen B., Tillman A-M., *LCI Data Modelling and a Database Design*; Published in The International Journal of Life Cycle Assessment, Vol. 3, No.2, pp. 106-113, 1998

II. Bengtsson M., Carlson R., Molander S, Steen B., *An Approach for Handling Geographical Information in Life Cycle Assessment Using a Relational Database;* Published in Journal of Hazardous Materials, vol. 61, pp. 67-75, 1998

III. Carlson R., Pålsson A-C., *Industrial environmental information management for technical systems*, Journal of Cleaner Production, 9, pp 429-435, 2001

IV. Carlson R., Forsberg P., Dewulf W., Ander Å., Spykman G., *A Full Design for Environment (DfE) Data Model*, PDT Europe 2001, April 24th-26th, 2001, pp. 129-135, 2001

V. Tivander J, Carlson R, Erixon M, Pålsson A-C., *OMNIITOX Concept Model Supports Characterisation Modelling for Life Cycle Impact Assessment* International Journal of Life Cycle Assessment, Vol. 9, No. 5, pp. 289-294, 2004

VI. Carlson R., Erixon M., Forsberg P., Pålsson A-C., *System for Integrated Business Environmental Information Management*; Advances in Environmental Research, 5/4, pp. 369-375, 2001

VII. Carlson R., *Learning from management of LCA data*, Journal of Life Cycle Assessment, Japan, Vol. 1, No. 2, pp 102-111, 2005

Examples of other material that the author has published in this area:

I. Pålsson A-C., Carlson R., *Maintaining Data Quality within Industrial Environmental Information Systems*, 12th International Symposium Computer Science for Environmental Protection, Bremen; Band 1/Volume 1 p. 252-265, 1998

II. Carlson R., *Environmental Performance Indicators*; INSIGHT, Vol 5 Issue 2, pp. 22-23, The International Council on Systems Engineering (INCOSE), 2002

III. Häggström S., Pålsson A-C., Carlson R., *Policy controlled environmental management work*, LCM 2005, 2nd International Conference on Life Cycle Management, Barcelona, September 5-7, 2005

IV. Flemström M., Erlandsson M., Carlson R., *Standards and tools for environmental design and supply chain management in railway industry*, The Sixth International Conference on EcoBalance, Oct. 25th - 27th, Tsukuba, Japan, 2004

V. Flemström K., Erixon M., Erlandsson M., Häggström S., Tivander J., Carlson R., Wiklund C., Riise E., Ågren U., *Implementation of integrated environmental information systems for sustainable development*, LCM 2005, 2nd International Conference on Life Cycle Management, Barcelona, September 5-7, 2005

VI. Carlson R., Erixon M., Erlandsson M., Flemström K., Häggström S., Tivander J., *Establishing common product life cycle data*, LCM 2005, 2nd International Conference on Life Cycle Management, Barcelona, September 5-7, 2005

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1 Introduction

1.1 The research project

The research presented in this thesis has aimed at addressing, and trying to solve two problems:

- Develop information structures for databases, communication files, reports and software for environmental management of industrial systems.
- Synthesize a general methodology or framework for how to develop such information structures.

This thesis will present how the problems have been approached and solved, by presenting the interdisciplinary toolbox, the methodological approach to solving the problem, three information structures that describe aspects of environmental management of industrial systems, and an interdisciplinary methodological framework. In addition, the thesis will highlight the insight that indicators are economically crucial when establishing information systems for environmental management of industrial systems.

The studies and the writing of this thesis have been financed and performed within the ten year governmentally financed Swedish national competence centre *CPM*[1], which is a joint research forum, equally financed by the Swedish government through *VINNOVA*[2], *Chalmers University of Technology* and *Swedish industry*[3]. The work has intended to strengthen the theoretical foundation of Swedish work with developing and integrating environmental product life cycle responsibility in industrial applications, and specifically the unique emerging new research area of industrial environmental informatics, developed out from the CPM research.

1.2 Information and environmental management

Few immediate physical relationships with Earth's natural environment are easily understood from the viewpoint of being within the industrial society. Societies of hunters, collectors and farmers have a much more direct relationship with the physical environmental consequences of their actions. Instead awareness about environmental consequences from actions within the industrial society must come only from second hand information about how energy, resources, emissions and waste are related to all the goods and services from which industrialised people benefit. Such second hand information needs to be both understandable to people, as well as correct with regards to the environmental aspects it addresses.

Time has proven the business relevance of environmental responsibility, and there are no indications of a change in the future. On the contrary; business relevance may be exemplified by commercial stakeholders and participants in, for example, development of international standards for environmental management and tools (ISO

[1] CPM: Center for environmental assessment of Product and Material systems, Chalmers University of Technology, Sweden, Göteborg
[2] VINNOVA: Swedish Governmental Agency for Innovation Systems
[3] Since the start of CPM in 1996 the following different companies have participated: ABB, Akzo Nobel, Assi Domän, Avesta Sheffield, Bombardier, Duni, Electrolux, Ericsson, IKEA, ITT Flygt, MoDo, Norsk Hydro, Perstorp, SAAB Automobiles, SCA, Stora Enso, SwedPower (Vattenfall), Telia Sonera (Telia), Tetra Pak, AB Volvo, Volvo Cars

14001, 2004), Environmental Product Declarations (GEDnet, 2005) (ISO, 2002) and the World Business Council for Sustainable Development (WBCSD, 2005).

Environmental management of industrial systems is exercised by different people with different responsibilities, different competencies and with different motivations. Depending on their responsibilities and what roles they play, they need different environmental information. The information needs to be understandable, relevant to the responsibility and have a suitable degree of complexity with regards to how much time can be spent on the information.

Because environmental realities change, information systems need to be designed for efficient updating of data and quality review. Unless data are updated, the data will not reflect the changes in reality. And without information quality management, data are not taken seriously.

This thesis shows how environmental information systems have been built with these practical requirements in mind. The information structures are based on different theories and techniques for data modelling, and the resulting information systems have proven to be stable, functional, understandable, relevant and in line with industrial economics. During the work a lack of general theoretical guidance for the work has been noticed. To improve this, general methodological principles have been identified and a general framework has been developed to support both ongoing and future work.

1.3 Sustainable development

In 1987, the World Commission on Environment and Development (the Brundtland Commission), agreed to define sustainable development as follows:

Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

Since the Brundtland commission the significance of sustainability and the urge for sustainable development was emphasized and globally accepted in 1992 at the world summit in Rio de Janeiro, as Agenda 21 (United Nations website, 2005) and in 2002 at the world summit in Johannesburg.

Sustainable development means that the way that mankind uses resources, structures global society and develops new technology needs to be improved. This implies a necessity to assess the consequences of our current and intended behaviour and actions. Such consequences include depletion of natural resources, economic inequality and global spreading of diseases. These are global issues, and they are strongly catalysed and amplified from the current globalization of production, trade and economy. Hence, sustainable development is tightly linked with global information sharing and global trade.

Chapter 40 of Agenda 21 describes the needs for data, information, experience and knowledge and also calls for development of indicators for monitoring progress towards sustainable development. This need may in general be described as a need for information structuring and information systems by

- National and industrial leaders to develop and maintain sustainability-oriented policies.
- Citizens to guide everyday lifestyle and political decisions.
- Business people to support their actions and goals, and to guide their business towards sustainability.

But still, sustainability is considered to hold a relatively low priority in most people's everyday lives. This paradox needs to be taken into account when designing solutions for provision of information for environmental management of industrial systems.

Complex environmental relationships need to be formulated and structured into information that makes sense in the situation, with reasonable cost and effort. Information about the environmental consequences resulting from a change in the design of a product needs to be followed by information about the economic and social consequences from that same change. Information about the environmental burden from the production of a product needs to be compared to the environmental burdens from the raw material extraction, the use phase, and the end of life phase. The environmental impacts associated with different chemicals need to be presented comparably.

1.4 The task of information structuring

This thesis presents an approach to structuring information in such a way that it efficiently and effectively helps people who take responsibility for environmental management to relate their actions to their environmental consequences. This includes formally relating information from different disciplines into interdisciplinary information structures, identifying information items to include with data structures, identifying logical relationships and flexibility between different related applications, identifying needs and possibilities for nomenclatures and distinguishing between numerical information, classifiers, and free descriptive texts. The practical cases presented in this thesis provide examples of these aspects of environmental information structuring.

There are many examples pointing to a critical need for a good framework and principles for developing good information structures for industrial environmental management and intelligence. A quote from Professor Sterner (Sterner, 2003) may further emphasize the relevance of the scope of this thesis: *Information plays a special role in policymaking, and in fact, information provision can be considered an instrument in its own right. On a general level, all policy depends on information; that is, policymakers must understand the technology and ecology of the issues under consideration.*

Many databases with valuable environmental data exist, but those will not suffice. In the report *Establishing common primary data for environmental overview of product life cycles* (Carlson et al, 2005) (Naturvårdsverket, 2005) the availability of environmental data is assessed, and it shows that the existing environmental databases have been developed for specific applications, such as emission control, chemical risk management or environmental reporting, but all new applications for environmental supply chain management, life cycle responsibility, scrapping manuals and design for environment in all sectors will require both more data and adaptations to new compatible nomenclatures and meta data. New databases will have to be developed for specific tasks, for shared or public applications or for environmental intelligence and management in commercial businesses. Guidance about how to develop structures for environmental information is needed.

Structuring of information is to a large extent practical interdisciplinary work. To do this work one needs to deal with the language and the logic of the future users of the information, and one needs to try to understand how the future users see the world. This thesis formulates some of the techniques, theories and procedures applied.

It also outlines a practical framework for structuring of environmental information, based on much practical experience and theoretical reasoning.

2 State of the art

The interdisciplinary scientific terrain navigated by this thesis is not very well investigated in literature, but there are authors in the literature pointing both at the needs and towards parts of the solutions. But in spite of the fact that the needs are quite clear both to industry and to society it has not been possible to find literature that addresses the problem in any similar way.

When the work started in the mid 1990s life cycle assessment (LCA) was about to become interesting for both academic and industrial applications. Hence, the needs were then concretely expressed as needs for LCA databases and data exchange formats (Ekvall et al., 1992) (Grisel et al, 1997). The results of trying to meet these needs were a number of competing public LCA data formats and databases (Singhofen et al, 1996) (Carlson et al, 1995) and the initialisation of an ISO standardisation that started in 1998 (ISO, 2002). The discussion throughout this work with structuring information has been confused, and has consisted either of listings of important data items identified by LCA experts (SPOLD, 1997) on the one hand, and on the other hand discussions of analysis of concept modelling and industrial application of LCA (Carlson, Löfgren, Steen, Tillman,1998) supported by computing science theories.

For example, the discussions during the international standardisation work aimed at including both environmental management experts from the technical committee responsible for developing the environmental management standards ISO 14000-series (ISO, 2004) and the information systems experts from the technical committee working with standardizations product data structuring (ISO, 1998) (ISO, 2004). This bridging did not work out, to some degree because environmental experts mistrusted data modelling experts, and the vice versa.

The resulting ISO document, *Environmental management – Life cycle assessment – Data documentation format* ISO/TS 14048 (ISO, 2002) is a document at the peak of formalism from the viewpoint of environmental expertise, but which was criticized for being vague and ambiguous by information systems experts within the CASCADE project (CASCADE, 2006). The conclusion is that there is a wide gap between the domain of experts in environmental management methods and tools and the information systems experts.

The problems that may arise from this communication gap between information systems experts and environmental experts, is that many of the environmental information systems that are needed for sustainable development and environmental management are built either by environmental experts without formal knowledge of the basics of information structuring, or by information systems experts based on an oversimplified view of the complexities of the field of environmental management and sciences.

Today the needs for environmental product information have gone beyond the LCA methodology, and instead encompass all environmental aspects of products and production. These needs are expressed at the European level (Nuij, Rentsch, Ryder, 2005), national level (IVL, 2002) (Kemikalieinspektionen, 2004) (Naturvårdsverket, 2005) and in international forums (UNEP/SETAC, 2006). Considering that it is likely that issues of sustainable development will never be simply based on consensus (Hopwood, 2005) it is also likely that environmental information will remain based on ambiguous and complex facts that cannot easily be simplified.

In his book *The skeptical environmentalist* Lomborg (Lomborg, 2001) presents an analysis of occasions when environmentalists seem to have pushed for their environmental cause at the expense of a minimal formalism and accuracy. Similar tendencies were noticed during the above mentioned development of the SPOLD format for LCA data. Consistency with LCA practice was more important than consistency with, for example, statistics describing the quantitative data and a formally structured format.

These examples from the literature, as well as experience, point to a need to facilitate discussions about the *quality of environmental information structuring*. This is not intended to concern computing science as such, since there is already a substantial literature available on that subject (Cornwell, 1990) (Elmasri, Navathe, 1994). For example, many systems, methods and tools exists to support business intelligence by acquiring, producing, interpreting and structuring business relevant information (Raisinghani, 2004) to design for example the database and communication formats (Hawryskiewysz, 1994).

But there definitely is a need for a practically based framework that can facilitate a formal discussion about good practice when structuring information for environmental management, and this framework needs to be formulated from the viewpoint of the environmental sciences.

Currently this discussion is mainly held between environmental experts and software or database vendors (DG Environment and DG JRC, 2006) (ecoinvent, 2006) (Pré, 2006). It is difficult to elevate the discussion to consider, for example, the fact that data need to be well-structured because in the long run the costs for data will far exceed the costs for all other parts of the information system. Figure 1 is intended to provide a simple picture to describe the fact that the structuring of data is important, since the costs for data are important in relation to the other costs of an information system. The picture is taken from a small handbook about product data structuring in industry (Celander, 1995).

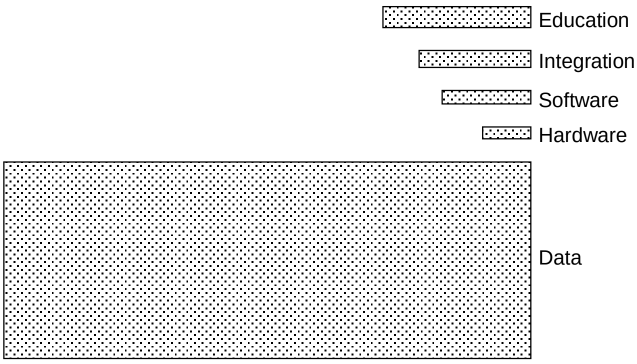

Figure 1. Schematic sketch of typical relative costs for creation of data and other costs for an information system (after Celander, 1995) Areas represent costs.

Attempts to combine environmental information structures and structured data handling to reduce costs and enhance quality have been made in different industrial sectors, such as within the Swedish paper and pulp sector (Pålsson et al, 2005), the Swedish iron and steel sector (Axelsson et al, 2004), and the international automotive manufacturers (IMDS, 2005) and another is currently being initiated within the Swedish building and construction sector (BASTA, 2006). The paper and pulp sector and the iron and steel sector approaches were based on one general principle and had the same aim. The idea was to use one integrated environmental information system to generate all of the various environmental reports within a company. The automotive and building sectors approach instead aims at sharing materials and components data between all suppliers and manufacturers in the two industrial sectors.

These four projects and the two different approaches have not had any common approach or idea of how to structure the information, and there is no common way to judge whether the structures used are good or bad from the environmental viewpoint.

The background of the paper and pulp approach is described in section 5.1 of this thesis. The basis was the PHASETS model, presented in Figure 26. The iron and steel approach was inspired by this same model and initiated and performed a project within that sector, with the same overall aim as the paper and pulp sector project. The automotive industry system is intended as an exclusive system, currently outsourced to the company EDS[4] that also developed the system. The Swedish building and construction sector system BASTA is based on similar principles but has nothing else in common with the IMDS. When paper and pulp, iron and steel, automotive and building and construction industries need to share data, or when the have the same sub-suppliers, the question of information structuring will arise as a compatibility and quality question.

Hence, the current societal and industrial needs for environmental information structures for different information systems, together with the apparent gap between environmental experts and computing experts, motivates the research behind this thesis.

It should be stressed that the thesis is not intended to address a lack in either of the domains of environmental science or computing science, but is intended to bridge the gap between these two scientific areas. Hopefully the practical experience in this strikingly unexplored interface between fields at least provides something new to both computing science and environmental sciences. Due to the kinship between information structuring and linguistics the focus is on the wording and language of the environmental experts, and on formal weaknesses introduced by the necessary breadth of this interdisciplinary field.

[4] http://www.eds.com

3 Concepts and terms

Concepts and terms relevant to this interdisciplinary thesis relate to the different competence areas of informatics, environmental management and some general aspects of industrial systems. The chapter is divided into five sections. The first section defines the meaning in this context of some terms that are generally used throughout the text. The next three handle the different competence areas, and the fifth one clarifies the view of environmental informatics in the context of this thesis. Each section is intended to present concepts from the different disciplines or competence areas involved.

3.1 General concepts, terms and distinctions

Concepts and terms with potentially ambiguous meanings will be used in different contexts throughout this thesis. Their meaning in the context of this thesis is defined here:

<u>DATA, INFORMATION AND FACTS</u>

- *Data*: refers to raw figures, letters or other symbols that are not yet subject to interpretation.
- *Information*: any form of data that is interpreted.
- *Fact*: information that describes some aspect of an ontology.

<u>DATA FORMAT</u>

- *Format (data f., data documentation f., database f.):* The term relates to how the data fields are structured in, for example a computer file, a questionnaire, or a relational database.

<u>CONCEPTUAL MODEL VERSUS CONCEPT MODEL</u>

- Both concept models and conceptual models are presented and discussed in this thesis. Conceptual models provide a simplified (conceptual) view of items in the real world, their constitutions and different physical, chemical, and biological relationships. Concept models describe the concepts and terms of a language and how these concepts and terms are logically related to each other.
  For example, Figure 4 provides a *conceptual model* of the life cycle of a product, from the viewpoint of how it impacts the natural environment. Figure 9 provides a *concept model* of basically the same thing. It illustrates the importance of the three concepts *Technical System*, *Nature System* and *Social System*, as well as their interrelationship.
  Note: It should be stressed here that this distinction is not made throughout the literature. In many publications there is no distinction at all between the meaning of conceptual and concept.

<u>ONTOLOGY</u>

- Ontology is the study or the theory of being or existence, and about how to describe reality and how to acquire knowledge about reality. In this thesis ontology represents an address to a physical reality, an address to the real world, as opposed to, for example, consensus, conventions or fiction.

3.2 Concepts of industrial systems

3.2.1 Scale and productivity

Concentration of production capacity into factories and work force into cities are two important factors behind the success of industrial society. These factors lead to many synergetic advantages of scale both due to increasing cost-efficiency and by larger, more concentrated and more homogeneous consumer markets. These elements of industrial systems are considered in this work by specifically addressing information systems that support large scale production systems, large markets, distributed supply chains and business competition. Large numbers and homogeneous markets stabilize supply chains and market demands. But the stability is different for different organizations and businesses, and also change over time. For an organization to be aware and respond to change it needs both intelligence and information strategies and systems.

3.2.2 Organisational intelligence and information

Organisations handle information for intelligence and management (Frankelius, 2001). Intelligence aims at building up the knowledge within the organisation, so that the organisation can plan and react in line with this. Management needs to control and develop the production capacities into best available productivity.

To be successful organizations need to maintain and update their *knowledge*, and adapt to a fragmented world, spontaneously react to unexpected facts, adapt to changed circumstances, take decisions based on uncertainties, be creative and flexible, and be able to handle generalizations. At the same time organisations need to be *productive*. Tasks, activities and functions need to be merged and integrated, spontaneity needs to be replaced with standards and formal routines, information systems need to be stable and trustworthy, work tasks need to be rational and efficient, new ideas need to be turned into operative functions, structures need to be cemented and specialized tasks need be developed. Successful organisations balance between knowledge maintenance and the productivity. Since environmental management concerns change in the world outside businesses, environmental information systems need to be designed for efficient updating of data when knowledge changes, as well as for effective quality review. Unless data are updated they will not reflect knowledge about the changes in the external reality. And without effective quality review, the data will not be taken seriously.

The focus of this thesis lies on productivity, with respect to the fact that a sound business needs both perspectives.

3.2.3 The life cycle of industrial information systems

Information systems are developed, exist, and remain within organisations during changes and development over time. Sometimes the development of the information system leads a change, and at other times the information systems need to be adapted to changes with other causes. For the *knowledge oriented* viewpoint (section 3.2.2) such information system life cycles are short. Dirk Vriens proposes an intelligence cycle of four stages to structure the process of intelligence (Vriens, 2004):

1. *Direction*: The organization determines the information requirements i.e. what aspects of the world to collect data about.
2. *Collection*: Determine what data sources to use, as well as actually collecting the data.

3. *Analysis*: The actual production of intelligence.
4. *Dissemination*: Forward results from intelligence to strategic decision-makers.

This cycle describes how organisations should look after their organisational environment, e.g. for competitors and other market relevant changes. The intelligence process also develops the organisation into core business areas and into its strategic directions and domains. But as the strategic domain becomes stabilized and familiar to the organization, the intelligence system needs to be established as a *productivity* information system (section 3.2.2), with more clearly defined information items and structures. This organisational maturity cycle leads to development and change in information systems.

During the life cycle of an information system functionality may be added, removed or redeveloped. Such changes may be the result of new requirements from the users, new requirements on the data, additions and removals of surrounding information systems, or due to changes in the business environment. Regardless of the reasons, any information system that is built for a real business environment must be designed for such future changes during its life cycle. In particular, the data in the system needs to be separable from choices of implementation on specific software or hardware platforms (see also Figure 6, section 3.4.1).

3.3 Concepts and terms of environmental management

3.3.1 Sustainable development

Sustainable development is a globally accepted agenda, the overall agenda for environmental management. The large scales of the industrial systems have been successful at producing commodities and economy to many people in a relatively short time. But in parallel to this successful development social and environmental drawbacks have increased as well. Exhaustion of natural resources, spreading of manmade substances and global social inequality may lead to the fact that poverty, health problems and wars are the main legacy of our industrial society.

In 1987, the World Commission on Environment and Development (the Brundtland Commission) said *Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs*. The significance of sustainability and the urge for sustainable development has again been emphasized and globally accepted both in 1992 at the world summit in Rio de Janeiro and in 2002 at the world summit in Johannesburg.

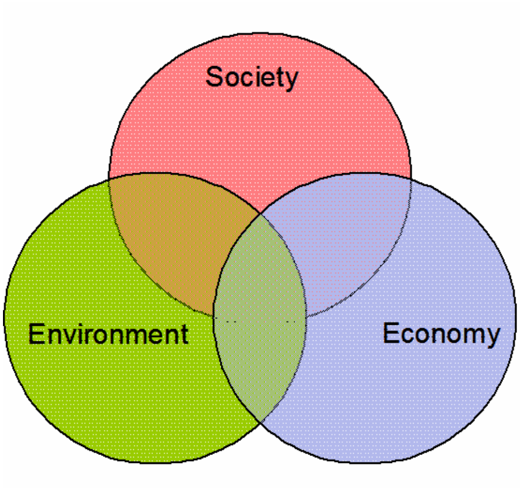

Figure 2. The target dimensions of Sustainable development: Environment, Economy and Society.

Sustainable development is often described as three circles for the target dimensions of *Environment*, *Economy* and *Society* (see Figure 2). It illustrates that *economic*, *social* and *environmental* processes are interlinked. Any public or private actions must take this into account. Also, sustainable development goes beyond environmental issues. In order to satisfy our material and immaterial needs, economic growth and stability is needed. Hence, sustainable development implies that *changes* are needed in the economic and social systems, to *reduce consumption* of the environment and resources, while *maintaining economy* and *social well-being*, global relationships included. In conclusion, sustainable development is intended to bring about long-term improvements for the majority of the people of today and the future.

This thesis focuses on the *environmental dimension* of sustainable development, with full awareness of that the different dimensions are closely interlinked, in time as well as globally.

3.3.2 Environmental management

Environmental Management is addressed here in the broad sense of sustainable development. Management of the environment is a responsibility for any person, at his or her position in society and with his or her role as citizen, professional or consumer.

Due to the large scales of the industrial systems (section 3.2.1), personal choices of individual actions may either be regarded as vain and pointless if they are driven by individual beliefs and convictions, since the individual actions does not make much difference, or as firm and powerful if they are performed in concert with a common agenda, since many individual contributions in the same direction combines into a strong force. This thesis considers sustainable development to be a common agenda for a concerted action, and hence considers individual decisions as controlling the total outcome of today’s industrial society into the future.

Figure 3 represents how such individual decisions are taken throughout the society. Individual decisions are taken by the *controller*, on the basis of how the controller appreciates the *current status*, the short time *goal*, and the *vision of the long term goal*. The model in figure 3 is a *cybernetic control system* (Wiener, 1991), which implies that all the variables *change dynamically*. The *vision of the sustainable society* changes, the short term *goals* changes, the current status changes, and even the *controller* and the *controlled system* change over time.

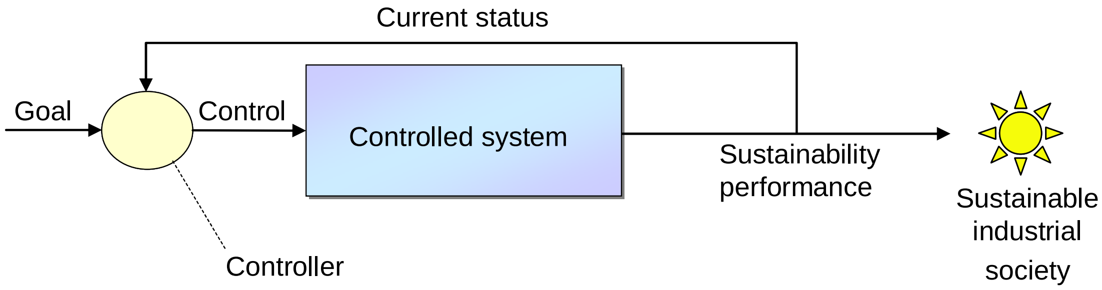

Figure 3. A conceptual cybernetic control model describing environmental management. All variables changes and the information therefore need to be relevantly updated.

A control system intended to control a real system relies on the fact that the controller has sufficiently correct *information*, so that the *controlled system*, the *current status* and the short term *goal* are appropriately updated when changes happen due to control actions or external changes. This means that the information needs to be *updated at all times*.

Methods, routines and processes of environmental management have been standardized within ISO, as the ISO 14000 series. The 14001 standard (ISO, 2004) specifically prescribes how to control the environmental performance of individual organizations in a continuously improving process. In terms of Figure 3 the ISO 14001 standard considers the controlled system to be, for example, a company or a production facility. The current status and goal are updated on, for example, a yearly basis to produce environmental reports. Each individual person in the company is responsible for taking environmental decisions in their everyday work, ranging from *purchase* decisions, *design* choices, *waste handling*, etc.

In support of environmental management there are many different methods and tools (Carlson et al, 2005). In the following subchapter the methodologies of environmental life cycle assessment (LCA) and design for environment (DfE) will be introduced.

3.3.3 Life cycle assessment

Life cycle assessment (*LCA*) is a method by which to study and assess the significant environmental impacts from the full life cycle of a product or a service, including all significant matter and energy needed. The life cycle is assessed upstream from resource extraction and downstream to waste management, including recycling or reuse.

Figure 4 shows a conceptual model of the different items and relationships addressed in LCA. An LCA is performed by a *subjective* individual, who decides which environmental issues to consider in the *natural environment*, which *upstream and downstream causal activities* to include with the assessment, which *resource use* and *emissions* (*elementary flows*) to include, and on the transparency and overall quality of the resulting study.

An LCA is performed by deciding on a product or the function for which the assessment should be performed. Examples of a product is ‘*kg of steel*’, and an example of a service is ‘*ton*km of passenger transportation*’. From the basis of the product or service all significant upstream and downstream processes are identified and linked into a flowchart, like the upper half of Figure 4. Identification of what is significant is quite difficult, and may be supported by principal policy decisions for the whole study, by specific knowledge or by ad hoc investigations during the work.

With a foundation in the flowchart, data for all significant elementary flows are described for each process. Each elementary flow is assigned to the category of environmental change to which it contributes, and the environmental consequences of each elementary flow are modelled as *characterization models*. Characterisation will be presented in more detail in the following.

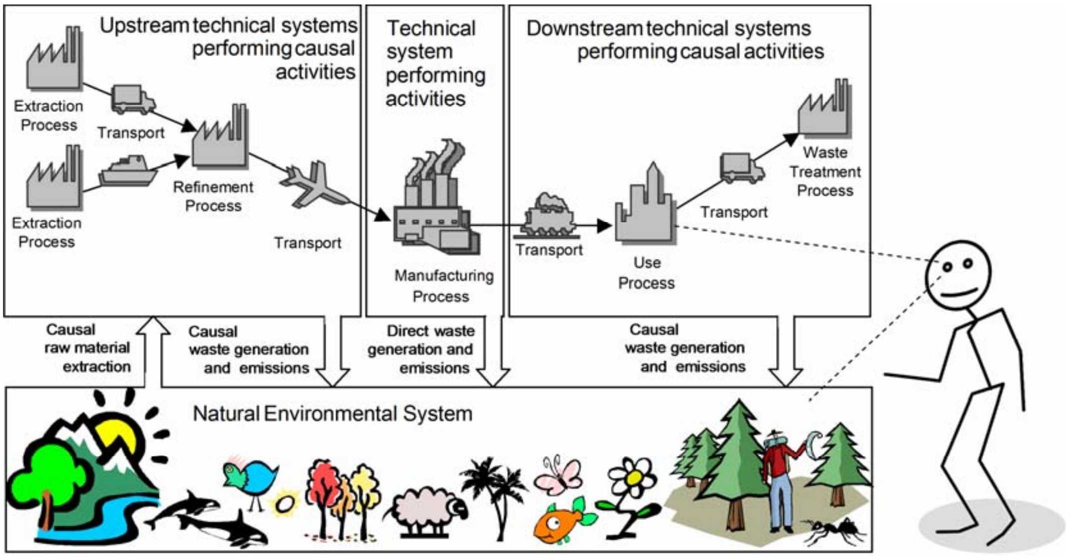

Figure 4. A conceptual model of the scope of the methodology of life cycle assessment (LCA) (after Carlson, Pålsson, 1998. The *Subjective mind* is added to stress the importance of choices during an LCA study).

Characterisation is an LCA term that describes characterisation of environmental impact on specified selected environmental issues, i.e. *environmental indicators* (such as *increased number of cases of cancer* or *depletion of oil resources*) from specific environmental *loads* from *elementary flows* (such as *emission of freon* or *extraction of crude oil*). *Characterisation models* that describe these relationships are used in LCA studies, but they are generally modelled by specialised experts with expertise in different *environmental impact modelling*. Figure 5 represents how a *load* enters a *natural system* and how its impact is represented by impact on the *indicator*. When describing this impact by a model, the nature is represented by a *framework of different properties*, for example *temperature* and *concentration of H^+-ions*, and *mechanisms*, such as *leaching*, *dispersion*, *permeation* and *biochemical reaction*, which describe how the *indicator* is *impacted* by the *load*.

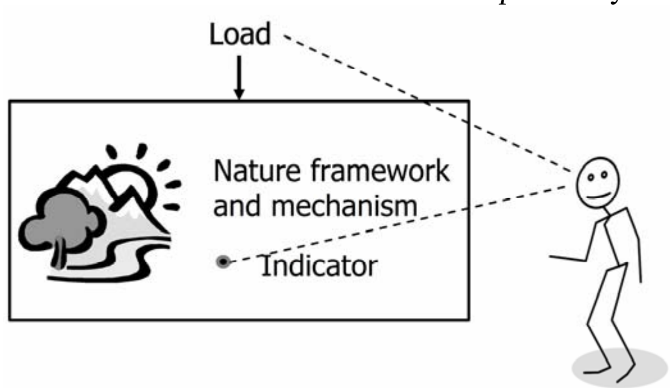

Figure 5. Conceptual model of the system of a characterisation model. This picture is partly borrowed from (Tivander, Carlson, Erixon, Pålsson, 2004), but with addition of the figure representing the subjective mind of LCA.

LCA also includes the steps of *weighting* and *interpretation*. *Weighting* means to systematically *prioritize between many different environmental changes*, such as *ozone depletion*, *acidification*, *depletion of natural resources* and *human health effects*. *Interpretation* is the way to interpret the result of the LCA study.

LCA may be performed in different ways, but there are four international standards that establish an international consensus about how to perform LCA:

- The framework is described in *Environmental management - Life cycle assessment - Principles and framework* ISO 14040 (ISO, 1997).
- The way to perform inventory of all material and energy flows of the life cycle is described in *Environmental management - Life cycle assessment - Goal and scope definition and inventory analysis* ISO 14041 (ISO, 1998). This stage of LCA is called LCI, life cycle inventory
- The way to perform environmental impact assessment is described in *Environmental management - Life cycle assessment - Goal and scope definition and inventory analysis* ISO 14042 (ISO, 2000).
- How to perform interpretation of results is described in *Environmental management - Life cycle assessment - Life cycle interpretation* ISO 14043 (ISO, 2000).

The ISO 14040 standard was updated, and a new version released by ISO, in 2006. The standards ISO 14041-14043 will be replaced by a new standard ISO 14044, also in 2006.

3.3.4 Design for environment

Design for Environment (*DfE*) is based on the idea that a significant part of the environmental impact from a product originates from choices made during the design of the product. The later in the design process one considers environmental issues, the more difficult and the more expensive will it be to introduce any changes. Hence, environmental benefits and improvements should be considered as early as possible during product design.

Introduction and management of DfE is the responsibility of environmental management, and as such it has been noticed as a technical report in the ISO 14000 series of standards ISO/TR 14062, *Guidelines to Integrating Environmental Aspects into Product Design and Development* (ISO, 2002).

3.4 Concepts of informatics

3.4.1 Basic concepts

The section about informatics concepts is introduced by presenting how two dictionaries describe informatics (The original dictionary texts are edited):

Wikipedia[5]: *Informatics is the study of information. It is related to database, ontology and software engineering, and is primarily concerned with the structuring, creation, management, storage, retrieval, dissemination and transfer of information. Informatics also includes studying the application of information in organizations, on its usage and the interaction between people, organizations and information systems.*

[5] http://en.wikipedia.org/wiki/Informatics, 2006-02-28

Oxford English Dictionary[6]: *Informatics is the discipline of science which investigates the structure and properties (not specific content) of scientific information, as well as the regularities of scientific information activity, its theory, history, methodology and organization. The problem falls into two parts: the preparation of decisions, which is a matter of informatics, and the making of the decisions themselves, which is a matter of 'politics'.*

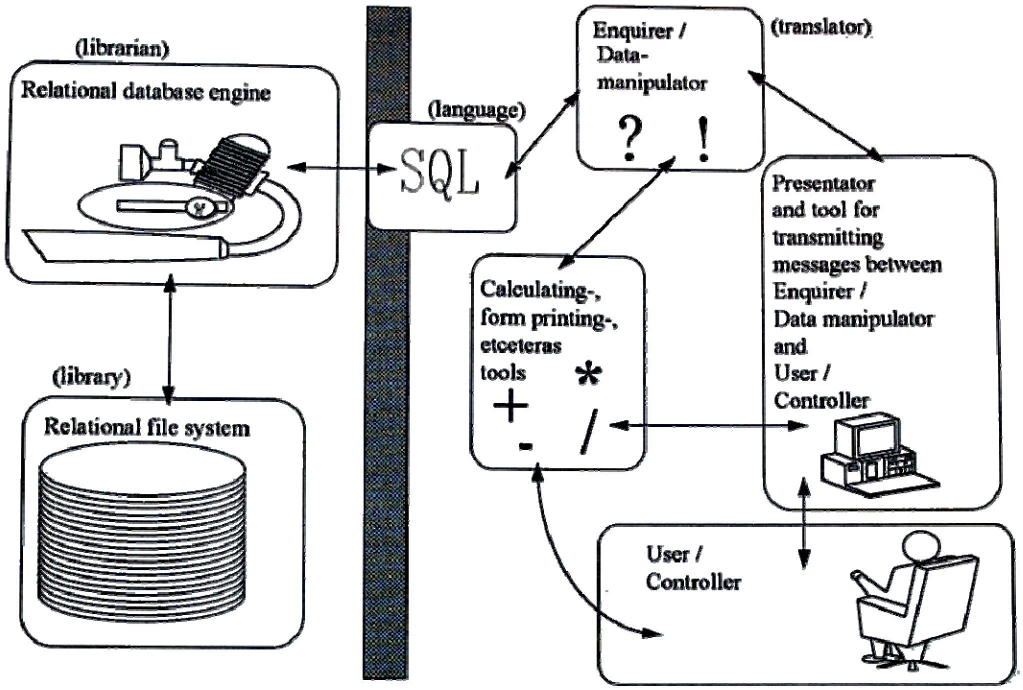

Figure 6. Basic functions and concepts of an information system. (Carlson, 1994)

Figure 6 shows by analogy the fundamental parts of an information system based on a database. The analogy is based on a *library*, with a *librarian* that speaks a *foreign language* (*SQL*, *Structured Query Language*, an ANSI/ISO standardised database language), a *translator*, *information handling and manipulating* tools and the *user or controller* of the information system. The *arrows* represent *information exchange* between the different parts. It should be understood that by using network technology, such as the Internet, the arrows can exchange data over very long physical distances.

Key issues for turning this information system into a functioning system are:

1. The correct understanding of how the user *perceives* the information presented to him or her.
2. The correct interpretation of all *the information and logic* of all the different data to store in the database.
3. The correct *storage, retrieval and updating* of information in the database and presentation of data into user interfaces and reports.
4. Correct *data manipulation* with regards to all intentions by the user and his or her intended *domain of applications*.

[6] http://dictionary.oed.com/cgi/entry/50116495?single=1&query_type=word&queryword=informatics%A8&first=1&max_to_show=10, 2006-02-28

Key issue 1 and 2 are the central themes of this thesis, since the meaning and the logic of the information is of core interest for information structuring. Both of these aspects of information define the structure of the database and the communication between different parts of the information system. Examples of database schemas that prescribe the structure of a relational database are presented in figure A1 and A2 in Annex A.

Key issue 3 is the central theme when designing the architecture (section 3.4.2) and the functionality of the information system and when programming the functionality.

Key issue 4 is the interdisciplinary responsibility when developing the entire information system for, for example the purpose of life cycle assessment (LCA) or design for environment (DfE), to understand how LCA or DfE is performed.

3.4.2 Information structuring

Information structuring addresses three major structuring types:

- *Concept modelling*: The result of an analysis of concepts, terms and the logic of the language of the application domain, such as the language used to perform a life cycle assessment (LCA) or to support design for environment (DfE). An example will be presented in section 3.5.2.
- *Vertical information structuring*: A model of all consequences of an information request. Models how a specific piece of information is consecutively aggregated into a resulting report, or how analysis of ideas are synthesised into an information system. Examples are presented in sections 3.4.3 and 3.4.4.
- *Information system architecture*: Descriptions of how an information system is modularised by separated components, and how these components communicate. Describes also the boundary of the scope of the information system. Figure 36 in section 5.2 and figure 37 in section 5.3 provide examples.

This thesis also addresses *conceptual modelling* (see section 3.1 for definition) and structuring of quality aspects of information (section 5.1).

3.4.3 The OSI reference model, vertical information structuring

The OSI[7] reference model is presented here as an example of a widely used *vertical information structure*. It has inspired some of the work presented in this thesis.

The OSI model describes how to consecutively aggregate data from the lowest physical layer of computer networks to the user interfaces of the applications, through increasingly meaningful layers. In the reverse direction it shows how information from applications is disaggregated into standardised signals on computer networks.

The OSI reference model was developed within ISO[8] to address problems of network *incompatibility*, and it is used to understand how information travels throughout a network. It explains how packets travel through the various layers between computers on networks, even if the sender and destination computers have different types of network media. The model consists of seven *numbered layers*, each

[7] OSI: Open Systems Interconnection Reference Model
[8] ISO: International Organization for Standardization

of which illustrates a particular *network function*. See figure 7. This vertical dividing into layers provides a number of advantages, such as that:

- It breaks complex computer network communication into small, *manageable tasks*.
- The division makes computer network communication *easier to understand*.
- It allows computers from different vendors to communicate.
- It *separates tasks*, and thereby prevents changes in one task from affecting other tasks.

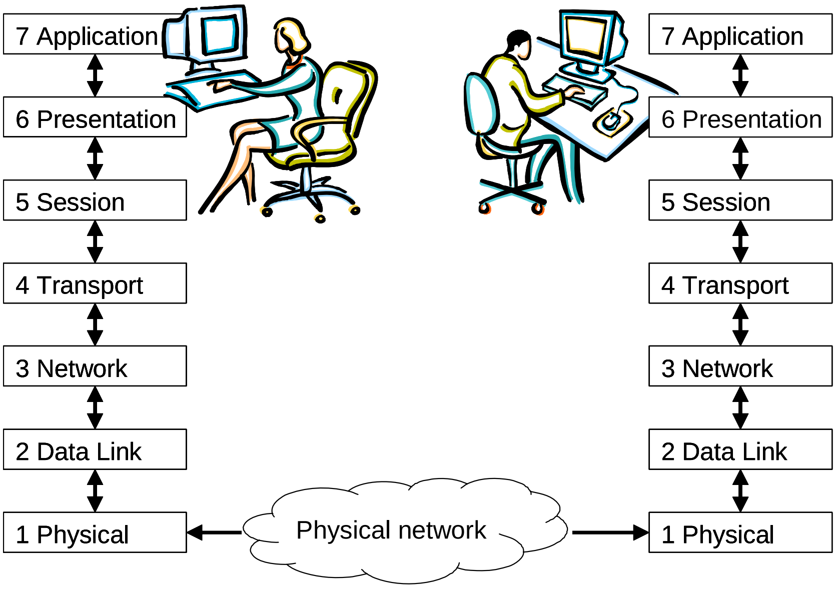

Figure 7. The OSI reference model describes how information is aggregated/disaggregated from/to physical network signals into/from application specific data, like file exchange protocols.

The specific functions of each layer in the OSI reference model are (NetworQuest, 2006):

1. *Physical Layer*: Handles the bits, connectors, voltages and data rates i.e. it deals with the *physical medium* like the cable and sends the data in forms of 0s and 1s.
2. *Data Link Layer*: Responsible for *reliable data transfer* of data through the media. Understands the physical address of the network device and helps in flow control and error correction during data transfer.
3. *Network Layer*: Provides reliable data transfer. Deals with the *logical Internet protocol* address.
4. *Transport Layer*: Responsible for *transportation issues* between computers. Responsible for fault detection and recovery of flow control.
5. *Session Layer*: Responsible for the *virtual circuits* for data transfer between computers.
6. *Presentation layer*: Responsible for decrypting data, and *formats the data as sent by the sender*.
7. *Application Layer*: *Provides the network services* to the applications, like *e-mail*, *file transfer* or *remote monitoring* of another computer.

Computer networking can be developed, established and understood without the OSI reference model, but it makes networking simpler to understand. Therefore compatibility and development of new compatible functionality gets easier as well.

3.4.4 Information structuring as structuring of ideas

Concepts and terms are the prime constituents of information systems. Examples of concepts or terms are *Greenhouse gas* or *Mass*. There is no clear difference between concepts and terms. Generally a term is a prime item while a concept can be expressed by a combination of terms and other concepts. In some applications *Greenhouse gas* may be a concept and in other applications it may be a term. Concepts and terms mediate content and provide meaning to data in, for example, databases, files and reports. Content is mediated by letting a container of data represent a concept or a term. An example of such a container may be a data field in a database, named *Mass*, which contains the data *kg*. In this case the data item *kg* is mediated by its data field *Mass*.

Meaning is provided to a data item when a user can make sense of the data from relating the concepts or terms into his or her context. Information structuring starts with identifying the concepts and terms for which an information system should hold content and provide meaning.

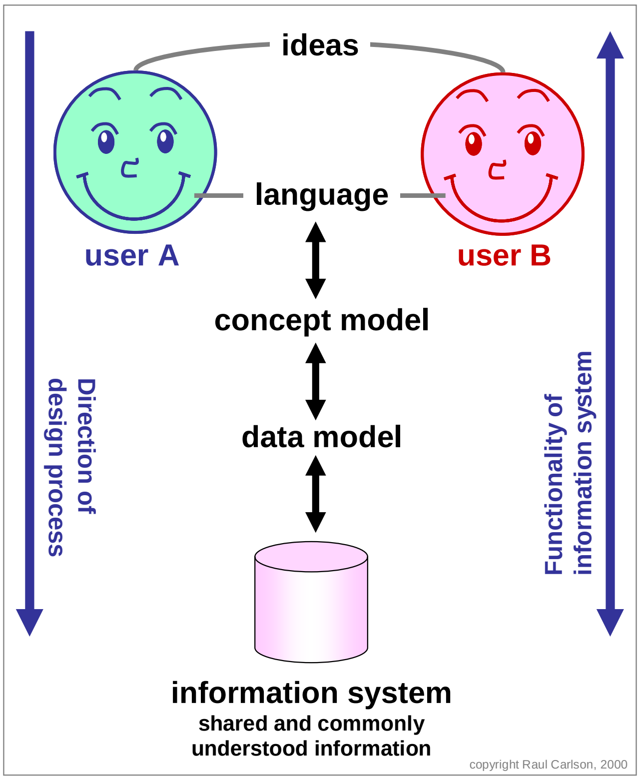

Figure 8. The figure describes how information systems are intended to mediate communication of ideas, and how the design and the use of information systems are related with the language and the ideas.

The vertical information structuring model presented in Figure 8 is partly inspired by the OSI reference model presented in the previous section. The model simultaneously presents two important aspects of information structuring:

- *Concept modelling*: How to design the data model for an information system based on a database like the one presented in figure 6.

- *Functional system architecture*: The information system is ultimately intended to mediate communication of ideas between its users.

Figure 8 illustrates that an information systems is intended to mediate communication of ideas. Here *idea* means a mental state with a specific meaning that can be formulated into a message. Exchange of ideas between people is naturally done by *language*. If users A and B are separated in space or time they need to communicate their message over some medium that transports or stores their language, in the form of *books*, *e-mail* or *databases*. The lack of direct contact introduces risks for misinterpretation. This risk increases if the two users have different competence, are in different situations, and if the information they exchange is not supplied with any explanatory additional information. The risk decreases if the users communicate about a specific issue that is common between the two, such as environmental management, LCA or DfE or if they take action to add extra explanatory text to their messages.

Design of information systems is accomplished by acquiring the meaning of the language of the field that the users intend to communicate about, and developing *concept models* of this language. It is stressed in this thesis that the *concept modelling* is facilitated by ensuring that the *conceptual models* are shared between the different intended users and the information structuring expertise. The resulting concept models are translated into the *data model* of *reports*, *communication files* and *databases* of the information system (section 3.5.2). The result is that users can mediate ideas and communicate meaning, even if A and B never meet.

Concept models and data models are intended to aid the design of *databases*, *communication files*, *questionnaires*, *reports*, *forms* or *web pages* for use in different control systems, like the one described by figure 3.

3.5 Concepts of environmental informatics

3.5.1 Environmental information

In this thesis environmental information has the purpose of supporting environmental management of different systems of industrial society (section 3.2.1), in the context of sustainable development (section 3.3.1). This means that information about the natural environment is always considered in relation to how it is impacted by activities in the industrial society, and in relation to how people or groups of people relate to these impacts.

Figure 9 is a high level concept model that describes how information from three different disciplinary areas together are needed to form a unit of interdisciplinary environmental information:

- *Technical System*: Represents information that describes *industrial processes* and systems of such processes i.e. data from e.g. engineering disciplines.
- *Natural System*: Represents information that describes *nature* i.e. data from e.g. medicine, biology, or ecological disciplines.
- *Social System*: Represents information about the non-physical aspects of human beings i.e. data from e.g. *economy* or *humanities* disciplines.

The diamonds between the three disciplinary boxes represents the interdisciplinary relations of environmental information:

- *TN*: Represents the relationships between *causes* in the *Technical system* that results in impacts in the *Nature System*.
- *SN*: Relates both to the fact that people or groups of people in the *Social system notice* impacts in the *Nature System*, and that people *prioritize* or give different weights to the different impacts that they notice.
- *TS*: Represents that people or groups of people in the *Social system benefit* from the *goods* produced by the *Technical System* of the industrial society.

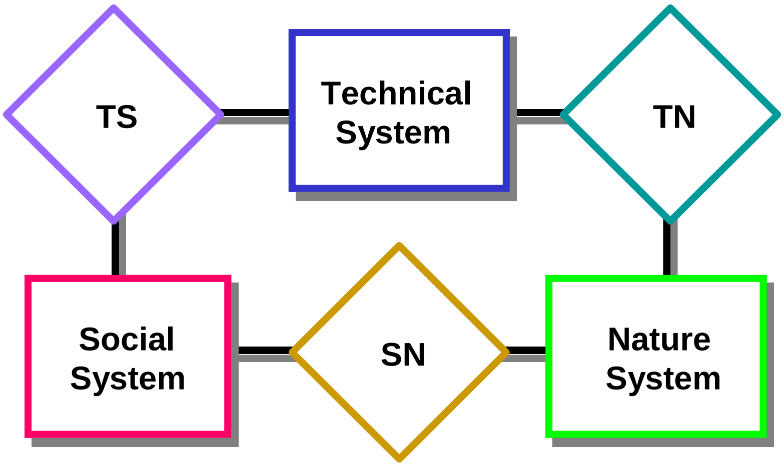

Figure 9 Three types of information that are related into environmental information. This concept model was developed by the author as a high-level entity-relationship model describing the SPINE (Carlson, Löfgren, Steen, 1995) information structure.

The concept model in Figure 9 was developed by the author of this thesis to serve as an overview of the SPINE information structure (Carlson, Löfgren, Steen, 1995), and as a pedagogic tool to describe the nature and structure of environmental product data, including e.g. the life cycle perspective.

3.5.2 Example of environmental information structuring

The following example describes in detail how concept modelling is performed on environmental information, using relational modelling by analysing *functional dependencies*[9] of concepts and terms used by the experts in the field. The example here is taken from the LCA impact assessment model presented in section 5.1, and is based on an analysis of the then ongoing standardization of LCA impact assessment within ISO (ISO, 2000). Thanks to the efforts made in the ISO working group, much of the work associated with identifying and defining important concepts was already done. But some freedom for interpretation still remained. Important concepts from ISO 14042 for this example are *Impact category*, *Category indicator* (*life cycle impact category indicator*) and *Weighting factor*.

According to the standard, the different concepts are defined in the following ways:

- An *impact category* is a class representing environmental issues of concern to which LCI results may be assigned.
- A *category indicator* is a quantifiable representation of an *impact category*.

[9] A functional dependency is when one concept or term uniquely determines another concept or term. This is written A → B, and means the same as saying "B is functionally dependent on A."

- *Weighting* is defined as converting and possibly aggregating *indicator* results across impact categories using numerical factors based on value-choices. *Weighting factor* is not formally defined in the standard, but is described as being used to convert the *indicator* results or normalized results in some way.
- The standard also defines the concept of *Category endpoint*, as an attribute or aspect of natural environment, human health or resources, identifying an environmental issue of concern.

During the concept modelling it was not possible to practically or logically distinguish between the two concepts *Category endpoint* and *Category indicator*. Examples of *endpoints* could also represent *indicators* and vice versa. Therefore only *Category indicator* is represented in the model. It may be interpreted as representing both of the two concepts in the ISO standard.

It was also not possible to individually distinguish between the two concepts *Impact category* and *Category indicator*. Examples of *Category indicators* could also represent *Impact categories* and vice versa. Semantic analysis led to the conclusion that the two concepts are defined in relation to each other, giving the result that *Category indicator* is an observed, quantified and measured environmental change, while *Impact category* is only observed as a class of environmental changes.

The *Impact category* is defined in terms of '*issues of concern*', which means that the selection or choice of *Impact categories* are chosen by a *subjective mind* (see also Figures 4 and 5). During the concept modelling it was concluded that a *Category indicator* or an *Impact category* needs to be identified in terms of the underlying reasoning. This introduced the new concept *Impact indication principle*, a concept not explicit in the standard. But it was implied by the definitions of the other concepts.

The resulting concept model is presented in Figure 10. The arrows represent *functional dependencies*, and the model may be read as:

- The underlying reasoning of the *Impact indication principle* needs to be defined and described before a *Category indicator* can be introduced.
- An *Impact category* first needs to be defined as a *Category indicator*, before it can become an *Impact category*.
- Each *Category indicator* may be a subclass of an *Impact category*.

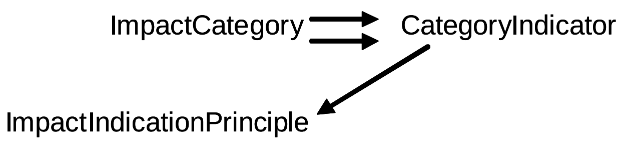

Figure 10. The concept model of *Category indicators* and *Impact categories*, as interpreted from the ISO standard *ISO 14042:2002 Environmental management — Life cycle assessment — Life cycle impact assessment* (see section 3.3.3).

In the standard ISO 14042 *weighting* is defined as the relative weights across *Category indicators* or *Impact Categories*. The standard also requests that all *weighting methods* used shall be documented to provide transparency. Figure 11 presents the concept model of *weighting*.

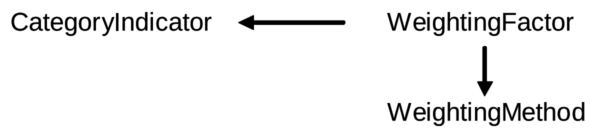

Figure 11. The concept model of *weighting*, as interpreted from the ISO standard *ISO 14042:2002 Environmental management - Life cycle assessment - Life cycle impact assessment*(see section 3.3.3).

The concept model in Figure 11 may be read as:

- Any *Weighting factor* must be assigned to *Category indicator*[10].
- Any *Weighting factors* are based on a transparently documented *Weighting method*.

The combination of Figures 10 and 11 is straightforward, and is presented in Figure 23 in section 5.1.2.2.

The result from the concept modelling is used to implement a data model, for example a relational database schema. Each concept presented above then comes to represent a table in that schema, and each table holds a number of fields or columns for different data. In the relational database schema the arrows are represented by foreign keys[11], which establish the logical relationships between the different tables of the database.

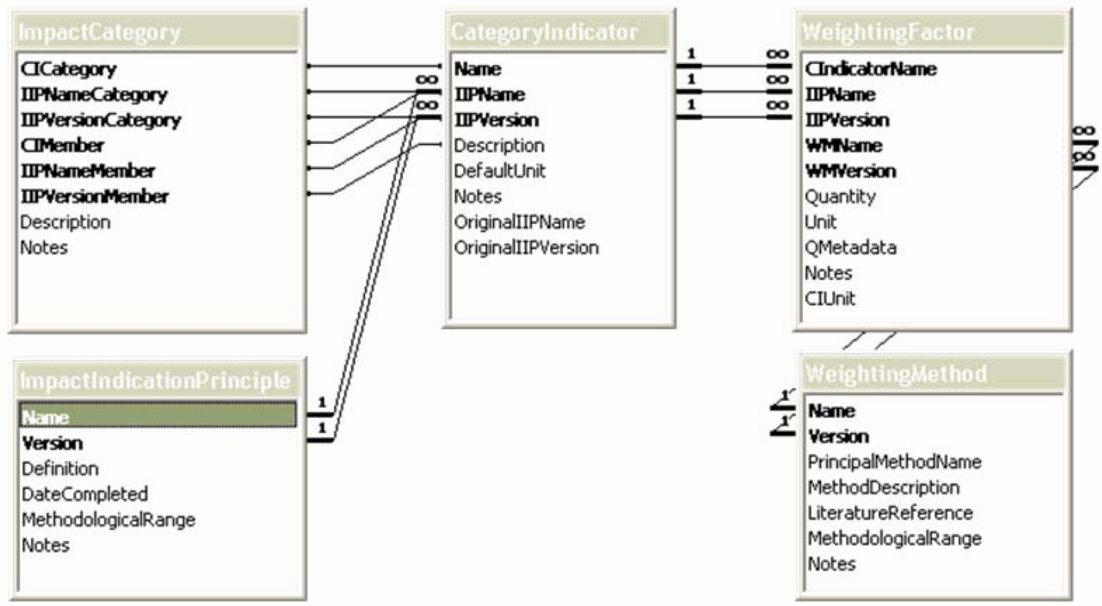

Figure 12. The relational database schema resulting from the concept models presented in figures 11 and 12, which is designed as an interpretation of concepts from the ISO standard *ISO 14042:2002 Environmental management - Life cycle assessment - Life cycle impact assessment*.

[10] To simplify notations in the concept models, the author has hesitantly but deliberately avoided cardinality of dependencies and relationships. Here it may be noted that *weighting factor* to *category indicator* should have a 2, n:m relationship, since *weighting* must concern the relative *weight* between at lest two *category indicator*s. *Weighting* of one indicator makes no sense. This also implies that *weighting factor* is *not* an attribute of a *category indicator*, but an attribute of a selected and defined *set of* category indicators.

[11] A foreign key is a set of selected fields in a relational database table, which matches the fields that uniquely identifies the rows of another table. The foreign key establishes the logical relations between the information in the relational database tables.

Figure 12 presents the relational database schema resulting from the concept models in Figures 10 and 11. Other examples of database schemas are presented in Figure A1 and A2 in Annex A.

The concept models of each of these three types of information systems will be presented in Chapter 5, and claims about generalized applicability of the model are presented in Chapter 6.

3.5.3 Example of an environmental information system

Figure 13 shows an example of an environmental relational database system built for industrial applications and scientific research (see also section 5.1). The system should be considered as a component in an environmental management system, like the conceptual model of the environmental management system presented in Figure 3.

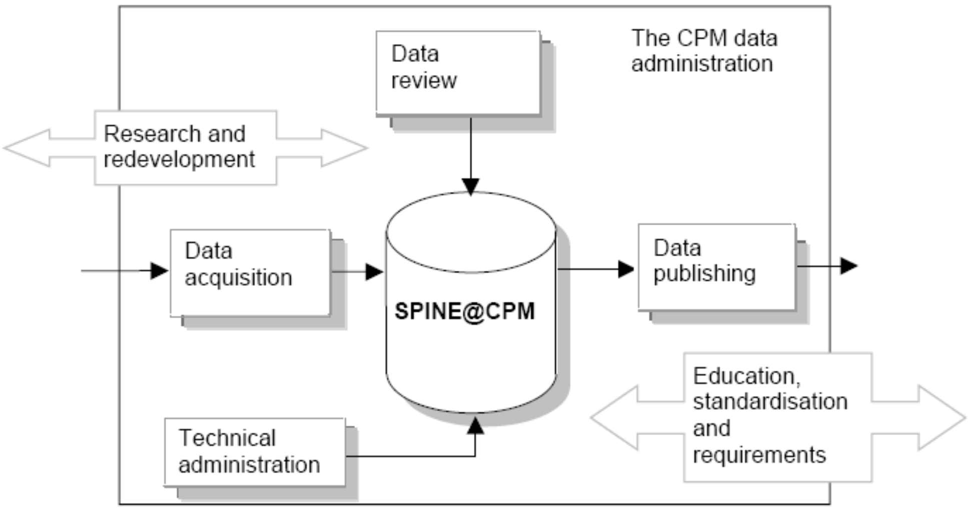

Figure 13. An environmental database system, consisting of both the database file and the necessary administrative functions. See also section 5.1.

The database system in Figure 13 is built around a relational database file (SPINE@CPM) (Carlson, Pålsson, 1998). The file is structured with all fields and logical relationships dictated by the information structure, like the relational database schema presented in Figure 12 in the previous section, or the examples in Figures A.1 and A.2 in Annex A. *Data acquisition* routines to build up the contents of the database are formalised, to ensure that information is provided with appropriate quality in the right form and with the right semantics according to the concept model. A *data review* process assesses all acquired information so that it fulfils the quality requirements. The quality review is essential to environmental databases, since environmental data generally cannot be verified (Carlson, Pålsson, 1998). Users access the information in the form that data are published with the intended meaning as prescribed by the concept model, and with the intended and reviewed quality. The *technical administration* of the information system is considered as being part of the information system, responsible for maintaining the information structure.

Environmental management and sustainable development facts and priorities are continuously changing due to new knowledge, increased public awareness and new policies. Therefore a functioning environmental database system needs a continuous relationship with *research and development* activities, and to be designed to receive and respond to user *requirements*.

Since environmental issues are not core business of most industries, the environmental information system also needs to be simple to use. Environmental issues do not come up on the daily agenda in the ordinary business life, and the issues are not discussed very often. They therefore also drop out of the mind of the intended users of the information systems. Therefore it is important if the information system itself supports and maintains the *education* of environmental issues within the organisation each time it is used.

The work with specifying the information structure of this information system is further described in section 5.1, where also the information system is presented in more detail.

4 Methodological approach

4.1 The aims

This research has aimed at solving two problems:

- Develop information structures for databases, communication files, reports and software for environmental management of industrial systems.
- Synthesize a general methodology or framework for developing such information structures.

In addition to its practical nature, the applied research also identifies the important relationship between information systems and indicators.

4.2 The interdisciplinary starting-point

The present work started out from a master's degree in engineering physics with specialization in environmental science, statistics and computing science. The master's thesis work was an interdisciplinary study, pertaining to structuring a relational database for life cycle assessment (Carlson, 1994), and it resulted in the initial input to the work described in this thesis. The work with that master thesis was based on the education from engineering physics, previous experience from practical work with *production quality management* in industry and the author's personal interest in industrial *total quality management* (Shingo, 1984), *cybernetic control* theories (Wiener, 1991), and on theories of *mass communication* (DeFleur, Ball-Rokeach, 1989) and *cognitive psychology* (Ellis, Hunt, 1989).

These different interests and competencies were combined into an ad hoc methodological approach for structuring information and building information systems for industrial environmental management, consisting of a blend of *classical physics*, *cognitive science*, *computing science* and *quality management*.

- *Classical physics*: The perspective of classical physics implies that environmental issues are based on a scientific study of matter and motion. The information systems are established from identification of simple physical properties, interactions, processes, and laws. The industrial environmental systems analytical approach is to study the natural or material world and phenomena.
- *Cognitive sciences*: Information is regarded from a human viewpoint and terms such as meaning, semantics, context etc. are handled from the perspective of cognitive sciences.
- *Computing sciences*: Methods and techniques from the area of computing science have been applied for data modelling, information systems design, etc.
- *Quality management*: Ideas of total quality management (TQM) are built in to industrial environmental information systems. It is considered that information systems and information management methods should be designed with both short- and long-term total quality in focus, and that such principles should also be economically sound for all sorts of organizations in the industrial society.

This interdisciplinary blend, and the different knowledge and principles behind the concepts and terms introduced in chapter 3 were the methodological starting points of the research work presented in this thesis.

4.3 The research project

The research behind this thesis began with 6 to 10 separate projects running between 1994 and 2004, and financed by the *Nordic Council of Ministers*[12], *VINNOVA*[13], the *European commission's 5:th framework*[14] and *6:th framework*[15] *programmes*, different large *Swedish and European industrial companies*[16], and by *Chalmers University of Technology*. The author of the thesis is employed by Chalmers University of Technology and has been *project manager*, *subproject leader* or *technical expert* with responsibility to *design*, *develop*, *implement* or *maintain* information structures and information systems in the different projects.

Having been responsible at different levels for the outcome of these projects, it has been necessary for the author to formulate practical principles for the development of information structures for environmental management of different industrial systems. The methodological framework presented in chapter 6 is based on this practical experience.

The aim formulated in section 4.1 and the interdisciplinary starting-point presented in section 4.2 have been the leading themes through all of these separate projects. In large, the work has consisted of building three different information systems aimed at supporting different environmental management methods and tools. Experience has been paired with theoretical studies aimed at understanding the underlying principles of information structuring for environmental management. Results have been reported in both scientific articles and in reports, and in the form of functioning information systems.

The three different information systems are for:

- Life cycle assessment (LCA) (see sections 3.2.3 and 5.1),
- Design for Environment (DfE) (see sections 3.2.4 and 5.2), and
- LCA characterization modelling (see sections 3.2.3 and 5.3).

Considering the practical nature of the development of the information structures and the actual testing and implementation of the information systems the research work may resemble technical *development*, but with respect to that most of the work has been pioneer work, and the fact that the overall aims and theoretical foundations have been deliberate, and has been consciously updated and reformulated during the work, the projects might instead rather be categorized as *action research*, according to Checkland (Checkland, 1998).

[12] The NEP-project: Nordic project on Environmentally sound Product development (see section 5.1)
[13] VINNOVA: Swedish Governmental Agency for Innovation Systems
[14] The RAVEL-project (see section 5.2)
[15] The OMNIITOX-project (see section 5.3)
[16] ABB, AB Volvo, Akzo Nobel, Alstom, Antonio Puig S.A., Assi Domän, Avesta Sheffield, Bombardier, Deutsche Bahn, DSB, Duni, Electrolux, Ericsson, Holmen, IKEA, ITT Flygt, M-real (MoDo), Norsk Hydro, P&G Europé, Perstorp, Rolls Royce, SAAB Automobiles, SCA, SJ, Stora Enso, SwedPower (Vattenfall), Södra, Telia,Volvo Cars, Woodville Polymer Engineering

5 The applied research work

This chapter presents the applied research on which the reasoning of this thesis is based. The work has been constituted by developing information structures for three separate and different information systems in support of environmental management methods and tools. During the projects additional effort has been taken to make the information systems compatible by striving to have them share some of the same data structures. In the presentations of the concept models in this chapter this compatibility will be pointed out, together with reasoning regarding how it was done.

The compatibility between information structures for different methods and tools is one of the benefits of having had a number of related projects over a long time. Through this it has been possible to learn how to integrate different industrial environmental information systems with each other, which in practice also means that the different *methods* and *tools* for industrial environmental management have been integrated with each other, concisely and cost-efficiently. In Annex C all concept models are listed together.

5.1 Environmental life cycle assessment

ARTICLES THAT PRESENT THIS PROJECT:

I. Carlson R., Löfgren G., Steen B., Tillman A-M., *LCI Data Modelling and a Database Design*; Published in The International Journal of Life Cycle Assessment, Vol. 3, No.2, pp. 106-113, 1998

II. Bengtsson M., Carlson R., Molander S, Steen B., *An Approach for Handling Geographical Information in Life Cycle Assessment Using a Relational Database;* Published in Journal of Hazardous Materials, vol. 61, pp. 67-75, 1998

III. Carlson R., Pålsson A-C., *Industrial environmental information management for technical systems*, Journal of Cleaner Production, 9, pp 429-435, 2001

5.1.1 Brief introduction to the project

In 1993 LCA practitioners in Swedish academia and industry were in need of a good information structure for LCA databases and LCA data exchange. The work started with modelling an LCI database format for storage and exchange of LCI data. This first pilot work was performed as a master's thesis project performed by the author (Carlson, 1994). It produced the information structure presented in figure A.1 in Annex A. This work fed directly into a governmentally supported Nordic project[17] with participants from academia, industry and research institutes. The project produced a specification of a relational database format named SPINE[18] (Carlson, Löfgren, Steen, 1995), presented in figure A.2 in Annex A.

With the SPINE format as a foundation, the Swedish national LCI database was established by CPM (see section 1.1). The establishment of the database started in May 1996. During the following months and years the activities in the project spun off several new research, development, testing and implementation projects (Carlson, Pålsson, 1998). Before users could add or retrieve data at the common database much work was needed to describe the practical implications of the information structure of the SPINE format. The work also initiated deepened discussions about data quality of LCI data, as well as initiated international standardization of a format for LCA data.

To meet the need for a complete LCA data format, rather than only an LCI data format (see section 3.3.3), a complementary format for impact assessment was developed between 1997 and 1998. The work was done in parallel with the finalisation of the ISO standard for LCA impact assessment (ISO, 2000) (see also section 3.5.2).

Today there is an ISO technical specification, *Environmental management – Life cycle assessment - Data documentation format* ISO/TS 14048 (ISO, 2002) partly based on many of the experiences from the development and industrial testing of the SPINE format. New tests are still in 2006 being performed in current CPM projects.

In the following sections practical details of the work will be described.

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[17] The NEP project, financed by the Nordic Council of Ministers
[18] SPINE: Sustainable Product Information Network for the Environment

5.1.2 The life cycle assessment information structuring

5.1.2.1 The ad hoc approach

Development of the SPINE format was divided into three distinct *methodological stages*. The first stage was performed largely on the basis of analysis of the concepts, meaning and logic of the language and conceptual models used by LCA experts, acquired through interviews and literature (Carlson, 1994), and based on the database design principles described by Elmasri and Navathe (Elmasri, Navathe, 1994). This first stage was a limited and well-defined task, performed intensively in a few months. The result was a data model in the form of a relational database structure. During the second stage the resulting data model was analysed from the perspective of e.g. *symmetric properties*[19], *redundant structures*[20] and *model analogies*[21]. The work was an isolated technical task performed by modelling experts. During the project many detailed decisions were taken regarding the resulting structure. The work resulted in a simpler model than after the first stage, with fewer concepts and a clearer logic (Carlson, Löfgren, Steen, 1995). The third stage was to *interpret*, *test* and *practically use* the resulting model, including its simplifications and to *develop an understanding* of how the model was related to the intended physical reality of LCA in practice (Carlson, Pålsson, 1998). This stage was clearly defined in the beginning, as the actual implementation of a database for use in industry and academia. But the work has then been stretched over many years, in parallel with that the number of users and stakeholders of LCA information structuring has increased. This stage has been a strong driver of the overall research quests of this thesis.

As already described above, the division into three stages was not strictly intentional at the time. At a large scale it was propelled by the practical establishment of the Swedish national LCI database within CPM and by the international ISO standardisation of the LCI data format ISO/TS 14048. And the work was also seen as a case study of the interdisciplinary theories that originally inspired the approach of the work.

5.1.2.2 The stages of information structuring

STAGE 1, CATCHING THE CONCEPTS, TERMS AND LOGIC

The first stage of the work was strongly guided by a physicist's scientific view, the strict school-book principles for modelling databases (Elmasri, Navathe, 1994), together with a layman's interest in cognitive science and experiences from industrial quality management (see also section 4.2).

Figure 14 shows an early conceptual overview of LCA, as interpreted for the initial concept modelling. An LCA study is performed by modelling the isolation of a *Technical system* from its physical environment, and to investigate its physical exchange (*Flows*: *Resources from nature*, *Emissions*) with the natural *Environmental system*. The *Technical system* consists of included linked technical systems. All physical flows of the studied system originate from these included technical systems. An LCA information structure needs to be designed to describe these items, their

[19] Example, identifying if similarities between different concepts may be interpreted as different types, sorts or instantiations of the same higher level concept.
[20] Example, identifying whether the same concept or terms has been identified with different names.
[21] Example, considering whether life cycle models resemble electric circuit models or organizational charts.

relationships, properties and this methodology, in a flexible way, so that information remains transparent during an LCA study.

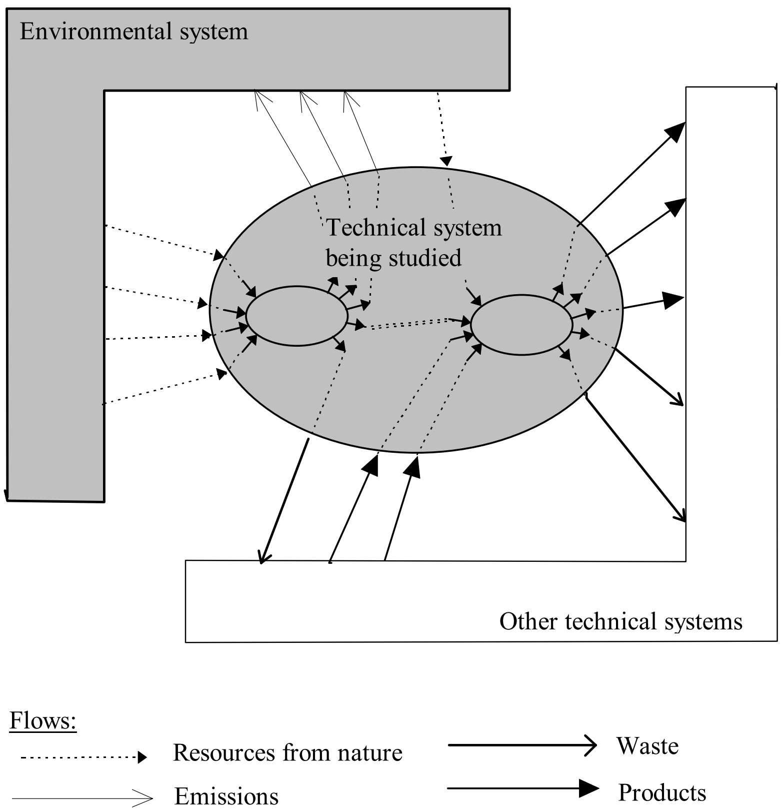

Figure 14. The conceptual model of the relationships between the systems of interest in an LCA (Carlson, Löfgren, Steen, Tillman,1998).

From interviews with LCA experts and from literature studies, it was evident that *data quality* was a very important aspect of LCA. All parts of LCA, from data collection to review and interpretation of results were subject to critique and scrutiny. The concept of LCA data quality had a complex and vague structure, with general references to undefined statistics and large faith in peer review.

The first attempt to support data quality through information structuring was made by attempting to restrict reuse of data. An LCA is produced from data acquired in some earlier situation. And those data often again originates from even earlier LCA studies etc., in a long chronological sequence, so that an LCA may be said to 'consist of' earlier LCA data (see Figure 15). The idea with restricting reuse of data was intended to insist that users should be aware of when data were reused over and over again, to minimise the risk of unlimited error propagation. This approach was soon abandoned in favour of facilitating data review by the aid of the data transparency, enabled by advanced documentation possibilities. LCA data quality issues were also included by structuring for statistical parameters like standard deviation on the numerical data.

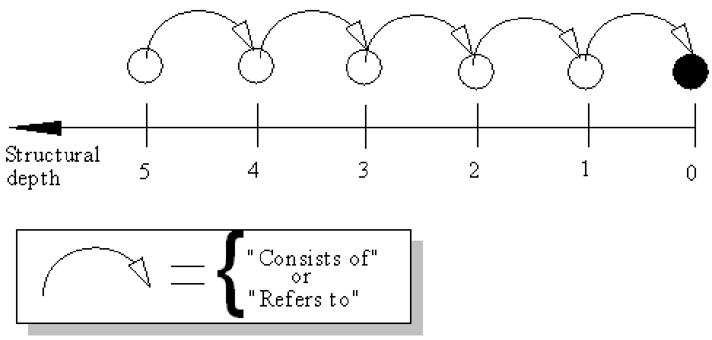

Figure 15. Model describing how error propagates when originally retrieved data (black circle) are reused and aggregated in LCA studies over and over again (white circles) (Carlson, 1994).

STAGE 2, CONCEPT MODELLING

The second stage of the structuring of information for LCA data was guided by focusing on the *economic life cycle* of a future LCA information system (section 3.2.3). It was expected that data acquisition would need to be coordinated with other environmental reporting, such as governmental reporting or reporting for environmental management systems. The focus was on producing a small model *without redundancy*[22] and *without unnecessary complexity*[23]. This was done to facilitate future data quality management (Liker, 2004), and to prevent from making errors (Shimbun, 1988) (Nikkan, 1988). These decisions were intended to integrate *continuous improvement* already in the design of the concept model of the intended information system.

Modelling The Concepts Of Life Cycle Inventory

During the second stage potentially inefficient modelling in LCA was recognized. *Transports* and *processes* were handled as different entities by LCA practitioners, but they were described almost identically. The same was true for resources, emissions, waste and products. In LCA calculations these concepts were treated differently and were therefore also modelled differently in available software and data sheets. To rationalise and to produce a minimal model these examples were noted as candidates for being merged into more general concepts, like '*General process*' and '*In- or outflow*'.

In the following the different modelling decisions and distinctions will be presented in the form of concept models, as was introduced by the example in section 3.5.2.

Activity ⟵ Flow

Figure 16. The concept model of the concepts Activity and Flow

The concept that represents general processes was named *Activity* and the concept that represents in- or outflow was named *Flow*. The concept model in Figure

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[22] In information structures redundancy means that the same data is stored in more than one place, which introduces the risk of missing to update at both places and to therefore leave the system in an incorrect state.

[23] Information structures with high complexity may have many dependencies, and may therefore be difficult to read and interpret. Complexity may introduce errors when programming or handling data.

16 states that *Activity* has *Flow* and that an *Activity* must have been defined before a *Flow* can be created. *Flow* cannot exist independent of *Activity*. The information used to describe *Flow* and *Activity* will be partly explained by the rest of the concept model, and will also be presented as an example after the presentation of the model.

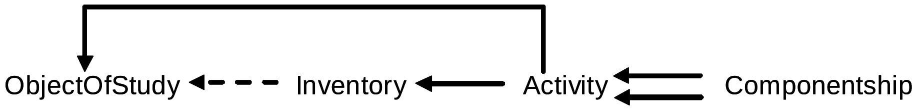

Figure 17. Concept model describing the technical system studied in LCA.

An *Activity* is a model of some real world occurrence, such as a production plant, a transport route, or a partial life cycle of a product. The concept of this real world occurrence was given the name *ObjectOfStudy* (see figure 17). One may produce different models of any such *ObjectOfStudy*. The concept of such model was given the name *Inventory*. The concept model states that first one needs to define an *ObjectOfStudy*, and then one can define an *Inventory* (the dotted arrow[24]) onto which one may define an *Activity*. The three concepts together constitute a technical system as presented in Figure 14. The fact that technical systems in themselves include technical systems is modelled by the concept *Componentship*. One arrow relationship between *Componentship* and *Activity* refers to that one *Activity* is the host of the other, and the other arrow refers to that the other *Activity* is included with the host[25]. An *Activity* can have an unlimited number of other *Activity* within itself.

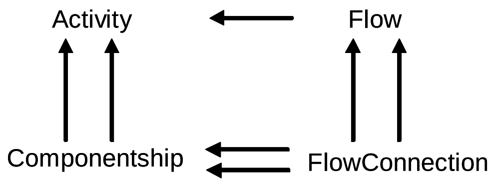

Figure 18. Concept model describing the technical system studied in LCA.

Figure 14 shows that any two or more *Activity* within an *Activity* may be connected with each other via an in and an out *Flow*. The concept model in Figure 18 shows that this connecting concept is named *FlowConnection*. A *FlowConnection* is defined by the two *Flow* that are connected and the two *Componentship*-related *Activity* that are connected by these *Flow*. Any two *Activity* cannot be connected, only those that are included by the same host *Activity*.

[24] Unfortunately SPINE is not modelled with the dotted arrow, but with the arrow between Activity and ObjectOfStudy. This is an error that was made during the modelling discussions.

[25] The two arrows could have been denoted by cardinality *Componentship Activity* relationship of 2n:0, m, which would mean that *Componentship* to *Activity* relations always needs to be paired, from the perspective of *Componentship*, but not from the perspective of *Activity*. The author decided to exclude cardinality notations, and to instead use the simpler notations of only logical functional dependencies.

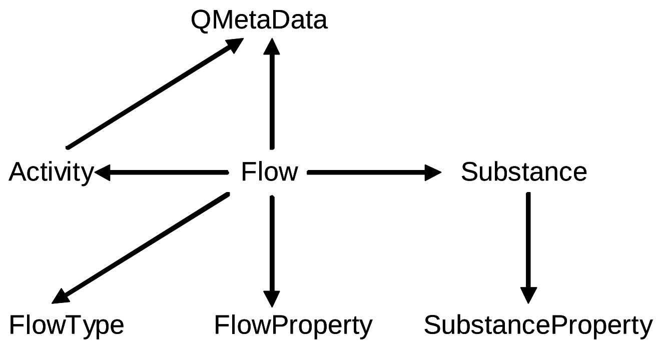

Figure 19. Model of the concept Flow.

Figure 19 shows that the concept *Flow* is defined in terms of whether it is an *emission*, a *natural resource*, a *product* or some other relevant *type* of *Flow*. The different types of *Flow* are listed in the concept *FlowType*. *Flow* is also defined in terms of the *matter* which flows. The matter is described in the concept *Substance*. For the purpose of environmental assessment of a specific flow it is sometimes valuable to know more about the substance, like its *temperature*, *price* or other *properties*. The concept model allows some properties to be stably related to the *Substance*, such as *density* or other chemical or physical properties. The concept of stable substance properties is named *SubstanceProperties*, and the concept of properties related to a specific flow of an *Activity* is named *FlowProperty*.

As described in the previous section, the model was designed to support LCA data quality management by facilitating data review. The concept *QMetaData* was introduced for this purpose. It allows for detailed qualitative meta data for the quantitative data of each *Flow*, as well as for all quantitative data of an *Activity*.

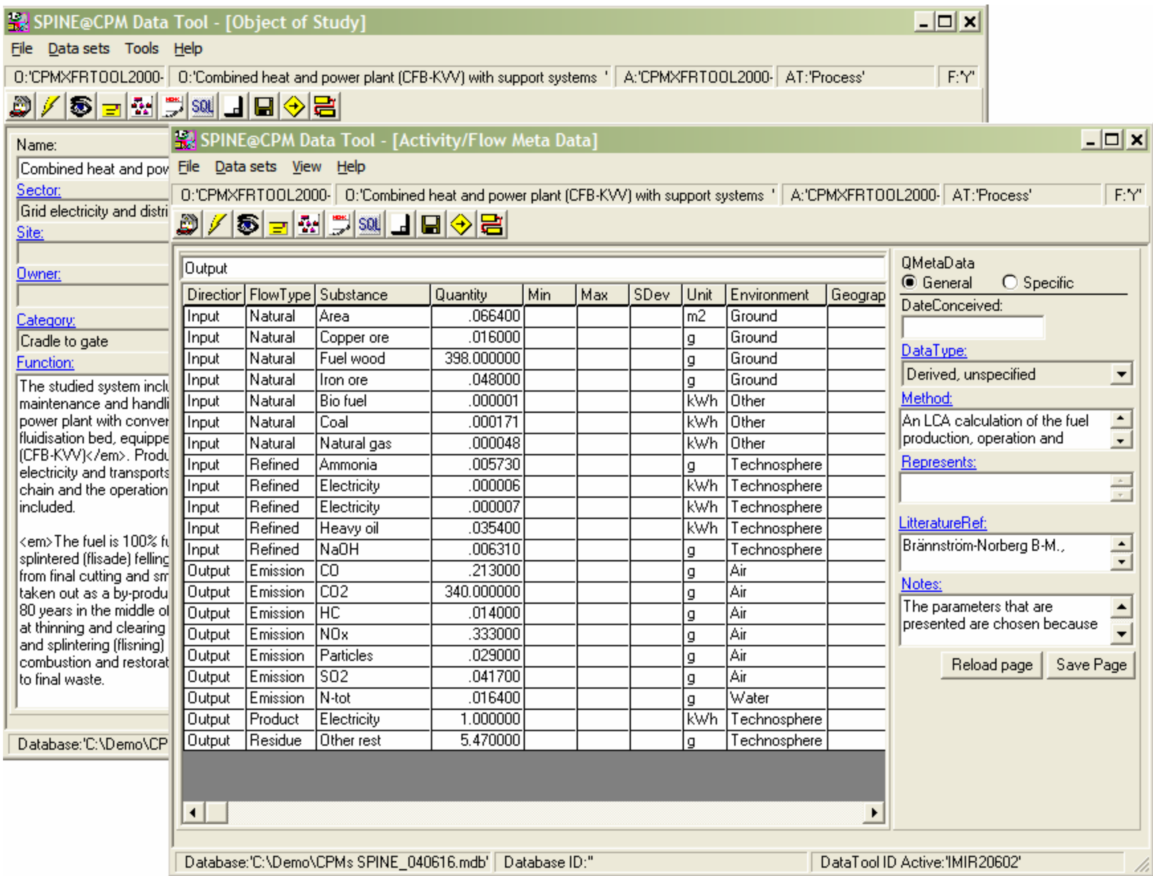

Figure 20. Screenshots of the software tool SPINE@CPM Data Tool, developed by the author for a relational database implementation of the concept model described here.

Figure 20 shows how some of the data based on the concept model described here is presented to users through a software developed by the author of this thesis. The different data fields that constitute the concepts *ObjectOfStudy*, *Activity* and *General* and *Specific QMetaData* are partly shown in the figure.

Annex B presents the architecture and user interfaces of the Swedish national LCI database network based on this information structure.

Modelling The Concepts Of Impact Assessment

The modelling of a information structure for impact assessment data was performed when the LCA impact assessment standard ISO 14042 was being developed within ISO (ISO, 2000). The draft concepts and the logic were clarified in the ISO consensus process, and it became possible to construct a good information structure based on this (see also the example in section 3.5.2).

The following text and figures presents the resulting concept model. The part which describes indicators and weighting is presented as the detailed example in section 3.5.2, and is therefore not again described here. A full and detailed description of all concept models are provided in the report *Documentation of environmental impact assessment, compatible with SPINE and ISO/TS 14048* (Carlson, Pålsson, 2002).

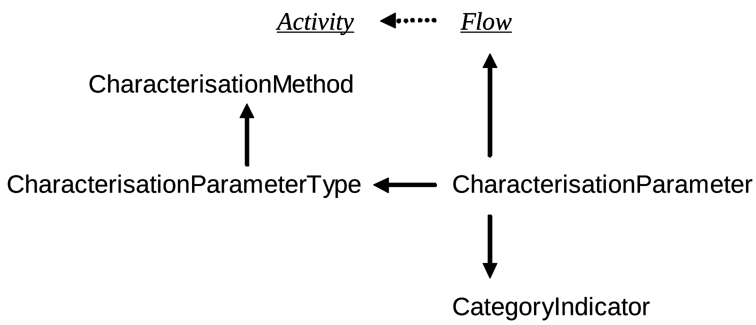

Figure 21. Concept model of LCA characterization.

Figure 21 presents the concept model of characterisation in LCA. Note that the concepts *Activity* and *Flow* were already defined in the previous section, and that *Category indicator* was defined in section 3.5.2. A *characterisation parameter* describes the quantitative impact from a flow on a *category indicator*. Since this quantitative impact is strongly dependent of how the environmental cause-effect chain has been modelled, a *characterisation method* needs to be documented for each characterisation parameter. A characterisation parameter is most often defined as a single value that should be multiplied with the quantity of the flow. But other mathematical forms are allowed by the model. The characterization parameter may be made up from calculation of more than one quantitative value, to form a nonlinear relationship that is defined by the method. Each such value is named in the list *CharacterisationParameterType.*

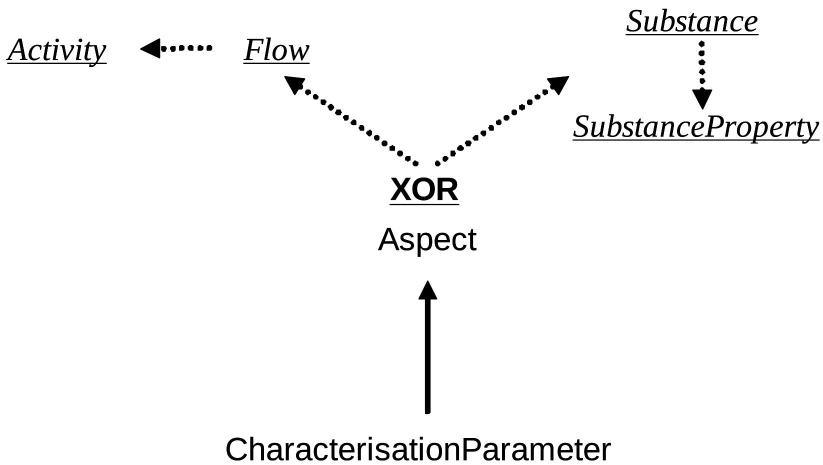

Figure 22. Model of concept of Aspect.

The concept model of Figure 22 was designed later than in the project described here. But it is introduced here since it is most naturally explained in this context. The concept model of characterization presented in Figure 21 states that a characterization parameter describes the impact from a *flow* on a *category indicator*. The concept *Aspect* generalizes this into that a characterization parameter may also describe the impact from a *substance*, without assigning it to a *Flow* of an *Activity*. This is suitable when for example assessing the environmental *properties* of materials of a product, or when making assessments of risks from use of substances. This will be presented in more detail when describing the concept model for design for environment in section 5.2.

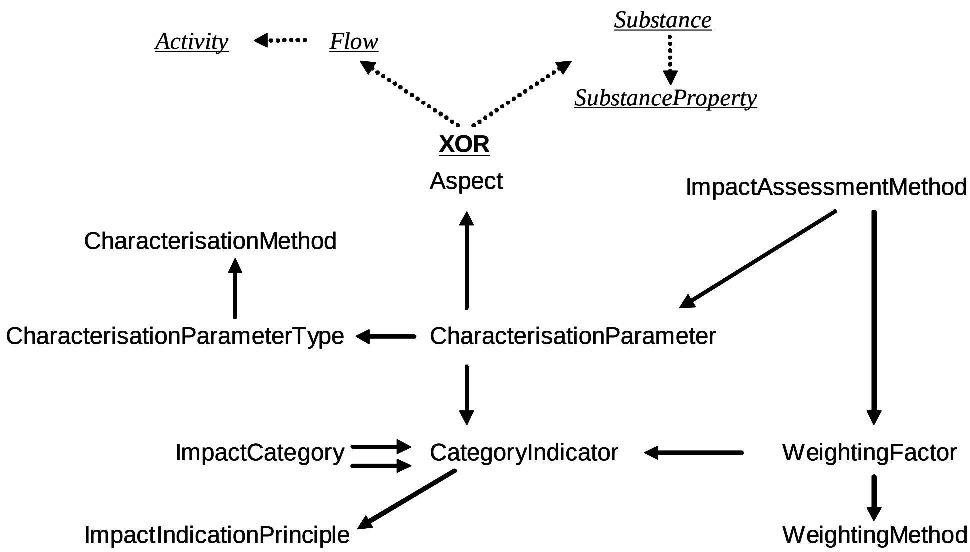

Figure 23. Concept model of LCA impact assessment.

In Figure 23 all partial models of LCA impact assessment are put together into one complete concept model for LCA impact assessment. This model is unique, in that there is no other known complete concept model for LCA impact assessment that transparently follows all steps of the LCA impact assessment standard ISO 14042.

ImpactAssessmentMethod combines weighting factors and characterization parameters in a systematic way to result in a useful package of impact assessment data for use in LCA studies.

The concept model in Figure 23 clearly shows how category indicator is needed to determine the characterisation parameter, and how the characterisation parameter in turn determines which flows or substances that are significant. It is economically crucial that it is only those flows and substances about which it is meaningful to collect data. If there is no identifiable relationship between how a flow or a substance contributes to the environmental impact of a category indicator, it is uneconomical to collect data about these flows or substances. This insight hints that LCA database build-up is uneconomical, unless the intended impact assessment methods are at least vaguely decided to begin with.

The model has been implemented as relational databases and works well. It has been successfully implemented and tested in for example the software system WWLCAW (World Wide LCA Workshop, 2006) since the year 2000, from which the picture in Figure 24 is taken.

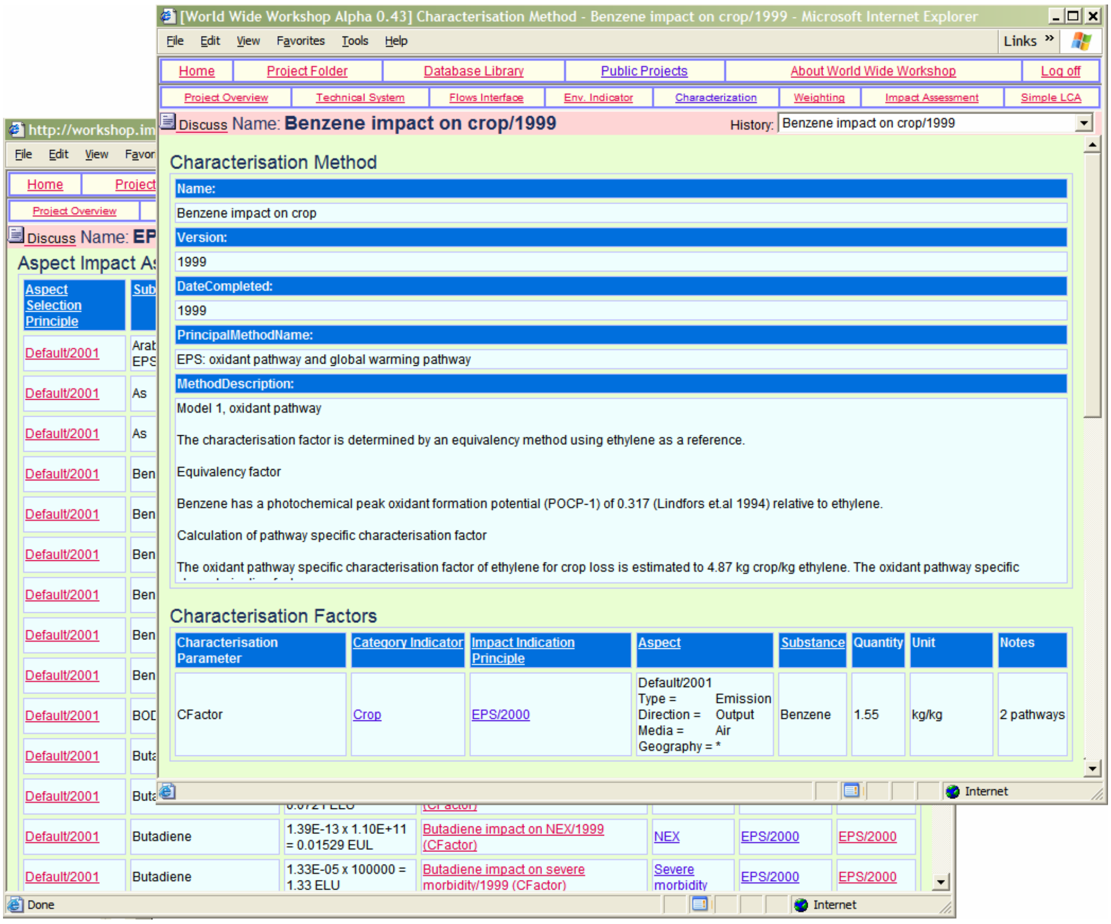

Figure 24. The software system WWLCAW (World Wide LCA Workshop) LCA impact assessment web documentation tool. The snapshot shows a characterisation model for *Benzene impact on crop*, from the *EPS method* (Steen, 1999).

Figure 24 shows a screenshot from the web tool WWLCAW, which is built on a relational database implementation of a combination of both the concept model for LCA impact assessment described here, as well as on the LCA inventory part described in the previous sections[26].

STAGE 3, CONCEPTUAL AND INTERDISCIPLINARY ONTOLOGY MODELLING

During the third stage of the information structuring, the concept models were tested together with users in practical situations, to ensure that the concept models actually describe the same view of the reality as the methodology of LCA.

The conclusion was that the concept models largely satisfied the user requirements. The fact that LCA data documentation was now expressed as different data fields in software and at web pages gave mixed feelings. The users of LCA data who acquired data from the databases highly appreciated the orderly structured and easily reviewed documentation, but the LCA practitioners who entered data into the systems became aware of their actual lack of documented data and considered the new data fields as a new obstacle for data collection. This asymmetry between data users

[26] The software was designed by the author of this thesis, but was programmed by Marcus Carlson between 1999 and 2000.

and documenters was, and still is, a consequence of the fact that LCA training and discussion focuses on the methods to assess the collected data, rather than on collection and documentation of the data.

The high-level concept model of environmental information presented in Figure 9 in section 3.5.1 was developed to provide users with 'the big picture' of the information structure. The model was a simplification of the overall LCA data model presented in article II of this thesis (Bengtsson, 1997)

When applying the concept model in software and databases, both industrial and academic users were addressing the quality of the resulting data. To understand the different questions and requirements from the users the structure of the dimensions of data quality of Figure 25 was produced. It shows that LCA data quality is a many-dimensional question, which cannot be handled by the information structure itself.

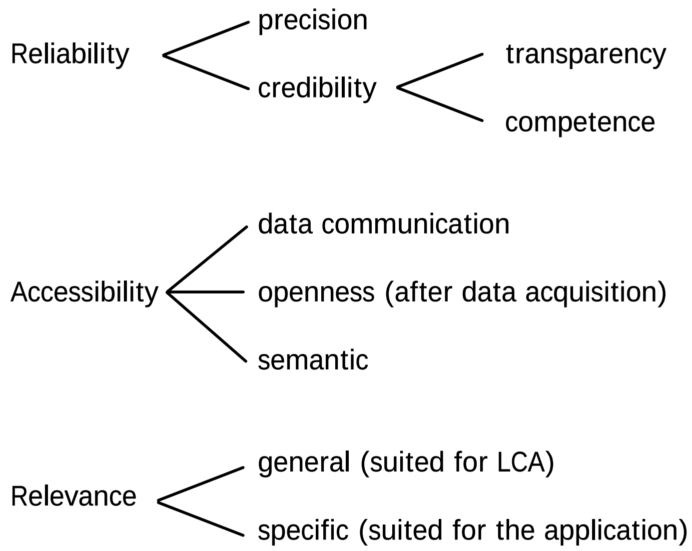

Figure 25. Dimensions of LCA data quality (Pålsson, 1999).

Figure 25 presents a structuring of the dimensions of LCA data quality, or information quality, developed to facilitate discussions and for practical and educational purposes. The three basic terms, *Reliability*, *Accessibility* and *Relevance*, were chosen quite arbitrarily on the basis of personal communication (Steen, 1996). To be practically useful for the task, the interpretation of the three terms were reformulated in terms that were meaningful for LCA data.

- *Reliability* is partly a matter of numerical *precision*[27] and partly a matter of *credibility* about that precision.
- *Accessibility* regards whether a data user can access the data, such as whether the data are in such a form that they can be *communicated* to the data user, so that data are not hidden from the user for *secrecy* reasons or so that data are not written in a *language or jargon* that the user is not familiar with.
- *Relevance* regards whether the data are relevant for *the type* of questions that the user has, and in *specific* whether data can exactly answer the question of the user.

[27] It may be more accurate to instead of *Precision* here instead spell *Accuracy*. But for practical reasons the terminology is here consistent with the terminology in the reference (Pålsson, 1999).

A fuller interpretation of Figure 25 for the purpose of LCA data is given in (Pålsson, 1999). This structuring substantially enhanced the efficiency of the discussions and the practical handling of LCA information quality, but it still left the question of *precision* unresolved.

Paper III of this thesis (Carlson, Pålsson, 1998) presents a model inspired by a combination of the ontology of classical physics, the OSI model presented in section 3.4.3 and general industrial quality management principles. The model was given the name PHASETS (PHASEs in the design of a model of a Technical System). PHASETS describes the phases needed for acquiring any numerical data item of a technical system model to be used in, for example LCA. In analogy with the OSI model PHASETS starts with the physical world at the bottom. Quantitative data originates from an explicit source, such as a measurement at a production site, a modelling tool or from an estimation made by an expert. At each consecutively higher layer the data is aggregated and reported upwards until it is used in an application for an environmental management purpose. PHASETS is presented in Figure 26.

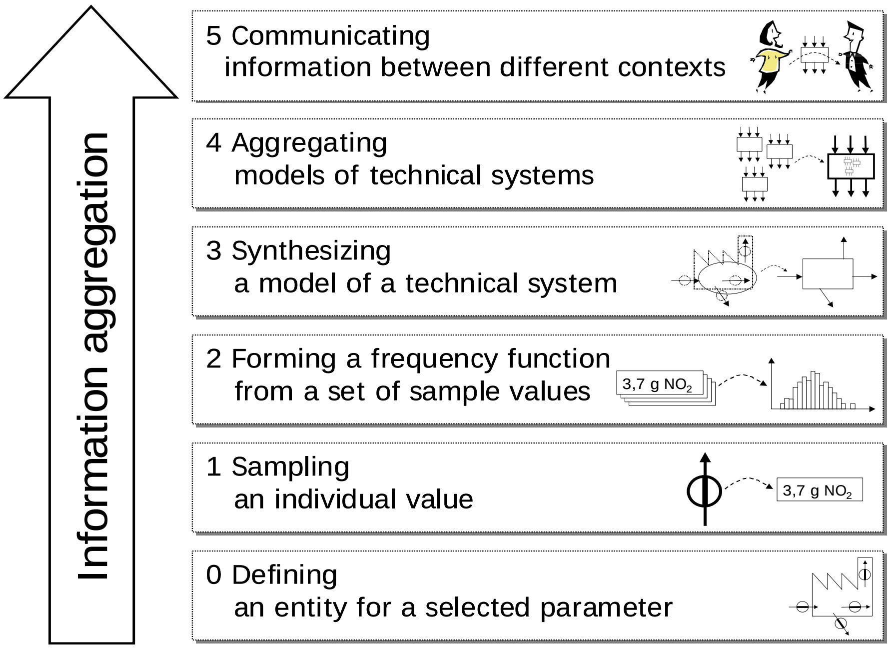

Figure 26. The PHASETS model for establishing a physical reference between LCA and the ontology of the real world (Carlson, Pålsson, 1998).

PHASETS is a conceptual model of the relationship between an LCA study and its underlying data, or the relationship between a model of system and the analytical data on which it is based. In analogy with the OSI reference model PHASETS is also a *reference model* for environmental data management. By utilising the reference model one may in principle achieve arbitrarily high precision and transparency of the environmental data. The relevant cost for the quality sets the limits[28]. The PHASETS model was later generalised into the PHASES model (PHASES: PHASEs in the design of a model of a System) (Carlson, Pålsson, 2000). PHASES in similar ways describe the data quality handling of data about also the *nature system* and *social system* (compare with Figure 9).

[28] The actual relevant costs are still to be investigated, but it may be expected to be based on *risk assessments*, the *precautionary principle*, and on *willingness to pay*.

5.2 Environmental design of products

ARTICLES THAT PRESENT THIS PROJECT:

IV. Carlson R., Forsberg P., Dewulf W., Ander Å., Spykman G., *A Full Design for Environment (DfE) Data Model*, PDT Europe 2001, April 24th-26th, 2001, pp. 129-135, 2001

5.2.1 The RAVEL project

The RAVEL[29] project (Dewulf et al, 2001) aimed at developing a methodology and a workbench that facilitates integration of environmental issues during the design of rail vehicles, such as trains, subway vehicles and trams. In the project plan it was stated that the methodology and the workbench should improve eco-efficiency[30] of rail vehicles by 25%. This quantitative goal introduced an important challenge for the project, and it forced the participants to actively think about how to define and collect quantitative data. The huge number of materials and components needed to produce a rail vehicle also forced the participants to think about how to structure the quantitative data and other relevant information in a practical way. With the experiences from having developed the LCA information structure described in section 5.1 the work could this time be performed much more straightforwardly.

5.2.2 The DfE information structuring

STAGE 1, CATCHING THE CONCEPTS, TERMS AND LOGIC

A first RAVEL concept analysis and concept synthesis was performed during an intensive three day workshop at Chalmers University of Technology, where all core expertise available in the RAVEL project attended actively. The result was a draft information structure that was discussed with the attendees at the end of the third day (see Figure 27).

In the rear view mirror one can see that the information structure after these three early days of intense and focussed work already included most of the important concepts and knowledge, which later was developed in more detail in the project.

[29] RAVEL = RAil VEHicLe eco-efficient design. The Brite-Euram project RAVEL was founded by the European Commission. Partners and subcontractors include rail operators (Swedish SJ and Danish DSB), a rail vehicle manufacturer (Bombardier Transportation), a supplier (Woodville Polymers), universities (KU Leuven, Chalmers University of Technology, and Linköping University), and consultants (ABB Corporate Research, GEP and Traintech Engineering). The duration was from November 1998 to October 2001.

[30] Eco-efficiency is a combined environmental and economic sustainability concept, meaning that a product, process or service is optimally better from both the environmental and the economic perspective.

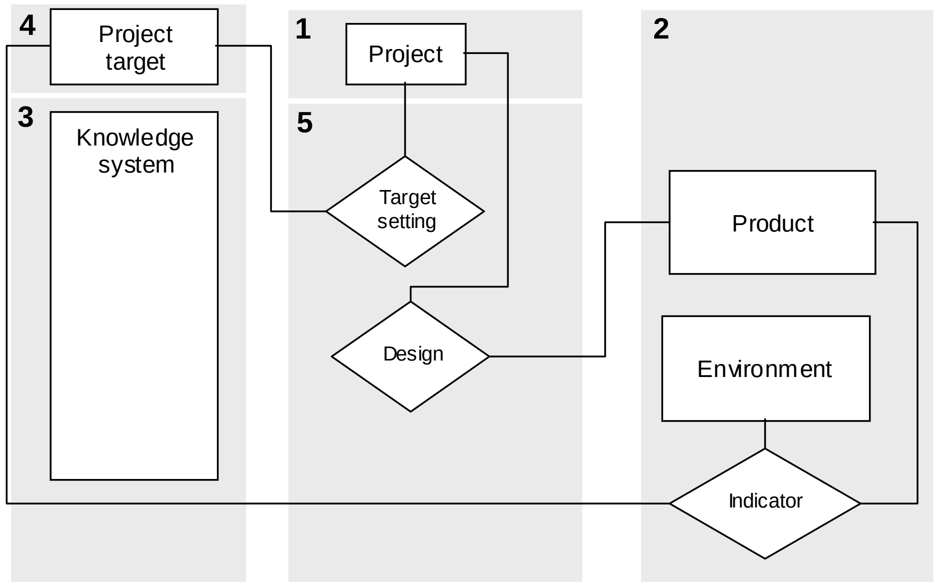

Figure 27. First concept model for the RAVEL information structure (*Carlson, 1999*).

During the workshop five major distinguishable and interdependent types of information were identified; the *design project* (1), the physical information that describe the *material* and the *components* of the rail vehicle in terms of the *environmental properties* (2), the background of guidelines and other built up *knowledge* (3), the environmental targets for the design (4), and the actual *methods and tools* needed to assess the environmental performance in terms of eco-efficiency (5).

During the analysis of the initial concept model it was concluded that environmental requirements should be handled as *any* other rail vehicle *design criteria*. They should be formulated by e.g. project management, customers or by strategists at the marketing department. This conclusion also led to the understanding that the environmental performance assessment of the product should exactly match how other ordinary design criteria were expressed. It was understood that environmental assessments with unclear stakeholders and targets would not be operative, and that such would introduce extra costs to implement, maintain and use. The implication of this understanding was that the RAVEL project directed efforts to develop methodology for environmental performance indicators (EPI) of rail vehicles, including the information structures and algorithms necessary to calculate such indicators. It was understood that in the same way as other design requirements may vary over time, the EPIs would also come to vary over time. Therefore, not only the data, but also the algorithms were intended to be stored in the RAVEL information structure as data.

In addition two conceptually different types assessment of environmental performance assessments were identified, *property based* assessment and *life cycle based* assessment. This means that one could perform an assessment of the physical product, either based on properties of the product structure or its materials and components (Figures 28), or based on life cycle assessments of the full product or its materials or components (Figure 29)

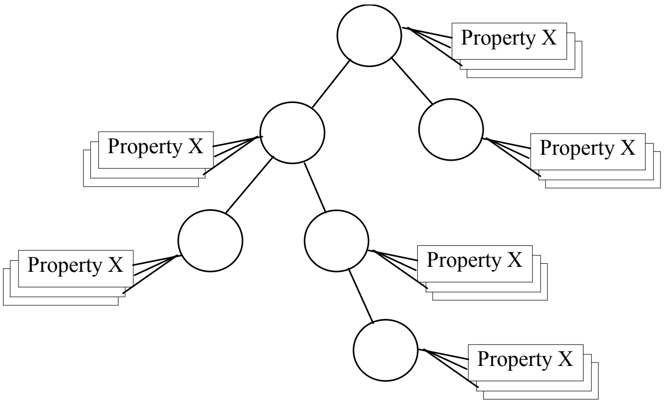

Figure 28. A conceptual component structure where each included component has a set of properties declared (Gernez, 2000).

The difference between the conceptual models presented in Figures 28 and 29 suggests that to assess the environmental performance of the product structure in Figure 28, one would need only to traverse the product structure and read a quantitative or qualitative property-value for each material and component. To assess the product structure in Figure 29, for each materials or component in the product structure one need to perform a full life cycle assessment and traverse the full LCA information structure (see subchapter 5.1 and compare also with Figure 4).

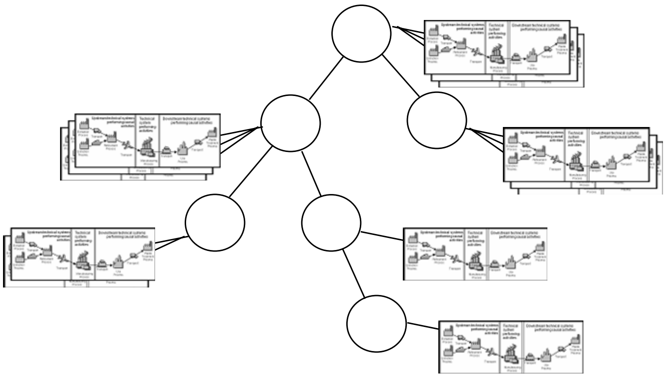

Figure 29. Conceptual representation of a material or component as being described in terms of its life cycle. This figure is a combination of the figures 4 and 28.

The performance assessment method conceptually presented in Figure 29 requires well-established supply chain relationships for it to be meaningful. The costs for acquiring LCA data for each component manually without well-established routines are unrealistic. However, the idea of relating components with supply chain based LCA studies came from the intended scope of application of the RAVEL workbench. See Figure 30.

Figure 30. The RAVEL methodology was intended for environmental design requirements and information exchange throughout the entire supply chain.

The RAVEL methodology was intended for environmental management of the design during the *entire supply chain*, from initial *call for tender* to final *delivery* of complete rail-vehicle. This should be facilitated by exchange of design requirements and information throughout the entire supply chain. The RAVEL workbench should be made available to all stakeholders throughout the supply chain.

STAGE 2,CONCEPT MODELLING

The concept model for design for environment in the RAVEL project was based in the same principles as the LCA concept model presented in section 5.1, as well as, when appropriate, some of the same concepts. When this is the case, this will be clearly explained, and denoted in the Figures 31 to 35. The LCA concepts are written in italic and are underlined, like *Substance*, while the new RAVEL concepts are written in straight fonts, like Project. A full presentation of all concepts and terms used in the RAVEL information structure is available in *The RAVEL Information Platform* (Carlson, Forsberg, 2000).

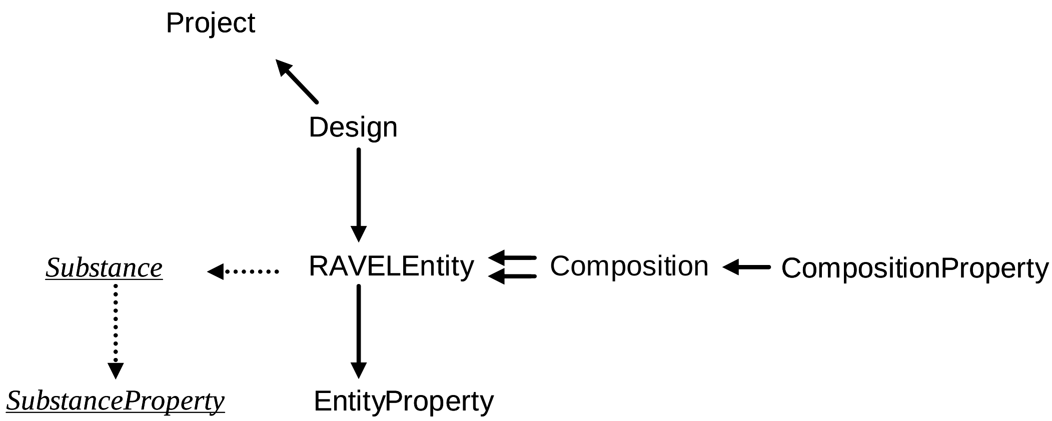

Figure 31. The concept model that describe a product design.

Figure 31 presents the concept model of a product design. The concept for the physical product is named *RAVELEntity*, and it is an exact copy of the LCA concept *Substance* (see figure 19 in section 5.1.2.2), like *EntityProperty* is an exact copy of the LCA concept *SubstanceProperty*.

Figures 28 and 29 describe that products are analysed as component structures. The concept *Composition* and *CompositionProperty* are introduced to handle this. *Composition* arranges *RAVELEntities* in a hierarchical structure, and *CompositionProperty* makes it possible to specify certain properties that are valid for the composition but not for each constituent. An example is that some materials are forbidden, *except* for in specific applications or when safely enclosed within specific encapsulations.

To keep track of the different products and component structures in the database of the RAVEL information system, each *RAVELEntity* may be addressed as a *Design* within a *Project*.

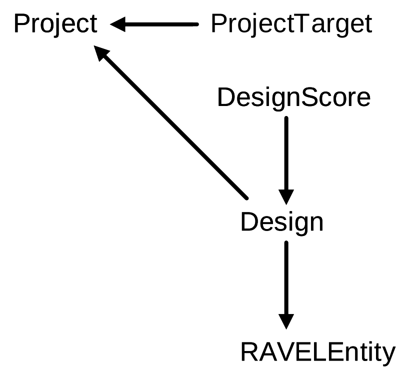

Figure 32. Model of concept of design targets and environmental performance results (score).

The concept model in Figure 32 introduces the two concepts *ProjectTarget* and *DesignScore*. The distinction of having the *target* as referring to the project and the *score* to relate to the design is important, since it implies that it is the responsibility of those who set up the project to also take responsibility for setting the targets, while the designers and other experts in the project have the responsibility to achieve scores that should be tested against the target.

This distinction is one of the methodologically most important outcomes from the RAVEL project, since it implies that a design project to begin with needs to have an explicit eco-efficiency performance target. The consequence is that the rail-vehicle customer, i.e. the operator of rail vehicles, needs to know how to set eco-efficiency targets on the design of the vehicle. The RAVEL project developed a complete methodology for this purpose, which is based on standardised agreements on environmental performance indicators (EPI) and standardised data format and materials database between railway operators and railway manufacturers. The responsibility for developing this standardised agreement today lies in a so-called eco-procurement board[31], mutually maintained by the rail vehicle manufacturers through UNIFE[32] and the rail operators UIC[33].

Figure 33 presents in detail how the concepts of scores and targets are handled in the RAVEL concept model.

[31] Eco-procurement board website: http://www.railway-procurement.org 2006-03-01
[32] UNIFE, the Union of the European Railway Industries
[33] UIC, the International Union of Railways

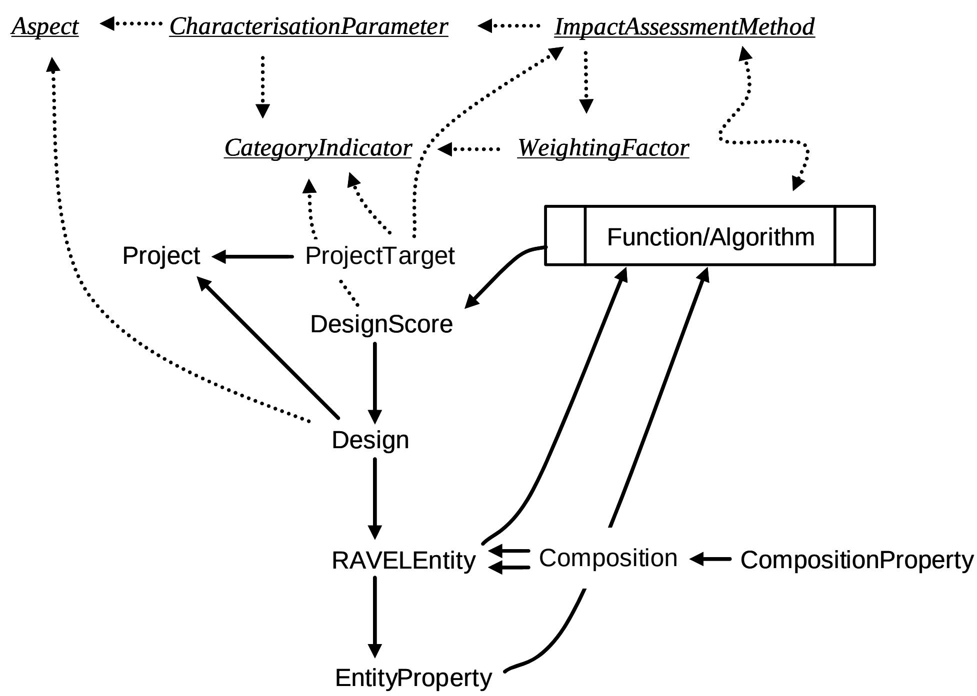

Figure 33. Concept model of how environmental performance is interpreted and calculated.

Figure 33 shows that both *DesignScore* and *ProjectTarget* refer to the LCA concepts *CategoryIndicator*. This means that the targets and the score are interpreted as indicators, in the same sense as LCA *category indicators*. Figure 22 in section 5.1 presented the concept *Aspect*. In Figure 32 the concept *Aspect* relates *Design* with an associated environmental impact on *CategoryIndicator* through the concept of *CharaterisationParameter*. The latter is the same LCA concept as was introduced in figure 21.

The box *Function/Algorithm* shows that the actual value for the *DesignScore* is *calculated* from the *EntityProperty* of each *RAVELEntity* in the product structure. The calculation is based on the *ImpactAssessmentMethod* specified by the *ProjectTarget*.

This integration of assessment of environmental design performance and LCA impact assessment has proven to be powerful beyond product design, and has after the RAVEL project were finished also been successfully used for environmental management systems (Policy controlled environmental management work) (Carlson, Häggström, Pålsson, 2004).

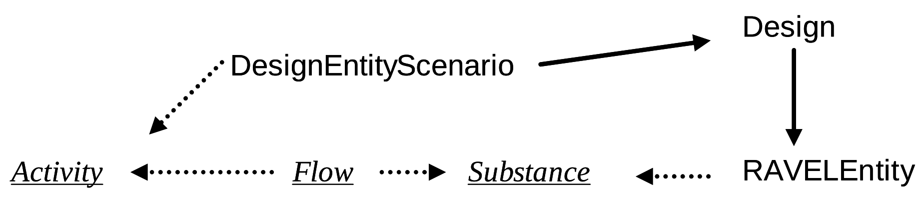

Figure 34. Concept model of the environmental properties of a material or component, in terms of its life cycle assessment. See also figure 29.

The concept model in Figure 34 describes the combination of the LCA concept model and the RAVEL concept model. Each component of the product is regarded as a substance that flows out from an activity in an LCA flowchart. The concept *DesignEntityScenario* describe complete LCIs of the *RAVELEntity*. This concept have not been implemented in any software, but has proven to have a strong pedagogic value, when discussing LCA in relation to DfE. Product design analyses based on the method has been successfully tested and assessed in a project with Toshiba Corporation in Japan, between 2005 and 2006.

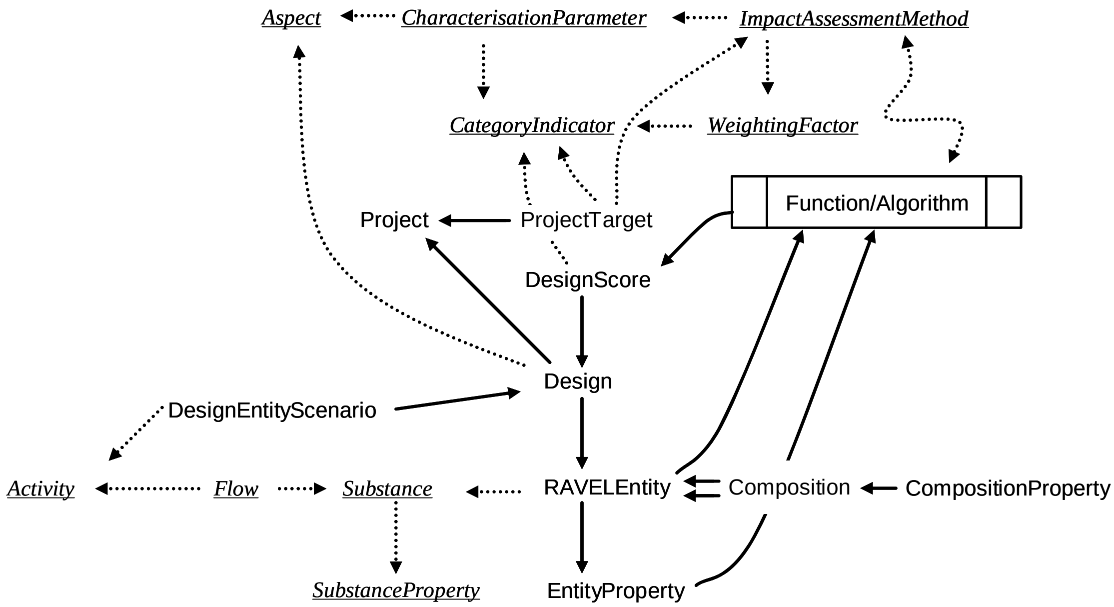

Figure 35. The full concept model of RAVEL design for environment.

Figure 35 presents the combined concept model of all concepts presented in this chapter. It should be noted how the RAVEL concept model is focused around the concepts *Substance* and *CategoryIndicator* from the LCA concept model. By having developed the concept model in the described way the relationships between environmental *indicators*, the product *design* and the *environmental data* become logical. It makes it possible to, for example, *plan* the *information acquisition* for databases of the information system very precisely, so that *only the requested* information and data are acquired to the database.

It needs to be stressed that these are not all the concepts in the RAVEL information platform. The presented selection is intended to give a detailed overview of how the RAVEL methodology was developed from the concept models, and how quantitative environmental assessments and knowledge about the industrial design situation was interpreted into the model. A full presentation of the information structure is provided in *The RAVEL Information Platform* (Carlson, Forsberg, 2000)

In the following the RAVEL information system architecture and prototype will be briefly presented.

STAGE 3, INFORMATION STRUCTURE AND INFORMATION SYSTEM DEMO PROTOTYPE

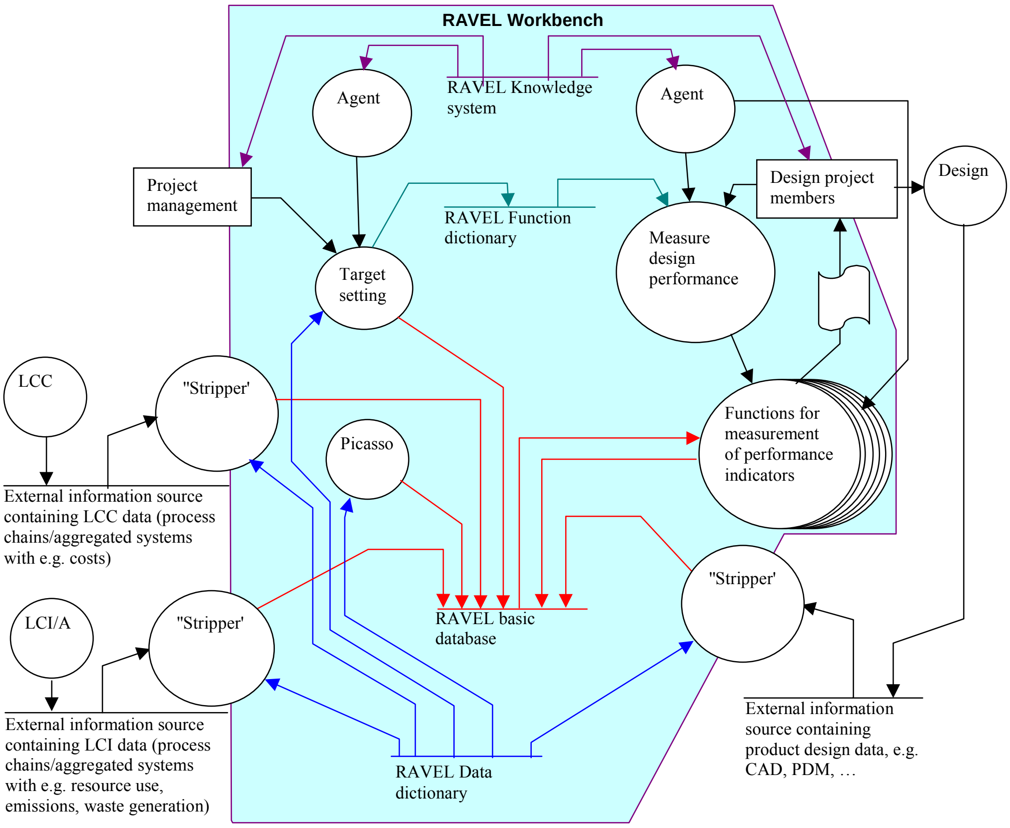

Figure 36. Overview of the scope of the RAVEL workbench (Dewulf et al, 2001).

Figure 36 describes the intended overall *RAVEL workbench architecture* (Dewulf et al, 2001). This architecture was designed by the author of this thesis to clarify the scope of the work and the role of the methodology in its organisational environment. It was intended to help illustrate many of the concepts of the RAVEL information structure. For example, the functions needed to calculate the design score are data stored in the RAVEL architecture since the environmental performance indicators (EPI) are flexibly defined. The principle of having flexible functions for calculating EPIs is implemented as the heart of the RAVEL methodology; when defining an EPI one shall not only specify the data needed for calculating the score, but also in detail specify the exact algorithm of the function that calculates it.

5.3 Environmental characterization modelling

ARTICLES THAT PRESENT THIS PROJECT:

V. Tivander J, Carlson R, Erixon M, Pålsson A-C., OMNIITOX Concept Model Supports Characterisation Modelling for Life Cycle Impact Assessment International Journal of Life Cycle Assessment, Vol. 9, No. 5, pp. 289-294, 2004

5.3.1 The OMNIITOX project

Many types of loads from elementary flows have quite simple mechanisms from the viewpoint of LCA methodology, such as depletion of global resources (like oil) or the simple mechanistic models of global warming potential (IPCC, 2005). Somewhat less simple are the models that describe, for example, acidification[34] or eutrophication[35], since it is necessary to also consider the soil and water chemistry in the natural system where the impact happens. Chemical properties are different depending on location, and this is a fact that needs to be taken into account when assessing the environmental impact by characterisation models. There are large variances, ranging from highly negative effects to highly positive. Modelling toxic impact on indicators is even more complex. In addition to taking into account the properties of the load and of the natural system, one also must consider e.g. dose of the substance and sensitivity of the organisms, population or ecosystem. It is a challenge to include such very specific mechanisms into the often globally smeared steady-state generality of the LCA methodology. But this was the goal of the OMNIITOX[36] project (Molander et al, 2004).

The OMNIITOX project aimed at developing characterisation models to produce characterization data for toxic substances for LCA studies and at developing an information system for such models and data. The layout of the information system presented in Figure 37 was sketched by the author of this thesis in the beginning of the project. The author was responsible for the planning and the management of the information system build-up in the OMNIITOX project[37].

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[34] Acidification: ongoing decrease in pH in soil and water, with environmental consequences both on the chemical properties of the soil and the water and on the biological reactions.

[35] Eutrophication: the enrichment of an ecosystem with chemical nutrients, leading to environmental consequences such as promoting plant growth, change species composition.

[36] OMNIITOX: Operational Models aNd Information tools for Industrial applications of eco/TOXicological impact assessments. EU project within the "Competitive and Sustainable Growth"-Programme. 2001-2204. Intended to facilitate decision-making regarding potentially hazardous compounds by improving methods and developing information tools necessary for Life Cycle Assessment (LCA) and (Environmental) Risk Assessment (E)RA. Contractors: AB Volvo (Volvo), Sweden, The Procter & Gamble Company (P&G Europe), Belgium, Stora Enso OY (Stora Enso), Sweden, Antonio Puig S.A. (PUIG), Spain, European Chemicals Bureau (JRC-ECB), Joint Research Centre, Italy, Randa Group S.A. (Randa), Spain, Technical University of Denmark (IPT-DTU), Denmark, Leiden University (UL-CML), Netherlands, University of Stuttgart (USTUTT), Germany, Ecole Polytechnique Federale de Lausanne (EPFL), Switzerland

[37] The practical implementation and detailed structuring of the information structure was performed by the systems developers M. Sc. Johan Tivander and M. Sc. Klas Geiron and the research engineers M. Sc. Maria Erixon and M. Sc. Karolina Flemström, all working in the research group IMI at Chalmers University of Technology

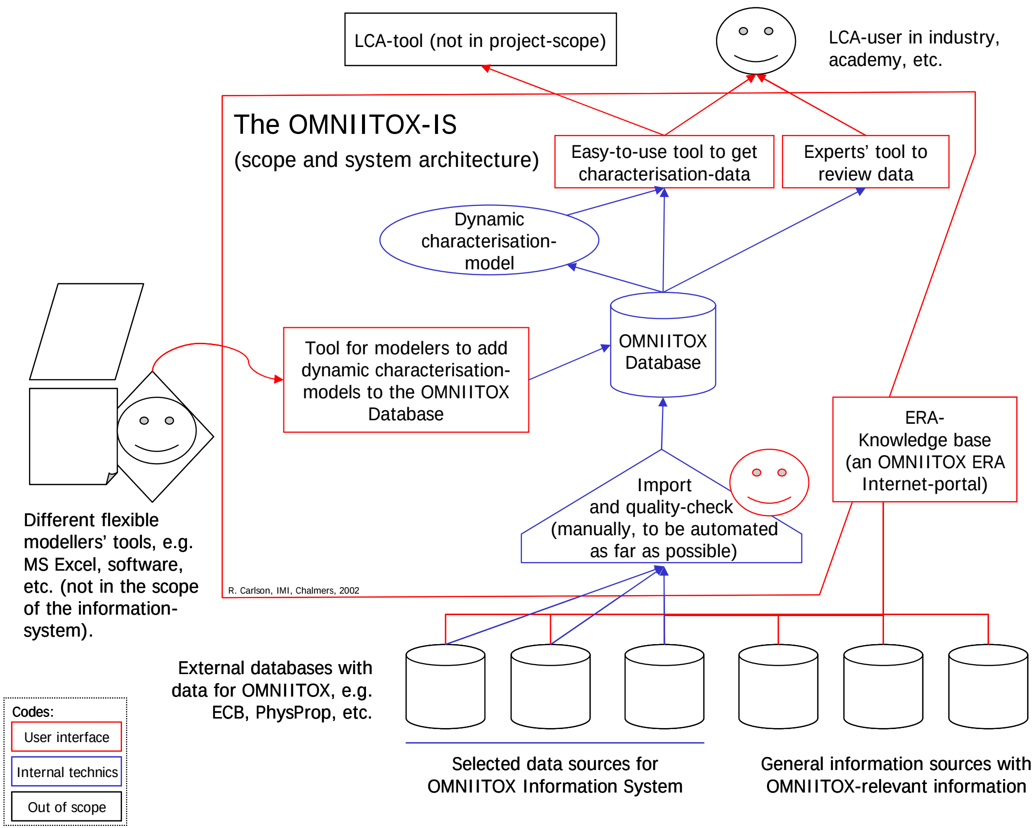

Figure 37 OMNIITOX information system architecture overview.

5.3.2 The LCA characterisation information structuring

STAGE 1, CATCHING THE CONCEPTS, TERMS AND LOGIC

Project planning for the OMNIITOX information system was based on the experiences from the LCA and DfE information systems presented in section 5.1 and 5.2, respectively. In the plan much time was allocated for the beginning of the project, the development of the information structure. Work tasks included an early workshop for the concept modelling, and follow-up time for discussing and testing the developed concept model among the LCA, risk and toxicology experts. The first workshop produced a result similar to the first workshop results during the modelling of the information structure in RAVEL project (see Figure 27 and subchapter 5.2). Many of the core concepts and terms had been identified, and a draft structure was outlined. Figure 38 presents a conceptual model of characterization as it was understood during this first stage. Compare also with Figure 5 in section 3.3.3.

After having produced the first important results from the basic conceptual model and the basic concepts, the actual concept modelling took much longer. This introduced a difficulty, but also provided better understanding of the process of concept modelling.

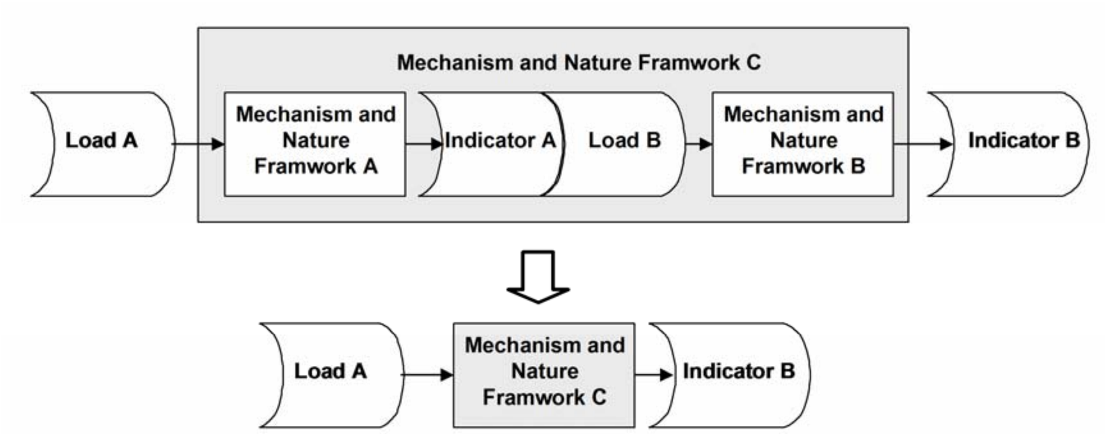

Figure 38. Conceptual model using core OMNIITOX concepts (Tivander, Carlson, Erixon, Pålsson, 2004).

STAGE 2, CONCEPT MODELLING

In the OMNIITOX information system the characterisation factor (compare Figure 21 in section 5.1.2.2) is calculated from underlying laboratory and model data. The details around those underlying data and the calculations are not handled here, since they are considered outside the scope of the expertise of the author of this thesis. The author mainly contributed with the concept modelling, and Figure 39 is the high level view of the OMNIITOX concept model of a toxicity characterization model.

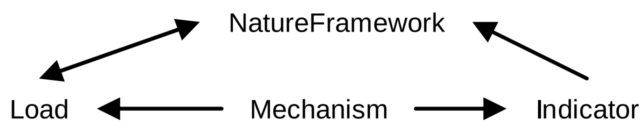

Figure 39. High level view of the core of the OMNIITOX concept model.

Figure 39 indicates that an environmental *Mechanism* is defined by the *Load* that causes an impact on the *Indicator*. The *NatureFramework* concept describes relevant properties of the natural system where the toxic substance is released and where the *indicator* is indicated, and in which the *mechanism* is valid. The concept of *Mechanism* holds the parameters of the characterisation model specified by the experts in the OMNIITOX project. This concept model is conceptually similar to the characterisation model presented in Figure 21, since the characterisation model has the same semantic meaning, including both *Load* (*Aspect* in Figure 22) and *Indicator* (*CategoryIndicator* in Figure 21). But it is still different since the *characterisation factor* itself does not have a concept in the model but is instead the *result from calculations* on data from the other concepts. Hence, the two concept models are compatible and not redundant, and they may reside in for example the same database system. The concept model of Figure 21 is more efficient when performing full LCA studies, since it holds a quantitative data value, while the OMNIITOX concept model in Figure 39 is a unique efficient tool when producing characterisation parameters considering different variables, such as different substances, different regions, or different time spans.

One benefit from concept modelling the information structure for the characterisation modelling is that it is easy to get an overview of the relationship between the different information needs. It is especially important to notice that it is not meaningful to collect any data before the indicators are defined.

6 Distillation of results from the applied research

<u>ARTICLES PRESENTED IN THIS SECTION:</u>

VI. Carlson R., Erixon M., Forsberg P., Pålsson A-C., System for Integrated Business Environmental Information Management; Advances in Environmental Research, 5/4, pp. 369-375, 2001

VII. Carlson R., Learning from management of LCA data, Journal of Life Cycle Assessment, Japan, Vol. 1, No. 2, pp 102-111, 2005

6.1 Integrated industrial environmental information management systems

The different concept models described in Chapter 5 influenced each other consecutively during the years of developments, and thereby also share some of the same concepts. This has led to the fact that the information systems for LCA, DfE and detailed characterization modelling in principle are compatible with each other. One practical implication of this is that they can be integrated with each other into common *integrated environmental information systems* for environmental management of industrial systems. The different tools can share and exchange common information and data so that, for example, LCA studies of products and components can be seamlessly used in design processes and so that characterization models produced by different experts are instantly put into use for LCA studies. And thanks to the modelling and technology choices the results are also enabled for integration in industrial business organizations.

The conceptual model of LCA presented in Figure 14 in section 5.1.2.2 works also as a conceptual model of the responsibilities of an environmental management system, according to for example ISO 14001. This similarity was noted early and scientific articles (Carlson, Pålsson, 1998) (Carlson, Pålsson, 2001) and industrial projects (Svending, 2003) (Carlson, Häggström, Pålsson, 2004) (Pålsson et al, 2005) have explored how the information structures for LCA match the need for information structures in environmental management systems.

Figure 4 presented in section 3.3.3 describes a conceptual model of LCA. The model was developed during the third stage, when the information structure should be understood and tested by the users. It did not exist before, and was created to aid with establishing a common understanding of the ideas behind the LCA methodology, the LCA information structures and its relationships with the responsibilities and information needs of an environmental management system.

The conclusion drawn here is that since the different methodologies have the same conceptual models the matching concept models can also be made to match and work for the information needs for both methodologies.

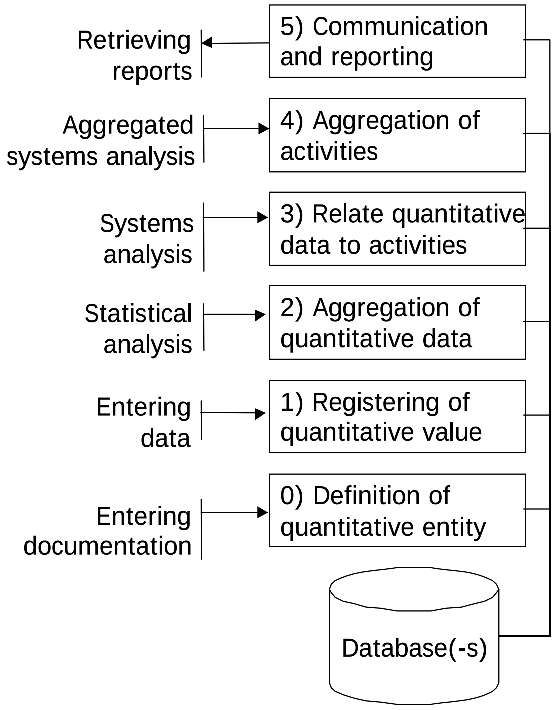

Figure 40. Schematic illustration of the IBEIM system modularisation

Figure 40 presents a figure from article VI, in which the PHASETS model presented in section 5.1.2.2 and Figure 26 has been combined with a database like, for example, the environmental database presented in Figure 13 in section 3.5.3. The figure presents how this system is *integrated* with the appropriate *organisational activities* needed to produce a report of the environmental production performance, of some kind. The figure states that *each phase* in the PHASETS model *represents a task* that needs to be done to produce and compile that report. The integrated system proposes that these *phases are linked* through the *common environmental database*. There would be many benefits from such an integration of environmental information handling:

- The data may be accessed by many *different users*, in *different applications*.
- When new data are needed for new types of reports, the overall *infrastructure* is already established.
- *Transparency* is established in the form of *traceability*.
- Since each data handling task is clearly defined, it is also easy to apply improved *quality control* management systems on the data handling, hence achieving better data quality in any dimension (see also Figure 25).
- Since each data handling task is well defined it is also possible to get an overview of cost drivers and *cost-efficiency* improvement potentials.

The method of the model has been tested in industry (Pålsson, 2005), and two major weaknesses were noted:

1. Even though the runtime costs are evidently lower, there are initial investment costs which exceed the ordinary budgets of environmental management and therefore would need project financing. *Investments are needed*.

2. Companies seem to consider the system as too transparent, which is feared to maybe lead to stricter legal requirements on their environmental reporting. Therefore, in spite of cost-savings there is a contradictory *lack of motivation*.

It is possible that the weaknesses are temporary, and that they will be overcome when costs for information handling for different responsibility and sustainability issues increase.

The integration approach is also tested in practice between 2004 and 2006 in the CPM project IMPRESS (Implementation of Integrated Environmental Information Systems)[38]. The project simultaneously tests integration of different methods and tools together with integration of information management tools with organisational tasks.

With currently 6 months left of the project period when this text is written, it seems as if the approach is *conceptually feasible*, and *pedagogically effective*. *Conceptually feasible* here means that an integrated prototype is being built, and that the specification seems very promising at the moment. *Pedagogically effective* here means that the work with integrating environmental methods and tools by integrating the information seems to be a very good way to *understand* how the different concepts of environmental management are linked to each other, concepts like *environmental policy*, *environmental indicators*, *characterisation*, *auditing*, *performance measurements* etc. The IMPRESS project will yield results which are valuable for exploitation and interesting for further industrial and academic research.

6.2 Beyond concept modelling

During these projects much has been learned about not only concept modelling and information structuring for environmental management, but also about information system design, development, implementation and maintenance for environmental management of industrial systems. Some important practical experiences are:

- An information structure for external responsibilities like LCA should be well-built and comply with industrial technology and quality standards. This facilitates integration with industrial data systems and (environmental) management systems.
- Environmental performance indicators (EPIs) and database strategy are two sides of the same thing; there is a direct relationship between environmental indicators and choice of contents in an environmental database for environmental performance measurements.
  This is one of the individually most important results from this research project.

When producing a new database one needs to solve interesting problems, which might lead farther than was intended by the actual database development. From the viewpoint of the new research field of industrial environmental informatics, the intensive work at the cross section between industry and academy during the establishment of the Swedish national LCA database was an ideal spot for evolution of new ideas. Development, rejection and redevelopment of tools, methodologies and a new scientific approach have been quick and have resulted in much new knowledge

[38] More information: http://www.imi.chalmers.se/impress.htm

and understanding of how to establish information structures for environmental management of industrial systems.

6.3 Need for indicators

Having developed the information structures for LCA by concept modelling, one resulting product is a set of pedagogical conceptual models of the entire field of LCA and industrial life cycle responsibility. Other results are the concept models that function as maps of how to design the information systems, including how to approach the strategy of populating the information systems with content, starting with the indicators. For example, the information structure for DfE (Figure 35 in section 5.2) provided important insights about indicators, or environmental performance indicators (EPI). In the concept model it can be seen how the different information is related. Both the project target and the design score are expressed in terms of indicators, and all environmental information about the design, its physical composition and their properties are defined on the basis of the algorithms needed to calculate the score. One can therefore see that environmental data should only be collected when they are needed to calculate such a design score. Hence, one must decide how the calculations are performed, and which material data to have in the database, *before* implementing any software functionality.

The applied research work presented in this chapter clearly indicates the necessity of anchoring an information system *in indicators* for environmental management of any industrial systems. This ensures that resources for building up databases are not wasted on data that is not requested, and it ensures that only those functionalities that are needed are implemented in the information system. It also ensures that users understand and appreciates the output from the information system, since it was requested to begin with.

Collecting data without clear indicator objectives is natural for building up knowledge and the strategic intelligence of an organisation, but not for the information systems that shall guide immediate decisions in a productive manner (see also section 3.2.2).

6.4 General principles from experiences

6.4.1 Economy of the information system life cycle

The experiences from over ten years of developing, maintaining and implementing the SPINE format for LCA information (section 5.1) show that the information structure works well. It is easy to develop quite advanced software for different types of LCA studies. Some improvements have been made over the years, but the format has mainly proven to be ahead of its time. But time is catching up. The ISO technical specification *ISO/TS 14048:2002 Environmental management – Life cycle assessment - Data documentation format* (*ISO, 2002*) was developed with many influences from the concept model developed for the SPINE format. The format has been an ISO Technical Specification (ISO/TS) since 2001, and in September 2005 it was again accepted as an ISO/TS until 2008.

The RAVEL information structure presented in section 5.2 also has shown strengths by the time. The fact that RAVEL and REPID[39] (REPID web-page, 2005) are on the agenda of the industry indicates the expected business values of the work

[39] REPID: Rail sector framework and tools for standardising and improving usability of Environmental Performance Indicators and Data formats

done. The software has been redesigned in different versions for different purposes, first in the RAVEL follow-up project REPID, by the consultancy firm Semcon, and then within different CPM projects at Chalmers University of Technology.

The REPID project successfully finalised a materials database, software for exchange of data between CAD (Computer Aided Design) tools and the REPID DfE assessment tool. In addition, the international rail industry eco-procurement board was set up to standardise indicators for the rail industry. Many resources have also been invested in real industrial standardisation efforts. Hence, the RAVEL results are practiced in the rail industry.

The RAVEL information structure and methodology is also currently (2005-2006) being tested practically outside the rail industry, in a CPM project together with the companies ITT Flygt and IKEA. There is also a separate project between the Industrial Environmental Informatics (IMI) group at Chalmers as one partner and the Power and Industrial Systems R&D Center at Toshiba Corporation as the other partner. In this project the RAVEL EPI methodology will be benchmarked to Toshiba's eco-efficiency method *Factor T* (Toshiba website on Factor T, 2006). Results are due in the first half of 2006.

During this applied research long term economical thinking has been a basis of the concept modelling and the information system design. Considering long term economy rather than quick development is experienced as one important principle for succeeding with building information structures for environmental information.

6.4.2 Cognitive sciences

Database modelling is necessarily based on availability of concepts, terms and logic of the intended user domain, and of the procedures and logic of the work processes described and performed by the users. When these are identified, database design is a straightforward engineering task. However, literature in data modelling provides little guidance about how to actually acquire the concepts. There are practical recommendations to use techniques like prototyping, interviews and workshops with different types of concept modelling. These are valuable techniques, but without a theoretical understanding they may seem subjective, and may be arbitrarily applied and interpreted.

One of the benefits from designing information structures using concept models and functional dependencies is that the databases and information become easy to adapt to new applications in the same or similar domains. If the concepts and their relations are correct in the first place, they will remain correct for a wide range of related applications. For example:

- LCA are equally valuable for environmental management systems,
- environmental product design of rail vehicles are equally valuable for any other product category,
- including toxicity in LCA is equally valuable and useful for including any other environmental characterization modelling in LCA.

It was noted quite soon when applying the LCA information structure in industry that users learn quickly how to think when applying the structure, both for advanced LCA studies and for different simplifying LCA tools.

Similar experiences were noted when developing the RAVEL methodology and the RAVEL information structure. Users and other stakeholders considered them easy to understand and easy to apply.

However, during the concept modelling in the OMNIITOX project, the term *indicator* was introduced as a concept. But the term *indicator* did not occur in this way in the language of the toxicity and environmental risk experts. They did not make any apparent references to any such physical item. In fact, they argued against the idea of the concept *Indicator*. Therefore the concept model and the information system were not fully accepted by the intended users, and one may therefore say that the OMNIITOX concept model failed its intended purpose.

Experiences from this applied research seem to suggest that one principle for succeeding with information structuring for environmental management of industrial systems, is that the intended users and stakeholders perceives the information structure as a tool that matches their own idea of the reality they work with. The relationship between the languages used to describe and understand the conceptual models of the user application, the meaning of the concept models and the definition and understanding of (environmental performance, condition or category) indicators are evident in this work. Therefore the relationship with the disciplines of cognitive sciences was extracted as a basic principle for information structuring in the interdisciplinary domain of environmental science for environmental management. The perspective of cognitive science needs to be applied to ensure user relevance.

6.4.3 Physical reality

When applying the LCA information structure it was noticed that there was a lack of a concise description of how LCA data relate to empirical data. With PHASETS (Figure 26 in section 5.1.2.2) it is in principle possible to relate an LCA study to physical reality of empirical data.

The RAVEL DfE method and its information structure connect the intentions of environmental policy with the decisions where they can be made operative and where they matters. The RAVEL information structure thereby comes to represent a control system like the one described in Figure 3. It controls the physical outcome of the design process.

The OMNIITOX concept model can handle any environmental characterisation model, regardless of whether it addresses toxic impact, acidification or eutrophication. It will be useful for modelling any local, regional or global impact associated with chemicals from activities in the industrial society. It is designed to flexibly handle very detailed or simple characterisation models. But the information structure is not used outside the work group where it was developed. Time is still needed before it is accepted by the intended users. Characterisation modelling in general can be modelled in similar ways. The actual data needed for toxicology modelling is not the same as the data needed for, for example, modelling acidification or eutrophication, but the detailed modelling modules of the OMNIITOX information system can be replaced. Since the information structure has proven to work practically for complex LCA characterisation modelling it will most likely be taken up in future industrial applications and in methodological research or development projects.

Hence, experience from this applied research indicates that identifying the physical reality, the ontology, is an important practical principle. The relationship between the information and its corresponding ontology can turn information systems into control systems, like the one presented in Figure 3 in section 3.3.2.

6.4.4 Quality

As was presented in section 4.2 total quality management (TQM) was one part of the methodological starting point of this applied research work. This gave rise to an effort to identify and implement significant quality dimensions into the results. Due to the physical nature of environmental management special considerations have been given to the quality of data, and due to the industrial applications specific consideration has been given to quality of information systems.

LCA is conceptually simple to understand, but it is difficult to perform due to complex information requirements. Therefore, both PHASETS and SPINE (section 5.1) aid users with systematic information handling of the documentation, quantitative data and calculated results. PHASETS was designed partly to support data quality management, and it has been used both explicitly and implicitly in different work. PHASETS was tested and implemented in the EU project CASCADE (CASCADE, 2006), as model for a procedural guideline for how to produce LCA quality data (Weidema et al, 2001). It was also tested for industrial environmental quality management in a project between CPM and the Swedish paper and pulp industry, between 1999 and 2001. That project led to development of a practical method for operative environmental information quality management (Pålsson et al, 2005), and also to the major content of a licentiate thesis on the subject (Svending, 2003).

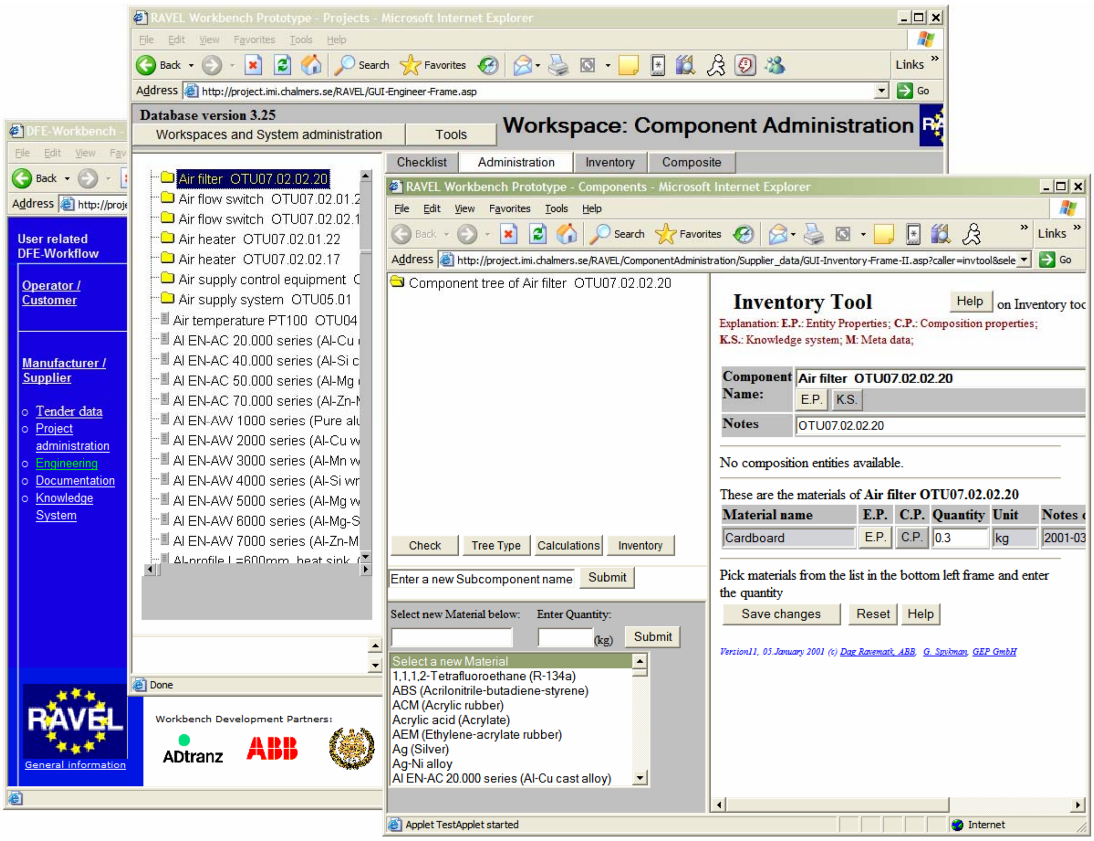

Figure 41. Snapshot of the RAVEL prototype workbench.

The RAVEL information structure serves as an example illustrating the importance of quality of information systems for industrial applications. The RAVEL information structure (Carlson, Forsberg, 2000) was proven meaningful and practically efficient when producing the prototype of the workbench within the RAVEL project. The information structure enabled the software developers[40] to produce a stable prototype software system with all major functionalities implemented. The concept model provided the necessary semantic support and the

[40] The author of this thesis was leader of the system development sub-project of the RAVEL project, and was also designer of the system architecture (see Figure 36), but the programming was performed by Dr Dag Ravemark at ABB, Sweden and Ing. Gerold Spykman at GEP consultants, Germany.

logic for the systems development. Figure 41 provides a picture of the RAVEL prototype workbench built on the RAVEL information structure

The success from developing concept models and information system with a specific emphasis on dimensions of quality, suggests that quality is an important principle when structuring information for environmental management of industrial systems.

6.4.5 Work procedure

Section 5.1.2.2 is structured according to the natural work stages applied when producing the LCA information structure. The different stages were stressed in the description because each was practically distinguishable from the other and because the work process produced successful results.

Also, the important failure in the process of the synthesis of the OMNIITOX concept model strongly suggested a need for a practical guideline for the work processes. Because a long time passed between the first and second versions of the OMNIITOX concept model, the many experts who had contributed with concepts and terms in the early workshop both forgot their contributions and lost track of the process. They lost interest and faith in the concept model, and they did not adopt the concept model as theirs. They regarded it as something of interest only to the information system developers. Considering the fact that the functionality of the information system successfully matches all needs and expectations of LCA, toxicity or environmental risk experts, it is very likely that the idea *Indicator* could easily have become a highly appreciated concept; maybe just with another name. If just the work process had been more explicit this could have been found out. It was evident that the concept model itself was not sufficient to succeed, but that it is equally necessary that the model is also adopted by its indented users. The delay with the concept model had different reasons, both project organisational and methodological, which are not elaborated here. But much was due to the lack of an explicit work process.

The experience is that the same process of three stages worked when developing the information structures for LCA and for DfE, and that the result failed when not applying the same process. Therefore these experiences suggest that the process should include all the three stages, and that they should be quite closely linked in time.

7 Synthesizing a methodological framework

7.1 General need for methodological guidelines

It has taken many years to build the different information structures presented in Chapter 5. The LCI part of the SPINE structure took about three years to develop, from initial concept analysis that started in 1993 to actual user acceptance and practical deployment in late 1996. The impact assessment part of SPINE took about three years as well, from concept analysis in 1997 to first implementations and tests with different impact assessment methods in 2000. The RAVEL and the OMNIITOX information structures each also took three years to build, test and implement. During the work much time has been spent on describing and explaining the importance of information structuring. The case studies have been scientific research projects, and therefore time for discussions has been in line with the intentions. But when building future *operative* information systems for, for example, governmental sustainable development or for integrated environmental information systems for globalised corporations the information structuring processes need to be more efficient and effective. Hence, there is a general need for methodological guidelines for effective and efficient operative build-up of information systems for environmental management and sustainable development.

General database design principles (Cornwell, 1990) (Elmasri, Navathe, 1989) do not supply enough guidance for the practical work of identifying the concepts and terms of sustainable development. Hence, in spite of the venerable intention to support global sustainable development, many environmental information systems are instead individually suboptimal, incompatible with each other, difficult for users to comprehend, and uneconomical. Examples of information systems and structures that are much used and important, but that may also serve to exemplify a lack of common principles are IUCLID (International Uniform ChemicaL Information Database) (ESIS: European chemical Substances Information System, 2005) maintained at European Chemicals Bureau (ECB) at the Joint Research Center (JRC) (ECB's website, 2005), the automobile industry's materials database International Material Data System (IMDS) (International Material Data System, 2005), and the SPOLD data format (Singhofen et al, 1996) for life cycle assessment (LCA) data. These three systems represent different types of issues that may be addressed from the viewpoint of a need for a common framework. However, it needs to be admitted that each of the systems are here criticised from a quite narrow viewpoint. A closer assessment of each system than what has been possible here may reveal that this specific viewpoint is not applicable on each specific information system. The following reasoning anyway exemplifies how a methodological framework could be applied, if the information systems were governed by a common agenda and a policy that aimed towards sustainable development.

The IUCLID database contains toxic risk information for the European chemicals regulation system. According to an analysis by Erixon and Flemström (Erixon, Flemström, 2005) the IUCLID database lacks a consistent structure and clear concepts. Review and maintenance is difficult and data acquisition is very difficult. These weaknesses are potentially critical if the same lack of principles is applied when moving into the new chemical regulation system REACH (Registration, Evaluation and Authorisation of CHemicals) (European Commission, 2001). The difficulties with quality review and data accessibility may lead to severe problems concerning chemical risk and public health and security. This exemplifies the fact that environmental information structures without concept models and consistency may be dangerous.

The IMDS is set up to facilitate the recycling of old cars in the future. All suppliers of the participating automotive industry[41] enter material data about the components that they supply to the cars. This is done to facilitate future recycling of the vehicles. The possibility is hypothetical, but if the automotive industry plans to adopt sustainable development by taking life cycle responsibility of their supply chains, the IMDS system would have been better designed if the life cycle costs were considered from the beginning. Substantial costs are needed to develop the system towards life cycle responsibility.

The SPOLD format has stood as a model for many questionnaires, databases and software formats. The SPOLD format was developed without any concept analysis or concept modelling. The format is largely an unstructured collection of words that prescribe some important elements of LCA and issues important to some specific applications of LCA. There are no principles for structuring or interpretation of the elements, and many elements are ill-defined (Erixon, Ågren, 1998). Today much proactive environmental work is based on life cycle responsibility, while many of the important databases are based on the SPOLD format. This might change as the ISO/TS 14048 Data documentation format (ISO, 2002) is disseminated.

Other examples of the need for a framework for information structuring are apparent when developing different simplified LCA approaches. Most simplified LCA tools relate to how easy it is to perform the LCA calculations, but considering that the major problem with LCA is to acquire data and to interpret the results it could be that the simplifications should have been made on data acquisition and on simplifying interpretation of results instead. Examples of the latter are so called environmental *communication tools*, where *simple interface* replaces both *factual* and *meaningful*. Simple graphical *representation* replaces simplicity in interpretation of *actual* complexity. A curious example is the BASF tool (Saling, 2002) presented as explicitly not being based on strategies for information handling or information improvements.[42] By not understanding the relationship between the value of the tool for credible communication and its underlying information, the representative of the company and the tool vehemently declined any plans for data quality or data improvements. Obviously the representative was not aware of the value of having a strategy for continuous quality improvement of the environmental information, and of the necessity for having a credible information structure behind that simple user interface.

This serves to suggest that a publicly understood methodological framework for information structuring is needed.

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[41] BMW, DaimlerChrysler, Fiat, Ford, Fuji Heavy Industries, General Motors, Hyundai, Isuzu, Mazda, Mitsubishi, Nissan, Nissan Diesel, Porsche, Suzuki, Toyota, Volkswagen, Volvo

[42] Andreas Kicherer, representing the BASF eco-efficiency communication method and tool at Chalmers University of Technology in Göteborg 9th of November 2004.

7.2 Outlining the framework

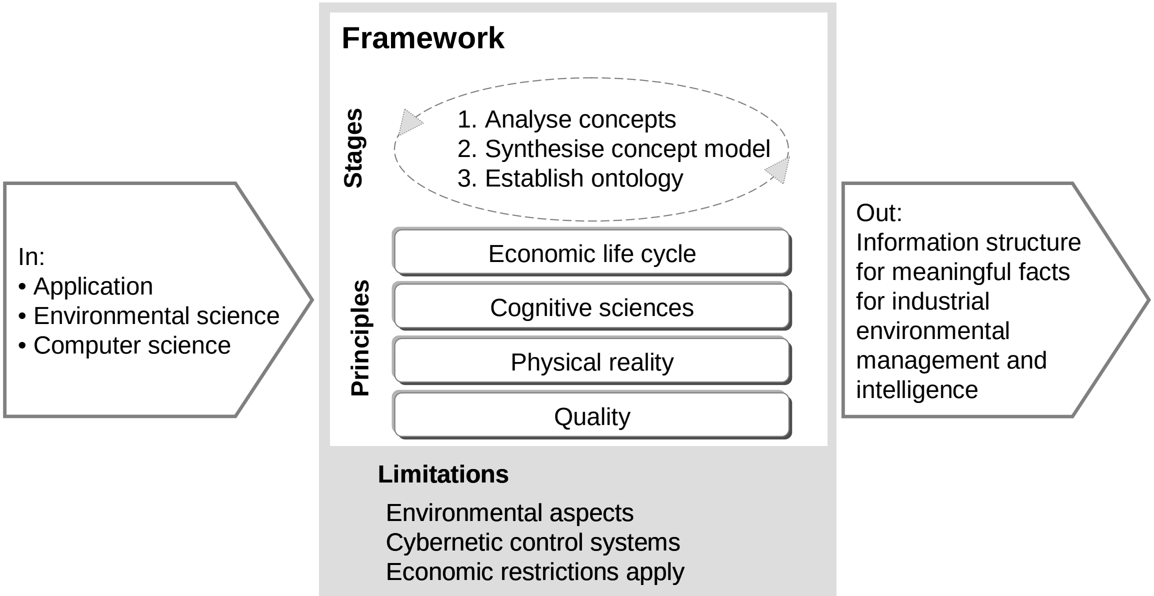

Figure 42. The framework of principles and work stages for developing information structures for environmental management of industrial systems.

Figure 42 provides an outline of the methodological framework developed by synthesising experiences from the applied research presented in Chapter 5.

The framework rests on four practically derived principles (see sections 6.4.1-6.4.4):

- *Economic life cycle*: the information structure shall be developed, maintained and used, as well as redesigned etc. for long term economic rationale.
- *Cognitive sciences*: the information system shall be built with the viewpoint of users as information processors and with perception guided by mental constructs.
- *Physical reality*: establish a reference with the physical world, and establish a logic of the model of the information structure that imitates the logic of the physical world as it is perceived by the intended users, i.e. the conceptual model.
- *Quality*: identify quality dimensions needed by the information structure to define a pragmatic trade-off between different quality dimensions and economics.

The framework also prescribes a practical work-process of three stages (see section 6.4.5):

1. Analysis of the concepts used by the users with environmental expertise.
2. Synthesis of a logical, economically rational, and physically meaningful concept model (draft information structure).
3. Iterative feedback of results with the intended user domain, to establish coherence between the meaning of the concept model and the ontology of the users, communicated by concept models, conceptual models and practical use of the information structure.

Variants of these three stages are part of most data modelling principles, but in combination with the four principles above they are anchored in relevant theories within the application domain of environmental management and sustainable development.

The framework is built on the conclusions from the practical experience that successful information structures for environmental management of industrial systems are developed from concept models. These concept models are synthesized from the language of the intended users or representative experts when they describe the physical reality that they study, or the conceptual models that they use in their work. This technique establishes the information structure on the ontology of the application domain, and thereby enables control systems that connect management activities with changes in the physical reality.

When designing an information structure in this way, an interdisciplinary blend of competency is needed, including knowledge and skill in environmental sciences and in software engineering[43] (the “In”-side of figure 42). The framework of principles can support an interdisciplinary group of competencies to efficiently and effectively develop information structures for environmental databases, reporting formats, questionnaires or data exchange files. The results from having applied this framework (the “Out”-side of figure 42) will have a number of benefits not achieved with *ad hoc* approaches, such as:

- The information structures will be aligned with the economic significance of the environmental aspects in the organization in which they are to be used.
- The data and information that environmental information systems need as input and produce as results make sense to the intended human users (i.e. not only appropriate for computer interpretation).
- The environmental information based on these principles will as closely as possible represent the natural environment in the real world. In other words, information in the information system will reflect facts of the physical world.
- It will be possible for owners and users of the resulting information system to decide on a sufficient and arbitrary information quality, based on conscious understanding of the relevant quality dimensions of the information handled in the system. Quality management will be built in to the design of the fundament of the information systems.
- The information will support decisions by communicating with its users in terms of well-defined and understood indicators, which can match the PHASETS model (Figure 26 section 5.1.2.2) from top to bottom, or from *control* signal to *currents status* of the cybernetic control model as presented in Figure 3 in section 3.3.2.

The following sections will give a more detailed presentation of each principle of the outlined framework.

7.2.1 Principle 1: The economic life cycle

Environmental work is a necessary part of business, hence needs to be scrutinised for economic rationality and efficiency improvements over its life cycle. Data acquisition is a major cost driver of industrial environmental information systems (Sterner, 2003). Aspects of the information structure that bring down costs for data acquisition improve the economic life cycle of information systems.

[43] Data modeling and structuring, such as relational database modeling and object modeling.

Mismatch between user expectations and the actual information produced by the information system are identified in many different studies, such as (Erixon, Ågren, 1998) (Johnson, 2003) (Medin, 2001) (Taprantzi, 2001). Information systems that do not produce what they are aimed to produce are not economical. Hence, one aspect of the economic life cycle of the information system is that the information structure shall improve the process of matching information to user expectations.

Economy of the life cycle of environmental information systems need to be built in to the information systems through proactive analysis of cost drivers and potentials for efficiency improvements. Different approaches for data acquisition for general business intelligence are described in (Raisinghani, 2004) and experiences with environmental information are provided in (Carlson et al, 2005) (Carlson, Dewulf, Karlson, 2001). It is necessary to acquire knowledge about possible future use scenarios of the environmental information system (Epstein, 1996) (Eriksson, 1989) (Hawryszkiewycz, 1994) and implicit future requirements on the information structures.

It is also important early-on to seek to identify the core indicators that are useful to the users, in the form of a logic concept model that are significant with regards to the conceptual models of the user domain. This will both reduce costs for data acquisition and for user training.

7.2.2 Principle 2: The cognitive science perspective

Environmental issues are known to people as information about, for example, environmental risks (KemI, 1999), potential environmental damage (Goedkoop, 2000), or physical environmental impact models (IPCC, 2005). Environmental facts are communicated through information media and are presented in the form of figures, pictures or analogies. The scientific field of the environmental sciences is still indistinct, with significant complexity, paradox, logical gaps, overlapping meaning, and poorly defined concepts. In terms of Kuhn this may be because of a lack of well-defined paradigms (Kuhn, 1992) or, in terms of de Mey because of a lack of mental constructs (de Mey, 1992).

There are many ways in which environmental data and information therefore might be misinterpreted (Lomborg, 2001) (Johnson, 2003), which may lead to environmental mistakes such as underestimating risks[44, 45]. Misinterpretation is an issue not only of information itself, but of both information and of how the mind handles information through its mental models. To understand and correctly use and value the techniques for concept analysis, this research has shown that one needs to consult theories of linguistics and mental models and images, that is, cognitive science (Gardner, 1987). Those theories provide an explanation about the relationship between the language of concepts and terms and the ontology of the user domain.

Findings from the area of cognitive science provide guidance. One cognitive science perspective sees the human brain as an information processor. Perception has

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[44] The Swiss-based company ABB bought the USA-based company Combustion Engineering, and hence became legally responsible for the workers who had been exposed to asbestos in the production at that company. The fact that there had been asbestos in the products and the production was know to ABB during the purchase. But this fact was misinterpreted as insignificant (ABB website, 2005).

[45] The Swedish companies Banverket and Skanska were responsible for drilling a tunnel through a Hallandsås (a ridge of stones and rocks since the ice age), and a) they drained lakes and streams from water, and b) used a strongly toxic seal to try to stop the drainage. The work is classified as a major environmental catastrophe due to the irreparable damages to nature (Tunneling and Trenchless Construction, 2003).

a limited bandwidth. Short term memory has a limited capacity (Stillings, 1998). In many cases it takes more time to process more information. Information is meaningful only if it can be associated with previous concepts in the mind. Information is interpreted through mental representations in the mind of the receiver (Sobel, 2001), the mental handling of language (deFleur, 1989), drawing conclusions and problem solving (Reisberg, 2001), and pattern recognition, attention and information processing capacity (Ellis, 1989). The cognitive perspective emphasizes that in almost all areas of human endeavour, perception and communication are possible only on the basis of mental models. They account for selectivity in information processing and directionality in action (Mey, 1992).

These insights from the interdisciplinary field of cognitive science explain some of the observations made in the practical work presented in Chapter 5. Changing values of the same well-understood indicator, are easier to comprehend than new information about new concepts. And concepts that are understood in terms of the conceptual model of a world are easier to understand than arbitrary concepts and terms.

Linguistic analysis of the semantics of concepts (Linell, 2003) (Dirven, 2004) is practically related to theories and algorithms of the normal forms of the relational database schemas (Elmasri, Navathe, 1994). A table or a column in relational database terminology is basically a concept in the linguistics terminology. Causal logic between concepts and terms in the language of the users are directly interpreted into functional dependencies in the relational theories (see also section 3.5.2 and the concept models in chapter 5).

7.2.3 Principle 3: The physical reality

Environmental responsibility concerns the real world, e.g. Earth's natural resources, the physical conditions for life, chemical interference of biological productivity, urban air quality and growing waste dumps. But the ways in which different experts deal with this physical reality may be exemplified with a toxic heavy metal like *cadmium*. The different conceptual models that represent the physical reality look different depending on discipline and field of expertise. It is dealt with by environmental risk analysts (Molak, 1997) in the form of *statistical models*, by empirical environmental toxicologist through *laboratory tests* (*Johnson, 2003*), by life cycle practitioners as a *characterisation factor* (Flemström, Carlson, Erixon, 2004) (section 5.1), by an environmental manager as an important *restriction policy* (Waddell), and by the environmental coordinator of a design project as an *environmental* p*erformance* i*ndicator* (EPI) (section 5.3).

Figure 3 in section 3.3.2 indicates that a control system is meaningful if it provides the controller with facts that represent real environmental performance and physical environmental impacts from the controlled system. To ensure and maintain relevant information about the reality, the information needs to be updated frequently, and the information system needs to facilitate traceability.

Unfortunately little guidance for how to relate environmental management systems and tools with reality is provided in such resources as the ISO 14000 series of standards (Pålsson, Flemström, 2004). Hence, neither LCA nor EMS describes how to reference a physical reality with the information.

The PHASETS model presented in section 5.1.2.2, and its generalisation PHASES (Carlson, Pålsson, 2000) are examples of how to use an information structure to relate an interdiscipline to an ontology. The author of this thesis has not found any complementary or alternative models for relating system model data with empirical data and analytical methods.

7.2.4 Principle 4: Quality

Feedback from environmental impact is often substantially delayed from the decisions that caused them, often years, tens of years or even longer. This means that users of environmental information will not in time see whether a specific action results in the consequence described by the information or not, so that any correcting actions can be made if the information was misleading. In situations where decisions ar based on information correct information will lead to correct actions and misleading information will lead to incorrect actions. Therefore quality needs to be taken more seriously when structuring environmental information. Since most environmental information is associated with uncertainty, lax handling of environmental information quality creates not only the risk of leading to wrong decisions, but also the risk of wrecking the credibility of all environmental information (Lomborg, 2001). People might come to ignore whatever environmental information they are presented.

The quality dimensions described in section 5.1 and Figure 25, together with the PHASETS model in Figure 26 suggest the overall perspective on information quality as provided by the industrial management systems of Total Quality Management (TQM). These management systems are formulated in, for example, the ISO 9000 quality management standards (ISO, 2000), the six sigma quality management systems (Breyfogle, 2003) and the Toyota production technology (Liker, 2004). An interpretation into management of quality of information was described by Swindells in 1995 (Swindells, 1995). Similar quality management principles have also been applied for the Swedish national LCA database since 1997 (see also section 3.5.2).

A research work on these quality aspects of environmental information systems is performed in parallel with this work, by the colleague[46] of the author.

7.2.5 General application of the framework

The practical experience from constructing the information structures as described in Chapter 5 show that there is a natural but indistinct division of tasks into three stages during the development. Experience shows that to succeed with establishing the *concept model* as a *representation* of the *conceptual model* of the physical reality for the users each of the three stages need to be traversed. Experience also shows that during the different stages different emphasis should be given to the four principles described in sections 7.2.1-7.2.4. The work should not seek to maximize the output in relation to any of the principles, but should seek an optimal operating point at which all four principles are considered in a balanced way. Figure 43 provides a rough graphical representation of how the emphasis is given to the different principles at the different stages of the information structuring.

[46] Pålsson, A-C, Chalmers University of Technology, ann-christin.palsson@imi.chalmers.se

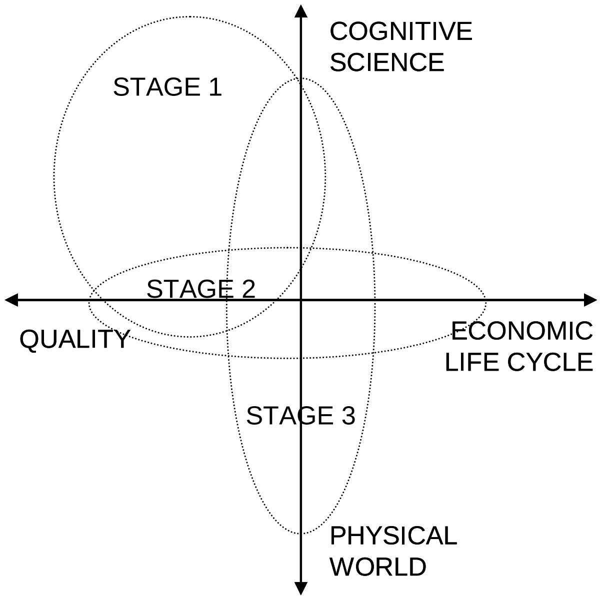

Figure 43. Applying the four principles of the framework during the different stages of the information structuring.

7.2.5.1 Stage 1. Analysis of concepts

Stage 1. Analysis of concepts used by the users in the environmental expertise:

The analysis of concepts is performed with strong emphasis on Principle 2, Cognitive science. The *language* of the users, which *terms* they use to describe their domain and their *conceptual models*, and how they *prioritize* and *logically structure* the concepts and terms. *Quality issues*, Principle 4, are also emphasised so that concepts and terms specifically addressing *sensitivity*, *credibility* and *reliability* are analysed with specific interest.

7.2.5.2 Stage 2. Synthesis of concept model

Stage 2. Synthesis of a logical, economically rational, physically meaningful concept model (draft information structure):

The synthesis of a concept model is performed with strong emphasis on both *quality issues*, Principle 4, and the *economical life cycle* of the information system, Principle 1. Quality aspects need to be considered with regard to how to *facilitate correct use* of the information structure, and how to *prevent incorrect use and errors*. Economic life cycle aspects are considered by analysis of the context of the intended *future* information system. *New skills* are likely to set new requirements on simpler use of the structure. New organisational restructuring are likely to lead to *integrated information structures* and *data exchange*. *New tools and methods* are likely to be developed on top of the information structure to make use of the same information structure and data.

7.2.5.3 Stage 3. Establish concept model with users

Stage 3. Iterative feedback of results with the intended user domain, to establish coherence between the meaning of the concept model and the ontology of the users:

The ontology of the users is established by strong emphasis on the relationship between the *concept models*, Principle 2, and the *real world*, Principle 3. All *concepts*, *terms*, *logic*, *functions*, *process models*, etc. are related with physically or otherwise scientifically *verified items*, *causalities*, *physical mechanisms* etc. in the real world. Different conceptual models are tested, developed and discussed together with the users. When ambiguity or confusion is observed further analysis of the users' concepts and terms needs to be performed. The resulting information structure should represent a causal structure of a physical real world as mutually understood conceptual models. A causal structure here means that the causal logic of the information structure should as closely as possible represent the causal physics of the conceptual model. Such causal structures are exemplified in the concept models presented in Chapter 5. For example, Figure 19 in section 5.1.2.2 states that a *Flow* cannot exist without an *Activity*, and that the substance that flows first needs to exist as a *Substance*. These are simple facts in the conceptual reality of LCA, and they need to be mirrored equally simple and factual in the concept model and information structure. Also, data should represent observable facts about observable states in the real world, the ontology intended by the users.

8 Conclusions

8.1 Quality of the research

The fact that the results from this research are consistent and coherent suggests that the initial methodological starting point presented in Chapter 4 was quite relevant. The information systems based on the information structures work well, and much has been disseminated to ISO and to other practical use in industry. The methodological framework has been updated and corrected during the work.

The approach to this work has been benchmarked and reflected upon in different ways over the years, and on two occasions this has been done through interview processes. In the fall of the year 2000 the author together with a colleague[47] visited a number of researchers and experts in Australia, Japan and Korea, to share the experiences accrued up to that point.

During these visits a handful of experts in the different countries were interviewed with regards to the then newly-developed representation of environmental management in sustainable development, shown in Figure 3 in section 3.3.2. In 2004 a number of CPM company representatives were interviewed from the viewpoint of the cognitive science approach. The results from these two series of interviews gave indications that the approach to environmental information structuring as described in this thesis was indeed both relevant and unique.

The interviews concerning whether environmental information was part of a cybernetic control or feedback system (Figure 3 section 3.3.2) were interesting. Only one of the interviewees had before the interviews reflected over this. But all interviewees considered it very helpful to change their environmental viewpoint into this utilitarian perspective. Also, all interviewees noticed that they were lacking a clear view of some of the important aspect of the feedback system. All became aware of an obvious lack of feedback to decision makers during the interviews.

It is not claimed that this interview result is scientifically significant (being anecdotal), but it is used here to argue that the framework at least has a pedagogic and relevant starting point in the model described by Figure 3.

The interview series within the CPM companies on the subject of cognitive science was intended to give a preliminary indication as to whether cognitive science could provide input to the everyday work of environmental experts in the CPM member companies. The intention was to conduct a series of deeper studies based on these initial interviews, but changes beyond the control of the author in the focus and scoping of this research and this thesis halted the continuation of this work. A simple report and a conference article were produced (Carlson, Pålsson, 2004) (Carlson, Pålsson, 2004).

The interviews were held in an informal way, and it is therefore not possible to draw explicit scientific conclusions from them. However, a few consistencies between the different interviewees in the different companies can be noted. The interviewees responded that improved understanding of how to structure environmental messages is relevant in all companies. This is especially important since environmental experts do not share language and conceptual models with representatives of the core business of the companies. Analysing environmental work from the viewpoint of how the world is perceived and described provides new and valuable questions and answers to environmental management work. The interview results hence indicated that beyond

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utilising the cognitive science toolbox for structuring database formats and reports the cognitive science perspective may also have a role in the general development of environmental management of industry.

8.2 Practical results

The information structuring projects described in Chapter 5 exemplify how an interdisciplinary framework, like the one presented in Chapter 7, may be applicable to practical problems of environmental information handling. The synthesis of a framework requires the existence of such practical problems, since otherwise none of the principles would have been meaningful.

The successful development of these information structures has led to the result that users of the information systems apply the concept models as part of their natural language. The concepts of the models are used both to describe the work itself and the tools. The relation between the design requirements and the product data has become part of the practical method, in terms of environmental performance indicators (see section 5.2). In contrast, in the case of the OMNIITOX method, the gap between the information structure modellers on the one hand and the toxicology, risk and LCA experts on the other hand led to the result that the language of the OMNIITOX information structure is not applied by its intended users (see section 5.3).

In addition, the RAVEL project in particular showed that the framework may result in information structures that mediate relationships between the market, the business agreement, and the product design process, as well as with purchasing activities and supply chain management (see Figure 30 in section 5.2.1). These same experiences unfortunately also show that the framework has the capability to overshoot the target. Industry, commercial forces and the legal systems are as yet way behind the capabilities of all the information structures presented here, (i.e. the SPINE, PHASETS, PHASES, RAVEL and OMNIITOX information structures).

Some practical benefits from modelling concepts drawn from conceptual models are that the information structures can then be used simultaneously for many different applications. This results from the fact that the area of environmental sciences and environmental management addresses basically the same conceptual model of how the industrial society interacts with natural environment, but with different tools and methods. By producing concept models of how mankind relates with the environment, rather than of the methods and tools, the information becomes a model of the physical world, independent of the methods and tools. In this way the same information can be viewed, manipulated and assessed in many different ways. Multiple use of the same information is probably more cost-efficient than collecting the data many times for different purposes[48].

One further important consequence of having developed the models using concept modelling techniques is that the role of indicators is evident. Information systems should be built for flexible choices of indicators, and indicators must be defined before any data are collected. It is obviously more cost-efficient to only collect the data that are requested.

The concept models also result in easily reviewed models, where the general data quality weaknesses may be assessed, and plans for data quality management may be developed.

[48] It needs to be stressed that the validity of this statement may be logically argued for, but that its validity has not been empirically proven.

Hence, the practical cases presented in Chapter 5 indicate that the resulting outlined methodological framework has the potential of producing practically useful results. The four principles and the three stages are crucial for information structuring.

It is essential that this framework becomes commonly known, so that requirements on environmental information can be made to match the actual state of the art concerning *accessibility*, *transparency*, *relevance* and *precision* (see Figure 25 in section 5.1.2.2). The state of art is far better than what is required in most environmental reporting systems, but this fact is not yet well-known, neither by the environmental experts who compile the information nor by the information receivers in governmental, non-governmental or business organisations. There is a need to further develop practical guidelines and pedagogical material.

8.3 Final conclusion about the research project

The research presented in this thesis addressed two problems: information structures for databases, communication files, reports and software for environmental management of industrial systems, and a synthesized general methodology or framework for developing such information structures:

- *Chapter 5* presents how the *practical results* have been achieved by applying concept modelling in practical information systems development. The work has produced practically useful results.
- *Chapter 7* presents a *methodological framework* for how to develop information structures for environmental management of industrial systems. This framework is synthesised from the practical research work described in Chapter 5.
- An additional crucial result from the research is the insight that environmental information systems for environmental management of industrial systems need to be based on indicators, and that the indicators should be defined before functionality is implemented in the information system and before any information is collected to the databases. This is a fundamental economic result of the research.
- The overall result from this work may contribute to the overall improvement of the quality of tools and methods that handle or produce information for the purpose of environmental management of industrial systems.

The author sees an urgent need for a support in structuring and making available environmental information for environmental management of industrial systems, and suggests the framework proposed in Chapter 7 as a way to meet this need.

9 Recommended future research

This thesis finalises an initial formulation of a methodological framework for structuring information for environmental management of industrial systems. But more important is that it also establishes a new foundation for research intended to facilitate sustainable development of our increasingly globalised industrial society. The need for such a new research foundation partly comes from the evolution and development of new concepts in environmental sciences and sustainable management practices, and partly from the increasing demand for data and information for these sciences and management practices.

The practical framework elaborated in Chapter 7 establishes methods for developing effective and economically efficient information systems for sustainable development and social responsibility. The vision is to help different stakeholders to acquire the correct understanding of the state of the environment, sustainability and social responsibility

From this thesis a number of major paths for further research can be chosen:

- Refinement of the framework.
- Evaluation of economic and practical consequences of improved environmental information structures.
- Development of methods and tools, and integration of methods and tools for improved information structuring
- Assessment of information systems based on indicators

9.1 Refinement of the framework

One future research path is to refine the framework of practical guides to apply when structuring environmental information. This may be needed when developing information systems for decision support, for reports, for databases, for software or for graphical presentations. The four principles of the outlined framework presented in Chapter 7 may be further developed in interdisciplinary scientific relationships, between different disciplinary scholars and in the context of relevant applications in industrial society.

9.1.1 Economic life cycle of environmental information systems

Studies and assessments of scenarios and models of the economic life cycle of existing and future environmental information structures and information systems are needed. Weaknesses, strengths, needs and experiences should be compiled into practical guidelines. Such guidelines would facilitate integration of the economic considerations in new work, and it would be of help for benchmarking and evaluation of results. Today many resources are spent because knowledge and guidelines about the economical life cycles of environmental information systems is missing.

9.1.2 Cognitive science

To further develop the understanding of cognitive science in the context of the framework, the disciplines of linguistics and cognitive psychology as applied to environmental decision making need to be further investigated. It seems specifically important to study cognitive models for mental imaging and constructs to better understand how to develop concept models and conceptual models. There are valuable parts of the toolbox of the linguist that are needed when describing meaning and logical relationships between concepts and terms. Relevant elements of that toolbox need to be identified for applications in environmental informatics. Improved practical understanding of cognitive psychology is needed to better understand the human limitations on handling environmental information. Environmental issues are based on complex relationships that include scientific difficulties and uncertainties as well as ethical elements. In addition environmental aspects are out of focus in most decision situations. How could information be structured to optimally fit the way the mind works?

Principle 3 of the framework states that the reference to the real world is important for information systems. It would therefore be valuable to better understand how the human mind apprehends reality. It is interesting to understand how people prioritize reality when presented as complex information in comparison to simpler concepts. If, for example, there are common principal concepts that all human minds share it could be interesting to establish primary environmental ontologies based on such common concepts. Through such knowledge it could be possible to identify new strategies for handling complex information about environmental systems. It would be valuable to find methods that are both intuitively comprehended by people as well as based in an ontology with a simple physical reference.

9.1.3 Establishment of the physical reference

When developing an information system, the understanding about the reference to the physical reality is established by involving experts that represents the intended user, such as toxicologists for toxicity information systems, LCA experts for LCA information systems etc. This is a sensitive dimension of the development, since the concept modelling performed by informatics specialists partly interferes with the work of the experts on the user side, and also often requires a certain measure of active criticism of the language and the formalism of the subject of the experts.

Research is needed to better understand the social difficulties of this interdisciplinary work, to avoid widening disciplinary gaps instead of building interdisciplinary bridges. Improved understanding of the social aspects of the interdisciplinary collaboration will become especially important when developing information systems for social and economic aspects of sustainable development and social responsibility. Practical work with identifying and describing the different ontologies of the different relevant disciplines would have a high practical value. This would much facilitate both interpretation and application of data and results of different environmental assessment tools.

9.1.4 Quality dimensions

The understanding of environmental information and data quality is of major importance. The issues of quality are not mainly in the regions of precision, which is well-handled by commonplace measurement technique, and may be guided by for example the PHASETS models (see section 5.1.2.2). The problem rather lies in quality management – e.g. how to make economic trade-off for sufficient quality for data, and how to overcome barriers of business secrecy. The latter is a major difficulty in, for example, the chemical industry. Recipes are both the core of the business and the root of the environmental problem.

The quality issues must be dealt with if meaningful environmental information will also become facts that actually tell us something about our physical environment.

In parallel to the research behind this thesis, other research financed by CPM is being performed on the quality aspects of industrial environmental information systems. Questions regarding these aspects are therefore mainly left to that work.

9.1.5 Generalising the framework to encompass sustainable development

The principles of the framework presented in Chapter 7 were both applied and developed during the different applied research projects presented in Chapter 5. The framework should not be limited to the environmental aspects of sustainable development. Currently environmental aspects constitute the only scope yet probed, analysed and experienced, but future work may show how the framework develops in the context of the new application domains of sustainability. The fact that everything changes is an argument for the conclusion that information systems need to be designed for efficient quality review and updating of data. Unless data are updated, they will not reflect changes in reality. Without information quality management, data will not be worth taking seriously. The information system needs to be developed for the needed flexibility within the control system, but it still needs to be designed as if the control situation was stable.

9.2 Research economic and practical consequences of improved environmental information structures

This thesis shows how information structuring helps with improving availability and transparency of environmental information. It strives to show how this can be done in practice and by examples from case studies (Chapter 5). But since information and data gaps are built into environmental methods and tools (Pålsson, Flemström, 2004) the methodological consequences from the proposed improvements need to be investigated. Organisational and societal scenario assessments of costs, benefits, risks and avoided risks from improved environmental data need to be studied. Such consequence analysis could be used to aid political discussions and guide how to prioritize investment decisions aimed at developing environmental information systems for organisations and societies.

9.3 Indicator information system

Information systems need to be established on understandable and physically relevant indicators for which information can be acquired and continuously updated. Research programmes should be established to set up a number of such key information systems. They need to be based both on models with physical ontology, like PHASETS and PHASES, and on cybernetic control models like the one shown in Figure 3. Many interdisciplinary research projects may be needed to establish such information systems so that they equally well support product design, professional and consumer purchases, business management and regional and international governance. The basic tools for the design and structuring of such information systems are provided through this thesis. Further theoretical and applied research and development are needed.

9.4 Development of methods and tools, and integration of methods and tools for improved information structuring

A rational person might assume that cost reductions and quality improvements should drive organisations to develop economic environmental information systems based on effective and efficient information structures. But there are significant barriers. Research should be performed to identify and understand these barriers. It is recommended that this is done in parallel with practical development of real information systems, since removing barriers in theory might be very different from removing barriers in an operative industrial system.

Such research may be performed with one or a few companies as case study objects. A handful of relevant environmental indicators should be selected for the study. The indicators should be chosen so that they collectively express the main environmental performance of the company. *Establish information channels* needed to acquire the information to *quantify* the *indicators*. Set up a *quality management* system for the information channels. Decide upon or *develop* the *information structures* for all the data needed. Start to *acquire and collect the necessary data*. While performing this data acquisition, *observe* when *problems* occur. Examples of important problems include difficulties with *understanding* the data, difficulties with *secrecy barriers*, or difficulties with *interpreting* the data for *quantifying* the indicator. Each such identified problem should then be analysed in detail, and further research and development should be addressed to find ways to overcome the problems.

The result from such a detailed study should provide a basis for finding focus areas for future research. It should provide guidance on how to prioritise deepened research into the four areas of *economic life cycle*, *cognitive sciences*, *physical reality* and *quality*.

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To all of you mentioned here, and to all of you others who I have much to thank for but who I have not mentioned here, Thank you!

Raul Carlson, 27th of March 2006

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Annex A

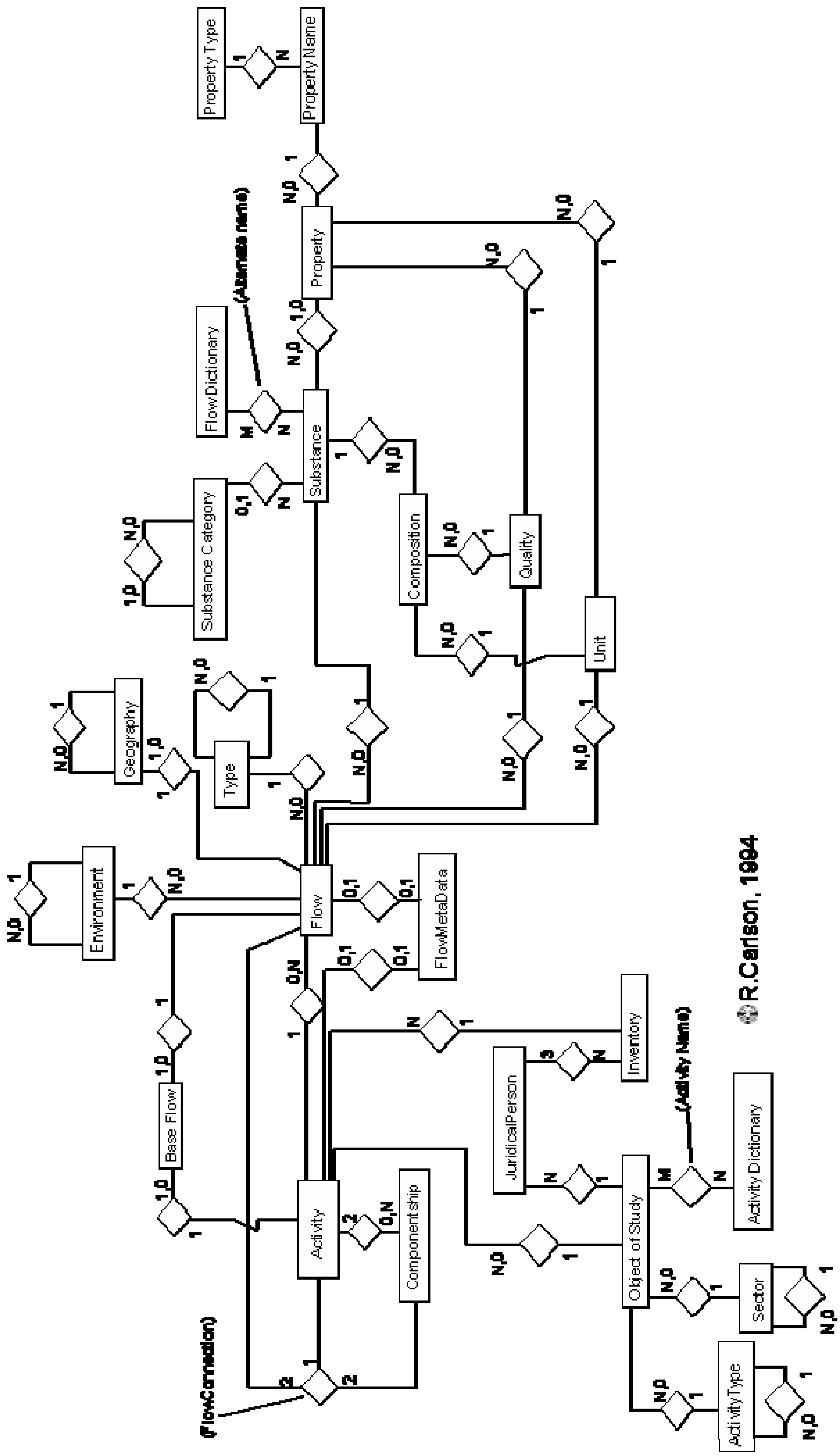


Figure A.1 The first LCI information structure, an entity-relationship diagram of the database.
Carlson R., "Design and implementation of a database for use in the life cycle inventory stage of environmental life cycle assessments", Master thesis in Engineering Physics at Department of Computing Science, Chalmers University of Technology, Göteborg, Sweden, 1994

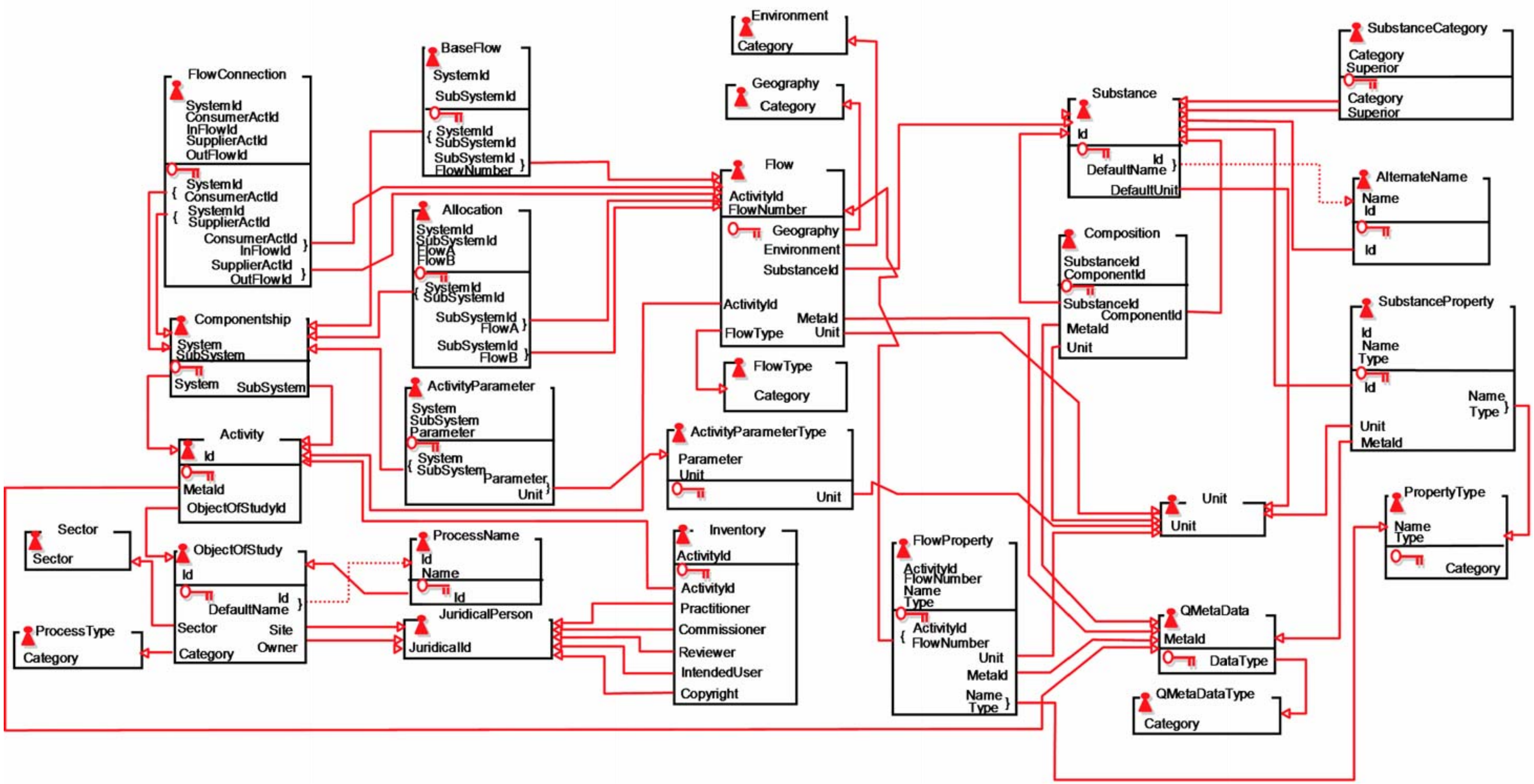


Figure A.2 The second LC! information structure, a relationaral database schema of the database. Carlson R., Löfgren G., Steen B., ”SPINE, A Relation Database Structure for Life Cycle Assessment”, Swedish Environmental Research Institute, IVL-Report B 1227, Göteborg, Sweden, 1995

Annex B

Information structure in information systems

The concept model developed for LCA information was implemented into the SPINE relational database structure, used as basis for the development of the Swedish national LCA database. Figure 20 in section 5.1.2.2 presents a screenshot from the software tool *SPINE@CPM Data Tool* that was developed entirely by the author of this thesis for this project. It was used for documenting data, sharing, reporting and collecting data to the Swedish national LCA *SPINE@CPM*. Figure B.1 shows how the data collection and database system was set up, using the SPINE@CPM Data Tool and a web-server for data publishing.

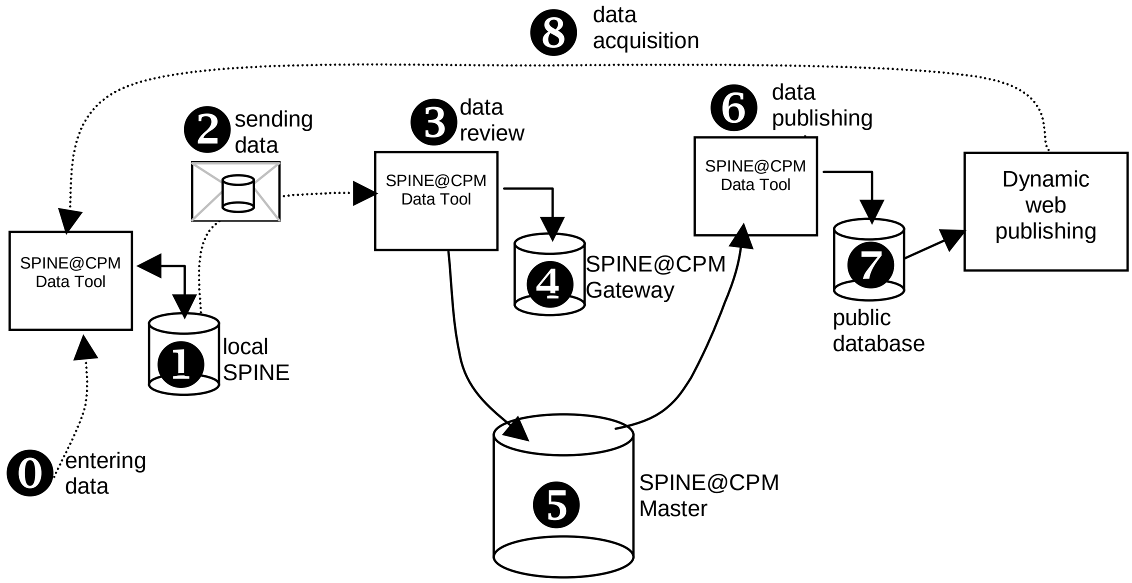


Figure B.1. The SPINE@CPM distributed database system. (Carlson, Pålsson, 1998)

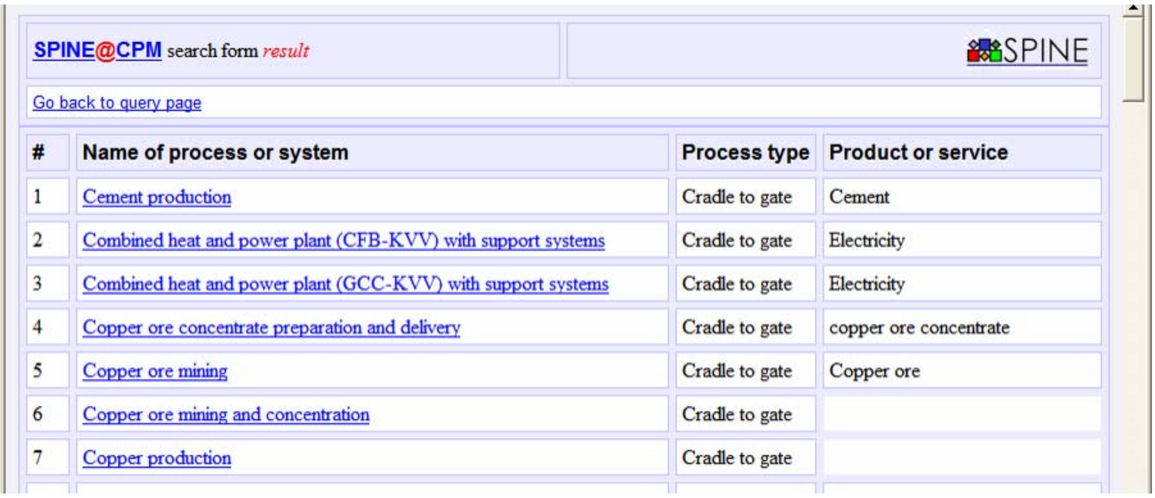
Figure B.1 shows a model of the distributed *SPINE@CPM* database system:

0. Data enters the system by being manually typed in to a local SPINE database by the use of *SPINE@CPM Data Tool*. This can be done anywhere at the CPM companies, at Chalmers or by any other data supplier.
1. The local copy of the SPINE database is supplied freely with the software.
2. Data is sent to CPM by attaching a whole database file in an e-mail. If only a few data sets are to be published from a larger database, these data can be moved from the larger database into a smaller SPINE database using the *SPINE@CPM Data Tool*.
3. The database sent to CPM is reviewed using the *SPINE@CPM Data Tool*.
4. When the review has accepted the data, it is moved into the *SPINE@CPM* Gateway database, a local copy of the SPINE database, used for refinishing and late reviews, before data is sent to the *SPINE@CPM* Master database.
5. Data entered into the *SPINE@CPM* Master database has been reviewed, and can be used for publishing. Any data in this database is sure to hold all *SPINE@CPM* data documentation and quality requirements.
6. When publishing data, data is copied from the *SPINE@CPM* Master database into a local SPINE database, using the *SPINE@CPM Data Tool*.

7. The local public database will hold a subset of the total *SPINE@CPM* data set, and is published through Internet.
    a) There are a number of ways in which the Internet-published data may reach the data users' databases.

The strength of the system presented her lie in its modularity. The *SPINE@CPM Data Tool* is standalone software. The local database shipped with the software can be copied and shipped to any other *SPINE@CPM Data Tool* user. And any data set from one such database can be moved to any other database, ensuring full data communication capabilities.

This information system was established in the beginning of 1997 and has been in practice in Swedish industry since then. In the following a number of screenshots from the SPINE@CPM web database will be presented and explained.


SPINE@CPM search form *result*

SPINE

Go back to query page

#	Name of process or system	Process type	Product or service
1	Cement production	Cradle to gate	Cement
2	Combined heat and power plant (CFB-KVV) with support systems	Cradle to gate	Electricity
3	Combined heat and power plant (GCC-KVV) with support systems	Cradle to gate	Electricity
4	Copper ore concentrate preparation and delivery	Cradle to gate	copper ore concentrate
5	Copper ore mining	Cradle to gate	Copper ore
6	Copper ore mining and concentration	Cradle to gate	
7	Copper production	Cradle to gate	

Figure B.2. Search result from the SPINE@CPM database.

Figure B.2 shows how the database content is listed on a web page. The user gets an indication about what each data set represents, from the name of the *object of study*, the type of process assigned to the *activity* and the name of the *flow* that is classified as *Product or service*.

Contents

Technical System	Administrative
Flow Data	System Boundaries
Flow Chart	About Inventory

SPINE

This data set transparently reported, including a flowchart where each process individually described

Administrative Back to Contents	
Finished	Y
Date Completed	1999-01-25
Copyright	
Availability	Public

Technical System Back to Contents	
Name	Production of CAN fertiliser
Functional Unit (see also *Functional Unit Explanation*)	1 kg of CAN fertiliser
ProcessType	Cradle to gate
Site	Europe
Sector	Materials and components
Owner	Europe

Figure B.3. Head of data sheet that present the technical system for which the data is valid. Compare *ObjectOfStudy* in concept model in figure 16 in section 5.1.2.2.

Figure B.3 shows the head of a data sheet as it appears on the web page. At the top of the page the user can navigate to the different parts of the document with hypertext links. The document structure starts with presenting a selection of data fields grouped as *administrative information* and then identifying information to increasingly technical levels.

Flow Table and Specific Meta Data
Back to Flow Data
Back to Contents

QMetaData	*Direction*	*FlowType*	*Substance*	*Quantity*	*Min*	*Max*	*SDev*	*Unit*	*Environment*	*Geography*
	Input	Natural resource	Dolomite	0.2				kg	Ground	
	Input	Natural resource	Hard coal	1.34				MJ	Ground	
	Input	Natural resource	Natural gas	10.7				MJ	Ground	
	Input	Natural resource	Oil, heavy fuel	1.53				MJ	Ground	
	Input	Refined resource	Diesel	0.253				MJ	Technosphere	
	Input	Refined resource	District heat	-2.06				MJ	Technosphere	Sweden
	Input	Refined resource	Electricity	0.102				MJ	Technosphere	Europe
	Input	Refined resource	Electricity	0.709				MJ	Technosphere	Sweden
	Input	Refined resource	Fuel oil, ship (2-stroke)	0.0258				MJ	Technosphere	
	Output	Emission	Acetaldehyde	0.0000107				g	Air	
	Output	Emission	Acetylene	0.000578				g	Air	
	Output	Emission	Al	0.000253				g	Air	
	Output	Emission	Aldehydes	0.00000179				g	Air	

Figure B.4. List of flow data in the SPINE@CPM database. Compare concept model of *Flow* in figure 19 and SPINE@CPM Data Tool screenshot in figure 20 in section 5.1.2.2.

Figure B.4 shows the list of *flow data* in the data sheet. The small document icons to the left of the table are *hyperlinks* that open up the specific *QMetaData* documentation for each flow. Compare with the concept model of *Flow* in figure 19 in section 5.1.2.2. The fields that specify a flow denotes the *direction* of the flow, its *type* (*emission*, *resource*, *product* etc.), the *substance* (compare figure 19 in section 5.1.2.2), the *quantity* (including *statistical information* if available) and its *unit*, a typing of the *environment* impacted, and information about the *geographic location* of the occurrence.

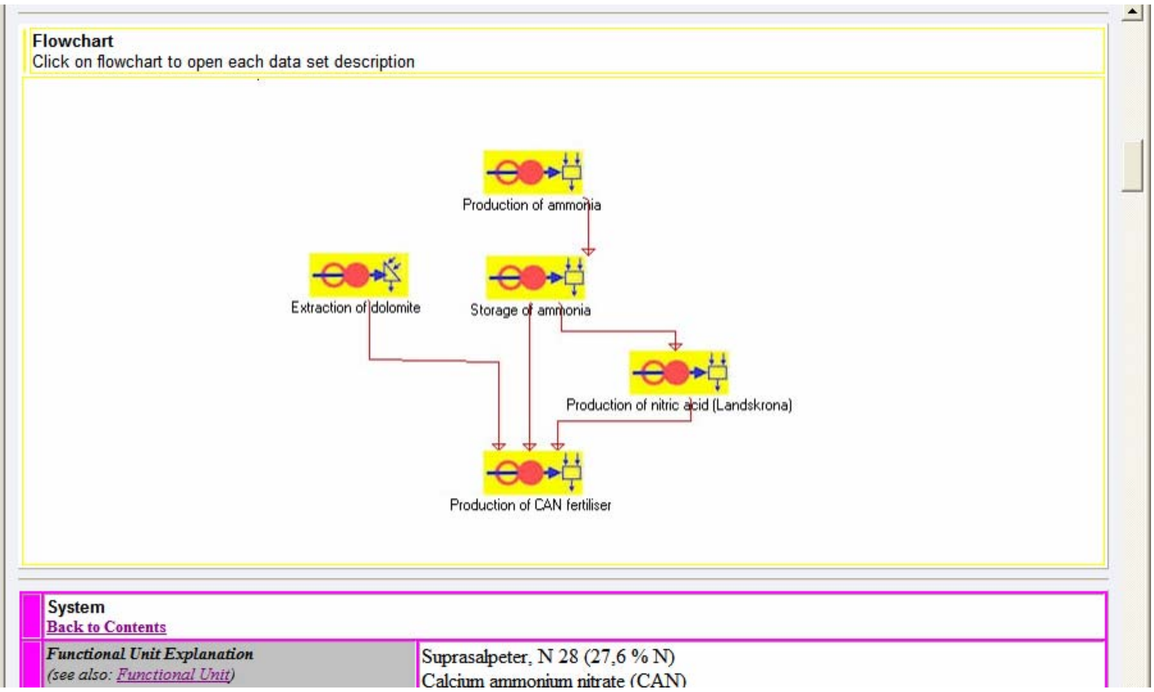


Figure B.5. An LCA flowchart presented on the SPINE@CPM database. Compare the concept of *Componentship* in figure 18 in section 5.1.2.2.

Figure B.5 presents the part of the data sheet that presents a flowchart if the technical system is based on documentation of underlying technical systems. Compare also figure 14 in section 5.1.2.2 that describe how it was intended that a technical system should consist of underlying technical systems, figure 16 that describe the *Componentship* concept and figure 18 in section 5.1.2.2 that describe the concept that describes how the flows are connected.

The full data sheet is presented on the following pages.

Contents		Administrative	SPINE
Technical System		System Boundaries	
Flow Data		About Inventory	
Flow Chart *This data set transparently reported, including a flowchart where each process individually described*			

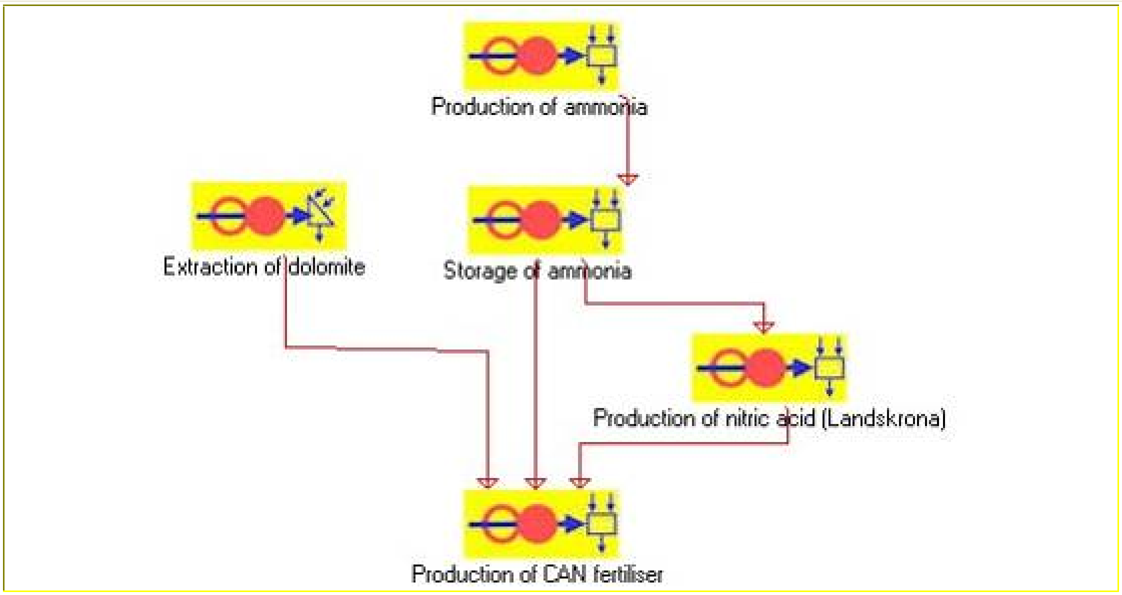
Administrative
Back to Contents

Finished	Y
Date Completed	1999-01-25
Copyright	
Availability	Public

Technical System
Back to Contents

Name	Production of CAN fertiliser
Functional Unit *(see also Functional Unit Explanation)*	1 kg of CAN fertiliser
ProcessType	Cradle to gate
Site	Europe
Sector	Materials and components
Owner	Europe
Function	The production route of CAN fertiliser produced at Hydro Agri AB in Landskrona can be seen in the aggregated activity window. For information about each separate production step, please see each included dataset. Emissions from transports, energy consumption and production of steam, district heat and electricity have been included in the system by using information and emission factors from the database in LCAiT 3.0. LCAiT 3.0 is a computer programme created by CIT Ekologik in Göteborg for practitioners of life cycle assessments. Production/consumption of steam is assumed to replace/be produced by combustion of oil (efficiency of 0.90). Oil has been chosen as fuel source, as it in terms of emissions lies between coal and natural gas. Included transports and assumptions made regarding transports are described below (transports cannot be seen in the aggregated activity window). The ammonia used in production of fertilisers in Sweden is purchased at the spot market in the Baltic Sea. This ammonia mostly originates from Russia and Poland. The ammonia has been assumed to origin from the area around Moscow. It has been assumed that the ammonia is transported by train from Moscow to the harbour in Ventspils in Latvia (1000 km, train, diesel) and then transported by boat to Landskrona (400 km, ship, bulk carrier). Dolomite used at Hydro Agri AB in Landskrona comes from Hammerfall in Northern Norway. It is transported by truck (5 km, medium truck, rural, full) to a harbour close to Bodø, from where it is transported by boat (1800 km, ship, bulk carrier) to Landskrona.

Flowchart
Click on flowchart to open each data set description



System [Back to Contents](#)	
Functional Unit Explanation *(see also: Functional Unit)*	Suprasalpeter, N 28 (27,6 % N) Calcium ammonium nitrate (CAN)
Nature Boundary	The system starts with extraction of raw materials and ends at the outgoing fertiliser factory gate. Emissions from transports, production of steam, district heat, electricity and combustion of energy resources have been included by using information and emission factors from the database in LCAiT 3.0. LCAiT 3.0 is a computer programme created by CIT Ekologik in Göteborg for practitioners of life cycle assessments. Production/consumption of steam is assumed to replace/be produced by combustion of oil (efficiency of 0.90). Oil has been chosen as fuel source, as it in terms of emissions lies between coal and natural gas.
Time Boundary	The time boundary varies for each included dataset; from 1996 to 1998 and in some cases unspecified (see each dataset for further information).
Geographical Boundary	Europe.
Other Boundaries	Coatings, micronutrient and small additives have not been taken into account. Packaging of fertiliser has also been left outside the system boundary. Production and waste treatment of catalysts and production of capital goods are not included.
Allocations	See each included dataset.
Systems Expansions	Production/consumption of steam is assumed to replace/be produced by combustion of oil (efficiency of 0.90). Oil has been chosen as fuel source, as it in terms of emissions lies between coal and natural gas.

Flow Data
General Activity QMetaData
Flow Table and Specific QMetaData

General Activity QMetaData Back to Contents	
DateConceived	
DataType	Derived, unspecified
Represents	
Method	Data are gathered from the official environmental report distributed by Hydro Agri AB in Landskrona, from personal communication with people working there and also from literature and reports on production of fertilisers. For further information, please see the facts under ''Method'' and ''LiteratureRef'' in each included dataset.

	Emissions from combustion of the energy demanded in each included process are not included in the separate datasets, but are included in this aggregated dataset. Emissions and use of resources due to transports are also included in this dataset. The transports are discribed under ''function''. Data for emissions related to the consumption of energy and transports have been taken from the database in LCAiT 3.0. LCAiT 3.0 is a computer programme produced by CIT Ekologik in Göteborg for practitioners of life cycle assessments. Production/consumption of steam is assumed to replace/be produced by combustion of oil (efficiency of 0.90). Oil has been chosen as fuel source, as it in terms of emissions lies between coal and natural gas.
Literature Reference	Besides references used in each included dataset, the database in LCAiT 3.0 has been used to provide data for use of resources and emissions from production and combustion of fuel and from transports. LCAiT 3.0 is a computer programme created by CIT Ekologik in Göteborg for practitioners of life cycle assessments. Please see information in each included dataset for further information.
Notes	Emissions from consumption of energy and transports are included in the outputs. Included transports are described under ''function''.

Flow Table and Specific Meta Data
Back to Flow Data
Back to Contents

QMetaData	*Direction*	*FlowType*	*Substance*	*Quantity*	*Min*	*Max*	*SDev*	*Unit*	*Environment*	*Geography*
	Input	Natural resource	Dolomite	0.2				kg	Ground	
	Input	Natural resource	Hard coal	1.34				MJ	Ground	
	Input	Natural resource	Natural gas	10.7				MJ	Ground	
	Input	Natural resource	Oil, heavy fuel	1.53				MJ	Ground	
	Input	Refined resource	Diesel	0.253				MJ	Technosphere	
	Input	Refined resource	District heat	-2.06				MJ	Technosphere	Sweden
	Input	Refined resource	Electricity	0.102				MJ	Technosphere	Europe
	Input	Refined resource	Electricity	0.709				MJ	Technosphere	Sweden
	Input	Refined resource	Fuel oil, ship (2-stroke)	0.0258				MJ	Technosphere	
	Output	Emission	Acetaldehyde	0.0000107				g	Air	
	Output	Emission	Acetylene	0.000578				g	Air	
	Output	Emission	Al	0.000253				g	Air	
	Output	Emission	Aldehydes	0.00000179				g	Air	
	Output	Emission	Alkanes	0.00126				g	Air	
	Output	Emission	Alkenes	0.000614				g	Air	
	Output	Emission	Aromates	0.000233				g	Air	
	Output	Emission	Aromates	0.00000825				g	Water	
	Output	Emission	As	0.00000523				g	Water	
	Output	Emission	As	0.0000916				g	Air	
	Output	Emission	B	0.00014				g	Air	
	Output	Emission	Be	0.00000938				g	Air	
	Output	Emission	Benzene	0.00606				g	Air	

	Output	Emission	Benzo(a)pyrene	0.00000017				g	Air	
	Output	Emission	BOD	0.00000498				g	Water	
	Output	Emission	Butane	0.00742				g	Air	
	Output	Emission	Ca	0.000123				g	Air	
	Output	Emission	Cd	0.00000253				g	Water	
	Output	Emission	Cd	0.0000734				g	Air	
	Output	Emission	CH4	0.869				g	Air	
	Output	Emission	Cl-	2.26				g	Water	
	Output	Emission	CN-	0.0000125				g	Air	
	Output	Emission	CN-	0.00000157				g	Water	
	Output	Emission	Co	0.000176				g	Air	
	Output	Emission	Co	0.0000004				g	Water	
	Output	Emission	CO	-0.0975				g	Air	
	Output	Emission	CO2	918				g	Air	
	Output	Emission	COD	0.00000126				g	Water	
	Output	Emission	Cr	0.00000493				g	Water	
	Output	Emission	Cr	0.00058				g	Air	
	Output	Emission	Cr3+	0.0000329				g	Water	
	Output	Emission	Cr3+	-0.000065				g	Air	
	Output	Emission	Cu	-0.0000000124				g	Water	
	Output	Emission	Cu	0.000486				g	Air	
	Output	Emission	Dioxin	0.000000000209				g	Air	
	Output	Emission	Dissolved solids	0.0435				g	Water	
	Output	Emission	DOC	0.000000000000319				g	Water	
	Output	Emission	Ethane	0.00174				g	Air	
	Output	Emission	Ethene	0.00348				g	Air	
	Output	Emission	F-	0.000676				g	Water	
	Output	Emission	Fe	0.000276				g	Air	
	Output	Emission	Fe	0.00579				g	Water	
	Output	Emission	Formaldehyde	0.00184				g	Air	
	Output	Emission	F-tot					g	Air	
	Output	Emission	H+	0.000035				g	Water	
	Output	Emission	H2S	0.0000106				g	Air	
	Output	Emission	H2S	0.0000000514				g	Water	
	Output	Emission	Hazardous waste	80.7				g	Technosphere	
	Output	Emission	HC	0.0000245				g	Water	
	Output	Emission	HCl	0.0627				g	Air	
	Output	Emission	Heavy metals	3.37E-19				g	Air	
	Output	Emission	HF	0.00331				g	Air	
	Output	Emission	Hg	0.00000421				g	Air	
	Output	Emission	Highly active rad ac waste	0.00321				g	Technosphere	

	Output	Emission	Metals	0.00000117				g	Air	
	Output	Emission	Metals	0.00000583				g	Water	
	Output	Emission	Mn	0.0000485				g	Water	
	Output	Emission	Mn	0.000509				g	Air	
	Output	Emission	Mo	0.00014				g	Air	
	Output	Emission	N2O	4.6				g	Air	
	Output	Emission	Na	0.00115				g	Air	
	Output	Emission	NH3	0.2				g	Air	
	Output	Emission	NH3	0.0000000461				g	Water	
	Output	Emission	Ni	0.00169				g	Air	
	Output	Emission	Ni	0.0000198				g	Water	
	Output	Emission	NMVOC	0.367				g	Air	
	Output	Emission	NO2	0.77				g	Air	
	Output	Emission	NOx	1.56				g	Air	
	Output	Emission	N-tot	0.669				g	Water	
	Output	Emission	Oil	0.0424				g	Water	
	Output	Emission	Organics	0.00000357				g	Air	
	Output	Emission	Organics	0.0376				g	Water	
	Output	Emission	PAH	0.000108				g	Air	
	Output	Emission	Particulates	0.23				g	Air	
	Output	Emission	Pb	0.000019				g	Water	
	Output	Emission	Pb	0.00041				g	Air	
	Output	Emission	Pentane	0.0127				g	Air	
	Output	Emission	Phenol	7.98E-15				g	Water	
	Output	Emission	Phosphate	0.0000156				g	Water	
	Output	Emission	PO43-	0.000127				g	Water	
	Output	Emission	Propane	0.00331				g	Air	
	Output	Emission	Propene	0.000568				g	Air	
	Output	Emission	P-tot	0.000000929				g	Water	
	Output	Emission	Radioactive emissions	-6340				kBq	Water	
	Output	Emission	Radioactive emissions	-675000				kBq	Air	
	Output	Emission	Radioactive waste	0.00134				g	Technosphere	
	Output	Emission	Rn-222	5840				Bq	Air	
	Output	Emission	Salt	0.0173				g	Water	
	Output	Emission	Sb	0.00000000561				g	Water	
	Output	Emission	Sb	0.0000567				g	Air	
	Output	Emission	Se	0.0000653				g	Air	
	Output	Emission	Sn	-0.00000176				g	Water	
	Output	Emission	Sn	0.0000000319				g	Air	
	Output	Emission	SO2	1.36				g	Air	
	Output	Emission	SO3					g	Air	

About Inventory

Scope

Data

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Scope

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Publication	Davis J, Haglund C (1999). ''Life Cycle Inventory (LCI) of Fertiliser Production - Fertiliser Products Used in Sweden and Western Europe''. SIK report no. 654. The Swedish Institute for Food and Biotechnology (SIK). Göteborg, Sweden.

	Data documented by: Jennifer Davis, SIK (The Swedish Institute for Food and Biotechnology). Documentation reviewed by: Ann-Christin Pålsson, CPM, Chalmers University of Technology
Intended User	The data are intended to be used by people working with life cycle assessments of food production systems.
General Purpose	To generate an inventory of emissions and use of resources due to the production of fertilisers used in Sweden.
Detailed Purpose	The purpose was not to compare the production of different fertilisers with each other, but to generate a thorough inventory of emissions and use of resources due to the production of different mineral fertilisers. The data are intended to constitute a useful basis of input information in life cycle assessments of food production systems.
Commissioner	SIK AB, The Swedish Institute for Food and Biotechnology Box 5401 SE-402 29 Göteborg Sweden .
Practitioner	Davis, Jennifer and Caroline HaglundSIK AB Box 5401 402 29 Göteborg Sweden.
Reviewer	

Data
Back to About Inventory
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Applicability	The data are applicable for production of CAN fertiliser produced and used in Sweden. It can be assumed that production of CAN in Sweden is representative for production of all CAN that is used in Sweden, but it is important to be aware of the fact that there may exist imports of CAN into Sweden.
About Data	Data are gathered from the official environmental report distributed by Hydro Agri AB in Landskrona, from personal comminication with people working there and also from literature and reports on fertiliser production. There are only two sites in Sweden that produce CAN fertiliser and the site in Landskrona is representative for Swedish production of CAN. Emissions from transports, combustion of energy carriers and production of steam, district heat and electricity have been included by using information and emission factors from the database in LCAiT 3.0. LCAiT 3.0 is a computer programme created by CIT Ekologik in Göteborg for practitioners of life cycle assessments.
Notes	Internal review of the report was performed by: Olle Ramnäs, CTH (Chalmers University of Technology), Berit Mattsson and Magnus Stadig, SIK (The Swedish Institute for Food and Biotechnology).

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Annex C

Concept models

This annex provides an overview of the concept models presented in chapter 4.

Figure 16. The concept model of the concepts Activity and Flow

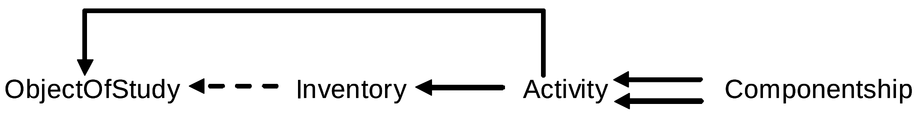

Figure 17. Concept model describing the technical system studied in LCA.

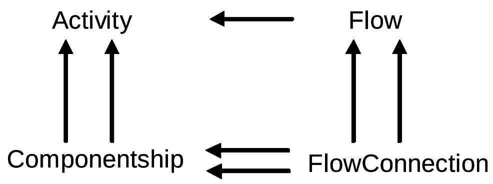

Figure 18. Concept model describing the technical system studied in LCA.

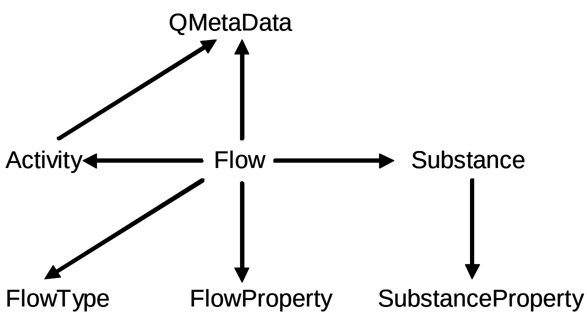

Figure 19. Model of the concept Flow.

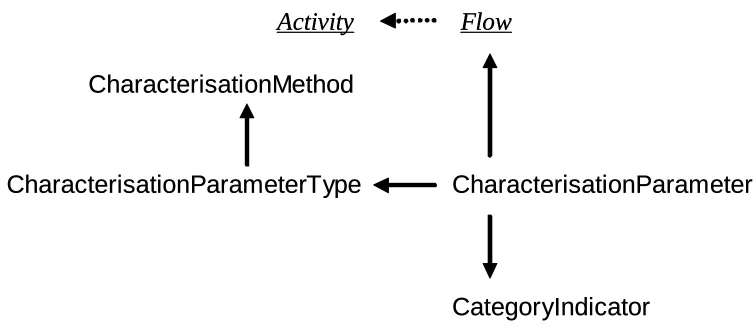

Figure 21. Concept model of LCA characterization.

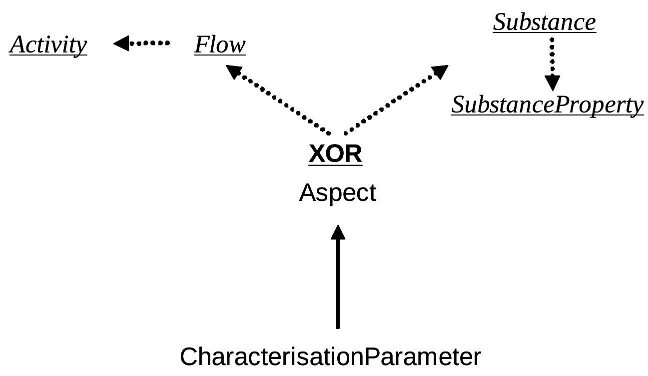

Figure 22. Model of concept of Aspect.

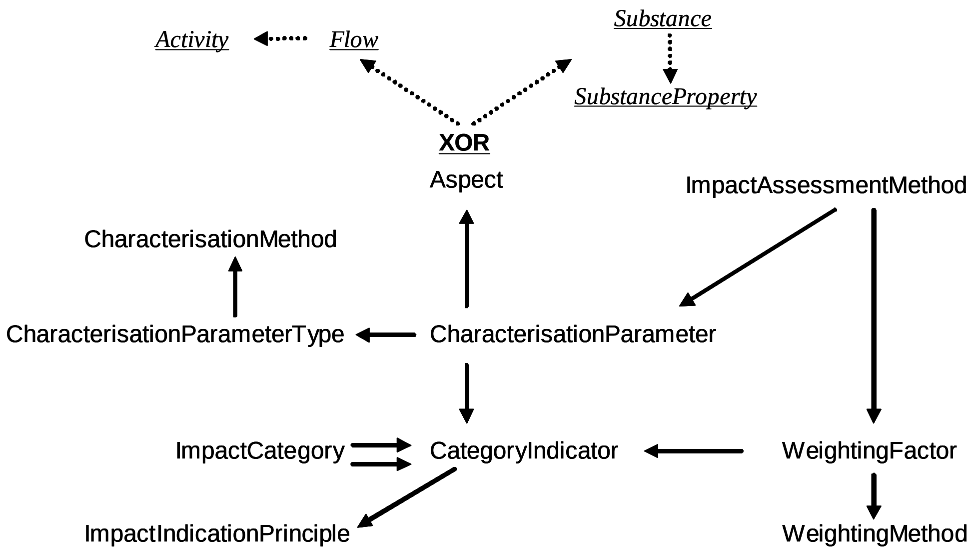

Figure 23. Concept model of LCA impact assessment.

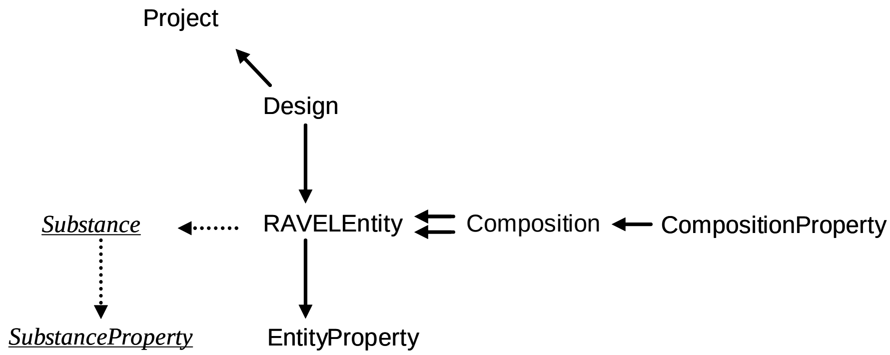

Figure 31. The concept model that describe a product design.

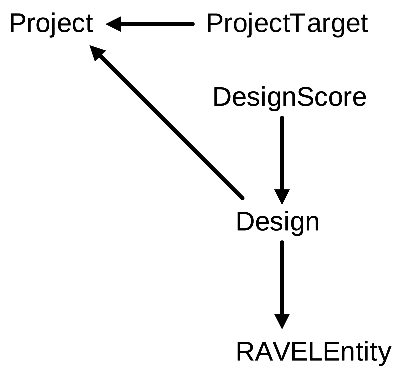

Figure 32. Model of concept of design targets and environmental performance results (score).

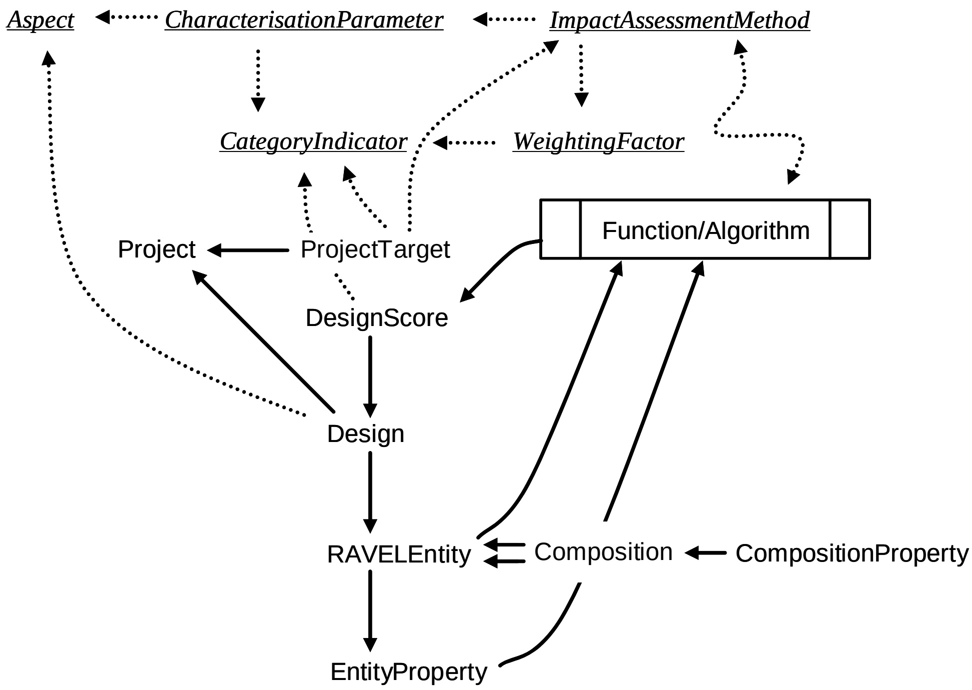

Figure 33. Concept model of how environmental performance is interpreted and calculated.

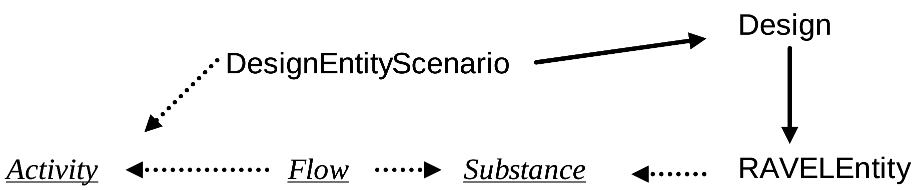

Figure 34. Concept model of the environmental properties of a material or component, in terms of its life cycle assessment. See also figure 29.

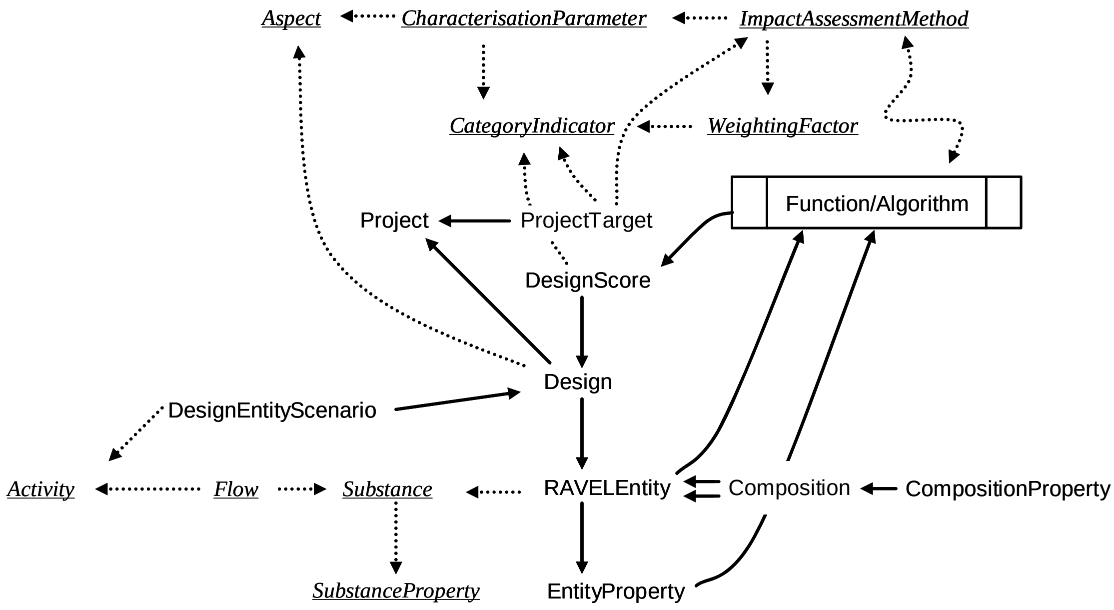

Figure 35. The full concept model of RAVEL design for environment.

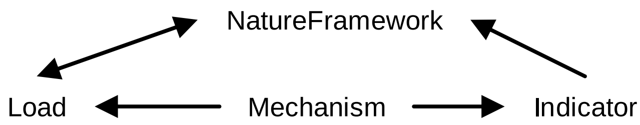

Figure 39. High level view of the core of the OMNIITOX concept model.