Uncertainties in LCA (Subject editor: Andreas Ciroth)

Scenario Modelling in Prospective LCA of Transport Systems

Application of Formative Scenario Analysis

Michael Spielmann*, Roland W. Scholz, Olaf Tietje and Peter de Haan

Federal Institute of Technology Zurich, Natural and Social Science Interface, ETH Zentrum HAD, 8092 Zurich, Switzerland

* **Corresponding author** (michael.spielmann@env.ethz.ch)

DOI: http://dx.doi.org/10.1065/lca2004.10.188

Abstract

Background. Tools and methods able to cope with uncertainties are essential for improving the credibility of Life Cycle Assessment (LCA) as a decision support tool. Previous approaches have focussed predominately upon data quality.

Objective and Scope. An epistemological approach is presented conceptualising uncertainties in a comparative, prospective, attributional LCA. This is achieved by considering a set of cornerstone scenarios representing future developments of an entire Life Cycle Inventory (LCI) product system. We illustrate the method using a comparison of future transport systems.

Method. Scenario modelling is organized by means of Formative Scenario Analysis (FSA), which provides a set of possible and consistent conerstone scenarios. Unit processes scenarios are generated for those unit processes of an LCI product system which are time dependent and of environmental importance. Unit process scenarios are combinations of levels of socio-economic and technological impact variables. Two core elements of FSA are applied in LCI scenario modelling. So-called impact matrix analysis is applied to determine the relationship between unit process specific socio-economic variables and technology variables. Consistency Analysis is employed to integrate various unit process scenarios into the overall cornerstone scenarios, based on pair-wise ratings of the consistency of the levels of socio-economic impact variables of all unit processes. Two software applications are employed which are available from the authors.

Results and Discussion. The study reveals that each possible level or development of a technology variable is best conceived of as the impact of a specific socio-economic (sub-) scenario. This allows for linking possible future technology options within the socio-economic context of the future development of various background processes. In an illustrative case study, the climate change scores and nitrogen dioxide scores per seat kilometre for three technology options of regional rail transport are compared. Similar scores are calculated for a future bus alternative and an average Swiss car.

The scenarios are deliberately chosen to maximise diversity. That is, they represent the entire range of future possible developments. Reference data and the unit process structure are taken from the Swiss LCA database 'ecoinvent 2000'. The results reveal that rail transport remains the best option for future regional transport in Switzerland. In all four assessed scenarios, two technology options of future rail transport perform considerably better than regional bus transport and car transport.

Conclusions and Recommendations. The case study demonstrates the general feasibility of the developed approach for attributional prospective LCA. It allows for a focussed and in-depth analysis of the future development of each single unit process, while still accounting for the requirements of the final scenario integration. Due to its high transparency, the procedure supports the validation of LCI results. Furthermore, it is well-suited for incorporation into participatory methods so as to increase their credibility.

Outlook and Future Work. Thus far, the proposed approach is only applied on a vehicle level not taking into account alterations in demand and use of different transport modes. Future projects will enhance the approach by tackling uncertainties in technology assessment of future transport systems. For instance, environmental interventions involving future maglev technology will be assessed so as to account for induced traffic generated by the introduction of a new transport system.

Keywords: Cornerstone scenarios; formative scenario analysis (FSA); life cycle inventory analysis (LCI); life cycle modelling; rail transport; regional transport; scenario modelling; transport; uncertainty assessment; uncertainty management

Introduction

Uncertainty of complex systems is important in strategic decision making in business and policy-making. Understanding uncertainty and having tools to evaluate uncertainty support the application of decision support tools such as Life Cycle Assessment (LCA), as well as improving their credibility. Uncertainty in decision making has been investigated in many research fields resulting in various characterisations of uncertainty. A comprehensive overview is given in van Asselt (1999).

Funtowicz (1990) distinguished three levels of uncertainty, which can be identified in the LCA model defined by Heijungs (1992). Firstly, technical uncertainties, which are connected with quality and appropriateness of the data used to describe the system. Secondly, methodological uncertainties are caused by the model layout and structure, e.g. the allocation method. Finally, epistemological uncertainties concern the conception of a phenomenon (whether and how a model represents the system being studied). Alternative approaches for classifying uncertainty in LCA are given by Huijbregts (1998a) and Björklund (2002).

Traditionally, the main focus of uncertainty research in LCA was on technical uncertainties, often referred to as data quality uncertainties. Probability-based tools have been utilised by many authors to assess this type of uncertainty (Kennedy et al. 1996, Weidema and Suhr-Wesnaes 1996, Coulon et al. 1997, Finnveden and Lindfors 1998, Huijbregts 1998b, Contadini et al. 2002, Huijbregts et al. 2003). In the Swiss Life Cycle Inventory (LCI) database, 'ecoinvent 2000', the input data are prepared to allow for the application of Monte Carlo simulation (Frischknecht et al. 2004).

Epistemological uncertainties, concerned with uncertainty in the knowledge about the state of the system under investigation (Kahnemann et al. 1982), have received less attention. Epistemological uncertainties are particularly important for prospective LCA due to the unpredictability of the future development of the system under investigation. A tool for addressing epistemological uncertainties is Scenario Analysis (Godet 1986, Scholz and Tietje 2002, Tietje 2003a). A general framework for scenario development in LCA has been proposed by Pesonen (2000) and Weidema (2003a) and a first, structured framework for scenario-based LCA has been proposed by Fukushima (2002).

The main goal of this paper is to address epistemological uncertainty in a prospective, attributional LCA. The key question with regard to this type of LCA is what the situation in the future will look like, with results providing a basis for strategic decisions. A specific procedure is proposed to generate a set of possible, consistent and diverse cornerstone scenarios representing future developments of an entire LCI product system.

The proposed procedure employs two core elements of Formative Scenario Analysis (FSA) and has two steps. Step 1 generates a set of possible and consistent scenarios for those unit processes of an LCI product system that exhibit considerable time dependency and are environmentally relevant. Step 2 applies Consistency Analysis to facilitate the integration of various unit process scenarios and to select a small set of possible, consistent and diverse cornerstone scenarios.

A case study is presented to illustrate the applicability and appropriateness of the developed approach. Climate change and NO_x-emissions per seat kilometre for three technology options of regional rail transport are calculated and compared. Similar scores are calculated for a future bus alternative and an average Swiss car.

1 The Principle of Formative Scenario Analysis

The history and applications of scenario analysis are described in Pesonen (2000) and Weidema (2003a). Gausemeier (1996) pointed out two concepts that demarcate scenario analysis from traditional forecasting approaches (such as trend analysis, Delphi panel, etc.): multiple futures and system thinking. The concept of multiple futures refers to the way in which scenario analysis provides a set of scenarios, each representing a possible future state of a considered system. 'System thinking' is critical for scenario analysis and goes beyond the scope of conventional analytical approaches. The development of the environment of an object or entity of interest is represented in so-called shell scenarios. In general, decision makers cannot control shell scenarios or can only partly do so.

The term Formative Scenario Analysis (FSA) was introduced by Scholz (1996) in order to distinguish impact variable based construction of future states of a system from intuitively and less transparently defined scenario constructions. The foundation of FSA is a formal description of a scenario **s** as a vector, which expresses a certain combination of levels n of impact variables d:

$$\mathbf{s}_k = \left(d_1^{n_{1k}}, \ldots, d_i^{n_{ik}}, \ldots, d_K^{n_{Kk}}\right)^T \tag{1}$$

In Eq. (1), n_{ik} denotes the level of impact variable d_i for scenario k. For the sake of simplification of the mathematical notation we substitute $d_i^{n_{ik}}$ with λ_i^{ik} (denoting the level of impact variable d_i). Hence, equation 1 can be expressed as follows:

$$\mathbf{s}_k = \left(\lambda_1^k, \ldots \lambda_K^k\right)^T \tag{2}$$

where $1 \le k \le k_0$, and k_0 is the total number of scenarios. K denotes the number of impact variables and m_i is the total number of levels (i.e. possible future states) that the i-th impact variable may exhibit. k_0 equals $\prod_{i=1}^{K} m_i$ and λ_i^k denotes the level of impact variable d_i for scenario k. For example, the impact variable d_1 named 'fuel type' has two possible levels, $d_1^1 = 1$ for 'CNG' or $d_1^2 = 2$ for 'diesel'. If then, for scenario k, fuel type is diesel, $\lambda_1^k \equiv d_1^{n_k} = 2$.

If we classify epistemological uncertainties in terms of scenario model variables we can distinguish two levels. Level A comprises truly unknown variables (a variable no human has ever thought about) and disturbance variables (variables which will fundamentally change the system under consideration; e.g. war events). Level B variables may be classified as known, but the knowledge about the quantitative interrelation of these variables with the rest of the system is incomplete.

FSA is a tool that can be used to address Level B variables; i.e. we assume that the nature of the impact variables of the system under consideration (e.g. an LCA unit process) is known. For instance, we know that the variables market mechanism and behavioural pattern have an influence on a certain unit process. However, the knowledge of their interaction is insufficient to allow for the formulation of quantitative relationships. In the absence of quantitative relationships between variables, conventional sensitivity analysis based on both fixed model structure and known quantified relationships of a model is not applicable. Seen in this light, FSA may be considered as a type of structured sensitivity analysis for cases characterised by a fixed model structure (in terms of variables), but unknown quantitative relationships between (parts of) the model variables.

2 Formative Scenario Analysis in LCI

2.1 Inventory data model

The scenario analysis approach presented here is based on the inventory matrix approach (Heijungs 1996). A unit process is expressed as a vector $\mathbf{p}_j = (a_{1j},...,a_{mj},b_{1j},...,b_{nj})^T$ where $\mathbf{b}_j = (b_{1j}, = (b_{1j},...,b_{nj})^T$ is called the environmental part, and $\mathbf{a}_j = (a_{1j},...,a_{mj})^T$ is the technology part. All unit process vectors together define the unit process matrix **P**:

$$\mathbf{P} = \begin{vmatrix} \mathbf{A} \\ \mathbf{B} \end{vmatrix} = \left| p_i \cdots p_m \right| \tag{3}$$

where **A** is referred to as the technology matrix (Rijckeghem 1967) and **B** is referred to as the intervention matrix. The environmental interventions, **β**, are calculated as follows (Heijungs and Frischknecht 1998):

$$\boldsymbol{\beta} = \mathbf{B} \cdot \mathbf{A}^{-1} \cdot \boldsymbol{\alpha} \tag{4}$$

where **α** denotes an external supply vector. The inventory model of transport systems is comprised of specific transport components (vehicle operation, vehicle manufacturing, maintenance and disposal, as well as infrastructure construction, operation and disposal) (Spielmann and Scholz 2004).

2.2 Applying formative scenario analysis in LCI

FSA distinguishes between objects of interest (usually under the control of the decision maker) and shell scenarios (usually not under the control of the decision maker). This corresponds to the formal distinction between foreground and background systems made in LCI (Frischknecht 1998, Hofstetter 1998). Shell scenarios are expressions of 'alternative futures' accounting for uncertainties in background processes. Foreground processes account for future technology alternatives (also called 'options') under the control of the decision maker. Scenario modelling addresses all options under various shell scenarios. Out of all technically possible shell scenarios, FSA then selects a small subset of highly consistent and diverse, so-called cornerstone scenarios.

We generate shell scenarios separately for those unit processes that exhibit considerable time dependency and that are environmentally important. These unit process scenarios are then integrated into the overall cornerstone scenarios.

Each unit process scenario, $\mathbf{s}_k$, is split into a technology scenario, $\mathbf{s}_t$, and a socio-economic scenario, $\mathbf{s}_e$:

$$\mathbf{s}_k = \begin{pmatrix} \mathbf{s}_t \\ \mathbf{s}_e \end{pmatrix} = \left(\lambda_1^t \ldots \lambda_T^t, \lambda_{T+1}^e \ldots \lambda_{T+E}^e\right)^T, \quad k = t + (e-1)T \tag{5}$$

where T is the number of technology impact variables d_t, $1 \le t \le T$, and E is the number of socio-economic impact variables d_e, $(T + 1) \le e \le (T + E)$ such that $K = T + E$.

So, we have a total of $t_0 = \prod_{t=1}^{T} m_t$ technology scenarios and a total of $e_0 = \prod_{e=T+1}^{T+E} m_e$ socio-economic scenarios. Their product is the total number of scenarios, $k_0 = t_0 e_0$.

Technology impact variables address consequences of uncertainties in the unit process specific technology development. Socio-economic impact variables express uncertainties in a unit process' environment.

2.3 A procedure for FSA-based scenario modelling

This section presents a two-step, bottom-up procedure for the generation of LCI cornerstone scenarios by applying elements of FSA. Step 1 comprises four Moves facilitating the generation of a set of quantified unit process scenarios, based on unit process specific technology scenarios and socio-economic scenarios (**Fig. 1**). Step 2, consisting of two Moves, facilitates the synthesis of the various unit process scenarios generated in Step 1. Finally, a set of two to four possible, consistent and diverse cornerstone scenarios is selected in Step 2.

Section 3 illustrates the proposed procedure for the comparison of different options of regional transport.

Step 1: Development of unit process scenarios

Move 1 – Selection of Scenario Impact Variables. The result of Move 1 is a preliminary list of impact variables for a selected unit process, $\mathbf{p}_j$, that distinguishes between technology impact variables and socio-economic impact variables. In order to develop an exhaustive list of impact variables, no method or research path is excluded *a priori*. Comprehensive literature studies are usually required, which may be complemented by expert and stakeholder knowledge. As outlined in Fig. 1, we recommend the separate generation of socio-economic, d_e, and technology impact variables, d_t.

Move 2 – Structural Analysis. Structural Analysis assesses the relation between technology and socio-economic variables and detects the socio-economic key variables of a unit process. For this, all impact variables (d_t and d_e) are interrelated in a so-called impact matrix (see Table 2 for an example). The impact matrix $\mathbf{M} = (a_{i,j})$, $i, j = 1,...N$, presents the direct impact of d_i on d_j (Scholz and Tietje 2002). In constructing the impact matrix, one has to assess and rate the direct impact of one impact variable on another. This raises the question of which scaling is appropriate for the ratings. There is no definite answer to this question and the actual selection is arbitrary. For application in LCA-studies we recommend a three level scale. A relationship between two impact variables d_i and d_j exists if variable d_i causally affects variable d_j, or vice versa. Following the assessment and rating of the direct impacts of all impact vajriables on other impact variables, activity and passivity scores are calculated for each impact variable in order to rank the various impact variables of a unit process and to identify the key impact variables. The activity score is the sum of all impacts that one variable has on all others. The passivity score is the sum of all impacts that other variables have on a variable.

Socio-economic key impact variables are characterised by a high activity score and a low passivity score. Ideally, the socio-economic component of the unit process scenario should be limited to these key variables and each selected technology variable should be linked to at least one socio-economic key variable.

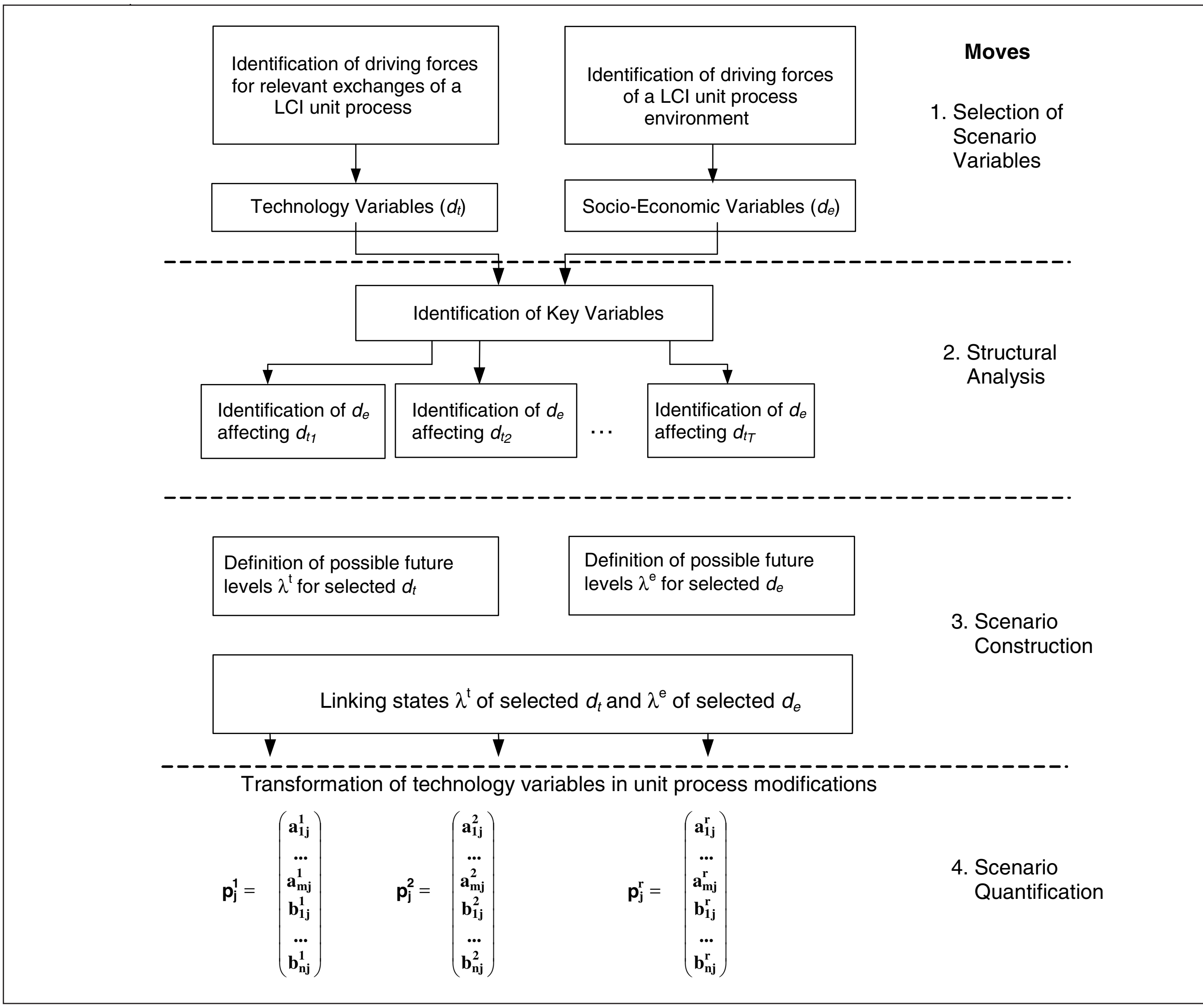

Fig. 1: Procedure for the generation of a set of unit process scenarios

However, in reality it is likely that a certain technology variable, e.g., d_{t_1}, is directly influenced by a socio-economic impact variable, say, d_{e_4}, which is not classified as a key impact variable. In such cases, a MIC-MAC analysis (Godet 1986) should be performed to assess the indirect relationships of socio-economic key variables and technology variables. Sometimes a socio-economic key impact variable, d_{e_3}, directly influences another variable, d_{e_4}, which in turn directly influences variable d_{t_1}. Consequently, d_{e_4} may then be eliminated, thereby reducing the number of impact variables and avoiding redundancies (for an example see Section 3).

Move 2 is supported by a software application that is available from the authors (Tietje 2003c). Results of Move 2 are a minimal, but satisfying set of socio-economic impact variables d_{e_1}...d_{e_q}, $q \le E$ that are sufficient and suitable for describing the current level of the investigated unit process. For each technology variable, d_t, at least one socio-economic variable d_e is identified which directly affects its current level.

Move 3 – Unit Process Scenario Construction. The result of Move 3 is a set of interrelated technology scenarios, $\mathbf{s}_t$, and socio-economic scenarios, $\mathbf{s}_e$. Each socio-economic or technology variable has at least two possible future levels; their possible future levels must be linked. For instance, for a given scenario $\mathbf{s}_k$, $\lambda^k_{t_1} = f\left(\lambda^k_{e_1}, \lambda^k_{e_2}\right)$.

Move 4 – Unit Process Scenario Quantification. Based on the description of the different levels of technology variables d_t, estimates for changes in the technology vector, $\mathbf{a}_j$, and environmental vector, $\mathbf{b}_j$, of a selected unit process, $\mathbf{P}_j$, can be made (see next section for an example). The results of Move 4 are a set of adjusted unit process vectors $\mathbf{p}^1_j$,..., $\mathbf{p}^u_j$,...,$\mathbf{p}^r_j$, with $1 \le u \le r$, representing changes in the level of technology variables, which in turn correspond to changes in the level of socio-economic variables. Thus, each adjusted unit process is determined by a unique combination of socio-economic variables, representing a unit process' socio-economic scenario.

Step 1 has to be performed separately for each background unit process included in the scenario modelling, resulting in various sets of unit process scenarios. In order to determine a set of cornerstone scenarios representing an entire product life cycle, scenario integration is required. This is done in Step 2.

Step 2: Unit Process Scenario Integration

Move 5 – Selection of cornerstone scenarios. The results of Move 5 are a set of cornerstone scenarios, $\mathbf{s}_c$, representing an entire LCI-product system. The selected scenarios are characterised by a) high consistency scores, b) no inconsistencies and c) diversity.

The identification of cornerstone scenarios, $\mathbf{s}_c$, is based on the integration of all E_c unit process specific socio-economic impact variables, as defined in Step 1, in shell scenarios $\mathbf{s}_{Sh}$. For example, if E_c =10 and each variable only has two levels, we will have 2^{10} different shell scenarios.

Consistency Analysis is applied to reduce the number of possible shell scenarios and ensure logical consistency of the resulting cornerstone scenarios. To do this, a single consistency measure, c, is determined for each pair of impact variables and possible levels (e.g. $d_i^{n_k}$ and $d_j^{n_l}$). The consistency scores are based on expert estimates. Again the question rises as to which scale is appropriate for the ratings. No definite answer to this question exists; however, a scale with only a few levels is generally recommended (Scholz and Tietje 2002). For application in LCA-studies we recommend a four level scale:

$$c\left(d_i^{n_k}, d_j^{n_l}\right) \in \{-1,0,1,2\}, \quad k \in \{1 \dots m_i\}, l \in \{1 \dots m_j\} \tag{6}$$

In Section 3.3, the various levels are precisely defined. The overall consistency of a shell scenario can then be calculated additively as:

$$C_{add}(\mathbf{s}_e) = \sum_{i=2}^{n} \sum_{j=1}^{i-1} c\left(\lambda_i^e, \lambda_j^e\right) \tag{7}$$

or can be calculated multiplicatively as:

$$C_{mult}(\mathbf{s}_e) = \prod_{i=2}^{n} \prod_{j=1}^{i-1} c\left(\lambda_i^e, \lambda_j^e\right) \tag{8}$$

In principle, the overall consistency of a scenario is rated with regard to its C_{add} score. C_{mult} is used to identify and remove shell scenarios that exhibit singular inconsistencies, because a single inconsistency, $c\left(\lambda_i^e, \lambda_j^e\right) = 0$, yields an overall consistency of zero, which is the measure for multiplicative inconsistency. Thus, for each possible scenario, the multiplicative consistency is calculated and any inconsistent scenarios are removed. For the remaining consistent scenarios, a certain minimum consistency score may be defined to further reduce the number of cornerstone scenarios. Therefore, additive consistency is usually employed.

Although Consistency Analysis may drastically reduce the number of scenarios, too many scenarios may still remain. Furthermore, scenarios with high consistency scores are often very similar and only differ in the level of a few impact variables. We use a simple mathematical algorithm to facilitate the identification of a small set of diverse and highly consistent cornerstone scenarios (Tietje 2003a). The approach is based on an additional scenario property, defined as distance Δ between two consistent shell scenarios $\mathbf{s}_{Sh}^u$ and $\mathbf{s}_{Sh}^v$:

$$\Delta(s_{Sh}^u, s_{Sh}^v) = \sum_{i=1}^{n} \begin{cases} 1 \text{ if } d_i(s_{Sh}^u) \neq d_i(s_{Sh}^v) \\ 0 \text{ otherwise} \end{cases} \tag{9}$$

We obtain a small number of consistent scenarios by choosing a minimum distance $\Delta_{\min}$. This means that remaining scenarios always differ in at least $E_c - \Delta_{\min}$ impact variables (E_c is the number of all socio-economic impact variables). Move 5 is supported by a software application, (Tietje 2003b), which is available from the authors.

Move 6 – Quantification of Cornerstone scenarios. The filtered cornerstone scenarios represent a combination of levels of socio-economic variables of unit processes tackled in the scenario modelling. For the quantification of cornerstone scenarios, we make use of the fact that each unit process specific socio-economic scenario, $\mathbf{s}_{e_j}$, is a subset of an identified cornerstone scenario; i.e. $\mathbf{s}_{e_j} \subseteq \mathbf{s}_c$. Furthermore, as outlined in Step 1, each level λ_i^t of a unit process specific technology variable, d_t, is directly linked to a certain level λ_i^e of a socio-economic variable, d_e, where the technology scenario $\mathbf{s}_t$ and the socio-economic scenario $\mathbf{s}_e$ combine to yield the overall scenario $\mathbf{s}_k$. In turn, modifications of a unit process vector p_j^u $(1 \le u \le r)$ are linked to certain levels of technology variables. Thus, there is an unambiguous link between an identified cornerstone scenario, $\mathbf{s}_c^u$, and a quantified unit process scenario, $\mathbf{p}_j^u$.

Consequently, the calculation of the cumulative environmental interventions for a complete product system of a future technology option is straightforward. For each cornerstone scenario $\mathbf{s}_c^u$, selected unit processes $\mathbf{p}_j$ in the process matrix **P**, as described in Section 2, are simply replaced with quantified unit process scenarios $\mathbf{p}_j^u$, (see Move 4, Step 1), corresponding with a specific combination of levels of socio-economic impact variables. Using Eq. 4, the environmental intervention for each scenario can then be calculated.

3 Case Study

3.1 Goal and scope of the case study

Three future regional passenger transport alternatives are compared: rail, bus and private car. The contractor of the case study is assumed to be a decision-maker in a regional Swiss rail company. Three options of future regional rail transport are considered (low cost, comfort, and ultra light, with a specific electricity consumption of 1.1E-02, 3.8E-02 and 5.6E-02 kWh/(seat*km), respectively). The goal of the study is to investigate whether the various options of regional rail transport are environmentally robust options for regional transport in the year 2020. Robust here means having no high environmental impacts in any particular cornerstone scenario and comparatively low environmental impacts in most cornerstone scenarios.

We compare the environmental performance of our three rail transport technology options with each other and with a regional bus alternative in four different scenarios. In addition, an average Swiss passenger car for the year 2020 (assuming 80% rural and 20% urban driving conditions) is modelled and compared. The functional unit is the supply of regional transport and all data is referenced to a seat kilometre. We investigate emissions of NO_x and greenhouse gases (CO_2, CH_4 and N_2O).

Seven unit processes $\mathbf{p}_j$ will be examined: Operation Train (j=1), Manufacturing Train (j=10), Operation Bus (j=30), Manufacturing Bus (j=40), Electricity Supply Switzerland (j=80), Extraction, Processing and Transport of Oil and of Gas (j=130 and 140, respectively). From the unit process matrix, **P**, supplied by the Swiss LCA-database ecoinvent 2000 (Frischknecht et al. 2004, Spielmann et al. 2004), these processes are likely to exhibit considerable change in the future.

Unit process $\mathbf{p}_1$ ('Operation Train') is treated as a foreground process. The remaining six unit processes are treated as background processes and unit process scenarios are separately developed for each unit process as outlined in Step 1 of the procedure (see Section 2). In Section 3.2, we illustrate this procedure for the unit process 'Operation Bus' and present basic assumptions for the other unit processes. Scenario integration (Step 2 of the procedure) is illustrated in Section 3.3 and final results for all scenarios and all unit process scenarios are discussed in Section 4.

3.2 Development of the unit process scenarios operation bus (Step 1)

Move 1 – Selection of Scenario Variables. Suitable socio-economic impact variables are derived from Scholz (2000). Technology impact variables determining future bus operation are based on our own studies. **Table 1** presents the technology and socio-economic impact variables used.

Move 2 – Structural Analysis. An impact matrix, **M,** comprising both socio-economic and technology impact variables has been scored using a three-level scale: 0 = no or little impact; 1 = medium impact; 2 = high impact. The scoring was first performed individually by two authors; they then discussed any differences and jointly decided on the final scoring. **Table 2** lists the scoring and the resulting activity and passivity scores for each variable.

Based on the scorings represented in the impact matrix M, an impact matrix analysis is performed. Firstly, those socio-economic impact variables determining the state of the three technology variables are identified: 'Emission Reduction Technology' is only affected by 'Significance of Environmental Issues'. 'Fuel Type' is affected by 'Fuel Price' and 'Significance of Environmental Issues'. 'Operating Conditions' is directly determined by 'Mobility Lifestyle', 'Passenger Transport' and 'Combined Mobility'.

Secondly, key socio-economic variables are identified by their activity and passivity scores. The impact variables 'Significance of Environmental Issues', 'Fuel Price', and 'Transport

Table 1: Technology impact variables and socio-economic impact variables for the unit process Operation Bus and possible future levels of each variable

Name	Description	Future levels (levels)
	Technology Impact Variable (d_t)	
Fuel Type	Fuel used for the operation of bus	Compressed Natural Gas (CNG)
		Diesel
Emission Reduction Technology	Technical measures to meet. EURO-Norms	PM-Kat/ Euro 4
		Particle-filter/ Euro 5
		DeNOx (SCR)/ Euro 5
Operating Conditions	Operation mode depending on type of road and traffic conditions (trip composition: 20% urban; 80% rural)	Urban: constant travel Rural: constant travel.
		Urban: stop and go (S&G) Rural: constant travel.
		Urban: 50% S&G and 50% constant travel Rural: Constant Travel
	Socio-Economic Impact Variable (d_e)	
Significance of Env. Issues	Orientation of environmental awareness and policy	Unimportant
		Global
		Global and local
Fuel Prices	Prices for conventional fossil fuels (diesel and petrol)	Decrease
		Slight increase
		Significant increase
Transport Policy	Promotion of certain means of transport.	Promotion of rail & road
		Promotion of rail
		Promotion of road
Mobility Lifestyle	Mobility demand; total amount of passenger kilometres	Constant
		Slight increase
		Sign. increase
Combined Mobility	Measures such as park & ride and car sharing	Excluded in Step 1,Move 2
Passenger Transport	Modal split of public and individual transport	Excluded in Step 1,Move 2
Electricity Prices	End-consumer prices of electricity	Excluded in Step 1,Move 2

Table 2: Impact matrix M and impact scores for the unit process 'Operation Bus'

Impact Variables	PT	TP	EP	FP	CM	SoEI	ML	ERT	OC	FT	Activity
Passenger Transport (PT)	0	0	0	0	0	1	0	0	2	0	**3**
Transport Policy (TP)	2	0	0	0	2	1	1	1	0	0	**7**
Electricity Prices (EP)	0	0	0	0	0	0	0	0	0	0	**0**
Fuel Prices (FP)	1	0	1	0	1	0	1	0	0	2	**6**
Combined Mobility (CM)	1	0	0	0	0	0	1	0	1	0	**3**
Sign. of Environ. Issues (SoEI)	1	1	1	1	1	0	0	2	0	2	**9**
Mobility Lifestyle (ML)	0	1	0	0	0	0	0	0	2	0	**3**
Emission Reduction Technology (ERT)	0	1	0	0	0	0	0	0	0	0	**1**
Operating Conditions (OC)	0	0	0	0	0	0	0	0	0	0	**0**
Fuel Type (FT)	0	0	0	0	0	0	0	0	0	0	**0**
Passivity	**5**	**3**	**2**	**1**	**4**	**2**	**3**	**3**	**5**	**4**	**32**

Scores: 0 = no or little impact; 1 = medium impact; 2 = high impact

Policy' are above average in activity and below average in passivity (average score = 3.2). They are potential key variables of the unit process' environment. However, 'Transport Policy' is not directly linked to any of the technology variables and, in turn, 'Mobility Lifestyle', 'Passenger Transport' and 'Combined Mobility' are not active variables. Thus, a second-order impact matrix analysis (MIC-MAC analysis) is performed. Two socio-economic variables ('Passenger Transport' and 'Combined Mobility') are directly influenced by, and therefore substituted with, 'Transport Policy'. 'Mobility Lifestyle' is kept as a socio-economic variable because its relationship with 'Transport Policy' is ambivalent. We thus reduce the six socio-economic variables to a functional minimum of four, sufficient for describing the unit process' environment. Furthermore, each technology variable is linked to at least one of the remaining socio-economic impact variables.

Move 3 – Unit Process Scenario Construction. Possible future levels of socio-economic and technology impact variables are listed in column 3 of Table 2. For interrelated technology and socio-economic impact variables, the future levels have to be matched. For the unit process 'operation bus', four socio-economic variables (Transport Policy, Significance of Environmental Issues, Fuel Price, Mobility Lifestyle) and three technology variables (Fuel Type, Emission Reduction Technology, Operating Conditions) are recorded. For the technology variable Emission Reduction Control, three future technologies representing future emission standards are related to one level of the variable Significance of Environmental Issues. Particle filters, reducing particulate emissions to below EURO V standards, are assumed to be the dominant technology in a world where both local and global environmental issues are important. $DeNO_x$ technology with Selective Catalytic Reduction (SCR) is assumed to be introduced if the focus is on global environmental issues, since they comply with the EURO IV particle standard and allow for higher engine-out NOx levels and, hence, lower fuel consumption. Finally, for the scenario where the significance of environmental issues is no longer of any importance, we assume that vehicles need only comply with EURO IV standards, which can be achieved by what are referred to as PM-Kat systems (UBA 2003).

The technology variable Fuel Type is linked to two socio-economic variables, each with three possible levels. In such cases, combinations of the levels of socio-economic impact variables determine the corresponding level of the technology variable. Only consistent combinations are taken into account. For instance, the level 'constant level' of the socio-economic variable Mobility Lifestyle and the level 'promotion of road transport' of the socio-economic variable Transport Policy are considered to be inconsistent.

Move 4 – Unit Process Scenario Quantification. For the quantification of the corresponding levels of socio economic variables, educated estimates have been made based on the definition of the technology variables to which they are linked. Fuel consumption and emissions of CO_2, NO_x and total hydro carbons (HC), accounting for different future EURO emission standards and specific driving behaviour on rural and urban roads, are taken from (Keller et al. 2004). We assume that 2.4% of HC emissions are CH_4 and that N_2O emissions are 3.30E-05 kg/vkm for all operating conditions (Spielmann et al. 2004). Effects of particle filters and DeNOx systems on fuel consumption are taken into account according to Nylund (2000) and Bárzaga-Castellanos (2001), respectively. For compressed natural gas (CNG) buses, fuel consumption (by mass) is assumed to be 25% higher compared to diesel (Nylund and Lawson 2000). CO_2, HC and NO_x emissions are 55 g/MJ, 0.02 g/kWh and 0.7 g/kWh, respectively, assuming a stoichiometric combustion system (Knecht 1999). 90% of HC emissions are CH_4, and N_2O emissions are 0.021 g/vkm (Nigge 2000). In order to relate the data to the functional unit, seat kilometre, we assume 50 seats per bus (Maibach et al. 1999).

3.3 Unit process scenario integration (Step 2)

Move 5 – Selection of cornerstone scenarios. We have eight socio-economic variables, each with two to three levels (**Fig. 2**). Pair-wise ratings of the single consistency of the various levels of socio-economic variables are performed. The scoring was first performed individually by two authors; they then discussed any differences and jointly decided on the final scoring. Additive consistency is employed to fill the consistency matrix. A four-level scale has been employed for the scoring: –1 = inconsistent; 0 = neutral, 1= partially consistent (i.e. a certain level of impact variable d_e may support a

Unit Process [a]	Scenario Label	Worldwide environmental focused regulation	Individual satisfaction	Moderate Environmental Regulation	Trend
	Scenario Number (u)	**1**	**2**	**3**	**4**
	Impact Variable	Level	Level	Level	Level
Socio-economic impact variable					
$\mathbf{p}_{30}$	**Transport Policy**	Road&Rail +	Road +	Rail +	Road&Rail +
$\mathbf{p}_{10,30,40}$	**Sign. of Environ. Issues**	global & local	vanished	global & local	global
$\mathbf{p}_{10,30,40,,80}$	**Fuel Prices**	significant increase	decline	slight increase	slight increase
$\mathbf{p}_{10,40}$	**Electricity Prices**	significant increase	constant	significant increase	constant
$\mathbf{p}_{130,140}$	**Climate Policy (Int)**	worldwide activities	no climate policy	Kyoto w/o USA	Kyoto w/o USA
$\mathbf{p}_{80}$	**Climate Policy (CH)**	+fossil	vanished	+nuclear	+ fossil
$\mathbf{p}_{80}$	**Electricity Demand**	slight increase	significant increase	slight increase	slight increase
$\mathbf{p}_{30}$	**Mobility lifestyle**	constant	significant increase	slight increase	sign. increase
	Mult. Consistency $c_{mult}(s_c^u)$	3.05E-05	1.53E-05	9.54E-07	9.54E-07
	Additive Consistency $c_{add}(s_c^u)$	13	12	8	8
Technology impact variable					
$\mathbf{p}_{11,12,13}$	**Energy Mix**	100% NG	no change	60 NG & 40 LFO	50 NG & 50 LFO
	Energy Consumption	–10%	constant	–3%	–3%
	Electricity Consumption	–10%	constant	–10%	constant
$\mathbf{p}_{30}$	**Fuel Type**	CNG	Diesel	Diesel	Diesel
	Emission Reduction Technology	n.a.	PM-Cat/ Euro 4	Particle-Filter/ Euro 5	DeNox (SCR) / Euro 5
	Operating Conditions	constant	20% S&G urban	10% S&G and 10% steady flow urban	20% S&G urban
$\mathbf{p}_{40}$	**Energy Mix**	100% NG	no change	substitution coal with NG	substitution coal with NG
	Energy Consumption	–10%	constant	–3%	–3%
	Electricity Consumption	–10%	constant	–10%	constant
$\mathbf{p}_{80}$	**n.a.**	Reduction and Combined Cycle & Co-Generat. with HP	Nuclear Plants as 2000	Reduction and Nuclear Plants & Co-Generation	Reduction and Combined Cycle & Co-Generation
$\mathbf{p}_{130}$	**Fare losses**	–35.00%	–10.00%	–20.00%	–20.00%
$\mathbf{p}_{140}$	**Energy Pipeline Transport**	Europe 1.6/1000km; RUS 2.4/1000km	Europe 1.7/1000km; RUS 2.6/1000km	Europe 1.65/1000km; RUS 2.5/1000km	Europe 1.65/1000km; RUS 2.5/1000km
	Leakage Pipeline & Extraction	0.10% extraction, 0.6% transport RUS,	0.25% extraction, 1.4% transport RUS	0.15% extraction, 1.0% transport RUS	0.15% extraction, 1.0% transport RUS
Unit Process Input Vectors [b]					
$\mathbf{p}_{11}^u$		$\mathbf{a}_{11}^1 = \begin{vmatrix} 0 \\ 0 \\ 194716 \\ 0 \\ 0 \\ 139508 \end{vmatrix}; \mathbf{b}_{11}^1 = \begin{vmatrix} 0 \\ 0 \\ 0 \\ 0 \end{vmatrix}$	$\mathbf{a}_{11}^2 = \begin{vmatrix} 0 \\ 0 \\ 0 \\ 216153 \\ 0 \\ 139508 \end{vmatrix}; \mathbf{b}_{11}^2 = \begin{vmatrix} 0 \\ 0 \\ 0 \\ 0 \end{vmatrix}$	$\mathbf{a}_{11}^3 = \begin{vmatrix} 0 \\ 0 \\ 125916 \\ 83944 \\ 0 \\ 139508 \end{vmatrix}; \mathbf{b}_{11}^3 = \begin{vmatrix} 0 \\ 0 \\ 0 \\ 0 \end{vmatrix}$	$\mathbf{a}_{11}^4 = \begin{vmatrix} 0 \\ 0 \\ 104930 \\ 104930 \\ 0 \\ 155009 \end{vmatrix}; \mathbf{b}_{11}^4 = \begin{vmatrix} 0 \\ 0 \\ 0 \\ 0 \end{vmatrix}$
$\mathbf{p}_{12}^u$		$\mathbf{a}_{12}^1 = \begin{vmatrix} 0 \\ 0 \\ 222045 \\ 0 \\ 0 \\ 159008 \end{vmatrix}; \mathbf{b}_{12}^1 = \begin{vmatrix} 0 \\ 0 \\ 0 \\ 0 \end{vmatrix}$	$\mathbf{a}_{12}^2 = \begin{vmatrix} 0 \\ 0 \\ 0 \\ 246716 \\ 0 \\ 167764 \end{vmatrix}; \mathbf{b}_{12}^2 = \begin{vmatrix} 0 \\ 0 \\ 0 \\ 0 \end{vmatrix}$,	$\mathbf{a}_{12}^3 = \begin{vmatrix} 0 \\ 0 \\ 143589 \\ 95726 \\ 0 \\ 159088 \end{vmatrix}; \mathbf{b}_{12}^3 = \begin{vmatrix} 0 \\ 0 \\ 0 \\ 0 \end{vmatrix}$	$\mathbf{a}_{12}^4 = \begin{vmatrix} 0 \\ 0 \\ 119657 \\ 119657 \\ 0 \\ 176764 \end{vmatrix}; \mathbf{b}_{12}^4 = \begin{vmatrix} 0 \\ 0 \\ 0 \\ 0 \end{vmatrix}$
$\mathbf{p}_{30}^u$		$\mathbf{a}_{30}^1 = \begin{vmatrix} 0 \\ 0.27 \\ 0 \\ 0 \\ 0 \\ 0 \end{vmatrix}; \mathbf{b}_{30}^1 = \begin{vmatrix} 0.68 \\ 1.8E-05 \\ 2.1E-05 \\ 2.4E-03 \end{vmatrix}$	$\mathbf{a}_{30}^2 = \begin{vmatrix} 0.31 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{vmatrix}; \mathbf{b}_{30}^2 = \begin{vmatrix} 0.99 \\ 1.9E-05 \\ 3.3E-05 \\ 8.0E-03 \end{vmatrix}$	$\mathbf{a}_{30}^3 = \begin{vmatrix} 0.28 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{vmatrix}; \mathbf{b}_{30}^3 = \begin{vmatrix} 0.88 \\ 1.4E-05 \\ 3.3E-05 \\ 3.3E-03 \end{vmatrix}$	$\mathbf{a}_{30}^4 = \begin{vmatrix} 0.29 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{vmatrix}; \mathbf{b}_{30}^4 = \begin{vmatrix} 0.93 \\ 1.9E-05 \\ 3.3E-05 \\ 4.2E-03 \end{vmatrix}$

[a] Unit Process Indices: 10 = Manufacturing Current Train; 11 = Manufacturing Low Cost Train; 12 = Manufacturing Comfort Train; 13 = Manufacturing Ultra Light Train; 30 = Operation Bus; 40 = Manufacturing Bus; 80 = Electricity Supply; 130 = Oil Extraction/Processing/Transport; 140 = Natural Gas Extraction/ Processing/Transport

[b] Unit process vectors are split into two sub-vectors a and b (Section 3). The index numbers presented in the table are illustrative and refer to the following commodities a_{ij} and environmental interventions b_{ij}. a_{1j} = diesel; a_{2j} = compressed natural gas (CNG); a_{3j} = heat natural gas, a_{4j} = heat LFO, a_{5j} = heat coal, a_{6j} = electricity, $b_{1j} = CO_2$, $b_{2j} = CH_4$, $b_{3j} = N_2O$, $b_{4j} = NO_x$. The values of $\mathbf{p}^u_{11}$ and $\mathbf{p}^u_{12}$ refer to one vehicle (MJ/vehicle) and the values of $\mathbf{p}^u_{30}$ refer to one vehicle kilometre (kg/vkm)

Fig. 2: Cornerstone scenarios and corresponding levels of socio-economic impact variables and technology impact variables for the investigation of future regional transport alternatives. In addition, the resulting unit process input data is presented for selected unit processes

Table 3: Excerpt from the consistency matrix C. For instance, the future level 'global and local focus' of the impact variable Significance of Environmental Issues, is not consistent with the level 'road' (indicating a promotion of road) of the impact variable Transport Policy. Consequently a consistency score of –1 is inserted in this cell of the consistency matrix C

Impact Variable		Transport Policy			Significance of Environmental Issues (SoEI)			Fuel Price (FP)		
	Level [a)]	Ro	Ro & Ra	Ra	v	g	g&l	–	+	+++
SoEI	v	1	0	0						
	g	–1	1	–1						
	g&l	–1	1	1						
FP	–	1	0	0	1	–1	–1			
	+	0	0	0	–1	1	1			
	+++	–1	1	0	–1	1	2			

[a] The following abbreviations are used for the future levels of the impact variables:
Transport policy: Ro = Promotion of road; Ro & Ra = Directed promotion of road & rail; Ra = Promotion of rail
Significance of Environmental Issues (SoEI): v = vanished; g = global focus; g&l = global and local focus
Fuel Prices (FP): –= decrease; + = slight increase; +++ = significant increase

level of impact variable d_{e_2}, but d_{e_2} does not necessarily support d_{e_1}) 2= dependent (i.e. d_{e_1} supports d_{e_2} and d_{e_2}supports d_{e_1}). An excerpt of the consistency matrix **C**, which results in more than 100 consistent shell scenarios, is shown in **Table 3**. Requiring that two cornerstone scenarios have identical levels in at most 5 variables (and hence differ in at least 3 variables), we arrive at four consistent shell scenarios referred to as cornerstone scenarios.

Move 6 – Quantification of Cornerstone scenarios. The quantification of cornerstone scenarios is performed according to the procedure outlined in Section 2. Fig. 2 presents the given label, impact variable levels, and selected resulting unit processes vectors $\mathbf{p}^u_j$ (j = 11, 12, 30) for each cornerstone scenario.

4 Results

The Climate Change (CC) scores (GWP for a time span of 100 years) and NO_x per seat kilometre for the three investigated rail options, together with results for bus and car transport, are illustrated in **Fig. 3**.

The scores for the 'ultra light train' and the 'low cost train' are lower than the bus alternative and passenger car. This is the case for all cornerstone scenarios and for both indicators (CC, NO_x). In contrast to buses, the scores for rail transport are dominated by infrastructure expenditures. Pre-combustion scores, representing the electricity contribution, remain low even if a change towards fossil electricity (e.g. scenario Worldwide Environmental Regulation) is made. Changes in pre-combustion are based on the weight per seat rather than on the supply mix.

The CNG Bus is more highly ranked than a 'comfort train' in the scenario Worldwide Environmental Regulation, which is characterised by a constant traffic flow for buses. The Climate Change impact of diesel buses, as illustrated in the remaining scenarios, is only slightly higher than the impact of a comfort train. However, a different picture arises for the NO_x-performance of diesel buses, with strong variations among the different scenarios. In the scenario Individual Satisfaction, the NO_x-score of the bus is even worse than the score for a passenger car. If we only consider direct emissions (due to vehicle travel), the diesel buses score worst in all

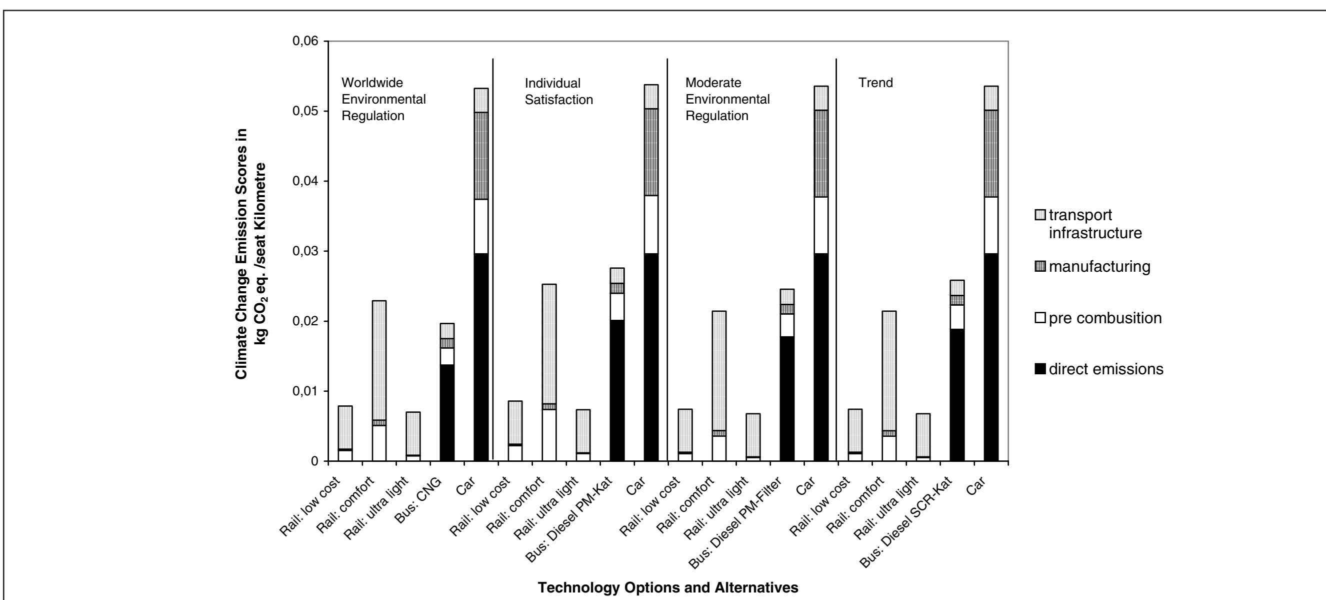

Fig. 3: Climate Change and Nitrogen Oxide emission scores for the investigated options and alternatives of regional rail transport in four cornerstone scenarios (continued on next page)

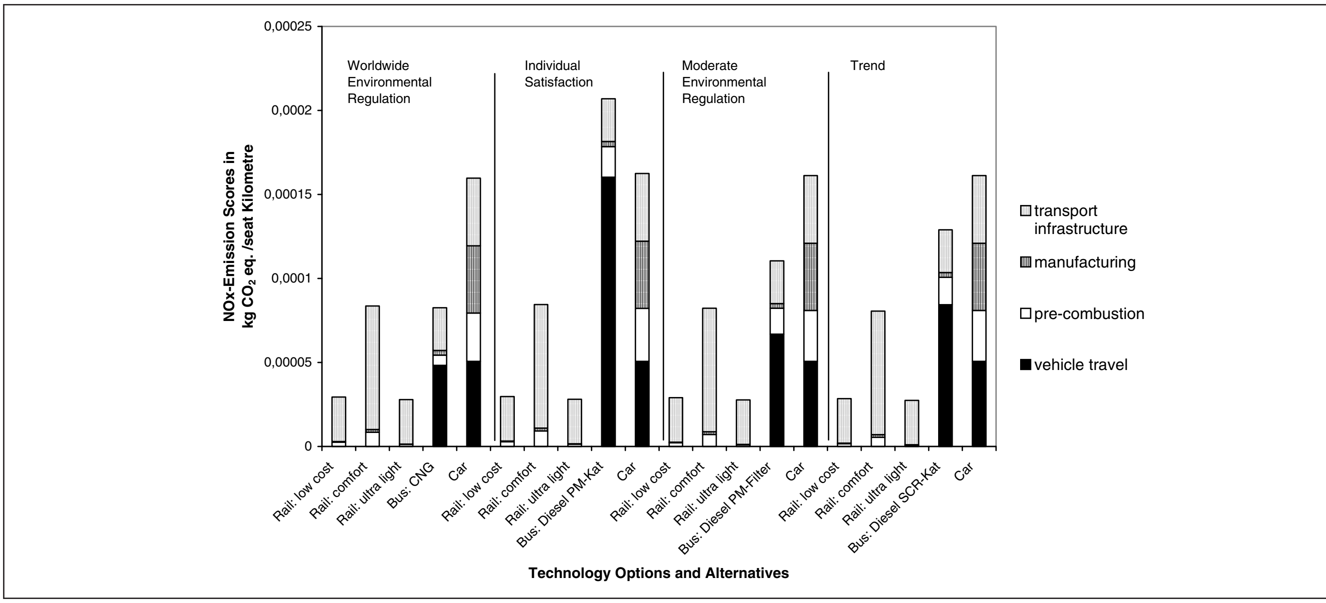

Fig. 3: Climate Change and Nitrogen Oxide emission scores for the investigated options and alternatives of regional rail transport in four cornerstone scenarios (continued from prevous page)

scenarios. These results demonstrate the importance of emission reduction technology for diesel buses. Thus, the results indicate that rail transport remains the best option for future regional transport in Switzerland. In particular, ultra light trains and low cost trains can be considered to be environmentally robust technology options for future regional transport. In a real world case study, however, a definite decision would require further consideration of the load factor.

5 Discussion and Conclusions

The objective of scenario modelling in LCI is to gain insight into the future development of LCI product systems. Various cornerstone scenarios may be used to identify the environmentally most robust option. Robust here means having no high environmental impacts in any particular cornerstone scenario and comparatively low environmental impacts in most cornerstone scenarios.

Scenario modelling benefits from two basic principles of the LCI model. First, we explicitly distinguish between issues within the influence of the decision maker (foreground processes), e.g. technology options, and issues that cannot be directly influenced by the decision maker, but may influence the investigated options (background processes). Second, scenario analysis is performed on the unit process level to account for the heterogeneous nature of a product system. The distinction made between a scenario's socio-economic and technology components, allows for the structured development and quantification of unit process scenarios and for increased transparency in a prospective LCA. Similar to the approach proposed by Fukushima (2002), the structure of the model permits the re-use of the developed unit process scenarios in other studies and is compatible with one of the most prominent LCI databases, 'ecoinvent 2000'.

The proposed procedure facilitates the generation of a small set of consistent and diverse cornerstone scenarios, representing the entire product life cycle. It allows for the investigation of interesting, meaningful and varied future states of a system in a manner different from that proposed by Huijbregts (2003).

The socio-economic component of each unit process scenario vector is used for the generation of cornerstone scenarios. In contrast to unit process specific technology variables, socio-economic variables are of a more general nature and may be used as descriptors for more than one unit process. No unit process specific knowledge and skill is needed to check the pair-wise consistency of the various levels of socio-economic impact variables.

As demonstrated in the case study, the proposed procedure is relatively straightforward and supported by two software applications. It is designed to deal with a number of different variables. The interpretation of the results focuses on the environmental robustness of the investigated options. For example, if regional train transport shows the best environmental performance in all cornerstone scenarios, it is considered to be an environmentally robust future option and no further decomposition of the effects of the individual variables is required. If the results are less clear, then a further decomposition may be helpful for the decision maker.

Finally the proposed procedure is well-suited to supporting participatory methods, in particular to structuring the process of scenario modelling. Thus, the procedure improves the credibility of LCA in the framework of participatory Technology Assessment (Contadini et al. 2002) and Policy Making (Klapwijk 1999). Furthermore, the proposed method provides a framework for the application of various forecasting methods (see e.g. Weidema (2003a) and Pehnt (2003)). For instance, in order to determine levels of one impact variable, regression analysis may be applied so as to extrapolate the expected development and trend of the impact variable under investigation. Participatory methods (e.g. one-to-one interviews) may also be employed to determine future levels of a certain impact variable. Scenario modelling, as presented here, provides an appropriate framework for combining various impact variables describing the future development of different unit processes and selecting a set of cornerstone scenarios. It can thus be regarded as a powerful tool for comprehensive uncertainty management in prospective attributional LCA. Further research will enhance the approach by tackling uncertainties in technology assessment of future transport systems. For instance, environmental interventions involving future maglev technology will be assessed so as to take into account traffic demand increases induced by a new transport system.

Acknowledgements. The authors would like to thank Peter Loukopoulos and Rolf Frischknecht for their support. We gratefully acknowledge financial support from the Swiss Federal Institute of Technology and from the Swiss Agency for the Environment, Forest and Landscape (SAEFL).

References

Bárzaga-Castellanos L, Neufert R, Markert B (2001): Life Cycle Assessment for the implementation of emission control measures for the fright traffic with Heavy Duty Vehicles in Germany. Phase 1: Life Cycle Inventory analysis. Int J LCA 6 (4) 231–242

Björklund AE (2002): Survey of approaches to improve reliability in LCA. Int J LCA 7 (2) 64–72

Contadini JF, Moore RM, Mokhtarian PL (2002): Life cycle assessment of fuel cell vehicles: A methodology example of input data treatment for future technologies. Int J LCA 7 (2) 73–84

Coulon R, Camobreco V, Teulon H, Besnainou J (1997): Data quality and uncertainty in LCI. Int J LCA 2 (3) 178–182

Finnveden G, Lindfors L-G (1998): Data quality of life cycle inventory data – Rules of thumb. Int J LCA 3 (2) 65–66

Frischknecht R (1998): Life Cycle Inventory Analysis for Decision-Making. Scope-Dependent Inventory System Models and Context-Specific Joint Product Allocation. Zürich.ETH Zürich, Dissertation, ETH Diss. Nr.: 12599 <http://www.ethz.ch/libraries/index>

Frischknecht R, Jungbluth N, Althaus H-J, Doka G, Dones R, Heck T, Hellweg S, Hischier R, Nemecek T, Rebitzer G, Spielmann M (2005): The ecoinvent Database: Overview and Methodological Framework. Int J LCA 10 (1) 3–9 <DOI: http://dx.doi.org/10.1065/lca2004.10.181.1>

Fukushima Y, Hirao M (2002): A structured framework and language for scenario-based Life Cycle Assessment. Int J LCA 7 (6) 317–329

Funtowicz SO, Ravetz JR (1990): Uncertainty and quality in science for policy. Dordrecht, The Netherlands, Kluwer

Gausemeier J, Fink A, Schlake O (1996): Szenario-Management. Planen und Führen mit Szenarien. München, Hanser

Godet M (1986): Introduction to 'la prospective'. Seven key ideas and one scenario method. Futures 18, 134–57

Heijungs R (1996): Identification of key issues for further investigation in improving the reliability of life cycle assessments. J Cleaner Production 4, 154–166

Heijungs R, Frischknecht R (1998): A special view on the nature of the allocation problem. Int J LCA 3 (5) 321–332

Heijungs R, Guinée JB, Hupper G, Lankreijer RM, Udo de Haes HA, Wegener Sleeswijk A, Ansems AMM, Eggels AMM, van Duin R, de Goede HP (1992): Environmental life cycle assessment of products: Guidelines and backgrounds. Leiden, The Netherlands, Centre of Environmental Science

Hofstetter P (1998): Perspectives in Life Cycle Impact Assessment: A Structured Approach to Combine Models of the Technosphere, Ecosphere and Valuesphere. Boston, Kluwer Academic Publishers

Huijbregts MAJ (1998a): Application of uncertainty and variability in LCA. Part I: A general framework for the Analysis of uncertainty and variability in Life Cycle Assessment. Int J LCA 3 (5) 273–280

Huijbregts MAJ (1998b): Application of uncertainty and variability in LCA. Part II: Dealing with parameter uncertainty and uncertainty due to choices in Life-Cycle Assessment. Int J LCA 3 (6) 343–351

Huijbregts MAJ, Gilijamse W, Ragas AMJ, Reijnders L (2003): Evaluating Uncertainty in Environmental Life-Cycle Assessment. A Case Study Comparing Two Insulation Options for a Dutch One-Family Dwelling. Environmental Science & Technology 37 (11) 2600–2608

Kahnemann DP, Slovic P, Tversky A (1982): Judgement under uncertainty. Cambridge, Cambridge University Press

Keller M, Zbinden R, de Haan P (2004): Handbook emission factors for road transport. v 2.1, UBA Berlin/ UBA Wien/ BUWAL Bern

Kennedy DJ, Montgomery DC, Quay B H (1996): Data quality. Stochastic environmental life-cycle assessment modelling. A probabilistic approach to incorporating variable input data quality. Int J LCA 1 (4) 199–207

Klapwijk RM (1999): Adjusting Life Cyle Assessment methodology for use in public policy discourse. Delft.Delft University of Technology

Knecht W (1999): The IVECO CNG engine range. Natural Gas Vehicles Conference, Sydney, IANGV/ Australian Natural Gas Vehicles Council

Maibach M, Peter D, Seiler B (1999): Ökoinventar Transporte: Grundlagen für den ökologischen Vergleich von Transportsystemen und den Einbezug von Transportsystemen in Ökobilanzen. Technischer Schlussbericht. Zürich, INFRAS

Nigge M-K (2000): Life Cycle Assessment of Natural Gas Vehicles. Development and Application of Site-Dependent Impact Indicators. Berlin, Springer

Nylund N, Lawson A (2000): Exhaust emissions from natural gas vehicles. Issues related to engine performance, exhaust emissions and environmental impacts. International Association for Natural Gas Vehicles (IANGV) Technical Committee

Pehnt M (2003): Assessing future energy and transport systems: The case of fuel cells. Part I: Methodological aspects. Int J LCA 8 (5) 283–289

Pesonen H-L, Ekvall T, Fleischer G, Huppes G, Jahn C, Klos Z, Rebitzer G, Sonnemann G, Tintinelli A, Weidema B, Wenzel H (2000): Framework for Scenario Development in LCA. Int J LCA 5 (1) 21–30

Rijckeghem W v (1967): An exact method for determining the technology matrix in a situation with secondary products. Review of Economics and Statistics 49, 607–608

Scholz R, Bösch S, Stauffacher M and Oswald J (eds) (2000): Zukunft Schiene Schweiz 1. Ökoeffizientes Handeln der SBB. ETH-UNS Fallstudie. Zurich, Verlag Rüegger, in Zusammenarbeit mit Pabst Publishers, Lengerich. To be obtained from: UNS, ETH-Zentrum HAD, CH-8092 Zurich

Scholz RW, Bösch S, Mieg HA and Stünzi J (eds) (1996): Fallstudie 1996: Zentrum Zürich Nord – Stadt im Aufbruch. Bausteine für eine nachhaltige Stadtentwicklung. Zürich, vdf. To be obtained from: UNS, ETH-Zentrum HAD, CH-8092 Zurich

Scholz RW, Tietje O (2002): Embedded Case Study Methods. Integrating Quantitative and Qualitative Knowledge. Thousand Oaks, SAGE

Spielmann M, Kägi T, Stadler P, Tietje O (2004): Life cycle inventories of transport services. Final report ecoinvent 2000 No. 14. Duebendorf, CH, UNS, ETH-Zurich, Swiss Centre for Life Cycle Inventories. To be obtained from: UNS, ETH-Zentrum HAD, CH-8092 Zurich

Spielmann M, Scholz RW (2005): Life Cycle Inventories for Transport Services: Background Data for Freight Transport. Int J LCA 10 (1) 85–94 <DOI: http://dx.doi.org/10.1065/lca2004.10.181.10>

Tietje O (2003a): Identification of a small reliable and efficient set of consistent scenarios. European Journal of Operational Research in press, available online <authors.elsevier.com/sd/article/S0377221703006337 >

Tietje O (2003b): KD-Consistency Analyis 2.0. Software application for Windows operating system 2.0, Manual and demo version <http://www.uns.ethz.ch>

Tietje O (2003c): MicMac. Software application for Windows operating system, Manual and demo version <http://www.uns.ethz.ch>

UBA (2003): Future Diesel. Abgasgesetzgebung Pkw, leichte Nfz und Lkw – Fortschreibubg der Grenzwerte bei Dieselfahrzeugen. Berlin, Umweltbundesamt

van Asselt I M (1999): Uncertainty in decision support: From problem to challenge. I99-E006. Maastricht, The Netherlands, Maastricht University, International Centre for Integrative Studies (ICIS)

Weidema B, Ekvall T, Pesonen H, Rebitzer G, Sonnemann G, Spielmann M (2003a): Scenarios in LCA. SETAC Working Group Scenario Development in LCA. Brussels, Society of Environmental Toxicology and Chemistry (SETAC) Europe

Weidema B, Suhr-Wesnaes M (1996): Data Quality management for life cycle inventories– An example of using data quality indicators. Journal of Cleaner Production 4, 167–174

Received: December 23rd, 2003
Accepted: October 19th, 2004
OnlineFirst: October 20th, 2004