



Theses of the Ph.D. dissertation entitled

**Integration of Life Cycle Assessment into Environmental
Process Engineering Practices**

submitted by

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Posters

- [22] **Tamas Benko**, Katalin Koczka, Agnes Szanyi, Peter Mizsey, Zsolt Fonyo: Agreements and Contradictions in the Environmental and Economic Evaluation of Waste Solvent Treatment Options. *The 3rd International Conference of the International Society for Industrial Ecology*, Royal Institute of Technology, Stockholm, Sweden, 2005.
- [23] **Tamas Benko**, Agnes Szanyi, Katalin Koczka, Peter Mizsey: Comparison of Flue Gas Desulphurization Processes Based on Life Cycle Assessment. *CAPE Forum 2005*, Cluj Napoca, Romania, **2005**.
- [24] **Benkő Tamás**, Szanyi Ágnes, Mizsey Péter: Fonyó Zsolt: Oldószerkezelési Eljárások Környezetvédelmi és Gazdaságossági Elemzése. *BME-Ipari Nyílt Napok, Budapesti Műszaki Egyetem*, Budapest, 2004. (in Hungarian)
- [25] **Tamas Benko**, Katalin Koczka, Agnes Szanyi, Gabor Rezessy, Peter Mizsey, Zsolt Fonyó: Ecological evaluation of comparison of treatment options of non-ideal solvent mixtures, *CAPE Forum 2004*, Veszprém, 2004.
- [26] Szanyi Ágnes, **Benkő Tamás**, Koczka Katalin, Mizsey Péter, Mészáros Alajos, Borus Andor, Fonyó Zsolt: Oldószer Regenerálás Extraktív Heterogén-Azeotróp Desztillációval. *AWARENET, Szimpózium az Agrár- és Élelmiszeripari Hulladékok Csökkentésének Lehetőségeiről*, Budapesti Műszaki Egyetem, Budapest, 2003. (in Hungarian)

Oral lectures and presentations

- [12] **Benkő Tamás**, Az életciklus elemzés integrálása a környezettudatos folyamat-tervezésbe. *Magyar Kémikusok Egyesülete*, Budapest, 2007. (in Hungarian)
- [13] **Benkő Tamás**: Életciklus elemzés integrálása a környezettudatos folyamat-tervezésbe. *MIPOET Szimpózium*, Tótvázsony, 2007. (in Hungarian)
- [14] **Benkő Tamás**, Mizsey Péter, Füstgáz kéntmentesítés regionális hatásának és hatékonyságának vizsgálata a Kárpát-medencében. *Budapesti Műszaki és Gazdaságtudományi Egyetem Vegyészmérnöki Karának 4. Doktoráns Konferenciája*, Budapesti Műszaki és Gazdaságtudományi Egyetem, Budapest, 2007. (in Hungarian)
- [15] **Tamas Benko**, Daniela Jacob: Untersuchung des Atmosphärischen Kreislaufs von SO₂ und Weiteren Spurenelementen im Karpatenbecken. *DBU Seminar*, Hamburg, Germany, 2006. (in German)
- [16] **Tamas Benko**, Daniela Jacob: Untersuchung des atmosphärischen Kreislaufs von SO₂ im Karpatenbecken. *DBU Seminar*, Stapelfeld, Germany, 2006. (in German)
- [17] **Tamas Benko**, Daniela Jacob: Investigation of the Transboundary Atmospheric Transport of SO₂ in the Carpathian Basin. *IMPRS-ESM Retreat 2005*, Bremen, Germany, 2005.
- [18] **Tamas Benko**, Agnes Szanyi, Katalin Koczka, Peter Mizsey, Zsolt Fonyo: Environmental and Economical Evaluation and Comparison of Non-ideal Waste Solvent Treatment Options. *31st International Conference of Slovak Society of chemical Engineering*, Tatranské Matliare, Slovakia, 2004.
- [19] **Benkő Tamás**: Az életciklus elemzés integrálása a környezettudatos folyamattervezésbe. *Budapesti Műszaki és Gazdaságtudományi Egyetem Vegyészmérnöki Karának 2. Doktoráns Konferenciája*, Budapesti Műszaki és Gazdaságtudományi Egyetem, Budapest, 2004. (in Hungarian)
- [20] **Benkő Tamás**, Koczka Katalin, Szanyi Ágnes, Rezessy Gábor, Mizsey Péter, Fonyó Zsolt: Nemideális oldószerkelegyek hulladékkezelési lehetőségeinek környezetvédelmi és gazdaságossági elemzése. *Műszaki Kémiai Napok '04*, Veszprém, 2004. (in Hungarian)
- [21] Szanyi Ágnes, **Benkő Tamás**, Koczka Katalin, Mizsey Péter, Mészáros Alajos, Borus Andor, Fonyó Zsolt: Négykomponensű nemideális elegyek szétválasztása extraktív heteroazeotróp rektifikálással. *Műszaki Kémiai Napok '04*, Veszprém 2004. (in Hungarian)

1 INTRODUCTION

During the last decades, the need for environmentally-consciousness and the establishment of sustainable practices have become guiding principles in the milieu of chemical engineering. These new challenges for engineering are referred to as the 'fourth paradigm' of the chemical process design.

During process design there must be an objective function that enables designers to rank design alternatives. If environmentally-conscious design is to be performed, the design alternatives should be evaluated according to how they meet environmental targets. To realise such design action, however, quantitative environmental measures are sought.

Among other concepts and tools of the environmental management, Life Cycle Assessment (LCA) is the only standardized and thus widely-accepted tool currently used to assess the environmental loads of products and recently of industrial processes.

The Life Cycle Impact Assessment (LCIA), as a part of LCA, is the scientific technique for assessing the potential environmental impacts of industrial systems and their associated products.

Despite of the standardized structure of LCA, a lot of individual choices are allowed in the LCA, for instance, definition of system boundaries, or the selection of the impact assessment method applied for the environmental evaluation. No consensus has been reached by LCA experts on these points of the LCA till now, therefore, there are still a lot of open questions has to be considered and discussed in the environmentally-conscious process engineering.

2 AIMS OF THE WORK

The main motivation of this thesis work is to investigate the applicability of LCA in process engineering in order to support environmentally-conscious decision making.

The fact that the selection of the LCIA method for the LCA study is based on subjective, individual choices, and several types of LCIA methods are available which differ in the impact pathway approaches and impact indicators they use, the selection between them is often a difficult task.

According to this, two important and frequently applied environmental impact assessment methods are investigated under the consideration of their data uncertainties.

Moreover, two important types of environmental evaluation used in chemical engineering are investigated:

- The construction and design selection, where alternative technical solutions of a prescribed problem are compared. In this case, environmental performance is determined for continuous and consistent operational parameters of the alternative techniques.
- Environmentally-conscious process engineering, where the optimal operational parameters of the selected technical solution or process are determined in order to enable selection of the option with the lowest environmental load.

The applicability and suitability of LCA to this end is demonstrated on several case studies related to real environmental problems on the field of air pollution prevention and waste solvent treatment. In my work, the emphasis is laid on those numerical tools in LCIA which apply aggregated, single score impact indicators for the expression of the environmental impacts.

Conference papers

- [5] **Tamas Benko**, Katalin Koczka, Agnes Szanyi, Peter Mizsey, Zsolt Fonyo: Agreements and Contradictions in the Environmental and Economic Evaluation of Waste Solvent Treatment Options. *The 3rd International Conference of the International Society for Industrial Ecology, Royal Institute of Technology*. Stockholm, Sweden, 2005, pp96-97.
- [6] Tamás Benkő: Environmental Evaluation and Comparison of Waste Solvent Treatment Options. *Periodica Polytechnica Ser. Chem. Eng.* 49 (2005), pp31-32.
- [7] **Tamas Benko**, Katalin Koczka, Agnes Szanyi, Gabor Rezessy, Peter Mizsey, Zsolt Fonyo: Environmental and Economical Analysis and Evaluation of Solvent Treatment Processes. *CAPE Forum 2004*, Veszprém, 2004.
- [8] **Tamas Benko**, Agnes Szanyi, Katalin Koczka, Peter Mizsey, Zsolt Fonyo: Environmental and Economical Evaluation and Comparison of Non-ideal Waste Solvent Treatment Options. *Proceedings - 31st International Conference of Slovak Society of Chemical Engineering*, Tatranské Matliare, Slovakia, 2004, pp115.
- [9] **Benkő Tamás**, Koczka Katalin, Szanyi Ágnes, Rezessy Gábor, Mizsey Péter, Fonyó Zsolt: Nemideális oldószerkegyek hulladékkezelési lehetőségeinek környezetvédelmi és gazdaságossági elemzése. *Műszaki Kémiai Napok'04*, Veszprém, 2004, pp250-252. (in Hungarian)
- [10] Szanyi Ágnes, **Benkő Tamás**, Koczka Katalin, Mizsey Péter, Mészáros Alajos, Borus Andor, Fonyó Zsolt: Négykomponensű nemideális elegyek szétválasztása extraktív heteroazeotróp rektifikálással. *Műszaki Kémiai Napok'04*, Veszprém, 2004, pp 248-249. (in Hungarian)
- [11] Szanyi Ágnes, **Benkő Tamás**, Koczka Katalin, Mizsey Péter, Mészáros Alajos, Borus Andor, Fonyó Zsolt: Oldószer regenerálás extraktív heterogén-azeotróp desztillációval. *AWARENET, Szimpózium az Agrár- és Élelmiszeripari Hulladékok Csökkentésének Lehetőségeiről*, Budapesti Műszaki Egyetem, Budapest, 2003, pp47-50. (in Hungarian)

6 PUBLICATIONS

Papers published in scientific journals

- [1] **Tamas Benko**, Claas Teichmann, Peter Mizsey, Daniela Jacob: Regional Effects and Efficiency of Flue Gas Desulphurization in the Carpathian Basin. *Atmospheric Environment* 41 (2007), pp8500-8510. (IF: 2.630)
- [2] **Tamas Benko**, Peter Mizsey: Comparison of Flue Gas Desulphurization Processes Based on Life Cycle Assessment. *Periodica Polytechnica Ser. Chem. Eng.* 51 Vol. 2 (2007), pp 1-18.
- [3] Peter Mizsey, Luis Delgado, **Tamas Benko**: Comparison of Environmental Impact and External Cost Assessment Methods. *International Journal of Life Cycle Assessment* (2007), Accepted by reviewers. (IF: 1.483)
- [4] **Tamas Benko**, Agnes Szanyi, Peter Mizsey, Zolt Fonyo: Environmental and Economic Comparison of Waste Solvent Treatment Options. *Central European Journal of Chemistry* 4 (2006), pp92-110. (IF: 0.561)

According to this, the aims of the study can be outlined as follows:

1. Single score impact indicators of the two important and frequently-used environmental impact assessment methods - Eco-indicator 99 (EI-99) and the marginal damage values of the Clean Air for Europe Cost-benefit Analysis (CAFE CBA) - are investigated under the consideration of their data uncertainties in order to show where there are dependencies and similarities between them. If similarities and dependencies can be found that might help by the selection of the proper impact assessment tool form the numerous ones.
2. Investigation of data uncertainties of the two impact assessment methods (EI-99 and CAFE CBA) is detailed. The population of impact indicators which expresses the environmental impacts due to annual air pollution is generated by Monte Carlo simulations for five industrialized cities. Overall mean values of the impact indicator populations are determined and compared.
3. The impact assessment results are obtained from two different numerical approaches: most likely impact indicator values obtained form the uncertainty analysis, and the aggregated single score indicators (without uncertainty data) are determined for the five industrialized cities. Calculation results are compared.
4. The area of environmental problems due to air pollution in industrialized cities is selected for investigation. The single score impact assessment method is used in order to rank different air pollutants to help determine their sources.
5. The environmental performances of basically different flue gas desulphurization (FGD) processes: (1) intra-furnace sulphur removal during coal combustion with limestone addition, (2) FGD with wet-limestone

scrubbing, and (3) regenerative copper oxide flue gas clean-up process are determined with the help of LCA in order to support selection of the process type with the lowest environmental load.

6. The effect of supplementary installed FGD units at high capacity power plants on regional air pollution in the Carpathian Basin is investigated. The dispersion and accumulation of the SO₂ air pollutant are determined and studied with the regional three-dimensional on-line atmosphere-chemistry model REMOTE. Changes in the SO₂ air pollution are investigated by parallel simulations in a case study, where the single modified parameter is SO₂ removal rate
7. Based on an industrial case study, environmental and economic evaluations of treatment alternatives are completed and compared for a non-ideal solvent mixture containing azeotropes to determine the preferable option. For the recovery of the solvent mixture, two different separation alternatives are evaluated: a less effective alternative and a novel design based on hybrid separation tools. The third investigated waste solvent treatment alternative is incineration with heat utilization.

Such engineering areas are (i) proper application of single score LCIA methods, (ii) environmental evaluation of airborne emission inventories for the sake of identification and ranking of air pollutants and their sources according to their environmental loads, (iii) proper selection and design of FGD techniques, (iv) determination of their operation policy considering seasonal weather conditions, and (v) waste solvent treatment. My waste solvent treatment LCA research results also show the importance of accurate, environmental oriented process engineering practice.

My work helps to recognise the purposes where LCA can be applied and how much effort is needed for such evaluations, and what kind of problems have to be considered to come to the environmentally-conscious decisions and to the proper selection and operation of process alternatives.

Besides the efficiency of removal of SO₂, dispersion and accumulation also depend on seasonal weather conditions. During winter, dispersion and accumulation are by at least 25% higher than in other seasons. Due to this phenomenon, higher SO₂ removal efficiency is needed during winter to guarantee similar air quality to other seasons [1].

4.3 Application of Life Cycle Assessment: Waste Solvent Treatment

Thesis 7) Contradictions between environmental and economic evaluations are detected: economic appraisal clearly favours total recovery; however, an environmental evaluation shows that if a recovery process of low efficiency is applied, its environmental burden can be similar or even higher to that of incineration [4].

5 APPLICABILITY OF THE RESULTS

My thesis work belongs basically to the field of fundamental research; however, the obtained results can help engineers to orient on the emerging field of environmental conscious process engineering.

The detected correlation between the two impact assessment methods (EI-99 and CAFE CBA) can mutually support and strengthen each other's merits; moreover, it helps the investigation and development of both methods in the future and such activities can be co-ordinated. Moreover, my research results in this area can support the proper application of LCIA methods and the interpretation of their results under consideration of their uncertainties. On the other hand, these research results may assist stakeholders and policy makers in making better decisions for the sake of environmental protection.

Several practical examples are presented in different areas of process engineering about the proper integration and application of LCA into environmental conscious process design and operation.

3 APPLIED DATA AND METHODS

The main numerical environmental impact assessment tool applied in this study is the Eco-indicator 99 (EI-99) methodology which uses aggregated, single score impact indicators. *Hierarchist* and *Egalitarian* versions of the method are considered with custom weighing sets. Work with the impact indicators is supported by the software SimaPro.

In addition, the Cost-benefit Analysis environmental impact assessment tool of the European Union's CAFE Programme (CAFE CBA) is used and investigated. Different sets of CAFE CBA marginal damage values, the impact indicators of the method, are considered and investigated.

Investigation *a)* of the uncertainties, *b)* the assessment of the aggregated indicators with the highest probability, and *c)* the statistical calculations related to these problems are carried out by using Monte Carlo simulations.

According to the investigation of effectiveness and efficiency of air pollution abatement techniques, atmospheric transport of the pollutants is modelled and simulated. Simulations are carried out by the regional atmospheric model REMOTE coupled with the chemistry package RADM II.

4 MAJOR NEW RESULTS

4.1 Investigation of Environmental Impact Assessment Methods

Considering their Uncertainties

Thesis 1) Clear linear dependency between the single score impact indicators of the EI-99 and CAFE CBA methods. This indicates a similarity in the relative ranking features of the two impact assessment methods, and a strong connection and dependencies between them. It is revealed that the detected similarities in the relative environmental valuations of environmental impacts do not depend on the assumptions used in the calculations of the CAFE CBA marginal damage values [3].

Thesis 2) It is detected that propagation of data uncertainties of the investigated impact assessment methods (EI-99 and CAFE CBA) results in barely distinguishable and interpretable environmental impact indicator intervals at the 90% confidence level. On the other hand, strong correlation (R^2 higher than 0.95) is found between the most likely values (determined as overall mean values of the generated populations) of the impact indicator populations if the results of the two different LCIA tools are compared [3].

Thesis 3) The most likely impact indicator values obtained from the uncertainty analysis and the aggregated single score indicators (without uncertainty data) are compared on the same environmental problem. It is determined that the difference between LCIA results obtained under consideration and omission by them is less than 10%. This allows the application of the single score indicators (*best guesses* in the case of EI-99, and marginal damage values in the case of CAFE CBA) in order to obtain clear environmental preferences that would not be possible if full spectrums of single scores' uncertainties were included in the analysis [3].

Thesis 4) It is detected and demonstrated through a comprehensive case study referring to the environmental evaluation of the annual airborne emission inventory of an industrialized city that aggregated, single score impact indicators such as EI-99 can successfully be applied to identify and rank air pollutants and their sources according to their environmental loads [3].

4.2 Application of Life Cycle Assessment: Air Pollution

A.) Environmentally-conscious process design: selection of the proper air pollution abatement technique

Thesis 5) It is determined that the three FGD processes investigated can create less environmental impacts than the uncontrolled release of sulphur oxides into air. The reductions range between 80 and 92%.

The results show that intra-furnace limestone addition and the wet scrubbing processes, techniques using similar physical and chemical principles, have similar environmental indices; however, FGD with wet-limestone scrubbing is found to be slightly better from environmental viewpoint.

The basis of the regenerative process is a sorption-reduction-oxidation cycle that has higher SO₂ removal efficiency than the two other processes. This higher efficiency results in significantly lower environmental impacts. This means, that recovery and recycling of SO₂ is the most preferable option from an environmental viewpoint [2].

B.) Study of effectiveness of flue gas desulphurization at a regional scale

Thesis 6) It is found that FGD units operating with constant 90% SO₂ removal efficiency significantly reduce both the annual mean horizontal (by 79%) and vertical (by 66%) dispersion of emitted SO₂, as well as its transboundary transport.