Subject review – *Pregledni rad*

Life Cycle Assessment (LCA) in Forestry – State and Perspectives

Hans Rudolf Heinimann

Abstract – Nacrtak

Environmentally sound technologies are a key to reduce resource use and environmental impact. The paper reviews the state of knowledge of an analysis tool, life cycle assessment (LCA), by addressing three issues: 1) methodological foundations of LCA, 2) lifecycle inventory modeling, and 3) environmental performance indicators for wood supply systems. The study results in the following findings: 1) LCA is still not widely used and accepted in the forest operations engineering. 2) Only a few studies are based on state-of-the-art life cycle inventory analysis. 3) The boundaries of the studied systems are often too narrow, limiting comparability with standard LCA studies. 4) Most forest-related studies are based on direct process energy input only and are neglecting environmental burdens of upstream processes. 5) »Truncated LCAs«, neglecting embodied burdens of road infrastructure and forest machines always result in an underestimation of environmental impacts or an overestimation of environmental performance, respectively. There is a need for LCA capacity building in the forest operations community, on the basis of which forest-related LCA studies should become more comprehensive and comparable with studies of the core LCA community.

Keywords: LCA, environmental performance, wood supply, eco-efficiency, industrial ecology

1. Introduction – *Uvod*

There is a broad consensus that mankind has to explore and implement pathways of development that minimize resource use while reducing emissions, waste and impacts to structures and functions of the environmental system to »near zero«. Environmentally sound technologies (ESTs) were identified as a key to achieve this broad, long-term goal. ESTs encompass technologies that have the potential to significantly improve environmental performance, compared with other technologies (UNEP-IETC, online). Following the quote »what gets measured gets done«, which is attributed to Peter Drucker, there is a need to apply and improve environmental analysis tools to produce reliable, comprehensible environmental performance indicators. The development since the early 1990s led to a whole set of tools, such as 1) lifecycle assessment (LCA) for product systems (ISO 2006b), 2) regional material flow analysis for geographical regions (Hendriks et al. 2000), or 3) carbon budget models for large-scale geographical areas (Kurz et al. 2009). Those tools, designed for different contexts, are somewhat embedded in the umbrella concept of »industrial ecology«, which looks at industrial systems the same way as ecologists have been looking at ecosystems (Erkman 1997). The key issue is to understand, model and manage the »industrial metabolism«, particularly the flow of materials and energy, to continuously increase environmental performance (for the history of the industrial metabolism thinking, see (Fischer-Kowalski 1998 a, b)). The ideas go back to pioneers such as Robert Ayres (Ayres and Kneese 1969); Charles Hall (Hall et al. 1979); and Howard T. Odum (Odum et al. 1977), whose thoughts stimulated Ulf Sundberg, a forest operations engineering scholar, to perform some preliminary energy analysis studies of forest operations systems (Sundberg and Svanqvist 1987).

Forestry has been a traditional supplier of renewable raw materials for industrial use (sawmilling, pulp and paper, particle boards, etc.), for household fuel wood, particularly in the Third World, and increasingly for biofuels. From a production context point of view, LCA is a suitable tool to assess wood supply systems, because it was designed for product systems (ISO 2006b). Recent efforts fostering the development and deployment of energy systems that are based on the renewable resources should follow eco-efficient pathways, whose performance has to be based on comprehensive assessment methods. The present paper aims to critically review environmental performance assessment from a LCA-perspective. The paper looks at wood-based raw material pathways only, and also neglects production impacts on forest soils. Assuming that LCA has not been widely applied and accepted within the forest operations engineering, the paper first reviews the methodological foundation of LCA, then looks at the state of lifecycle inventory modeling, and finally synthesizes the state of knowledge on environmental performance indicators for wood product, forest road and bioenergy product systems.

2. LCA Methodology – *Metode analize životnoga ciklusa*

Although LCA was standardized at the beginning of the 1990s, the underlying methodology is not widely known and accepted within the forest science community. Therefore, it is useful to position LCA within the whole set of environmental tools, to explain the LCA framework, and to present the generic approach to model life cycle inventories in the following paragraphs.

2.1 Positioning of LCA within the set of environmental tools – *Položaj analize životnoga ciklusa unutar grupe alata za procjenu utjecaja na okoliš*

Life cycle assessment (LCA) is a method to quantify and improve our understanding of possible impacts associated with products aiming 1) to identify

Table 1 Positioning of LCA within set of environmental assessment and policy tools. LCA addresses the level of product systems by modeling the life cycle of a product

Tablica 1. *Položaj analize životnoga ciklusa unutar grupe alata okolišne politike i alata analize utjecaja na okoliš. Analiza životnoga ciklusa odnosi se na razinu sustava proizvoda, određujući životni ciklus proizvoda*

Level of Action *Razina djelovanja*	Definition – *Definicija*	Environmental Policy Tools *Alati okolišne politike*	Environmental Analysis Tools *Alati analize učinka na okoliš*
Policy *Politika*	A defined course of action, for guiding present and future decisions, as a result of a political weighting of interest *Definirane smjernice aktivnosti za donošenje sadašnjih i budućih odluka, a rezultat su političkoga interesa*	Strategic Environmental Assessment SEA *Strateška procjena okoliša* Sustainability Impact Assessment SIA *Procjena učinka na potrajnost*	
Program *Program*	A portfolio of actions, directed to a sectorial policy and usually allocating financial resources *Područje aktivnosti usmjereno na politiku sektora i dodjelu financijskih sredstava*		
Plan *Plan*	Localization and temporal definition how and with what priority public actions should be implemented *Lokaliziranje i privremeno definiranje aktivnosti koje će se i s kojim prioritetom provesti*		
Project (public) *Javni projekt*	A set of activities that is 1) limited in time, 2) directed to create a clearly defined output, 3) considering financial constraints, and 4) fulfilling quality requirements *Skup aktivnosti koji je 1) ograničen vremenom, 2) ima jasan zadatak, 3) ograničena financijska sredstva i 4) zadovoljava uvjete kakvoće*	Environmental Impact Assessment EIA *Procjena učinka na okoliš* Sustainability Impact Assessment SIA *Procjena učinka na potrajnost*	
Project (private) *Privatni projekt*			
Product System *Sustav proizvoda*	Collection of materially and energetically connected unit processes which perform one or more defined functions (ISO 14050) *Skup materijalnih i energetskih postupaka kojima se izvršava točno zadana zadaća (ISO 14050)*	Eco-Labeling *Ekoobilježavanje* Eco-Auditing *Ekoispitivanje*	Life Cycle Assessment LCA (E-LCA, S-LCA) *Procjena životnoga ciklusa*

opportunities for environmental performance improvement, 2) to inform industrial decision-makers on the development of products and on the design or redesign of manufacturing processes, 3) to select and quantify environmental performance indicators, and 4) to prove environmental soundness for eco-labels or environmental claims (ISO 2006a). However, LCA is embedded in a whole set of environmental tools (Table 1), and there is still some confusion about the purpose and scope of different tools and about which tool is most appropriate to tackle a specific problem.

The success of environmental policies, aiming to mitigate and limit exhaustive resource use, pollution and waste disposal, is only visible after actions affecting the environment have been implemented on the ground. A whole set of environmental tools was developed to foster a process of change, leading to environmentally more sound behavior. Table 1 presents an overview, organized along two dimensions. The first dimension represents the level of action, from policies to programs, projects and product systems, whereas the second dimension characterizes the type of tools: 1) analysis tools and 2) policy tools (Udo de Haes 1996a). Analysis tools address the quantification of eco-efficiency metrics, aiming at answering questions like »how does a package system perform compared to a new, alternative system«. Policy tools, on the other hand, are »instruments through which governments seek to influence citizen behavior and achieve policy purposes« (Schneider and Ingram 1990).

Strategic environmental assessment is a policy tool to influence environmental soundness of policies, programs and plans, whereas environmental impact assessment aims at improving the environmental soundness of projects (Anonymous 2002, 2009). The purpose of impact assessment is to ensure that environmental considerations are explicitly incorporated into the development decision-making process (Anonymous 1999, 2002, 2009); it therefore aims to influence the behavior of mainly public decision-makers, e.g. the authorities responsible to approve project proposals. Sustainability impact assessment has its origins in the family of environmental assessment processes (SEA and EIA) and reflects the »triple bottom line« approach to sustainability by concurrently assessing environmental, economic and social impacts of proposed interventions (Pope et al. 2004). Eco-labels and eco-auditing are two policy tools addressing to change the values and perceptions of consumers and producers, respectively. Eco-labeling is a statement, symbol or graphic that indicates an environmental aspect of a product, a component or packaging, whereas eco-auditing is a systematic verification process to determine where activities or management systems comply with normative standards (ISO 2002).

Lifecycle assessment began to emarge at the end of the 1960s when the Midwest Research Institute conducted a study on resource requirements, emissions and waste of different beverage containers for the Coca-Cola Company (Guinée et al. 2010). Similar studies followed in the US and in Switzerland, investigating environmental burdens of containers made of PVC, glass, sheet metal and cardboard. However, there was a lack of a common theoretical framework and of methodological consistency (different names were in use, such as »eco-balance« or »resource and energy production analysis«), affecting the comparability of results and preventing LCA to become an accepted analytical tool (Guinée et al. 2010). By the end of the 1980s, SETAC, the society of environmental toxicology and chemistry, took responsibility for the theoretical foundation and the standardization of LCA, which resulted in a code of practice (Consoli et al. 1993). In Europe, the two guidelines developed by the center of environmental science in the Netherlands (Heijungs 1992a, b) had a considerable impact on the LCA practice because they presented a mathematical framework to handle even huge sets of interrelated processes. The mathematical formalism is based on former work of (Ayres and Noble 1978; Koopmans 1951a, b). In 1994, ISO – international standards organization – started to develop the ISO 14000 standards series (Marsmann 1997), addressing all aspects of lifecycle management (ISO 2006a), particularly LCA principles and framework (ISO 2006b), LCA requirements and guidelines (ISO 2006c), LCA vocabulary (ISO 2002), and environmental performance evaluation (ISO 1999).

In 2002, SETAC together with UNEP – United Nations environment program – started the so-called lifecycle initiative (Guinée et al. 2010), aiming to foster lifecycle thinking and to integrate the »triple bottom line« (economic, social, and environmental) philosophy for goods and services. Lifecycle assessment, now called environmental lifecycle assessment – E-LCA has mainly been focusing on impacts on the natural environment, whereas lifecycle costing – LCC addresses the direct costs and benefits for people, planet and prosperity (UNEP and SETAC 2009). A tool to assess the impact of a product system on human well-being and corporate social responsibility was missing, and the lifecycle initiative resulted in framing and conceptualizing a new tool, social lifecycle assessment – S-LCA to fill this gap (UNEP and SETAC 2009). This broader, more holistic approach covers all aspects of the triple bottom line – people, planet, and prosperity

Table 2 Definition and positioning of LCA phases as defined by the ISO standard
Tablica 2. *Određivanje i pozicioniranje faza analize životnoga ciklusa, opisanih u normama ISO*

Phase – *Etapa*	Definition – *Opis*	Required knowledge *Potrebno znanje*
Goal and scope definition *Cilj i značaj definicije*	Goal definition, e.g. environmental performance comparison of alternative systems *Definicija cilja, npr. usporedba okolišne pogodnosti alternativnih sustava* Scope definition, particularly determination of 1) system boundaries, 2) functional unit. *Značaj definicije, poglavito određivanje 1) granica sustava, 2) funkcionalnih jedinica*	Systems theory *Teorija sustava*
Inventory analysis – LCI *Analiza zaliha – LCI*	Inventory modeling of input/output flows for specified product system(s) *Modeliranje ulaznih i izlaznih tokova za određeni proizvodni sustav*	Systems theory, process engineering *Teorija sustava, tehnike postupaka*
Impact assessment – LCIA *Procjena učinaka – LCIA*	Impact assessment: assignment of LCI results to specific impact categories *Procjena utjecaja: zadatak utjecaja životnoga ciklusa na određene kategorije*	Environmental science, Eco toxicology *Znanost o okolišu, Ekotoksikologija*
Interpretation Tumačenje	Conclusions and recommendations for process improvement. *Zaključci i prijedlozi za poboljšanje postupka*	Critical thinking – *Kritičko promišljanje* Decision making – *Odlučivanje*

– and is also called lifecycle sustainability analysis – LCSA (Guinée et al. 2010).

The standardization efforts triggered the introduction of LCA into forestry and forest industries. One of the fathers of LCA (Udo de Haes 1996b) presented the »bottlenecks« that primary production was facing, particularly the definition of the upstream system boundary and co-production, which require special allocation rules. At the same time a first conference was organized in Germany (Frühwald 1995), and the main LCA activities related to forest sector emerged in LCA pioneering countries (Guinée et al. 2010), such as the US, Sweden, Switzerland, Germany and Finland. The Nordic pulp and paper industry started an initiative to develop a joint methodology for lifecycle inventories for forest industry in 1993 (Kärnä and Ekvall 1997), resulting in the definition of parameters and units of measure and in a proposition of allocation rules. At the same time, the first LCA studies on forest operations and long-distance transportation of timber (Karjalainen and Asikainen 1996) and on eco-inventories of forest machines and processes (Berg 1995; Knechtle 1997; Zimmer and Wegener 1996) appeared, yielding operational performance indicators, particularly related to energy consumption and CO_2 emission. Harmonization efforts continued with the European COST-action »lifecycle assessment of forest and forest products«, which published the findings in 2001 (Karjalainen et al. 2001). Lifecycle inventories of forestry and forest industry processes started to be investigated systematically and entered into lifecycle-inventory databases, such as ecoinvent (ECOINVENT, online), or ProBas (PROBAS, online). A new wave of LCA-type studies for forest operations appeared after 2005, e.g. (Valente et al. 2011a; Valente et al. 2011b), probably triggered by the increasing interest in renewable energy. However, the stream of research seems somewhat to be delinked from the LCA community.

2.2 LCA framework – *Okosnica analize životnoga ciklusa*

The procedural LCA framework, consisting of 1) goal and scope definition, 2) inventory analysis, 3) impact assessment and 4) interpretation has been the foundation of LCA. Table 2 presents the four phases of LCA and the definition following the ISO 14,000 standards. There are two critical issues in scope definition, 1) the determination of system boundaries and 2) the definition of the functional unit. As we will show later, system boundaries are often not clear, particularly in the »upstream« direction. The environmental system has to be part of the analysis, characterized by input flows such as CO_2, solar energy, mineral resources and land (occupied and transformed). Inventory analyses consists of mapping the structure and functions of the product system, usually in the form of a process flow diagram that is the basis for the following modeling of materials, energy, emission and waste flows. Inventory analysis is the heart of LCA, taking a considerable amount of time and being extremely data intensive.

Lifecycle impact assessment assigns the result of inventory analysis to specific impact categories, such as depletion of nonrenewable and renewable resources, greenhouse effect, ozone depletion, human toxicity, acidification, etc. (Heijungs 1992b). Finally, lifecycle interpretation formulates conclusions and recommendations as to how the environmental performance of product systems may be improved, or what alternative of different product systems performs best.

2.3 Life Cycle inventory modeling of a product system – *Životni ciklus zaliha proizvodnoga sustava*

Inventory analysis consists of three major steps: first the identification of functions and flows of the product system; second, the quantification of flows; and third, the quantitative modeling of all flows converting into a specific set of output flows. The simplest approach, tabular balancing, is very limited to handle complex networks of flows, resulting in so-called »truncated« system inventories (Joshi 1999) that do not fulfill the cradle to grave requirement. Therefore, we will present the formal mathematical approach below, which to our knowledge is not well known in the forest science community, and illustrate it with a practical example.

Production economics provides a formal approach to investigate process networks or even economic sectors, which relies on two fundamental concepts: 1) commodities, and 2) activities (Koopmans 1951b, 1951c). An activity, also called a process, consists of a specific technology, which transforms specific input-flows into output-flows according to well-defined procedures. The mapping of process networks as flows on a graph has become an important approach to analyze environmental impacts (Koopmans 1951b, 1951c). Activities are represented as nodes, while arcs represent flows of goods, resources, emissions, and wastes. The resulting

Table 3 Flow of materials, equipment components and services into the functional unit – one productive machine hour PMH of a Stihl 026C chainsaw (Knechtle 1997). Source flows are positive, whereas sink flows are negative

Tablica 3. *Tok materijala, sastavni dijelovi i servis radne jedinice na temelju jednoga proizvodnoga sata Stihl 026C (Knechtle 1997). Ulazni su tokovi pozitivni, dok su izlazni negativni*

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}
Steel, high alloyed, kg *Visokolegirani čelik,* kg	1	0	0	0	0	0	–1.166	–1.06	–0.24	–0.35	0
Steel, non-alloyed, kg *Nelegirani čelik,* kg	0	1	0	0	0	0	–0.088	0	0	–0.026	0
Aluminum, kg *Aluminij,* kg	0	0	1	0	0	0	–2.268	0	0	–0.681	0
Plastic, kg *Plastika,* kg	0	0	0	1	0	0	–1.127	0	0	–0.338	0
Gasoline, kg *Gorivo,* kg	0	0	0	0	1	0	0	0	0	0	–1.245
Chainsaw oil, kg *Ulje za motornu pilu,* kg	0	0	0	0	0	1	0	0	0	0	–0.296
Manufacturing, unit *Proizvodnja, komada*	0	0	0	0	0	0	1	0	0	0	–8E-04
Guide bar, unit *Vodilica, komada*	0	0	0	0	0	0	0	1	0	0	–0.005
Chain, unit *Lanac, komada*	0	0	0	0	0	0	0	0	1	0	–0.017
Maintenance, unit *Održavanje, komada*	0	0	0	0	0	0	0	0	0	1	–8E-04
Chainsaw deployment, PMH *Rad motorne pile, radni sat*	0	0	0	0	0	0	0	0	0	0	1

graph is non-cyclic, directed, and finite. Additionally, several source nodes and sink nodes may exist, being located outside of the system's boundaries. This type of graph has also become known as GOZINTO-graph, following »the part that goes into« (Vazsonyi 1954).

Life-cycle assessment began to emerge in the late 1960's, when Ayres and Kneese published a paper on »production, consumption, and externalities« (Ayres and Kneese 1969). They started from the premise that the capacity of the environment to provide resources and assimilate emissions and waste has become scarce, and that there is a strong need to relief the concept of »free economic goods«, such as water, air, etc. Their guiding idea was that resource extraction and environmental pollution and its control is a »materials balance problem«. They formulated a mathematical approach to model the materials balance problem with an input-output approach, considering the products of photosynthesis and mineral resources as inputs, and CO_2 and waste as final outputs.

Flows on a graph may be represented by a system of linear equations, an example of which is presented in Table 3 for a Stihl 026C chainsaw from (Knechtle 1997). Each row represents the flow of a commodity from the source process (positive unit values) to sink processes (negative unit values).The first row represents the flow of high alloyed steel, of which –1.16 kg are flowing into the manufacturing process, –1.06 into the guide bar, –0.24 into the chain and –0.35 into maintenance (spare parts). Rows 2 to 11 follow the same representational logic, and the whole system is represented by 11 commodities (rows) flowing between 11 processes (columns). Assuming that each process can be scaled by a variable x_i, whereas $i = 1...11$ the system of 11 equations can be solved for X, whereas X is the vector (x_1,..., x_{11}), if the total system output Y is known. For Table 3, the elements of the output vector Y are 0, except for x_{11}, which is equal to one unity of the functional unit.

The 11×11 matrix of Table 3 defines the chainsaw technology and is called »technology matrix« A (Koopmans 1951b). A unique solution requires 1) a quadratic technology matrix A, and 2) a known balance of inflows and outflows for all commodities. In matrix notation, the equation system (1) of Table 3 is written as

$$A \cdot X = Y \tag{1}$$

Model analysis is complete, if we know the vector X. It can be found by solving matrix equation (1) for X (2).

$$X = A^{-1} \cdot Y \tag{2}$$

Equation (2) completely describes the flow of commodities for a specific process network. Assuming an output vector Y as below, equation (2) results in the following solution for X.

$$Y = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \qquad X = \begin{bmatrix} 1.10E-02 \\ 9.56E-05 \\ 2.46E-03 \\ 1.22E-03 \\ 1.25E+00 \\ 2.96E-01 \\ 8.33E-04 \\ 5.41E-03 \\ 1.67E-02 \\ 8.33E-04 \\ 1 \end{bmatrix}$$

The scaling vector X has the following meaning: x_5, gasoline consumption, means that 2.96 kg of gasoline are used for a productive machine hour PMH; x_1, consumption of high alloy steel, means that about 10 g of steel are consumed per PMH. However, the model just describes materials and energy flows, and it has to be enhanced to analyze the flows of environmental burdens. There is a well-documented approach (Koopmans 1951b; 1951c) that assumes the flow of commodities to be proportional to the flow of environmental burdens (linearity assumptions). A single type of environmental burden may be represented by a vector B, which has the same length as the scaling vector X. Table 4 presents eight environmental burden vectors, written as rows. The burdens of materials and energy carriers were taken from ecoinvent (ECOINVENT, online), whereas the burden associated with chainsaw deployment (x_{11}) characterizes the engine-specific emission profile of a two-stroke engine. The x_7 to x_{10} processes do not have direct burdens, but are used to logically link the flows.

The figures in Table 4 define the so-called burden matrix B, which by multiplication with the scaling vector X results in the burden vector b of the total system (3), resulting in the following values for the Stihl 026C example.

$$b = B \cdot X \tag{3}$$

$$B = \begin{bmatrix} 16.1 \\ 65.8 \\ 4.79 \\ 0.29 \\ 0.01 \\ 0.17 \\ 0.01 \\ 0.01 \end{bmatrix} \qquad \begin{bmatrix} E_{emb} \\ E_{proc} \\ CO_2 \\ CO \\ CH_4 \\ HC \\ NO_x \\ SO \end{bmatrix}$$

Table 4 Environmental burden matrix *B* for the Stihl 026C chainsaw. The figures for x_1 to x_6 were taken from the ecoinvent database (ECOINVENT, online) (grey shaded), whereas the values for x_{11} characterize the combustion process in the 2-stroke engine (dark shaded)

Tablica 4. B *matrica okolišnoga opterećenja motorne pile Stihl 026C. Izvor je podataka* x_1 *do* x_6 *baza Ecoinvent, dok je vrijednost* x_{11} *rad dvotaktnoga motora*

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}
Embodied energy, MJ *Ugrađena energija,* MJ	109.7	33.3	231.4	93.32	9.216	9.21	0	0	0	0	0
Process energy, MJ *Utrošak energ. pri radu*	0	0	0	0	42.7	42.7	0	0	0	0	0
CO_2, kg	5.282	1.614	9.964	3.229	0.505	0.503	0	0	0	0	3.926
CO, kg	0.029	0.03	0.004	0.001	9E-04	9E-04	0	0	0	0	0.285
CH_4, kg	0.016	0.009	0.022	0.008	0.004	0.004	0	0	0	0	2E-04
HC, kg	0.005	0.001	0.011	0.011	0.009	0.009	0	0	0	0	0.16
NO_x, kg	0.01	0.003	0.02	0.007	0.003	0.003	0	0	0	0	0.004
SO_x, kg	0.343	0.005	0.058	0.019	0.003	0.003	0	0	0	0	0.001
	Imported from Ecoinvent (2012) – *Izvor Ecoinvent (2012)*						No direct burden *Bez izravnoga opterećenja*				Engine combustion *Sagorijevanje*

The use of a productive machine hour PMH of a chainsaw consumes 65.8 MJ of process energy, 16.1 MJ of embodied energy, and emits 4.79 kg of CO_2, 0.29 kg of CO and 0.17 kg of HC. This chainsaw specific burden vector B can be reused for the analysis of production systems, which contribute to comparability of results.

3. State of Modeling Approaches – *Pristupi modeliranja*

3.1 Conceptual Models – *Konceptualni modeli*

Life cycle inventory analysis has to be based on a conceptual model that defines the building blocks of analysis from »cradle to grave«. The author proposed a conceptual model that is presented in Fig. 1 (Heinimann et al. 2006). Product systems are hierarchically organized. The highest level of organization is the product system level (Fig. 1, level 2, right), consisting of a network of humans, machinery and facilities. The underlying level consists of machines, made of different kinds of materials during the manufacturing process. Combustion engines have been the backbone of forest machinery and the quality of the combustion process is crucial for all subsequent results. Machines consume resources through maintenance, which should also be considered in the analysis process. The materials of which a machine is manufactured embody environmental burdens that have to be considered to fulfill their »cradle to grave« requirement. Environmental burdens of materials are documented in databases, such as ecoinvent (ECOINVENT, online).

The ecoinvent database contains international industrial life cycle inventory data on energy supply, resource extraction, material supply, chemicals, metals, agriculture, waste management services, and transport services. It is used by about 4’500 users in more than 40 countries worldwide and is included in the leading LCA software tools as well as in various eco-design tools for building and construction, waste management or product design (ECOINVENT, online). Similar databases are spine@cpm (SPINE@CPM, online), ELCD (ELCD, online), or ProBas (PROBAS, online).

Fig. 2 presents the product system for solid wood production, as represented in the ecoinvent database (Werner et al. 2007). The first function, biomass growth, consists of three input flows from the environment, the capture of solar energy, the sequestration of CO_2, and land occupation. The second function, forest management, has three input flows, too, energy input (diesel combustion), the use of gravel for road maintenance, and the conversion of forest land into industrial land, which is caused by the area occupied by forest roads. The third function, harvesting, has two input flows, energy input (diesel combustion) and chainsaw use (in PMH).

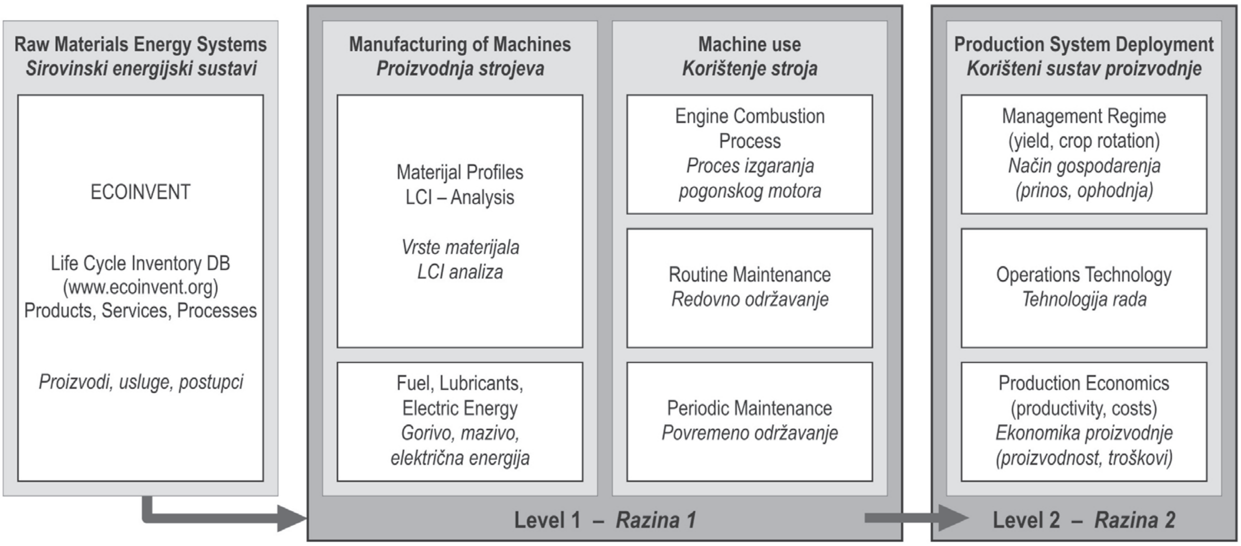

Fig. 1 Components of the framework of life cycle inventory analysis (Heinimann et al. 2006). Recycling of materials, such as steel is assumed to be included in raw material burdens

Slika 1. *Dijelovi okvira analize zaliha životnoga ciklusa. Recikliranje materijala, poput čelika, pretpostavlja se da ulazi u granice sirovih materijala*

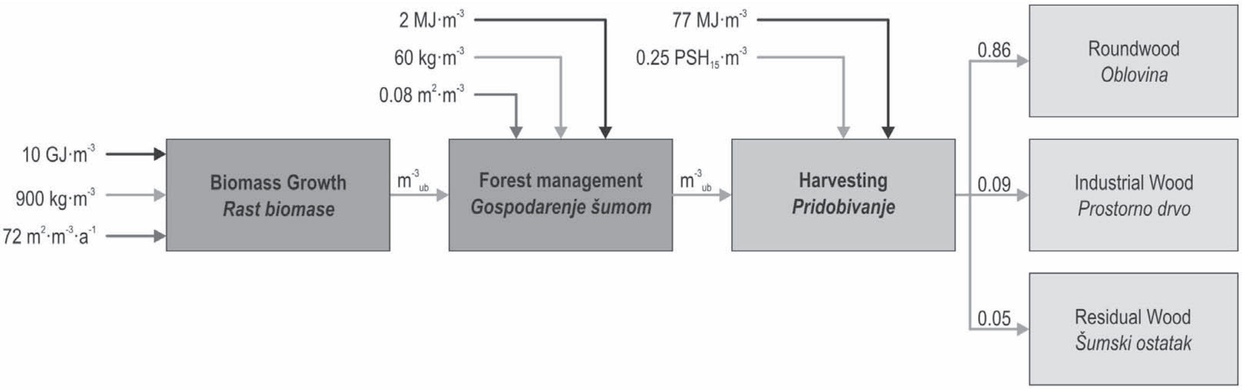

Fig. 2 Conceptual mapping of energy, material and area flow for wood product systems (Werner et al. 2007)

Slika 2. *Konceptualno kartiranje tokova energije, materijala i područja u proizvodnji drva (Werner i dr. 2007)*

The harvesting function is a typical case of co-production, which is a term for multiple products coming out of one function (ISO 2002). Co-production requires rules as to how to allocate upstream environmental burdens to a set of products, which is often done proportionally to the economic value of the output products. In the ecoinvent database, the allocation factors are 0.86 for roundwood, 0.09 for industrial wood, and 0.05 for residual wood. The nature of allocation factors is normative, and there is no right or wrong solution to this problem. The re-presentation in ecoinvent does not fully comply with the »cradle to grave« requirement that would request to include environmental burdens that are embodied in forest machines, tools, and in forest roads. Taking into account these shortcomings, (Heinimann et al. 2006; Knechtle 1997) eco-inventories for forest machines and for the construction and maintenance of forest roads were modeled.

4. State of environmental performance knowledge – *Stanje znanja o okolišnoj učinkovitosti*

The selection and quantification of operational performance indicators (OPIs) is a main purpose of LCA (ISO 2006a). OPIs are indicators to measure and compare eco-efficiency (Huppes and Ishikawa 2007), which is a relationship between resource consumption, emitted pollutants or deposed waste per a unity of the functional unit. Materials-related indicators are the mass of materials, or the quantity of water used per product unit, which is e.g. a performance indicator for pulp product systems. Energy-related OPIs specify the quantity of energy used per product unit, and emission-related OPIs the mass of specific emissions per product unit (ISO 1999). Below, we present two typical OPIs, energy consumption and CO_2 emission per functional unit, as reported in the scientific literature.

4.1 OPIs for solid wood product systems – *Pokazatelji ekološke učinkovitosti za drvne proizvode*

Table 5 presents OPIs for the »solid wood product system«. A first problem that we encountered during the screening of the literature was that the system boundaries were either not clearly specified or differing across studies. The upstream boundary should include the environmental system (Udo de Haes 1996b) as represented in the ecoinvent model (Fig. 2). However, some of the studies start with the forest management function (see Fig. 2), whereas others seem to consider the harvesting function only. In the Nordic countries, the downstream boundary is usually at the mill gate, whereas in Central European studies, the boundary is at the forest road. Considering the early findings of (Karjalainen and Asikainen 1996) that about two third of the environmental burden of the forest to mill product system are caused by road construction and long distance transport, it would make sense to report two separate OPIs, one for forest management and harvesting, and the other one for long distance transportation, including road infrastructure. A second problem that we encountered was the fact that most of the forestry studies were of level 2 only (see Fig. 1), considering only direct materials and energy consumptions during system deployment and neglecting embodied environmental burdens of upstream functions. According to (Knechtle 1997), the embodied energy in machines like harvesters and forwarders equals to about 40 to 50% of the direct process energy. The higher emission values from the eco-in-

Table 5 Energy input and CO_2 output for harvesting operations. The underlying harvesting systems are of harvester-forwarder type, with a motor-manual system for ecoinvent

Tablica 5. *Utrošak energije i emisija CO_2 pri pridobivanju drva sustavom harvester – forvarder, osim u slučaju »Ecoivent« gdje je u pitanju ručno-strojni rad*

Source – *Izvor*	CO_2 (kg m^{-3}_{ub})	Energy – *Energija* (MJ m^{-3}_{ub})	Level – *Razina*	
			2	1+2
Ecoinvent 2012	12.4[1]	4.07 kg crude oil *4,07* kg *sirove nafte*		x
ProBas 2012	17.9[2]	50[1]		x
SPINE@COM 2012		57	x	
Berg 1997	2.4	–	x	
González-García et al. 2009, Spain[3,4]	~22	~90	x	
González-García et al. 2009, Sweden[3,4]	~14	~40	x	
Karjalainen and Asikainen 1996[3]	6.4	–	x	
Knechtle 1999[3]	7.4	110		x
Lindholm 2006[3]	5.9	63–66	x	
Schwaiger and Zimmer 2001	2.4–4.3	36	x	
Valente et al. 2011[3]	4.4	52	x	

[1] road maintenance included – *uključeno održavanje cesta*

[2] functional unit: 1 kg, conversion with 0.007 m3 per kg – *funkcionalna jedinica 1* kg*, pretvorba s 0,007* m^3 *po kg*

[3] without silvicultural operations – *bez uzgojnih radova*

[4] including transport to mill – *uključujući prijevoz do pilane*

ventory databases (Table 5) (ECOINVENT, online, PROBAS, online) may also be explained by the embodied burden.

Median values of the studies reported in Table 2 are about 7.5 kg $CO_2 \cdot m^{-3}_{ub}$ and about 60 $MJ \cdot m^{-3}_{ub}$, both with considerable variability and uncertainty. There is a need to improve the quality and comparability of future studies by standardizing the definition of system boundaries for the solid wood production system and by defining and investigating identical flows. This has to be achieved on the conceptual level, as illustrated in Fig. 2.

4.2 OPIs for the construction and maintenance of forest roads – *Pokazatelji ekološke učinkovitosti pri gradnji i održavanju šumskih cesta*

Taking the evidence that about 60% of the overall environmental burdens of forest production are caused by road network infrastructure and long-distance transport (Karjalainen and Asikainen 1996; Winkler 1997; Heinimann 1999) as a starting point, Heinimann and Maeda-Inaba (2004) presented an LCA study that followed the conceptual approach presented in Fig. 1, performing both level 1 and level 2 analysis and using eco-inventories for materials and energy carriers from ecoinvent (ECOINVENT, online). Table 6 presents a summary of the results.

On moderate slopes up to 40 percent, construction of one unit length (m) of forest road consumes about 350 MJ of energy while emitting about 20 kg of greenhouse gases. This amount of energy consumption is equivalent to the heating value of about 10 l of diesel fuel, and about 10 kg of wood mass that has to be grown to sequestrate the amount emitted greenhouse gas. Transport distance of base course materials is the most sensitive factor of influence. Compared to on-site preparation of aggregates, a 50-kilometer transport increases energy consumption by a factor of about five. Slope demonstrated to be the second important factor that shows a nonlinear influence on energy consumption and greenhouse gas emissions. Increasing slope to about 50 percent, doubles energy consumption and greenhouse gas emissions, while a slope of 70 percent almost triples them. Roadbed width is the third factor of influence. Energy consumption doubles by increasing it from 4.2 m to 6.2 m.

Assuming a life cycle of a forest road of 40 years, a road density of 25 m ha^{-1}, an average yield of 10 $m^3 ha^{-1} a^{-1}$, and allocating the OPIs of Table 6 to the functional unit (m^3_{ub}) of the wood product system results in an amount of embodied energy of 20–40 MJ m^{-3}, which is considerable, compared to the energy input of harvesting operations (Table 5). If the annual yield is lowered to about 5 $m^3 ha^{-1} a^{-1}$, the road-induced embodied energy reaches the same order of magnitude as the impact of the product system itself. These findings illustrate that neglecting the forest road infrastructure results in a considerable overestimation of environmenttal performance, particularly for low-yield forests and for difficult terrain.

4.3 OPIs for truck transport systems – *Pokazatelji ekološke učinkovitosti pri prijevozu drva kamionima*

Road transportation with trucks has been the main mode for long-distance hauling. Allowable gross vehicle mass (GVM) was standardized within the European Union, defining the following limits for trucks: 2-axle 18 tons, 3-axle 26 tons, 4-axle 32 tons, and 5-axle 38 tons. Typical configurations for timber transport are a 3-axle motor vehicle plus 2- or 3-axle trailer with a GVM of 40 tons, and a 3-axle motor vehicle plus 4-axle trailer with a GVM of 60 tons in the Nordic countries.

Table 6 Energy input and CO_2 output for the construction and maintenance of forest roads. Functional unit: 1 m of road length. Assumptions: (1) roadbed width of 4.2 m, (2) cut slope angle of 1:1, (3) fill slope angle of 4:5, (4) base course thickness of 0.3 m, (5) surface course thickness of 0.08 m, and (6) base course materials transport distance of 10 kilometers, (6) increasing rock excavation on slopes steeper than 50%

Tablica 6. *Utrošak energije i emisija CO_2 prilikom gradnje 1 m šumske ceste širine planuma od 4,2 m, nagiba usjeka 1 : 1, nagiba nasipa 4 : 5, debljine donjega stroja 0,3 m, debljine gornjega stroja 0,08 m, s prijevozom građevnoga materijala na udaljenost od 10 km i povećan iskop materijala na nagibima > 50 %*

Terrain conditions – *Terenski uvjeti*	CO_2 (kg m^{-1})	Energy – *Energija* (MJ m^{-1})	Level 2 *Razina 2*	Level 1+2 *Razina 1+2*
Slope >10% – *Nagib >10 %*	19	315	x	–
Slope ~ 40% – *Nagib ~ 40 %*	25	405	x	–
Slope ~60% – *Nagib ~ 60 %*	47	735	x	–

Table 7 gives an overview of energy input and CO_2 emissions for these two configurations.

The German Pro Bas database (PROBAS, online) provides the most up-to-date eco-inventories for truck transportation, considering euro-5 emission standards, however, without figures for 60 ton configurations. The Swedish Spine database (SPINE@CPM) provides figures for 60 ton configurations, which are based on analysis work done in the late 1990s. Forest-specific figures are only available for Sweden (Lindholm and Berg 2005) and for Finland (Karjalainen and Asikainen 1996), whereas some results, e.g. (Valente et al. 2011b), are not comparable. The ProBas data illustrate that environmental performance depends on the traffic mode (highway, over land, in the city), yielding an increasing gradient from highway to in the city transport. The Swedish data (Lindholm and Berg 2005) give a preliminary hint that timber haulage has its own, forest-specific traffic mode (in the forest, over land, highway) that is not well understood, but probably results in burdens that are close to the »in the city« mode. Assuming a 40 ton configuration, over land mode, and a timber load of 28 m^3 yields an energy consumption of about 0.55 MJ $m^{-3}{}_{ub}$. Compared to an average energy input of 60 MJ $m^{-3}{}_{ub}$ (Table 5), a road transport distance of about 100 km results in an environmental burden of the same order of magnitude as from the harvesting process, however, neglecting the embodied energy of the forest road infrastructure (see Table 6), which adds between 20 and 40 MJ $m^{-3}{}_{ub}$ (see 4.2).

4.4 Environmental performance of bioenergy product systems – *Okolišna učinkovitost sustava za proizvodnju bioenergije*

IEA (2011, 2012), assumed that low-carbon technologies would contribute to the reduction of greenhouse gas emission. There are several bioenergy pathways (Fig. 3), 1) biomass in unprocessed form such as firewood, forest residues; 2) biomass intermediates, such as pellets or biomethane from manure or landfill; 3) first-generation biofuels, made of seed, grain, or sugar; 4) second-generation biofuels, manufactured from lignocellulosic biomass, and 5) third-generation bio fuels, manufactured from algae or seaweeds (IEA 2011, IEA 2012, Nigam and Singh 2011). Environmental performance, particularly CO_2- and energy-efficiency, is a decisive criterion to choose the best course of action for future biomass-based energy supply.

Comparability of results of environmental performance assessment requires first a clear definition of system boundaries, and second, an agreement on the functional unit, which is used to normalize the results. System boundaries should be of a »well to plant« for wood chips, »well to stove« for pellets, and »well to wheel« type for biofuels. As a consequence, functional units should be defined as a unit of energy produced in a plant or stove (MJ), or a unit of transportation service produced (t·km, person·km). The screening of the LCA literature for forest fuel supply indicates that system boundaries are far too narrow, particularly in the downstream direction, and the functional unit is, in most cases, defined in traditional forestry units, such as bulk volume, bulk mass, solid timber volume, etc.

The key question still is what technology route out of the possibilities outlined in Fig. 3 is most cost-effective and most environmentally performing. The EIA technology roadmap hypothesizes that the following

Table 7 Energy input and CO_2 output for long-distance truck transportation
Tablica 7. *Utrošak energije i emisija CO_2 pri daljinskom transport drva kamionima*

Source – *Izvor*	Gross vehicle mass, t *Masa vozila*, t	Load capacity, t *Masa tovara*, t	Emission standard *Standardi emisije*	CO_2 ($kg \cdot t^{-3} \cdot km^{-1}$)	Energy ($MJ \cdot t^{-3} \cdot km^{-1}$)
ProBas 2012 (over land, no highway – *izvan autoceste*)	40	24	Euro 5	0.057	0.67
ProBas 2012 (highway – *autocesta*)	40	24	Euro 5	0.050	0.59
ProBas 2012 (in the city – *gradska vožnja*)	40	24	Euro 5	0.084	0.99
SPINE@COM 2012	40	26	Euro 2	0.050	0.68
SPINE@COM 2012	60	40	Euro 2	0.041	0.57
Karjalainen and Asikainen 1996	60	40	?	0.038	–
Lindholm and Berg 2005	60	40	?	–	0.99

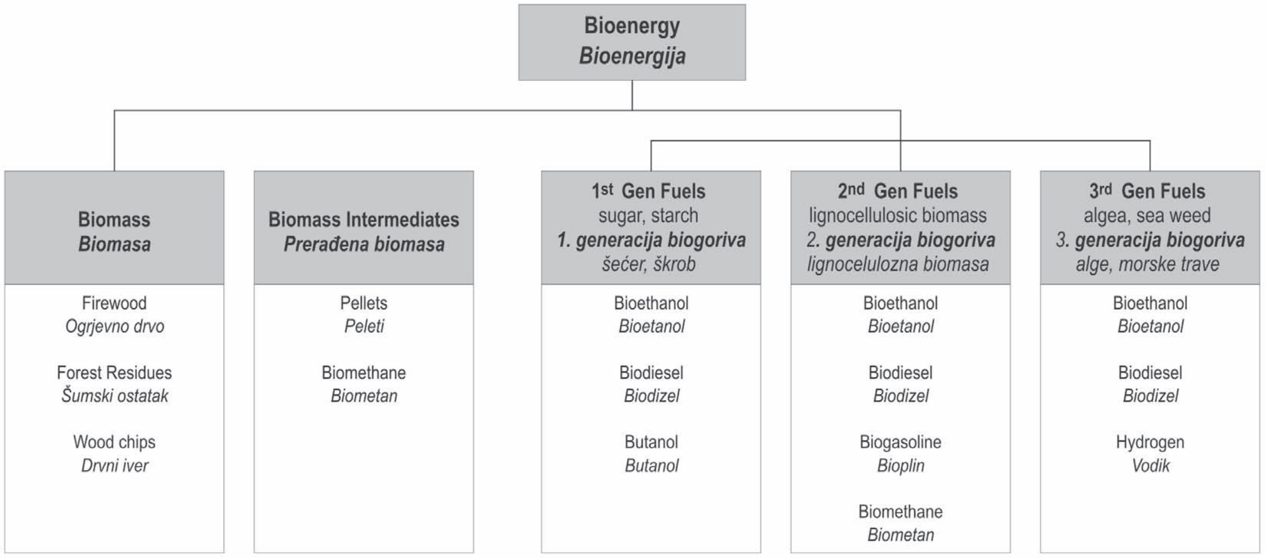

Fig. 3 Classification of Biofuels (Nigam and Singh 2011), modified
Slika 3. *Podjela biogoriva (modificirano prema Nigam i Singh 2011)*

bioenergy systems are the most promising: 1) the replacement of traditional biomass by advanced biomass cook stoves and household biogas systems, 2) cogenerating heat-power plants CHP (IEA 2012). EIA hypothesizes that advanced biofuels, such as cellulosic ethanol, advanced biodiesel, bio-syntactic gas BSG from lignocellulosic biomass or algae are more cost-and eco-efficient than first generation biofuels made of sugar and starch (Cherubini et al. 2009). A review paper (Cherubini et al. 2009) assesses the state of knowledge of different technology pathways. The authors conclude that the available studies indicate that electricity or heat generation of biomass have a better environmental performance than biofuels, and that bioenergy chains based on the waste and residue raw materials outperform chains based on dedicated crops. They also mentioned that the »cascading« use of biomass (e.g. first use as building material, followed by use for fiber, followed by energetic use) have the potential to further enhance greenhouse gas savings. A recent LCA-study (Stucki and Jungbluth 2012) on second-generation biofuels presents evidence that systems based on molasse, waste oil glycerine and purified biogas performed best with an amount of CO_2-emissions of about 120 g pkm^{-1}, whereas oil-based diesel and gasoline emit about 180 g pkm^{-1} and 200 g pkm^{-1}, respectively. However, there are still considerable challenges (Cherubini et al. 2011), particularly methodological inconsistencies due to the selection of different system boundaries, alternative approaches to estimate greenhouse gas emissions, or alternative allocation rules. The authors also stress that an increasing number of LCA-studies on lignocellulosic biomass, sugarcane, or palm oil is available, whereas contributions on promising feedstocks, such as algae, or advanced biomass processing are still scarce.

There are still interesting forestry short rotation crops, usually based on willow or poplar (Björeson 2006; Göranson 2009; Gyuricza et al. 2011). A comparison of alternative bioenergy cropping systems (Adler et al. 2007) showed that systems based on corn, soybean, and alfalfa outperformed a poplar-based system in terms of CO_2 emissions by a factor of about 1.5.

A study comparing two pellet production systems (sawdust, chips) (Heinimann et al. 2007) resulted in the finding that chip-based supply systems outperform sawdust-based systems in terms of energy efficiency, carbon dioxide emission, eco-toxicity, and particle emissions (PM10) caused by higher moisture content of sawdust. The pellet manufacturing process, consisting of raw materials supply, pellet manufacturing, and pellet distribution, caused about 60 to 80% of the total energy input. The drying process is the most important step of pellet manufacturing with a share of 60 to 80%, and therefore offering potential for efficiency improvement by using e.g. superheated steam dryer technology.

IEA technology roadmaps (IEA 2011, IEA 2012) stress that alternative bioenergy pathways require raw material supply chains that are tailored to the end use and optimized for both economic and eco-efficiency.

However, to our knowledge, there are no comprehensive LCA-studies available that investigate supply chains tailored to specific bioenergy pathways as illustrated in Fig. 3. Available studies on supply chains are limited in scope, as they investigate the process energy use only, and calculate the emissions due to engine combustion with rules of thumb. Therefore, there is a strong need to do further research on biomass supply chains for different bioenergy pathways (Valente et al. 2011a; Valente et al. 2011b).

5. Conclusions – *Zaključci*

The guiding idea of LCA is to improve our understanding of the impacts of alternative product systems on the environment and to quantify environmental performance indicators, characterizing the contribution of products to the main environmental risks. The present contribution reviewed the state of LCA-related research for product systems with forest biomass as raw material.

The study resulted in the following findings. 1) Whereas LCA-methodology is looking back on about thirty years of experience, it is still not widely used and accepted within the forest operations engineering research community. 2) Only a few forest-related LCA-studies are based on a quantitative, mathematical stringent methodology that uses systems of linear equations to characterize and model commodity, energy, and substance flows from »cradle to grave«. 3) Although LCA is following a »well to use« philosophy, many forest related LCA-studies are based on quite narrow system boundaries, and on forest-specific functional units, thus limiting the comparability with state-of-the-art LCA-studies. 4) Most of the forest-related LCA-studies are based on direct process energy consumption, measured as fuel consumption, and emission figures that are calculated from fuel consumption by general assumptions. 5) »Truncated LCAs«, neglecting embedded environmental burdens of machines and forest road infrastructure, results in an underestimation of environmental impacts of forest product systems.

Whereas environmental analysis tools seem to converge, for example by bringing exergy analysis, which is a traditional field in process engineering, together with LCA-methodology (Hau 2002; Hau and Bakshi 2004), a new, forest-specific research stream has been emerging, sustainability impact assessment of wood supply chains, for which a specific, made-to-purpose software tool was developed, ToSIA (Lindner et al. 2012). This new initiative seems not to be well linked to sustainability impact assessment (SIA) that emerged out of the strategic impact assessment (SIA) and environmental impact assessment (EIA) traditions, being designed as policy, and not as analysis tools. Additionally, it is only weakly linked to the ongoing lifecycle management initiative, which addresses the »triple bottom line« with three tools: environmental lifecycle assessment (E-LCA), social lifecycle assessment (S-LCA), and lifecycle costing (LCC) (UNEP and SETAC 2009).

The study has several implications for the forest operations research community. First, it has to invest in capacity building to better understand mainstream lifecycle assessment methodology. Second, there is a strong need to develop standards for system boundaries and functional units of typical bioenergy pathways (see for example Fig. 3), which is the basis to improve the comparability of future studies. Third, lifecycle inventories for road construction, road maintenance and road transportation need to be updated because previous studies demonstrated that long-distance transportation and forest road infrastructure account for about two third of the total impact for typical forest productivity systems (Heinimann and Maeda-Inaba 2004; Karjalainen and Asikainen 1996). And forth, future lifecycle inventories have to be linked to LCI databases, such as Ecoinvent (ECOINVENT, online), ProBas (PROBAS, online), etc., to account for materials and energy systems of very upstream processes like the manufacturing of machines. And fifth, future studies should provide information on the standards for the assessment of compliance of machine engines, e.g. Tier 1 to Tier 4 standards in the US (DIESELNET, online-b), Stage I to IV for the European Union (DIESELNET, online-a), because there is a considerable decrease of allowable emission with increasing Tier and Stage.

6. References – *Literatura*

Adler, P. R., Grosso, S. J. D., Parton, W. J., 2007: Life-cycle assessment of net greenhouse-gas flux for bioenergy cropping systems. Ecological Applications 17(3): 675–691.

Anon., 1999: Principles of Environmental Impact Assessment Best Practice. IAIA special publications. Accessed [Feb-04-2012]. [http://www.iaia.org/publicdocuments/specialublications/Principles%20of%20IA_web.pdf]

Anon., 2002: Strategic Environmental Assessment. Performance Criteria. IAIA Special Publication Series, (1). Accessed [Feb-04-2012]. [http://www.iaia.org/publicdocuments/special-publications/sp1.pdf]

Anon., 2009: What is Impact Assessment? IAIA special publications. Accessed [Feb-04-2012]. [http://www.iaia.org/publicdocuments/special-publications/What%20is%20IA_web.pdf]

Ayres, R. U., Kneese, A. V., 1969: Production, consumption, and externalities. The American Economic Review 59(3): 282–297.

Ayres, R. U., Noble, S. B., 1978: Materials/energy accounting and forecasting models. In Resources, environment, and economics, R. U. Ayres, Editor. John Wiley & Sons: New York, etc.: p. 95–125.

Berg, S., 1995: The environmental load of fossil fuels in Swedish forestry-an inventory for a LCA. In LCA–a challenge for forestry and forest products industry, eds. Frühwald, A. and Solberg, B., p. 57–65, Hamburg. European Forest Institute.

Berg, S., 1997: Some aspects of LCA in the analysis of forestry operations. Journal of Cleaner Production 5(3): 211–217.

Björeson, P., 2006: Livscykelanalys av Salixproduktion, Lunds University, Luns Tekniska Hôgskola. Lund. Master Thesis, 21 p.

Cherubini, F., Bird, N. D., Cowie, A., Jungmeier, G., Schlamadinger, B., Woess-Gallasch, S., 2009: Energy-and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations. Resources, Conservation and Recycling 53(8): 434–447.

Cherubini, F., Strømman, A. H., Hertwich, E., 2011: Effects of boreal forest management practices on the climate impact of CO_2 emissions from bioenergy. Ecological Modelling 223: 59–66.

Consoli, F., Allen, D., Boustead I., Fava, J., Franklin, W., Jensen, A., De Oude, N., Parrish, R., Perriman, R., Postelthwaite, D., 1993: Guidelines for life-cycle assessment: a »Code of Practice«. Society of Environmental Toxicology and Chemistry (SETAC).

Dieselnet, 2012a: Emission Standards – European Union – Nonroad Diesel Engines. [Accessed Aug-30-2012. Available from www: [http://www.dieselnet.com/standards/eu/nonroad.php]

Dieselnet, 2012b: Emission Standards – United States – Nonroad Diesel Engines. [Accessed Aug-30-2012. Available from www: [http://www.dieselnet.com/standards/us/nonroad.php]

Ecoinvent, 2012: Ecoinvent – Swiss Centre for Life Cycle Inventories. ['Accessed' Aug-30-2012]. [www.ecoinvent.org]

ELCD, 2012: European Reference Life Cycle Database. ['Accessed' Aug-30-2012]. [www.ecoinvent.org]

Erkman, S., 1997: Industrial ecology: an historical view. Journal of Cleaner Production 5(1): 1–10.

Fischer-Kowalski, M., 1998a: Society's Metabolism. The Intellectual History of Materials Flow Analysis, Part I, 1860–1970. Journal of Industrial Ecology 2(1): 61–78.

Fischer-Kowalski, M., 1998b: Society's Metabolism. The Intellectual History of Materials Flow Analysis, Part II, 1970–1998. Journal of Industrial Ecology 2(4): 107–136.

Frühwald, A., 1995: LCA–a challenge for forestry and forest products industry. In LCA–a challenge for forestry and forest products industry, eds. Frühwald, A. and Solberg, B., p. 9–14. Hamburg. European Forest Institute.

González-García, S., Berg, S., Feijoo, G., Moreira, M. T., 2009: Environmental impacts of forest production and supply of pulpwood: Spanish and Swedish case studies. The International Journal of Life Cycle Assessment 14(4): 340–353.

Göranson, M., 2009: LCA of transport fuels from short rotation forestry in a long term perspective. Department of Energy and Environment, Division of Environmental Systems Analysis, Chalmers University of Technology, Göteborg, Master Thesis, 56 p.

Guinée, J. B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall, T., Rydberg, T., 2010: Life Cycle Assessment: Past, Present, and Future. Environmental science & technology 45(1): 90–96.

Gyuricza, C., Hegyesi, J., Kohlheb, N., 2011: Experience of energy willow (*Salix* sp.) production in short rotation coppice (SRC) experiment and results of life cycle analysis (LCA). Növénytermelés 60(2): 45–65.

Hall, C., Lavine, M., Sloane, J., 1979: Efficiency of energy delivery systems: I. An economic and energy analysis. Environmental Management 3(6): 493–504.

Hau, J. L., 2002: Integrating life cycle assessment, exergy and emergy analyses. Department of Chemical Engineering, Ohio State University, Master Thesis, 142 p.

Hau, J. L., Bakshi, B. R., 2004: Promise and problems of emergy analysis. Ecological Modelling 178(1): 215–225.

Heijungs, R., 1992a: Environmental life cycle assessment of products: backgrounds [transl. from Dutch]. Leiden NL: Centrum voor Milieukunde, 130 p.

Heijungs, R., 1992b: Environmental life cycle assessment of products: guide [transl. from Dutch]. Leiden NL: Centrum voor Milieukunde, 96 p.

Heinimann, H. R., Haessig, J., Wollenmann, R. A., 2007: Eco-Efficiency of Pellet Production – Comparison of Log Wood and Sawmill Byproduct Systems. In Austro2007/FORMEC. Meeting the Needs of Tomorrows Forests – New Developments in Forest Engineering, eds. Steinmuller, T. and Stampfer, K., Vienna. Forest Engineering Institute, University of Applied Life Sciences BOKU, Vienna, Austria.

Heinimann, H. R., Maeda-Inaba, S., 2004: Environmental Performance Indicators EPIs for Forest Roads Network Systems. In 2004 International Mountain Logging Conference. A joint FERIC, UBC, and IUFRO D3 conference, eds. Hedin, I. B. and Krag, R., published on CD. Vancouver, BC, Canada. Forest Engineering Research Institute of Canada, FERIC.

Heinimann, H. R., Wollenmann, R. A., Knechtle, N., 2006: Environmental Performance Analysis of Forest and Agricultural Production Systems. In Life cycle approaches for Conservation Agriculture. SETAC-Europe 16th Annual Meeting, eds. Guinée, J., et al., 156. The Hague, Netherlands, May 08, 2006. Department of Industrial Ecology & Department of Environmental Biology.

Hendriks, C., Obernosterer, R., Müller, D., Kytzia, S., Baccini, P., Brunner, P. H., 2000: Material flow analysis: A tool to support environmental policy decision making. Case-studies on the city of Vienna and the Swiss lowlands. Local Environment 5(3): 311–328.

Huppes, G., Ishikawa, M., 2007: Quantified eco-efficiency. An introduction with applications. Eco-efficiency in industry and science. Dordrecht: Springer, 330 p.

IEA, 2011: Technology Roadmap. Biofuels for Transport. ['Accessed' Aug-30-2012]. [http://www.iea.org/papers/2011/biofuels_roadmap.pdf]

IEA, 2012: Technology Roadmap. Bioenergy for Heat and Power. ['Accessed' Aug-30-2012]. [http://www.iea.org/publications/freepublications/publication/2012_Bioenergy_Roadmap_2nd_Edition_WEB.pdf]

ISO 1999: ISO 14031 Environmental management – Environmental performance evaluation – Guidelines. Geneva: ISO, 32 p.

ISO 2002: ISO 14050 Environmental management – Vocabulary. Geneva: ISO, 29 p.

ISO 2006a: ISO 14001 Environmental management – Life cycle assessment – Principles and framework (2nd ed.). Geneva: ISO, 29 p.

ISO 2006b: ISO 14040 Environmental management – Life cycle assessment – Principles and framework (2nd ed.). Geneva: ISO, 20 p.

ISO 2006c: ISO 14044 Environmental management – Life cycle assessment – Requirements and guidelines. Geneva: ISO, 46 p.

Joshi, S., 1999: Product Environmental Life – Cycle Assessment Using Input – Output Techniques. Journal of Industrial Ecology 3(2–3): 95–120.

Karjalainen, T., Apneseth, T., Esser, P., Finér, L., Jungmeier, G., Košir, B., Kvist, K. E., Roda, J. M., Schaiger, H., Berg, S., Zimmer, B., Welling, J., 2001: Identification of problems using case studies. In Energy, Carbon and Other Material Flows in the Life Cycle Assessment of Forestry and Forest Products. Achievements of the Working Group 1 of the COST Action E9Discussion Paper 10]. EFI, European Forest Institute.

Karjalainen, T., Asikainen, A., 1996: Greenhouse gas emissions from the use of primary energy in forest operations and long-distance transportation of timber in Finland. Forestry 69(3): 215–228.

Kärnä, A., Ekvall, T., 1997: Guidelines on life cycle inventory analysis in the Nordic pulp and paper industry. Paperi Ja Puu – Paper and Timber 79(2): 83–85.

Knechtle, N., 1997: Materialprofile von Holzerntesystemen – Analyse ausgewählter Beispiele als Grundlage für ein forstechnisches Ökoinventar. [Material profiles of harvesting systems – analysis of selected cases as a foundation of an eco-inventory for forest operations]. Department of Forest Sciences, ETH Zurich, Diploma Thesis, 66 p.

Knechtle, N., 1999: Materialprofile von Holzerntesystemen als Ausgangspunkt für Ökoinventare. Schweizerische Zeitschrift für Forstwesen 150(3): 81–87.

Koopmans, T. C., 1951a: Activity analysis of production and allocation, Cowles Foundation Monograph. Vol. 13. Yale University Press: New Haven, London, 404 p.

Koopmans, T. C., 1951b: Analysis of production as an efficient combination of activities. In Activity Analysis of Production and Allocation, Koopmans, T.C., Editor. Yale University Press: New Haven, London: p. 33–97.

Koopmans, T. C., 1951c: Introduction. In Activity Analysis of Production and Allocation, Koopmans, T.C., Editor. Yale University Press: New Haven, London: p. 1–12.

Kurz, W., Dymond, C., White, T., Stinson, G., Shaw, C., Rampley, G., Smyth, C., Simpson, B., Neilson, E., Trofymow, J., 2009: CBM-CFS3: a model of carbon-dynamics in forestry and land-use change implementing IPCC standards. Ecological Modelling 220(4): 480–504.

Lindholm, E. L., 2006: Energy Use in Swedish Forestry and its Environmental Impact. Department of Biometry and Engineering, Swedish University of Agricultural Sciences Uppsala, SE, Licenciate Thesis, 28+10+11+8 p.

Lindholm, E. L., Berg, S., 2005: Energy requirement and environmental impact in timber transport. Scandinavian Journal of Forest Research 20(2): 184–191.

Linder, M., Werhahn-Mees, W., Suominen, T., Vötter, D., Zudin, S., Pekkanen, M., Päivinen, R., Roubalova, M., Kneblik, P., Brüchert, F., 2012: Conducting sustainability impact assessments of forestry-wood chains: examples of ToSIA applications. European Journal of Forest Research 131(1): 21–34.

Marsmann, M., 1997: Current LCA-ISO Activities. International Journal of Life-Cycle Assessment 2(1).

Nigam, P. S., Singh, A., 2011: Production of liquid biofuels from renewable resources. Progress in energy and combustion science 37(1): 52–68.

Odum, H. T., Kemp, W., Sell, M., Boynton, W., Lehman, M., 1977: Energy analysis and the coupling of man and estuaries. Environmental Management 1(4): 297–315.

Pope, J., Annandale, D., Morrison-Saunders, A., 2004: Conceptualising sustainability assessment. Environmental Impact Assessment Review 24(6): 595–616.

ProBas, 2012. Prozessorientierte Datenbasis für Umweltmanagement-Instrumente. [‚Accessed' Aug-30-2012]. [http://www.probas.umweltbundesamt.de/]

Schneider, A., Ingram, H., 1990: Behavioral assumptions of policy tools. Journal of Politics 52(2): 510–529.

Schwaiger, H., Zimmer, B., 2001: A comparison of fuel consumption and greenhouse gas emissions from forest operations in Europe. In Energy, Carbon and Other Material Flows in the Life Cycle Assessment of Forestry and Forest Products. Achievements of the Working Group 1 of the COST Action E9Discussion Paper 10]. EFI, European Forest Institute.

SPINE@CPM, 2012: CPM Life Cycle Inventory Data. [‚Accessed' Aug-30-2012]. [http://cpmdatabase.cpm.chalmers.se/]

Stucki, M., Jungbluth, N., 2012: LCA of biogas from different purchased substrates and energy crops. Accessed [Aug-30-2012]. [http://www.lcaforum.ch/portals/0/df47/DF47-01%20Stucki.pdf]

Sundberg, U., Svanvist, N., 1987: Fuel consumption as indicator of the economics in mechanization. Scandinavian Journal of Forest Research 2(1-4): 389–398.

Udo de Haes, H., 1996a: Discussion of general principles and guidelines for practical use. In Towards a methodology for life cycle impact assessment, Udo de Haes, H., Editor. Society of Environmental Toxicology and Chemistry: Brussels: p. 7–30.

Ude de Haes, H., 1996b: LCA: Approaches and bottlenecks when applied to agriculture, food and forestry. CML, NL, Leiden.

UNEP-IETC, 2012: What are environmentally sound technologies (ESTs)? [Accessed Aug-30-2012. United Nations Environment Program. International Environmental Technology Centre. Available from www: [http://www.unep.org/ietc/WhatareESTs/tabid/56309/Default.aspx]

UNEP and SETAC, 2009: Guidelines for Social Life Cycle Assessment of Products. [,Accessed' Aug-30-2012]. [http://www.unep.fr/shared/publications/pdf/DTIx1164xPA-guidelines_sLCA.pdf]

Valente, C., Hillring, B. G., Solberg, B., 2011a: Bioenergy from mountain forest: a life cycle assessment of the Norwegian woody biomass supply chain. Scandinavian Journal of Forest Research 26(5): 429–436.

Valente, C., Spinelli R., Hillring, B. G., 2011b: LCA of environmental and socio-economic impacts related to wood energy production in alpine conditions: Valle di Fiemme (Italy). Journal of Cleaner Production 19: 1931–1938.

Vazsonyi, A., 1954: The Use of Mathematics in Production and Inventory Control. Management Science 1(1): 70–85.

Werner, F., Althaus, H. J., Künniger, T., Richter, K., 2007: Life Cycle Inventories of Wood as Fuel and Construction Materials. ecoinvent report. 9. Accessed [Aug-30-2012]. [http://db.ecoinvent.org/ecoquery/files/09_WoodFuelConstruction.pdf?area=463ee7e58cbf8]

Zimmer, B., Wegener, G., 1996: Stoff-und Energieflüsse vom Forst zum Sägewerk. European Journal of Wood and Wood Products 54(4): 217–223.

Sažetak

Analiza životnoga ciklusa u šumarstvu – stanje i perspektiva

Okolišno prihvatljive tehnologije ključne su za smanjenje potrošnje ograničenih resursa i smanjenje utjecaja na okoliš. U radu je opisano stanje poznavanja analitičkoga alata i analize životnoga ciklusa uz razradu triju problema: 1) metodološke postavke analize životnoga ciklusa, 2) modeliranja zaliha životnoga ciklusa i 3) pokazatelja okolišne učinkovitosti pri proizvodnji drva. Rezultati istraživanja ogledaju se u sljedećim nalazima: 1) Analiza životnoga ciklusa nema široku primjenu u šumarskoj zajednici. 2) Samo je nekoliko istraživanja napravljeno temeljem najsuvremenijih analiza zaliha životnoga ciklusa. 3) Postavljene granice istraživanja često su preuske, što smanjuje mogućnost usporedbe s uobičajenim istraživanjima životnoga ciklusa. 4) Većina se istraživanja analize životnoga ciklusa u šumarstvu zasniva samo na izravnom utrošku energije te time zanemaruje opterećenje okoliša daljinjim postupcima. 5) Takva »skraćena« analiza životnoga ciklusa zanemarivanjem opterećenja koja nastaju gradnjom šumskih cesta i uporabom šumskih vozila podcjenjuje učinak na okoliš ili precjenjuje okolišnu učinkovitost. U šumarstvu je potrebno dodatno razviti analizu životnoga ciklusa kako bi buduća istraživanja bila što obuhvatnija i kako bi se što lakše mogla usporediti s osnovnim istraživanjima analize životnoga ciklusa.

Ključne riječi: analiza životnoga ciklusa, okolišna učinkovitost, proizvodnja drva, ekološka učinkovitost, industrijska ekologija

Author's address – *Autorova adresa:*

Prof. Hans Rudolf Heinimann, PhD.
e-mail: hans.heinimann@env.ethz.ch
Institute of Terrestrial Ecosystems
Department of Environmental Systems
ETH Zürich
Universitätsstrasse 22
8092 Zurich
SWITZERLAND

Received (*Primljeno*): July 14, 2012
Accepted (*Prihvaćeno*): September 14, 2012