BUILDING TECHNOLOGY
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Environmental Impact of Coated Exterior Wooden Cladding

Preface

Technology Development Centre (TEKES), Akzo Nobel Deco Oy, Rohm and Haas Nordiska Ab, Finnish Wood Research Ltd, Teknos-Winter Oy, Tikkurila Paints Oy and Uula-Tuote Oy started with a co-operation of VTT Building Technology a project "Environmental Impact of Coated Exterior Wooden Cladding" in 1996. The project was included in the programme "Environmental technology in construction" funded by TEKES.

Mr Antero Liusvaara (UPM-Kymmene Oy) first acted as a chairman of a management group and he was followed by Mr Aarni Metsä (Finnish Wood Research Ltd). Other members of the management group were Mr Ilmari Absetz and Mr Arto Räty (TEKES). Ms Hilkka Teljo-Tuominen (Akzo Nobel Deco Oy), Mr Juha Ilomäki (Rohm and Haas Nordiska Ab), Mr Timo Pöljö (FW International), Mr Ismo Heinonen (Vapo Oy), Mr Jari Schneider (Teknos-Winter Oy), Mr Ilkka Sarvimäki followed by Ms Seija Varila (Tikkurila Paints Oy) and Mr Jouni Uunila (Uula-Tuote Oy). Moreover, industry representatives have actively participated in the project group which has enabled to obtain data on environmental impacts. Members of the project group were Ms Hilkka Teljo-Tuominen, Ms Seija Varila, Mr Rolf Widlund (Teknos-Winter Oy) and Mr Jouni Uunila together with the authors.

We thank all the members of the management and project groups. Their contribution has enabled to complete the project.

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Abstract

The life cycle inventory (LCI) process is generally understood as an evaluation of the environmental burdens associated with a product system by identifying and quantitatively or qualitatively describing the energy and materials used and wastes released into the environment. When the results are used for comparing products or product systems, the comparison should always be based on equivalent functional units. With reference to building products, this means that it is crucial to pay attention to the service life of product systems.

The objective of the study was to outline the service life systematics of coated exterior claddings in connection to environmental assessment. The functional unit in the LCI was one square metre of coated exterior cladding during a 100 year service life in outdoor exposure in Finland. The inventory covered production of coating raw materials and coatings, all transportation, application, maintenance and renewal of the coating during the 100 years including recycling and final disposal.

The studied formulations of priming oils, primers, undercoats and topcoats were designed by the paint manufacturers participating in the research. The 13 water-borne and solvent-borne model formulations were based on average proportions of the coating constituents used in commercial products. 15 opaque and semi-transparent coating systems were formed by means of these formulations.

A criterion to maintenance coating was defined as incipient flaking and in the case of the wood stains and the barn red paint as erosion. A coating used in maintenance was determined as one coat of the same topcoat as the previous coating. A maintenance interval of 10 or 15 years was defined for the opaque coating systems. A maintenance period of wood stains was 5 years. Surface preparation prior to maintenance painting was defined as mechanical scraping of the paint film and as washing the coating surface with hypochlorite solution, rinsing and drying. In assessing impacts of the removal of old coating film, IR-method, sand blasting and new cladding were considered as alternative methods.

Based on the described systematics, the alternative coating systems within the time frame of 100 years were studied and compared to each other. The differences with regard to environmental burdens between the systems were three fold in maximum, with the exception of VOC-emissions where the differences were roughly 100 fold in maximum. The differences are mainly caused by the different coating components in coatings systems. The environmental advantages of the acrylic coating systems are the low VOC emissions. However, the other studied environmental burdens were highest in the acrylic systems within the studied coating systems. In addition to the composition of the coating system, also the predicted service life would significantly affect the results. The method of paint removal had no significant effect on the results according to the studied model.

In order to minimise environmental burdens of wood coatings, various factors like coating formulations and weather resistance and their optimisation should be considered.

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1 EVALUATION OF THE ENVIRONMENTAL IMPACT OF BUILDING PRODUCTS ON THE BASIS OF LIFE CYCLE ASSESSMENT

1.1 Ecologically sustainable development

The maintenance of biodiversity in nature and adaptation of man's actions to natural resources and to nature's tolerance ability are generally considered the cornerstones of ecologically sustainable development [1]. If we examine the assessment of building in the same light, the basic ecological criteria of the development and choice of building products and buildings seem to be the possible impacts on nature's biodiversity, birth of hazardous emissions and waste of natural resources.

1.2 Evaluation of environmental impact

Life cycle assessment means defining the potential environmental effect of a product or function considering all the environmental burdens that are caused by raw material acquisition until the use and final disposal of the product. Life cycle assessment is based on data concerning energy and material inputs in the manufacture, use and disposal of the product and data concerning emissions and waste caused by the processes. Environmental burdens caused by building are e.g. the waste of energy and raw material resources and emissions hazardous to health and environment, such as carbon and sulphur dioxide and nitric oxide. Potential environmental effects are e.g. hazardous changes in the environment caused potentially by environmental burdens like the impact of carbon dioxide emissions on the warming of the climate and the impact of sulphur and nitric oxides on acidification.

According to the Nordic Guidelines on Life Cycle Assessment, life cycle assessment includes target setting, inventory analysis and impact assessment [2] [3] [4]. Impact assessment includes classification of burdens according to their potential impact and characterisation or weighting on the basis of impact potential. The end result can be normalised or valuated. In normalisation potential impacts are compared with reference values. The approximate total impact in a certain area, e.g. in Europe is generally chosen as the reference value. The result of an inventory is sometimes valuated directly. In this case environmental burdens like carbon dioxide and nitric oxide emissions are valuated with each other. However, valuation across categories or issues is an optional part of an overall interpretation of a study. It is impossible to conduct a scientific comparison of different categories. Social and organizational value judgments must be applied. It is also necessary that valuation procedures are explicit and transparent, and that these are seen as separate from classification and characterization [5]. In many cases it is enough to examine the environmental burdens of the product or function in

[1] Sustainable development. Measures during the following few years in Finland and in Finnish international cooperation projects. The Finnish committee on sustainable development. 1995. Helsinki 208 p.
[2] Nordic Guidelines on Life Cycle Assessment. Nord 1995:20, 222 p.
[3] LCA-NORDIC, Technical Reports No. 10 and Special Reports Nos. 1-2. TemaNord 1995:503. Copenhagen. 102 p.
[4] LCA-NORDIC, Technical Reports Nos. 1-9. TemaNord 1995:502. Copenhagen. 150 p.
[5] Life-Cycle Impact assessment: The state-of-the-Art. 2nd edition. SETAC (Society of Environmental Toxicology and Chemistry). Florida, USA. 1997, 1998. 145 pp.

question, i.e. the waste of resources and hazardous emissions. In this case only the first part of life cycle assessment, i.e. the inventory phase, is implemented.

Life cycle assessment often aims at defining the birth of those hazardous environmental burdens having potential impact on the following environmental effects:

- climate change,
- acidification,
- nutrification,
- development of photochemical oxidants,
- ozone depletion,
- health hazards, and
- environmental hazard (ecotoxicity).

Sometimes also other factors are considered, such as the impact of noise and smell on health at work and at home. As to the waste of resources life cycle assessment always takes into consideration the waste of the raw materials for energy, sometimes also the waste of other materials and the use of land and water. In life cycle assessment the use of land can either be handled as use of resources or in accordance with the ecological effects caused by the use.

In life cycle inventory the data gathered and handled may change in quality according to the examination target. The data can consist of the implemented material and energy flows of a certain production plant, average values of different production plants or those of the best or weakest technologies. Life cycle assessment aims at defining all considerable raw material flows of the system. No material flows probably having a considerable impact on the energy content of the system or on hazardous emissions caused can be left undefined.

In practice there are, however, system boundaries in life cycle inventory. The boundaries are defined according to the demands of the target. Nordic Guidelines on Life Cycle Assessment [6] include a list of the facts normally left outside examination. Among these facts we find e.g. the creation of infrastructure, accidents, human resources and environmental burdens caused by the workforce. The end result of life cycle assessment is influenced considerably not only by system boundaries, but also by the allocation of environmental burdens caused by the processes to different products born in connection of the same process. According to the Nordic Guidelines on LCA the factors constituting the allocation basis in order of importance are:

- natural causality,
- economic causality, or
- some other physical parameter.

The ISO standard on life cycle inventory [7] suggests a measure of trying to avoid the allocation by dividing the process into sub-processes. In practice allocation is mostly based on a mass of co-products or on an economic value.

In life cycle assessment the energy resources can be classified into renewable and non-renewable resources. The target is to define the total waste of the energy resource caused

[6] Nordic Guidelines on Life Cycle Assessment. Nord 1995:20, 222 p.
[7] ISO 14041 Environmental management. Life cycle assessment. Goal and scope definition and inventory analysis. 1998

during the whole life cycle of the product. Also electric energy used in the processes should be included in the Nordic Guidelines on LCA according to the energy content of the different kind of energies used for the production of electricity. In the end results of life cycle assessment one of the most essential facts is whether the energy value includes the heating value of the raw materials of the product. Both SETAC's Code of Practice [8] and the Nordic Guidelines on LCA recommend that the feedstock energy of the product and its raw materials are included in the total energy content.

As a result of the inventory phase of life cycle assessment we get a list of hazardous emissions and waste of resources caused during the whole life cycle of the system under examination. As a result of the evaluation of the impacts we get an estimate on the potential environmental impacts of the product. The meaning of the normalisation of the result or the valuation is the effort to express the result by one figure. The difficulty of the valuation is in the lack of generally accepted principles concerning the harmfulness of different environmental burdens or the seriousness of the environmental impacts caused by them.

Life cycle impact assessment focuses on relative comparisons of systems using a functional unit approach. The comparative measures are resource use and emission loadings in relation to possible environmental issues. However, it does not deal with actual impacts or risks. Environmental impact assessment and risk assessment work with absolute measures such as actual concentrations. These techniques address actual events and environmental concentrations and are often used to estimate the likelihood or probability of specific events [9].

Life cycle assessment method is developed to serve as a tool for decision making. When the results are used for comparing different products or product systems, the comparison should always be based on equivalent functional units. The method is very suitable for assisting product development and product design. However, the method can also be used as help for focusing goals and targets when environmental management systems are created. The results of life cycle assessment also give basic data for environmental declarations of products. The data received with the aid of life cycle assessment is not suitable as such to be used in consumers' decision making. This is because of plenty of information and issues to take into account. However, the results from life cycle assessment should be made use of, when creating environmental labelling criteria for products.

1.3 Standards and guidelines on life cycle assessment

The following ISO standard proposals have been made on the framework and first phase of life cycle assessment (CD = Committee Draft):

- ISO 14040: Environmental Management . Life cycle assessment. Principles and Framework,

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[8] Guidelines for Life Cycle Assessment: A Code for Practice, Edition 1. From the workshop held at Sesimbra, Portugal 31.3 – 3.41993 Ed. By Consoli, F. et al. Published by SETAC (Society of Environmental Toxicology and Chemistry).

[9] Life-Cycle Impact assessment: The state-of-the-Art. 2nd edition. SETAC (Society of Environmental Toxicology and Chemistry). Florida, USA. 1997, 1998. 145 pp.

- ISO 14041: Environmental Management. Life cycle assessment. Goal and scope definition and inventory analysis.
- ISO CD 14042: Environmental Management. Life cycle assessment. Impact assessment, and
- ISO CD 14043: Environmental Management. Life cycle assessment. Interpretation.

Other methods and guidelines widely accepted in the Nordic countries or Europe are:

- The Swiss "Ökopunkte"-method is one of the first holistic LCA-applications [10].
- The CLM-method is a method developed by the Dutch University of Leiden the greatest merit of which is particularly the development of the methods of impact evaluation [11].
- "Nordic Guidelines on LCA" is the LCA guide published by Scandinavian research scientists and consultants [12].
- The Swedish EPS-method (Environment Priority Strategies) aims at developing an LCA-method particularly supporting product development [13].
- The EDIP-method (Environmental Design of Industrial Products) is an LCA-method developed by a group of research scientists of the Technical University of Denmark [14].
- "Eco-balance methodology" [15] is a series of life cycle assessments of the products of the plastic industry ordered by PWMI (European Centre for Plastics in the Environment).

All the above methods follow the same framework of life cycle assessment. The essential differences of the methods concern the handling principles of the environmental burdens in the inventory, i.e. the classification and characterisation, valuation or normalisation.

1.4 Life cycle assessment of building products

The environmental properties of building products depend on the material and energy flow and use of land during the entire life cycle. The ecological criteria and the basic methodologies to assess the environmental impacts of building products should be in accordance with the generally accepted guidelines.

The environmental impact of building products come from the use of resources and inducing harmful emissions during:
- the extraction of raw materials,
- production processes,
- transportation,

[10] Ahbe, S. Braunschweig, A. & Müller-Venk, R. Methodik für Ökobilanzen auf der basis ökologischer Optimierung, Bundesamt der Umwelt, Walt und Landschaft (BUWAL), Schriftenreihe Umwelt No. 133, Bern 1990.
[11] Heijungs, R. Environmental life cycle assessment of products, Volume 1: Guide, Volume 2: Backgrounds. Center for environmental science (CML) University of Leiden, the Netherlands 1992.
[12] Nordic Guidelines on Life Cycle Assessment. Nord. 1995:20. Nordic council of ministers, Copenhagen 1995.
[13] Ryding, S.O. Environment-oriented product development. Förlags AB Industrial literature, Stockholm 1995.
[14] Wenzel, H. Hauschild, M. & Alting, L. Environmental Assessment of Products, Vol. 1: Methodology, tools and case studies in product development. Chapman & Hall. 1997. 543 p.
[15] Eco-balance methodology for commodity thermoplastics. Ian Boustead. PWMI, European Centre for Plastics in the Environment. Brussels 1992. 25 p.

- assembling and building,
- use and maintenance,
- demolition, and
- final disposal or recycling.

However, the environmental quality of building products does not only depend on the material and energy flows connected to the production and use of the product, but also on the length of the service life. When comparing the LCAs of building products to those of other products attention should be paid to the special characteristics of building products, first being the long service life of building products. Because of the long service life of building components a significant part of the environmental burdens of building components occurs many years after the production process. Thus the following items should be taken into account in an LCA of a building product:

- prediction of service life,
- future environmental burdens (due to care, maintenance and final disposal),
- potential reuse or recycling of building components after the service life.

By the initiation of the Finnish Building Industry Association, a research project was carried out that aimed at the formulation of environmental declaration of building products. Attention was paid on the "life cycle responsibility" of the producers with respect to the products. That means that the environmental declaration of building products should not only include the ecological parameters of the production stage, but also guidance given by the producer concerning the environmentally harmless use, demolishing, recycling and final disposal of the products (Table 1.1). The suggested principles for environmental assessment of building products are listed in Table 1.2. The project report includes the environmental profiles of basic building materials produced in Finland [16]. The assessment is based on the material and energy flows reported by the producers.

[16] Häkkinen, T. et al. Environmental prifiles of building products and the principles for assessment. Technical Research Centre of Finland, VTT. Espoo 1998. VTT Research notes 1836. 138 p. + app. 10 p.

Table 1.1. Environmental declaration of building products.

Product Identification Name Trade name	**Product description** Range of use Product dimensions Density
Service life Design service life Required service conditions	**Category of indoor emissions**
Energy and resources Energy content (MJ/kg): Energy content, renewable Energy content, non-renewable Use of raw materials (kg/kg) Renewable and secundary materials Other materials	**Instructions to avoid health hazards during use** Storage at site Surface finish Precautionary time before use Service conditions
Emissions (g/kg) Global warming potential (CO_2-equ) Acidification potential (SO_2-equ) Photochemical oxidant formation potential (ethylene-equ)	**Recycling and final disposal of product, package and loss** Instructions for reuse and recycling Instructions for use as fuel in households

Table 1.2. An overview of the suggested principles for environmental assessment of building products.

① The life cycle inventory of building products covers extraction of raw materials and energy raw materials and auxiliary materials production processes and transportation assembling, use and maintenance and recycling or disposal.
② The assessment of environmental burdens is based on the material and energy flows reported by producers. The material and energy flows are annual input and output values. The LCI should cover >95% of the raw material flows of the products studied.
③ The system boundaries exclude the infrastructures, accidental spills, impacts caused by personnel, human resources, the production of working machines and vehicles and modernisation of production.
④ Energy raw materials are divided in renewable and not-renewable raw materials. Fuel flows reported by companies are converted into emissions and consumption of energy. The total use of energy comprises the HHV (High Heating Value) of the energy raw material and the energy consumed during procurement. The precombustion values are national averages. If the gases of combustion are not measured and analysed, those too are national averages. The vehicular emissions are national averages. The energy content of electricity is based on the energy raw materials used for production of electricity. The inherent energy of organic materials that can be used as fuels is included in the calculations. The inherent energy of sawn timber is not included if timber can be recycled as fuel.
⑤ The CO_2-emissions from burning of wood-based materials as fuels is excluded, because of binding of carbon dioxide in growing trees during relatively short time-scale. However, the carbon “stored” in long-lived timber products is not considered as “savings in emissions”.
⑥ The environmental burdens are not allocated on simultaneous by-products of significantly lower value.

⑦ The life cycle assessment is based on virtual practice rather than theory. Consequently, the reuse or recycling of the products is only taken into account, if the collecting, delivery etc. has been organised.
⑧ The design service life of the products and its necessary conditions must be reported. Also the predicted service life can be estimated, if necessary information is available.
⑨ The data quality is described as follows:
- data source (the name of the company),
- representativeness of data (year, production plants),
- methods used to obtain the data concerning input and output values (measuring, estimation, calculation etc.) and
- reliability of data (estimated range).
⑩ When different products are compared the data is dealt with respect to
- equivalent functions of the products
- chosen reference period.

1.5 Ecological building design

The basic requirements of ecological building design can be stated as follows:
- the ability of the client to present environmental requirements,
- the readiness of the designer to produce a solution corresponding to the environmental requirements, and
- the willingness of the producer to declare the environmental properties of the products.

However, the environmental design of buildings and making use of environmentally harmless building products emphasises the importance of the cooperation between designers and producers. In building sector, LCAs should first of all be understood as tools for developing environmentally improved building concepts and products. If this is not the case, but the LCA-data of products is only used to guide the selection of products, very high data quality requirements are directed towards the environmental data given by producers. Unambiguous data concerning the environmental properties of building products is needed. This means that product declaration formats and assessment methods should be agreed upon. Also the delivery and up-dating of data should be organised.

The quality of the environmental data of building products is characterised by the representativeness of the results, coverage of the results which depend on the boundaries of the studied systems and the accuracy and completeness of the results which depend on the acquisition methods. In order to use environmental data of building products in building design, the quality of the data should be known. This is a necessary condition in order to evaluate the significance of the environmental differences between alternative products or building concepts.

In a building process all the decisions that deal with the use of land, materials and energy affect the environmental impacts of the designed building. The required tools and systematics for environmental assessment of a building solution can thus be listed as follows:
- assessment of energy consumption (programme),
- bill of quantities (programme),
- assessment of the environmental impact of building products (systematic procedure and data base), and
- assessment of service life (systematic procedure).

By the initiation of the Finnish Building Information Institute, a research project was carried out [17] aiming at the formulation of the basic ecological criteria for building design and building product design. Environmental properties of buildings depend on the material and energy flows during the entire life cycle. Decisive solutions with respect to these are:

- dimensioning of spaces,
- design of flexibility and service life, and
- design of mechanical engineering (HVAC).

[17] Häkkinen, T. & Kaipiainen, M. Environmental criteria in building design. RTS-report, 1996. Helsinki. 52 p.

2 LITERATURE REVIEW ON LIFE CYCLE ASSESSMENTS OF COATINGS

2.1 Environmental burdens of paints according to the study of ECOBILAN [18]

The paint products involved in the life cycle study of Ecobilan are presented in Table 2.1.1. The functional unit compared in the study was the amount of paint covering 20 m2 of surface with 98% coverage (French Standard NF 30 075). The amounts of paint corresponding to this standard are presented in Table 2.1.2.

Table 2.1.1. Paint products studied.

		Solvent/ medium	Binder	Solvent type
A	Mat	Water	Styrene-acrylate	
B	Glossy	Water	Styrene- acrylate	
C	Semi-glossy	Solvent	Alkyd	White spirit >5%
D	Glossy	Solvent	Alkyd	Isoparaffin
E	Mat	Solvent	Styrene- acrylate	Isoparaffin
F	Glossy	Solvent	Alkyd	Isoparaffin
G	Glossy	Solvent	Alkyd	White spirit >1%
H	Mat	Solvent	Linseed oil	Isoparaffin
I	Mat	Water	Linseed oil emulsion	
J	Glossy	Solvent	Alkyd (high content of solid matter)	White spirit >1%
K	Mat	Water	Styrene- acrylate (micro-voids)	

[18] The life cycle analysis of eleven indoors decorative paints. Euiropean ecolabe. Project for application to paints and varnishes. Volume 5. Project carried out by the ECOBILAN COMPANY for the ministry of Environment in France. 150 p.

Table 2.1.2. The amounts of paint corresponding to functional unit (the amount of paint covering 20 m² of surface with 98% coverage).

	Amount of paint (l)
A	2.47
B	2.08
C	1.90
D	1.96
E	2.99
F	1.77
G	1.77
H	3.13
I	2.94
J	1.16
K	2.47

The system examined in the report includes the whole life cycle of the paints starting from the acquisition of raw materials. The input data concerning the different phases of the life cycle of paints do not include such material flows with smaller than a 5% share of the total material flow. As far as the end result is concerned this meant that the result was based on 80 - 100% of all the inputs. The approximate figure is 95%. The use of fuels has, however, systematically been considered. In the examination the packing materials are mentioned as material flows but the emissions and waste of resources caused by the manufacture of the packing materials have not been included in the calculation.

Data concerning the following components and emissions were used for all paints in the study:

- titanium dioxide,
- kaolin,
- calcium carbonate,
- white spirit,
- styrene acrylate adhesive (paints A, B and K),
- alkyd (paints C and D),
- process data concerning the manufacture of paints E, F, G, H and J (process emissions into the air and water and solid waste), and
- process data concerning the manufacture of paints A and K (use of energy, process emissions to the air and water and solid waste).

In most cases allocation rules were not applied (no by-products). If many products were born in the process, allocation took generally place on the basis of the mass. This was e.g. the procedure with raw tall oil. Raw tall oil was thus not handled as a by-product to which no environmental burdens were allocated. In the study the environmental burdens of the use of electricity have been evaluated according to the European average value (Table 2.1.3).

Table 2.1.3. Production sources of electricity (European average).

Source of energy	Share (%)	Production efficiency (%)
Coal	18	32
Brown coal	9.8	32
Industrial fuel oil	10	31
Natural gas	8,7	31
Nuclear power	38	33
Hydro power	15	90

In the study the VOC emissions from painting have been evaluated on the basis of the volatile solvents of the paint, the adhesive and the additives.

The report makes the following presumptions on the material flows connected to painting per functional unit (20 m^2 of painted surface):

- 2 litres of water or 0.2 litres of solvent is needed for the cleaning of the painting equipment,
- 30 grams of paint remains in the cleaning water or solvent,
- 0.05 litres of water or 0.05 litres of solvent is needed for thinning down the paint and
- the waste of paint is 30% of the amount used. The waste has not, however, been included in the functional unit.

The comparison of the paints in view of the use of energy, chemical oxygen demand, CO_2-, SO_2- , NO_x - , and VOC-emissions is presented in Table 2.1.4. Table 2.1.5 presents the most important factors regarding different environmental burdens according to the reference results.

Table 2.1.4. The comparison of the paints in view of the use of energy, chemical oxygen demand, CO_2-, SO_2- , NO_x - , and VOC-emissions.

	Binder	**Energy-content** [1]	**COD** [2]	**CO_2** [3]	**SO_2** [4]	**NO_x** [5]	**VOC** [6]
A	Styrene acrylate	110	15	5100	33	19	180
B	Styrene acrylate	90	14	4100	28	16	220
C	Alkyd	170	18	5900	38	17	810
D	Alkyd	190	20	6100	38	20	850
E	Styrene acrylate	300	17	9200	59	39	1500
F	Alkyd	210	24	7000	37	24	820
G	Alkyd	180	24	6500	39	19	840
H	Linseed oil	310	30	11000	55	38	1700
I	Linseed oil emulsion	68	4,6	3600	27	23	34
J	Alkyd (high content of solid matter)	100	12	2500	24	12	320
K	Styrene acrylate, micro voids	100	12	4400	32	19	170

1) Background intensification when <100 MJ
2) Background intensification when < 5 g
3) Background intensification when < 5000 g
4) Background intensification when < 30 g
5) Background intensification when <15 g
6) Background intensification when < 400 g.

Table 2.1.5. The most important factors with reference to different environmental burdens.

	Binder	Energy-content	COD	CO_2	SO_2	NO_x	VOC
A	Styrene acrylate	TiO_2, Acrylate	TiO_2, Acrylate	TiO_2, Acrylate	TiO_2, Acrylate	TiO_2, Acrylate	Coating
B	Styrene acrylate	TiO_2, Acrylate	TiO_2, Acrylate	TiO_2, Acrylate	TiO_2, Acrylate	Acrylate, TiO_2,	Coating
C	Alkyd	Alkyd, TiO_2	TiO_2, Alkyd	TiO_2, Alkyd	TiO_2, Alkyd	TiO_2, Alkyd	Coating
D	Alkyd	Alkyd, TiO_2	TiO_2, Alkyd	TiO_2, Alkyd	TiO_2, Alkyd	TiO_2, Alkyd	Coating
E	Styrene acrylate	Solvent, Isoparaf.	TiO_2, Isoparaf.	TiO_2, Isoparaf.	Isoparaf., TiO_2	Isoparaf., Solvent	Coating
F	Alkyd	TiO_2, Alkyd	TiO_2, Alkyd	TiO_2, Alkyd	TiO_2, Alkyd	TiO_2, Alkyd	Coating
G	Alkyd	TiO_2, Alkyd	TiO_2, Alkyd	TiO_2, Alkyd	TiO_2, Alkyd	TiO_2, Alkyd	Coating
H	Linseed oil	Solvent, TiO_2	TiO_2, Lins. oil	TiO_2, Solvent	TiO_2, Solvent	TiO_2, Solvent	Coating
I	Linseed oil emulsion	Pigments, Alum.sil.	Pigments, Lins. oil	Pigments	Pigments	Pigments	Pigments
J	Alkyd (high content of solid matter)	TiO_2, Alkyd	TiO_2, Alkyd	TiO_2	TiO_2, Alkyd	TiO_2, Alkyd	Coating
K	Styrene acrylate, micro voids	Resin, TiO_2	TiO_2, Resin	TiO_2, Resin	TiO_2, Resin	Resin, TiO_2	Coating

According to the end result of the study the paints causing the smallest environmental burdens (compared per functional unit) are:

- I (linseed oil emulsion),
- J (alkyd, high solid matter content),
- K (styrene-acrylate paint, micro-voids) and
- B and A (styrene-acrylate paints).

According to the study the reason why linseed oil emulsion paint I has so little environmental impact is that:

- it does not contain solvents and
- its titanium dioxide content is small.

As to paint J with high solid matter content the reason is mainly:

- its good coverage and
- low solvent and titanium dioxide content.

The higher environmental burdens of paints E and H compared to other paints are mainly due to:

- their high solvent content,
- the isoparaffin solvent (energy content of the isoparaffin solvent is approximately 1.6 times higher compared to white spirit), and
- the high titanium dioxide content of paint H.

2.2 Environmental burdens of paints on the basis of STORA-report [19]

Two paint systems were examined during the study: Falu red ochre (Falu rödfärg) and alkyd paint (Täcklasyr). The last-mentioned paint system consists of three parts, i.e. oil base, alkyd paint and surface glazing.

The functional unit under examination was 100 m^2 of painted surface assuming that the recommendations of the manufacturer concerning the use of the paint would be followed.

The examination method is life cycle assessment taking into consideration the acquisition of raw materials, manufacture of the components, manufacture of paint, painting and all transports. However, it has not been possible to gather all data and for these parts the examination is incomplete. For example the examination of wheat flour used in the manufacture of red ochre is insufficient. Also the data concerning pentaerythritol and isophtalic acid anhydride used in the manufacture of alkyd is missing.

The study does not demonstrate allocation rules used. The interim results of the study show that for example raw tall oil has been handled as a by-product and not a by-product to which the environmental burdens due to production are not allocated.

The end result of the study is presented in Table 2.2.1 in the form of a list of hazardous emissions and energy consumption per functional unit. According to the end result the environmental burdens of the alkyd paint system concerning most components are approximately 2-10 times bigger compared to the red ochre system.

[19] Johansson, M. & Österlöf, B. Livscykelanalys på två färgsystem för träfasad – Falu rödfärg och täcklasyr – samt värdering av miljöbelastningen med EPS-systemet. Luleå tekniska högskola och Stora Corporate Research. 1997. 20 p. (Life cycle analyses of two paint systems, in Swedish)

Table 2.2.1. Environmental burdens based on life cycle inventory with regard to 100 m^2 painted surface.

	Swedish red paint	Alkyd paint
Emissions		
CO_2 (g/100 m^2)	11000	89000
SO_2 (g/100 m^2)	43	330
NO_x (g/100 m^2)	76	260
N_2O (g/100 m^2)	2.2	0.090
NH_3 (g/100 m^2)	0.36	-
Particles (g/100 m^2)	7.0	60
CH_4 (g/100 m^2)	0.023	0.039
VOC_{tot} (g/100 m^2)	9.0	60
COD (g/100 m^2)	0.14	480
BOD (g/100 m^2)	-	100
N_{tot} (g/100 m^2)	0.023	6.7
P_{tot} (g/100 m^2)	-	0.82
Phenol (g/100 m^2)	0.00070	0.0012
Energy		
Fossil (MJ/100 m^2)	140	550
Renewable (MJ/100 m^2)	-	290
Electricity (MJ/100 m^2) *	160	214

* Delivered electricity.

2.3 Environmental burdens of paints on the basis of the BUWAL report [20]

The BUWAL publication presents a method for the comparison of the environmental impacts of paints. The method is based on life cycle assessment gathering in the first phase data concerning the material and energy flows of the paints under examination from the period of their whole manufacturing process. The assessment itself aims at taking into consideration both the ecological, toxicological and work hygienic point of view by using the following criteria:

- the environmental profile of the total manufacturing process of the paints as a meter of environmental pollution caused by the components of the paint,
- CO_2 emissions as a meter of raw materials non-renewable in the atmosphere,
- toxicological and allergenic potential as a parameter of user risk,
- ecotoxicity as a meter of pollution of water and soil caused by paints during painting, service life and final disposal, and
- organic emissions evaporating into the air during painting.

[20] Vergleichende ökologische Bewertung von Anstrichstoffen in Baubereich. Schriftenreihe Umwelt Nr. 186. Umwelgefährende Stoffe. Herausgegeben vom Bundesamt für Umwelt, Wald und Landschaft (BUWAL). Bern 1992. Band 2:Daten, 151 p.

In addition correction coefficients describing paint coverage, thickness of the layer of paint and durability of painted surface are used in the comparison of paints. The method does not suggest, however, how to choose the correction coefficient describing durability.

In the BUWAL-method the environmental profile of the product consists of the energy content and the so-called critical volumes. By critical volumes we mean the sum of those fresh air and water quantities needed to weaken the emissions of the materials to a harmless level. For example:

Critical volume (m^3 of air/1 kilo of product) =
((the emission quantity (mg/kg) / maximum content (mg/m^3)).

In the assessment of toxicological, eco-toxicological and allergenic potential the method uses inter-classification of the substances and compounds. The classification is partly based on Swiss directives, partly on EU directives and partly on other values concerning the harmfulness of substances.

Part "Daten" [21] of the BUWAL-report presents the environmental burdens of the components of fuel, average European electricity, transports and paints evaluated on the basis of life cycle assessment. In the publication the environmental burdens are divided into use of energy, use of raw materials and emissions into the air and water. The evaluation of environmental burdens takes into consideration the whole manufacturing process of the components starting from the acquisition of raw materials for energy and other raw materials. As to the components of paints the publication presents also the environmental profile calculated on the basis of environmental burdens. The results of the report are partly presented in chapter 4 as literature reference when data given by the producer of the component are not available or when wishing to compare the results with each other.

The publication is meant to be used as a guide for the comparison of the environmental impacts of paints and it presents only exemplary results due to the use of different paints (Table 2.3.1).

[21] Vergleichende ökologische Bewertung von Anstrichstoffen in Baubereich. Schriftenreihe Umwelt Nr. 186. Umweltgefährende Stoffe. Herausgegeben vom Bundesamt für Umwelt, Wald und Landschaft (BUWAL). Ber 1992. Band 2:Daten, 151 p.

Table 2.3.1 An example of the environmental impact of different kinds of paints assessed according to BUWAL-method.

	Acrylate lacquer	Alkyd lacquer	Resin oil lacquer from natural resources
Energy (MJ/kg)	38.7	65.1	30.8
Air (1000 m^3/kg)	433	888	712
Water (l/kg)	498	967	613
Wastes (cm^3/kg)	391	709	492
CO_2 (g/kg)	1840	3720	1810
Toxicity (-)	5.6	1.7	1.69
Allergenic potential (-)	2	0	8
VOC emissions (-)	5	28.1	15.9
Eco-toxicity (-)	0.5	28.4	16.1

3 ENVIRONMENTAL IMPACT OF PAINTED EXTERIOR WOODEN CLADDING

3.1 Targets and definitions of the study

The target of the study is to create a system for the evaluation of the environmental impact of the coated exterior cladding considering the service life and care of the surface. Here the term service life denotes the service life originally given by the manufacturer as background data for planning purposes. The requirements connected to the actual work performance, care and service condition are included in the service life. According to the reference [22] design life denotes service life defined by the designer and given for example to support the decision-making of the customer.

The target of the study is to develop a working method helping the paint industry in the evaluation of the environmental impact of the coated system and in the use of this data in supportive product development and informative marketing. It also works as background material in the creation of environmental systems and in the target-setting required by this work.

The examination concerns wooden, coated cladding during a period of one hundred years. The examination includes:

- manufacture of raw materials for paint,
- manufacture of paints,
- transports,
- painting,
- care and renewal, and
- recycling and final disposal.

Service condition denotes an exterior wall of a house in Finland in the environmental condition class 7 according to the reference [23] of the RT-card. Environmental condition class 7 denotes heavy climate loading outside. Such a loading occurs outside in the climate burdened by impurities. The system is valid in city climate, marine climate and industrial climate as well as in ordinary climate loading in the countryside defined by the milder environmental condition class 6. It is also valid in mild climate loading defined by the mild environmental condition class 5 in the circumstances where the surface to be painted is not exposed to solar radiation and rain.

The evaluations of the environmental loads of the products are made on the basis of life cycle assessment using the manufacturer's data concerning raw material acquisitions, transports and material and energy flows in connection of manufacture, painting and care as primary background material. If this kind of data is not available literature and expert arguments are used as the source of the background material. Life cycle inventories explain the causes of the

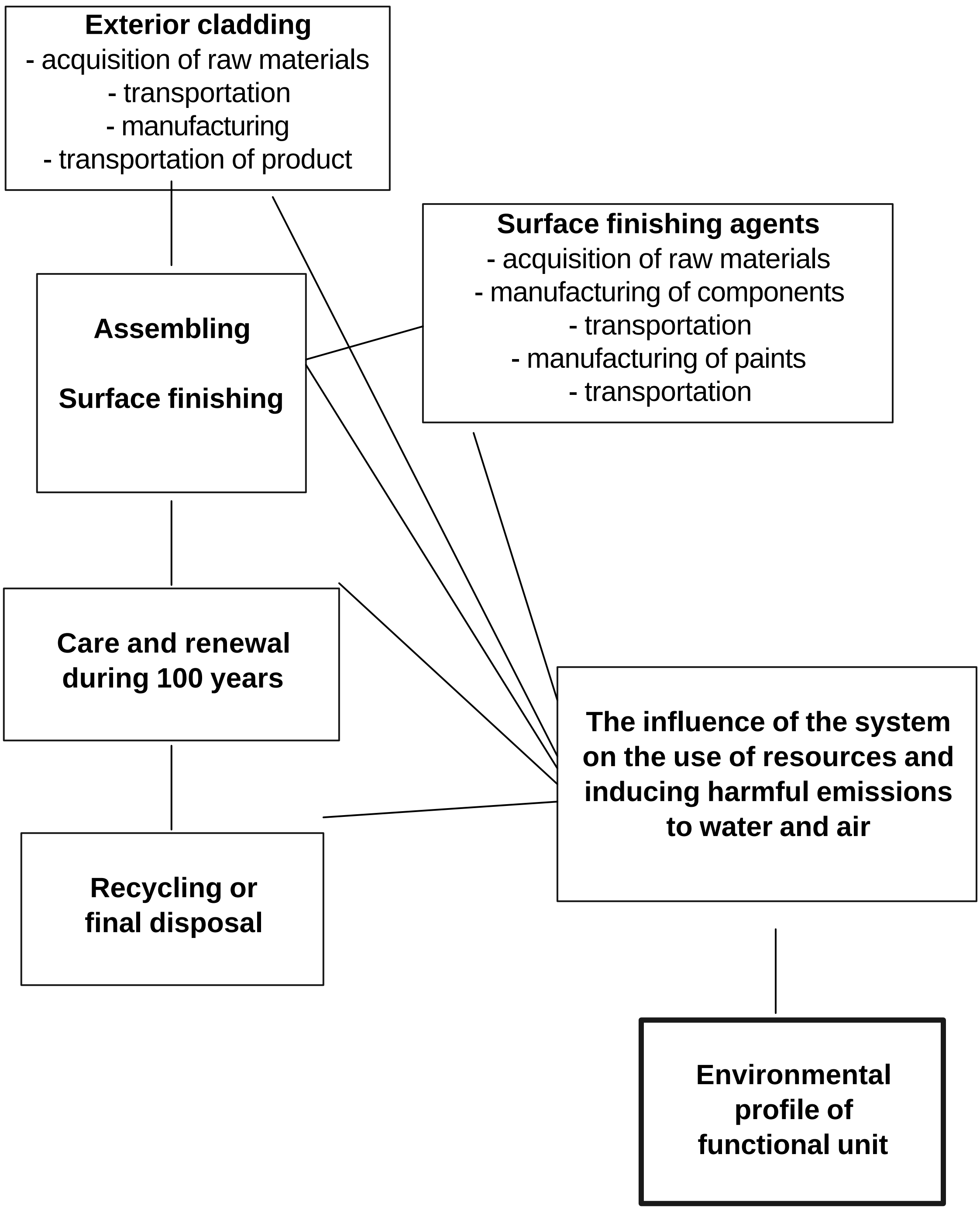
22 ISO/TC59/SC3/WG9, 17.10.1997. Design life of buildings. 61 p.

[23] SFS 4596, metallien korroosio, ympäristöolosuhteiden luokitus. Suomen Standardisoimisliitto. Helsinki 1983. RT-kortti 29-10267.

environmental loads, i.e. waste of resources and hazardous emissions per chosen functional units. The report follows the basic principles of ISO 14040 [24] and ISO 14041 [25].

3.2 Definition of a functional unit

In the life cycle assessment the functional unit indicates 1 m^2 of coated wooden cladding within a period of 100 years in Finland in the circumstances of environment condition class 7 (Chart 3.2.1).



[24] ISO 14040 Environmental management. Life cycle Assessment. Principles and framework. 1997-09-22.1 + 23 p.
[25] ISO 14041 Environmental management. Life cycle Assessment. Goal and scope definition and inventory analyses. 1998-11-30. 1 + 39 p.

Charter 3.2.1 Description of functional unit.

4 ENVIRONMENTAL BURDENS OF THE COMPONENTS OF COATING

4.1 Introduction

The following presents the environmental profiles and the basis of the evaluation of the environmental profiles of the components of coating and of the manufacture and transportation of coating as well as of the application itself. The results concerning the components are always presented as use of resources and emissions caused per one kilogram of material transported to a Finnish paint factory. Part of the data is based on information received from the producer concerning the material and energy flows of the production. In this case the calculation of the environmental profile follows the principles of Table 1.2. Part of the original data is based on literature. Also in this case the principles of Table 1.2 have been implemented whenever possible. The presumptions made and the coverage of the report as well as the reference material are presented in connection with each environmental profile.

4.2 Titanium dioxide manufactured by using the sulfate method

The data concerning the manufacture of titanium dioxide and material and energy flows of the manufacturing process on which the assessment is based were received from the Finnish producer. In addition the results are compared with the data of the reference literature [26] [27] [28] concerning the environmental burdens of titanium dioxide.

A sulphate method using ilmenite mineral and sulphuric acid as main raw materials is in use at Finnish production plant. In the first phase of the process finely ground ilmenite mineral reacts with strong sulphuric acid making the titanium of ilmenite mineral turn into soluble titanyl sulphate. In the following phases the solution is cleaned and iron is separated as crystalline ferrous sulphate. In the coagulation phase the black titanyl layer turns into white sludge containing amorphous titanium hydride which is calcinated into crystalline titanium dioxide pigment in a temperature of approximately one thousand degrees. The calcinated finely ground titanium dioxide may also be after-treated with different coating chemicals to obtain the desired product qualities.

Life cycle assessment included:

- acquisition and transportation of ilmenite mineral,
- transportation of the by-product sulphur and manufacture of sulphuric acid,
- manufacturing chain of lye and sodium carbonate used as additives and transportation of these products, and

[26] Reck, E. & Richards, M. TiO2 – Manufacture, Environment and Life Cycle Analysis. 1997. In: Proceedings of the 15th SLF Congress in Lillehammer, Norway 1997. 5 p.

[27] European Ecolabel for paints and varnishes. Results of the extension phase. The life cycle analysis of elelven indoors decorative paints. Volume 5. Ministry of Environment France. ECOBILAN. December 1993. 150 p.

[28] Vergleichende ökologische Bewertung von Anstrichstoffen in Baubereich. Schriftenreihe Umwelt Nr. 186. Umwelgefährende Stoffe. Herausgegeben vom Bundesamt für Umwelt, Wald und Landschaft (BUWAL). Bern 1992. Band 1:Methode, 50 p., Band 2:Daten, 151 p.

- transportation of other additives.

The junk used in the process was regarded as secondary product to which no environmental burdens caused by the manufacture of steel were allocated. The examination did not take into consideration the manufacture of other additives (amount used 170 g/1 kilo of product, approximately 3% of the raw materials) than those mentioned above. Other additives were hydrochloric acid, aluminium hydroxide and others.

The environmental burdens of the acquisition of ilmenite mineral have been evaluated on the basis of the data concerning the energy consumption given by the Norwegian producer. As to the composition of energy it was assumed that half of it is heavy fuel oil and half Norwegian electricity. Norwegian electricity was considered not to cause any emissions. The amount of packing material is approximately 8 per mil. of the amount of the end product. Due to the small amount packing material was disregarded.

The process emissions due to the manufacture of titanium dioxide and sulphuric acid and due to the power plant serving the processes are figures given by the producer, partly measured, partly estimations based on calculations. VOC-emissions and heavy metal emissions into the air have, however, been added to the end result on the basis of the data on approximate emissions due to the use of fuels and electricity.

Except those emissions due to the use of fuels the assessment pays attention to the following factors in the manufacturing process of titanium dioxide:

- solid waste by-product (reaction product and ferric sulphate),
- hazardous waste,
- particle emissions,
- solid matter into water,
- SO_4 into water,
- H_2SO_4 into water,
- Fe into water,
- Pb, Cd, Cr and Hg into water, and in the manufacture of sulphuric acid, and
- SO_2-emissions into water.

The environmental profile of sodium hydroxide is from reference [29] and that of sodium carbonate from reference [30]. These results represent European average.

The environmental profile of titanium dioxide calculated on the basis of material and energy data received from the producer is presented in Table 4.2.1. For the sake of comparison the same table also presents results from reference literature.

[29] Boustead, I. Eco-profiles of the European polymer industry. Report 6:Polyvinyl chloride. APME 1994. 22 p.

[30] Ceuterick, D., Mazijn, G. & Wouters, G. Life cycle Analysis and its potentials for sustainable development. VITO, Flemish Institute for Technological Research, Mol, Belgium. 12 p.

Table 4.2.1. Environmental profile of titanium dioxide based on sulphate method.

	FINLAND	ECOBILAN [31]	BUWAL [32]
Emissions			
CO_2 (g/kg)	5000	5900	4700
SO_2 (g/kg)	29	32	96
NO_x (g/kg)	21	12	11
Particles (g/kg)	14	6.4	14
CH_4 (g/kg)	12	15	-
VOC_{tot} (g/kg)	14	55	33
Heavy metals to air (g/kg)	0.0027 *	-	0.00
SO_4 to water (g/kg) **	250	-	910
Cr to water (g/kg)	0.004	-	-
Pb to water (g/kg)	0.002	-	0.00
Cd to water (g/kg)	0.00004	-	0.00
Hg to water (g/kg)	0.00002	0.00002	0.00
H_2SO_4 to water (g/kg)	0.00	-	-
COD (g/kg)	0.0033	21	0.00
BOD (g/kg)	0.00024	0.0013	0.69
Wastes			
Ferro sulphate (g/kg)	1000	-	1 800 ****
Reaction waste (g/kg)	700	480 ***	-
Problem waste (g/kg)	0.60	0.94	-
Energy			
Non-renewable energy (MJ/kg)	69	54	76
Renewable energy (MJ/kg)	6.5	3.0	2.1
Natural raw materials			
Ilmenite (g/kg)	2500	2400	-

* From fuels
** In the directive concerning titanium dioxide industry 92/112, the following limits are presented: SO_2 < 10 g/kg TIO_2, SO_4 < 800 g/kg TiO_2
*** Industrial waste
**** Waste

The majority of emissions and energy consumption in the whole manufacturing chain of titanium dioxide is caused by the manufacture of titanium dioxide and sulphuric acid and the energy production serving these processes.

[31] European Ecolabel for paints and varnishes. Results of the extension phase. The life cycle analysis of eleven indoors decorative paints. Volume 5. Ministry of Environment France. ECOBILAN. December 1993. 150 p.
[32] Vergleichende ökologische Bewertung von Anstrichstoffen in Baubereic. Schriftenreihe Umwelt Nr. 186. Umwelgefährende Stoffe. Herausgegeben vom Bundesamt fur Umwelt, Wald und Landschaft (BUWAL). Bern 1992. Band 1: Methode, 50 p., Band 2: Daten, 151 p.

4.3 Titanium dioxide manufactured by using the chloride method

The environmental burdens of titanium dioxide produced by the chloride method are examined according to references [33] and [34]. Basic raw materials for titanium dioxide are either ilmenite mineral or rutile mineral. The TiO_2 content ($FeTiO_3$) of ilmenite mineral is approximately 45 - 60%. Instead of original ilmenite mineral also concentrates can be used as raw material in the process. The TiO_2 content of rutile mineral is approximately 95%. The main impurities consist of iron compounds. The main phases of the sulphate method are explained in chapter 4.2.2. In the chloride method mineral is conducted to chlorinating equipment where it forms a sludge bed in the air current. Crushed coke is fed into the process in order to increase the temperature. When the temperature is approximately 1000^o C the air current is replaced by chlorine which causes the formation of titanium tetrachloride vapour. Titanium tetrachloride coagulates and crystallises during cooling. Combustion produces pure titanium dioxide and chlorine cycled into the chlorinating equipment or stored for re-use.

In reference [31] examination is focused on titanium tetrachloride products of six production plants situated in northwest England. As environmental parameters the reference gives the energy content, SO_2 emissions into the air, solid waste, sour and metal emissions into water. The results are presented in Table 4.3.1. In addition table 4.3.1 also includes corresponding figures from chapter 4.2 and from the studies of ECOBILAN and BUWAL.

Table 4.3.1. Environmental burdens of titanium dioxide according to different references.

Reference	Raw-material	Energy-content MJ/kg	CO_2 g/kg	SO_2 g/kg	Solid waste g/kg	Metals to water mg/kg	Acid emiss. to water g H^+/kg
Chloride method							
ENGLAND	Slich	110	-	75	1000	1.5	2
ENGLAND	Synth. Rutile	100	-	90	2500	1.5	1
BUWAL	Rutile	79	4100	28	1700	2.2	-
Sulphate method							
ENGLAND	Ilmenite	79	-	100	500	10	15
ENGLAND	Ilmenite	75	-	55	2000	5	8
ENGLAND	Ilmenite	75	-	50	5000	0.5	1
ENGLAND	Slich	100	-	60	1000	4.5	11
BUWAL	Ilmenite	80	4700	96	1800	59	-
ECOBILAN	-	90	5900	30	4500	25	-
FINLAND	Ilmenite	75	5000	30	1500	6	0

[33] Reck, E. & Richards, M. TiO2 – Manufacture, environment and Life Cycle Analysis. 15th SLF Congress in Lillehammer, Norway, 1997. 5 p.
[34] Vergleichende ökologische Bewertung von Anstrichstoffen in Baubereich. Schriftenreihe Umwelt Nr. 186. Umwelgefährende Stoffe. Herausgegeben vom Bundesamt für Umwelt, Wald und Landschaft (BUWAL). Ber 1992. Band 1:Methode, 50 p., Band 2:Daten, 151 p.

The environmental burdens of titanium dioxide manufactured by using the chloride method are presented in Table 4.3.2 according to reference [35].

Table 4.3.2. Environmental profile of titanium dioxide. Chloride method.

Emissions	
CO_2 (g/kg)	4100
SO_2 (g/kg)	28
NO_x (g/kg)	12
HCl (g/kg)	0.070
Dust (g/kg)	5.0
CH_4 (g/kg)	-
VOC_{tot} (g/kg)	33
Heavy metals to air (g/kg)	0.00
SO_4 to water (g/kg)	2.5
Cl^- to water (g/kg)	92
Metals to water	2.2
Cr to water (g/kg)	-
Pb to water (g/kg)	0.00
Cd to water (g/kg)	0.00
Hg to water (g/kg)	0.00
COD (g/kg)	0.01
BOD (g/kg)	0.03
Wastes	
Solid wastes (g/kg)	1700
Problem wastes	-
Energy	
Non-renewable energy (MJ/kg)	73
Renewable energy (MJ/kg)	6.5
Natural raw materials	
Rutile	-

4.4 Calcium carbonate powder

Data on which the assessment is based were received from Omya Oy. The starting point of the assessment was a report received from Omya Oy [36].

The examination is based on the result of the report in question concerning the product MILLICARB which due to the granule size distribution and no surface treatment can be compared with the products used by the Finnish paint industry. The average particle size of

[35] Vergleichende ökologische Bewertung von Anstrichstoffen in Baubereic. Schriftenreihe Umwelt Nr. 186. Umwelgefährende Stoffe. Herausgegeben vom Bundesamt fur Umwelt, Wald und Landschaft (BUWAL). Bern 1992. Band 1: Methode, 50 p., Band 2: Daten, 151 p.

[36] Ecological Balance Findings for MILLICARB and HYDROCARB 95T, Polypropylene and a mixture of Polypropylene and MILLICARB, Based on EMPA Test Report No 116’580 of August 13th 1992 (released for publicity purposes).

MILLICARB (d50%) is 2.7 micrometers. The most favourite products used in the paint industry are Omyacarb 10 GU, Myanit 0-30 and Microdol 1. The average particle size d50 of all these products is 7 micrometers. Thus the energy consumption is smaller in the production of the most frequently used products than in the production of MILLICARB. Here the energy values have not, however, been lowered.

Limestone powders marketed by Omya Oy are based either on Austrian calcite or Swedish or Norwegian dolomite. Omya Oy's market share of limestone powders used in Finland is 80%.

The production process under examination includes:

- acquisition of raw materials for energy and production of electricity,
- mining and transportation of limestone,
- milling,
- manufacture and transportation of packing material, and
- transportation of the product.

The report by EMPA concerns limestone powder called MILLICARB produced in southern France in Orgon. MILLICARB is a dry-ground product with no surface treatment. The report covers the mining of limestone, transportation to the factory, milling and manufacture of packing material. The result of the report is given as energy content of fuels and energy used and as evaluated emissions. The emissions have been calculated by using the Swiss BUWAL-method. The result is given as a so-called critical amount of air (i.e. amount of air that theoretically would be needed for an accepted content).

This assessment is based on the primary energy values of electricity and fuels used given in the report. As to the distribution of fuels it was assumed that 40% of them are heavy fuel oils, 40% light fuel oils and 20% diesel oils. The estimated emissions are based on quantities and qualities of fuels used. In addition it was estimated that the process emissions, i.e. dust emissions due to mining and milling are 3 grams/1 kilo of product (EMPA, VTT Building Technology: LCA reports on other mineral building powders [37]).

The report assumed that half of the powder is manufactured in Austria and half in Sweden. According to the reference [38] the efficiency multiplier of electricity was 70% for Austria and 48% for Sweden. Transfer loss was not taken into consideration. This accounts for approximately 5%. The environmental profiles of Austrian and Swedish electricity are from reference [39].

It was assumed that the product would be imported from Austria and transported by electric train to Travemünde and by boat from there to Helsinki and by truck to the paint manufacturer or it would be imported from Öreby and transported by truck to Stockholm, from there by boat to Helsinki and by truck to the paint producer. It was presumed that German electricity would be used in the transportation by electric train.

The environmental profile of calcium carbonate powder is presented in Table 4.4.1.

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[37] VTT Building Technology: Life Cycle Assessment on Mineral Building Materials.

[38] Boustead, I. Eco-profiles of the European plastics industry. Report 2: Olefin feedstock sources. PWMI 1993. 24 p.

[39] LCA Inventory Tool. Chalmers University. Sweden.

Table 4.4.1. Environmental profile of calcium carbonate powder.

Emission	
CO_2 (g/kg)	91
SO_2 (g/kg)	0.37
NO_x (g/kg)	0.90
Particles (g/kg)	3.1
CH_4 (g/kg)	0.077
VOC_{tot} (g/kg)	0.13
Heavy metals to air * (g/kg)	0.000017
Energy	
Non-renewable energy (MJ/kg)	0.99
Renewable energy (MJ/kg)	0.0069
Natural raw materials	
Limestone	-

* From fuels

4.5 Talc powder

The data on which the assessment is based were received from Finnminerals Oy. The data given by Finnminerals concern the description of the production process and the consumption of materials, fuels and electricity in the manufacturing processes and the transports of the raw materials and the product.

The production process of talc includes:
- the mining of mineral talc from an open pit and transportation by truck,
- mineral benefaction and manufacture of talc powder (Contration Plant and Micro Talc Plant) and
- transportation of the product by truck.

The energy values given concern the talc produced by Finnminerals used in the Finnish paint industry. The result has been calculated as an approximate value of all talc products produced by Finnminerals. The energy data concerning the acquisition of raw materials has been estimated on the basis of energy data1 on other minerals of the same type. The calculation presumed that the consumption of energy in an open pit would be 0.05 MJ/1 kilo of heavy fuel oil mineral.

The environmental burdens of the transports are based on national average values. Mineral is mined in three different places. The approximate transportation length of the raw material has been calculated as weighted mean.

As process emissions the examination considered:
- fixed waste in mining (secondary stone),
- fixed waste in mineral benefication (magnesium sand), nickel and arsenic into water,
- particle emissions in the manufacture of micro talc.

Other emissions have been evaluated on the basis of fuels and electricity used.

The environmental profile of talc powder is presented in Table 4.5.1.

Table 4.5.1. Environmental profile of talc powder.

Emissions	
CO_2 (g/kg)	500
SO_2 (g/kg)	2.3
NO_x (g/kg)	1.7
Particles (g/kg)	0.72
CH_4 (g/kg)	0.51
VOC_{tot} (g/kg)	0.59
Heavy metals to air * (g/kg)	0.000095
As to water (mg/kg)	1
Ni to water (mg/kg)	7
Energy	
Non-renewable energy (MJ/kg)	7.1
Renewable energy (MJ/kg)	0.44
Natural raw materials	
Talc ore (g/kg)	2400

* From fuels.

4.6 Synthetic ferric oxide pigment

The data on which the assessment is based were received from Bayer Oy. The letter "Life Cycle Assessment of Beyferrox Pigmente" gives a short account on the manufacturing process and energy consumption in production.

The production process under examination includes:

- acquisition of raw materials and raw material for energy,
- oxidation and combustion and
- transportation of the product.

Secondary materials (by-products and junk) are used as raw material of the process. Ferrous secondary materials are oxidised in the Laux-process. Heat production of the exothermic process is approximately 7 MJ/1 kilo of pigment. (According to reference [40] the forming temperature of hematin (Fe_2O_3) is 198.5 kcal/mol. The forming temperature per one kilo of iron is thus 7.4 MJ/kg Fe and Fe_2O3 and 5.4 MJ/kg Fe_2O_3). The energy released is exploited in the reduction of iron ore in the blast furnace. Altogether 33000 tons of coal can be replaced by this method which correspondingly diminishes carbon dioxide emissions by 110000 tons. The pastas and suspensions formed in the Laux-process are spray-dried (yellow and black pigments) or combusted (red pigments). This process needs energy to evaporate the water. With red pigments the energy consumption is approximately 3 MJ/kg, with the black ones approximately 1.8 MJ/kg and with the yellow ones approximately 6.6 MJ/kg. The main process emission is water vapour saturated air. A process emission of sulphur trioxide caused by combustion is collected with the help of water and the acid is exploited in the process. The

[40] Chemical Engineers' Handbook, ed. Perry & Chulton, 5th Ed., McGraw-Hill, Tokio 1974, P. 3-140.

energy values given concern the ferric oxide pigments produced by Bauer AG which are used in the Finnish paint industry.

According to the assessment the expected net energy consumption of the process is 0 MJ/kg provided that exactly the same amount of energy can be exploited of the theoretic forming temperature of ferric oxide than that used in the combustion of red pigment. Process emissions and "saved emissions" were not taken into consideration. It was furthermore assumed that the net emissions of the process are correspondingly 0 g/1 kilo of product. As to the transportation of the product it was assumed that the product would be transported by train to Travemünde, by boat to Finland and by truck to the paint manufacturer.

The environmental profile of synthetic ferric oxide pigment is presented in Table 4.6.1.

Table 4.6.1. Environmental profile of synthetic ferric oxide pigment.

Emissions	
CO_2 (g/kg)	60
SO_2 (g/kg)	0.5
NO_x (g/kg)	1
Particles (g/kg)	0.1
CH_4 (g/kg)	0.1
VOC_{tot} (g/kg)	0.1
Heavy metals to air * (g/kg)	0.00001
Energy	
Non-renewable energy (MJ/kg)	1
Renewable energy (MJ/kg)	0
Natural raw materials	
-	0 **

* From fuels
** Secondary materials

4.7 Red ochre pigment

The assessment is based on the data received from Stora Timber AB [41]. The manufacturing process of red ochre pigment includes:

- the washing of the sludge,
- combustion and
- milling of the pigment.

Sodium hydroxide is used for the cleaning of smoke gases during combustion. Sodium hydroxide is manufactured at EKA Nobel of sodium chloride imported from Holland.

The examination takes into consideration the acquisition of raw materials and raw materials for energy, manufacturing processes and transports. The environmental burdens of the

[41] Johansson, M. (Luleå tekniska högskola) & Österlöf, B. (Stora Corporate Research). Livcyckelanalys på två färgsystem för träfasad. FALU rödfärg och täcklasyr – samt värdering av miljöbelastningen med EPS-systemet. STORA 1997. 4 p + attachments 43 p.

manufacturing processes have been calculated on the basis of the data received from the manufacturers and concerning the consumption of fuels and electricity and the most important process emissions. As process emission the estimate considers SO_2, SO_3 and particle emissions in the combustion of red ochre sludge and particle emissions in milling.

The emissions of fuels, transports and electricity have been calculated according to the Swedish national average values. The database concerned does not present methane emissions separately. It was assumed that the share of CH_4-emissions of the total VOC-emissions would be 75%. The examination also includes the transportation of the pigment to Finland. It was presumed in the report that the pigment would be transported by truck and by boat.

The environmental profile of red ochre pigment is presented in Table 4.7.1.

Table 4.7.1. Environmental profile of red ochre pigment.

Emissions	
CO_2 (g/kg)	1100
SO_2 (g/kg)	5.9
SO_3 (g/kg)	1.6
NO_x (g/kg)	3.5
Particles (g/kg)	0.49
CH_4 (g/kg)	0.36
VOC_{tot} (g/kg)	0.48
Heavy metals to air (g/kg) *	-
Energy	
Non-renewable energy (MJ/kg)	22
Renewable energy (MJ/kg)	2.8
Natural raw materials	
**	-

* Not known

** The main material source is by-product from steel industry

4.8 Yellow ochre pigment

The examination is based on the data given by the producer concerning the manufacturing processes of yellow ochre pigment and the consumption of electricity, fuels and raw materials in the manufacturing process. The manufacturer is Sté des Ocres de France. The data were received in 1997.

The examination target was the natural yellow pigment, which consists of clay dyed by ferric hydroxide. The manufacturing process of the paint pigment includes

- the elutriation of the pigment from the ground,
- mechanical filtration, collection into the basin, storing and evaporation of moisture,
- collection and drying of evaporation cakesheets,
- milling, screening and packing.

The majority of the energy used in the process is used in connection with milling.

The examination considers the acquisition of raw materials and raw materials for energy, manufacturing processes and transports. No other emissions than emissions due to the use of fuels and electricity were taken into consideration in the examination. The environmental burdens of the manufacturing process have been calculated on the basis of data received from the manufacturer and concerning the consumption of fuels and electricity. The emissions of electricity have been calculated according to the French national average value. The examination also includes the transportation of the pigment to Finland. It was presumed in the report that the pigment would be transported by truck and by boat.

The environmental profile of yellow ochre pigment is presented in Table 4.8.1.

Table 4.8.1. Environmental profile of yellow ochre pigment.

Emissions	
CO_2 (g/kg)	140
SO_2 (g/kg)	0.91
NO_x (g/kg)	1.7
Particles (g/kg)	0.12
CH_4 (g/kg)	0.12
VOC_{tot} (g/kg)	0.24
Heavy metals to air (g/kg) *	-
Energy	
Non-renewable energy (MJ/kg)	2.7
Renewable energy (MJ/kg)	0.097
Natural raw materials	
Clay (g/kg)	8 500

* Not known

4.9 Zinc oxide

The data concerning the environmental burdens due to the acquisition, transportation and processing of the raw materials of zinc oxide were received from Kuusakoski Oy. The manufacturing process of the product includes the melting of scrap-zinc, vaporisation of melted zinc, combustion of zinc vapour and collection of zinc oxide into the filter.

The examination considers the transports of the raw materials, consumption of electricity and fuels, manufacturing processes, transportation of the product and the waste due to the process. The raw material used in the manufacture of zinc oxide is scrap-zinc. Scrap-zinc comes from different sources. Scrap used in the process includes e.g. Zn-scrap assorted by hand (e.g. toys, car parts, big zinc castings), bottom sediment and floating slag of the hot galvanising plants, Zn-bars and zinc ash. The environmental profile of zinc oxide does not take into consideration the environmental burdens due to the breaking up of the Zn-scrap coming from the car breaking plants and scrap dealers. Other zinc raw materials are presumably waste to which environmental burdens are not allocated.

The environmental profile of zinc oxide is presented in Table 4.9.1.

Table 4.9.1. Environmental profile of zinc oxide.

Emissions	
CO_2 (g/kg)	790
SO_2 (g/kg)	0.55
NO_x (g/kg)	1.1
Particles (g/kg)	0.37
CH_4 (g/kg)	0.36
VOC_{tot} (g/kg)	0.50
Heavy metals to air (g/kg)	0.0025
Solid waste	660
Energy	
Non-renewable energy (MJ/kg)	14
Renewable energy (MJ/kg)	0.64
Natural raw materials	
- (g/kg) *	

* Scrab-zinc

4.10 White spirit

The data concerning the environmental burdens due to the acquisition, transportation and processing of the raw materials of white spirit were received from Neste Oy. The manufacturing process of the product includes the acquisition, transportation and processing of crude oil.

The environmental data concerning the production of crude oil are from reference [42]. The environmental profile of white spirit has been calculated at Neste Oy by exploiting the reference data. However, the environmental profile does not include the energy contents of the materials (so called feedstock energy). Here the presumption is that the energy content is 45 Mj/1 kilo of product on the basis of references [43] and [44]. In addition it was presumed that all energy would be non-renewable energy. As to methane emissions it was presumed that the share of methane of the hydrocarbon emissions would be 50%.

The environmental profile of white spirit is presented in Table 4.10.1.

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[42] Life cycle data for Norwegian Oil and Gas, K.K. Bakkane, TAPIR 1994.
[43] Vergleichende ökologische Bewertung von Anstrichstoffen im Baubereich. Band2:Daten. Schriftenreihe Umwelt Nr. 232. Umweltgefährdende Stoffe. BUWAL. Bern 1995, p. 23.
[44] Life cycle data for Norwegian Oil and Gas, K.K. Bakkane, TAPIR 1994.

Table 4.10.1. Environmental profile of white spirit.

Emissions	
CO_2 (g/kg)	150
SO_2 (g/kg)	0.30
NO_x (g/kg)	0.70
Particles (g/kg)	0.20
CH_4 (g/kg)	0.20
C_xH_y+VOC_{tot} (g/kg)	0.40
Heavy metals to air (g/kg) *	-
Wastes	
Problem wastes	0.20
Other wastes	6.1
Energy	
Non-renewable energy (MJ/kg)	47
Renewable energy (MJ/kg)	0.44
Natural raw materials	
Raw oil	-

* Not known

4.11 Linseed oil varnish

The environmental profile of linseed oil is based on reference [45]. The production process of linseed oil includes:

- production of crude oil by pressing linseeds and
- cooking of linseed oil.

According to the reference, life cycle assessment includes:

- production of ammonia (in Germany),
- production of nitric acid (in Germany),
- production of potassium nitrate (in Israel),
- production of ammonium nitrate (in Sweden),
- production of ammonium phosphate (in Belgium),
- transportation of fertilisers,
- flax growing (in Sweden),
- manufacture and transports of crude oil,
- cooking of linseed oil (in Gothenburg) and
- transportation of linseed oil.

As to flax growing it was presumed that a crop of 1500 kilos/hectare of linseed would be received and that the need to use machines would be 8 hours/hectare. The quantity of fertilisers used is expected to be 225 kilos/hectare and consumption NPK 20/4/8 (nitrogen 20%, phosphorous 5% and potassium 8%). Flax growing is not expected to cause nutrification of water in connection of emissions. The mass ratio of linseed and crude oil is

[45] Johansson, M. & Österlöf, B. Livcyckelanalys på två färgsystem för träfasad – FALU rödfärg och täcklasyr – samt värdering av miljöbelastningen med EPS-systemet. STORA 1997. 4 p. + attachments 43 p.

expected to be 0.25. Linseed oil will be transported to Finland by boat. The share of methane is expected to be half of the hydrocarbon emissions. Heavy metal emissions into the air have been calculated according to the average Finnish energy database systems on the basis of the amounts of fossil fuels. Electricity consumption according to the original reference has been changed into primary energy by using value 0.48 as efficiency multiplier.

The majority of the energy consumption in the life cycle of the manufacture of linseed oil is, according to reference [46], caused by the use of electricity in the manufacture of linseed crude oil in connection of drying, pressing etc. According to the reference, electricity consumption in the manufacture of crude oil is 45 MJ/1 kilo of linseed crude oil. When this is changed into primary energy, according to reference [47], the total energy consumption in the manufacture of linseed crude oil is 94 MJ/kg.

The environmental profile of linseed oil varnish is presented in Table 4.11.1.

Table 4.11.1. Environmental profile of linseed oil varnish.

Emissions	
CO_2 (g/kg)	750
SO_2 (g/kg)	2.1
NO_x (g/kg)	12
NO_3 (g/kg)	0.15
N_2O (g/kg)	0.81
NH_3 (g/kg)	0.13
Particles (g/kg)	0.80
CH_4 (g/kg)	0.50
HC and VOC_{tot} (g/kg)	1.0
Heavy metals to air (g/kg)	0.000427
Phosphor (g/kg)	6.0
Energy	
Non-renewable energy (MJ/kg)	59 MJ
Renewable energy (MJ/kg)	50 MJ
Natural raw materials	
Linseed	-

4.12 Acrylate binder

The environmental profile of acrylate binder is based on references [48] and [49]. The result of reference 47 is based on the data received from the European companies. The report covers

[46] Johansson, M. & Österlöf, B. Livcyckelanalys på två färgsystem för trefasad – FALU rödfärg och täcklasyr – samt värdering av miljöbelastningen med EPS-systemet. STORA 1997. 4 p. + attachments 43 p. (In Swedish)
[47] Boustead, I. Eco-profiles of the European plastics industry. Report 4:Polystyrene. PWMI 1993. 24 p. Table 12 p. 10.
[48] Vergleichende Ökologische Bewertung von Anstrichstoffen im Baubereich. Band 2:Daten. Schriftenreihe Umwelt Nr. 232. Umweltgefährdende Stoffe. BUWAL. Bern 1995.

the whole production process of the binder starting from the acquisition of raw materials and raw materials for energy.

The manufacturing process of acrylate binder is presented in Figure 4.12.1.

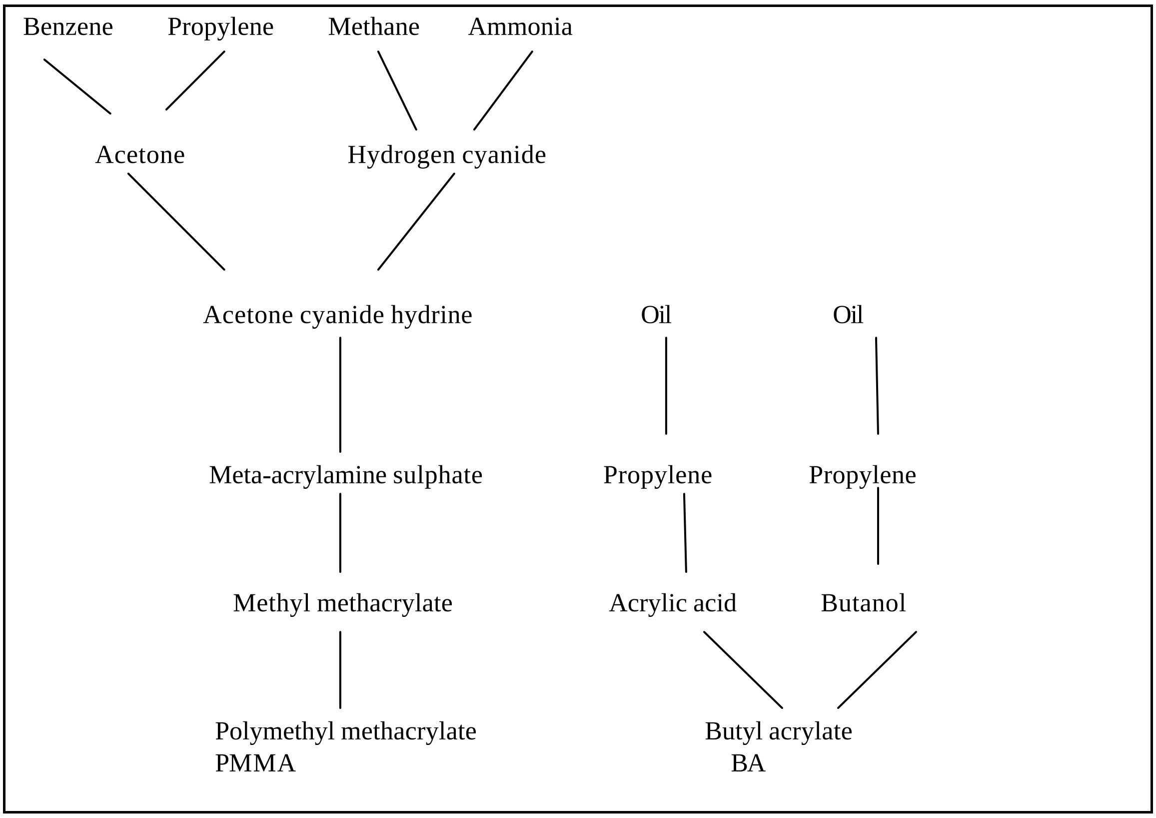

Figure 4.12.1. Manufacturing process of acrylate binder.

The environmental profile of acrylate binder has been calculated assuming that the glass transition temperature of acrylate copolymer (T_{gko}) of exterior emulsion paints is 10 ^oC. The shares of methyl methacrylate (MMA) and butyl acrylate (BuA) in the binder have been calculated by means of the equation

$$T_{gko} = T_{gw1} W_1 + T_{gw2} W_2.$$

The share of methyl methacrylate was 40%, when T_{MMA} = 105 ^oC. The share of butyl acrylate is 60%, when T_{gBuA} = -50 ^oC. The information is based on the data given by Rohm and Haas Nordiska Ab and Tikkurila Paints Oy.

The environmental profile of acrylate binder is presented in Table 4.12.1.

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[49] Eco-profiles of the European plastics industry. Report 14: Polymethyl Methacrylate. Ian Boustead. Brussels 1997.

Table 4.12.1. Environmental profile of acrylate binder.

Emissions	
CO_2 (g/kg)	4100
SO_x (g/kg)	20
NO_x (g/kg)	16
Particles (g/kg)	3.5
CH_4 (g/kg)	11
HC and VOC_{tot} (g/kg)	23
Heavy metals to air (g/kg)	0.004 *
COD (g/kg)	3.5
BOD (g/kg)	0.94
Energy	
Non-renewable energy (MJ/kg)	100
Renewable energy (MJ/kg)	0.91
Natural raw materials	
Fossil raw materials	

* Metals

4.13 Tall oil alkyd

The data concerning the manufacture of crude tall oil in connection with the pulp process on which the assessment is based were received from the Äänekoski pulp mill of Metsä-Botnia. The data concerning the transportation of crude tall oil, manufacture of tall fatty acid and transportation of the tall oil fatty acid to the manufacturer of tall oil alkyd were received from the Oulu plant of Arizona Chemical Oy. The data concerning the manufacture of tall oil alkyd from McWhorter Technologies Oy and Tikkurila Oy.

Production process of crude tall oil, tall fatty acid and tall oil alkyd is presented in Figure 4.13.1.

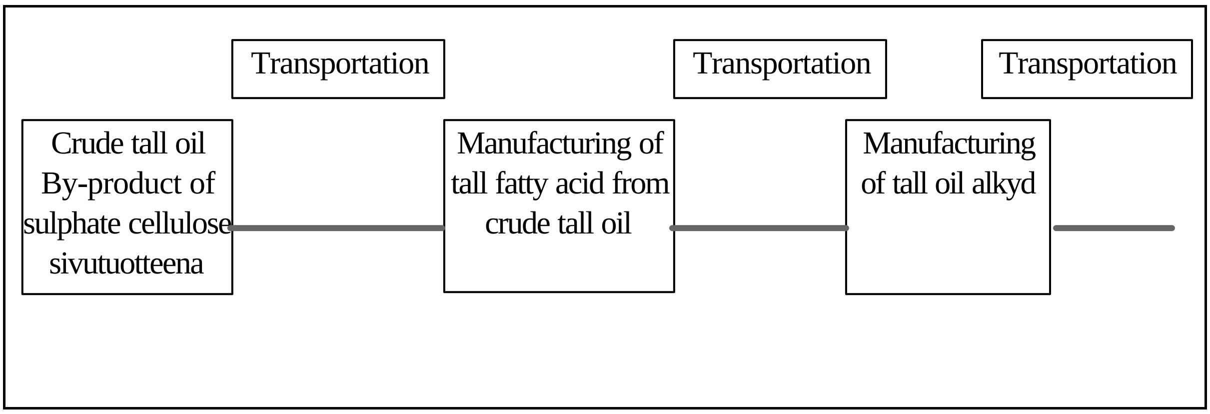

Figure 4.13.1. Production process of crude tall oil, tall fatty acid and tall oil alkyd.

Crude tall oil is a by-product of the pulp industry. It is produced of tall oil sopa. Tall oil fatty acid is manufactured by distilling crude tall oil. Tall oil alkyd is manufactured from tall oil fatty acid, acid anhydride and alcohol.

The examination of life cycle assessment includes:
- energy content of raw tall oil, presumably 38 MJ/kg,
- transportation of raw tall oil to the plant manufacturing tall oil fatty acid (200 km),
- distilling of tall oil fatty acid from tall oil,
- transportation of tall fatty acid to the manufacturer of tall oil alkyd (120 km),
- manufacture of tall oil alkyd, and
- transportation of tall oil alkyd to the paint factory.

Raw tall oil is considered to be a by-product of pulp industry and no environmental burdens of the pulp industry are thus allocated to it, but all environmental burdens due to the manufacture of sulphate cellulose are allocated to pulp [50].

The environmental profile of tall oil alkyd is presented in Table 4.13.1.

Table 4.13.1. Environmental profile of tall oil alkyd.

Emissions	
CO_2 (g/kg)	1100
SO_2 (g/kg)	9.1
NO_x (g/kg)	4.5
Particles (g/kg)	1.9
CH_4 (g/kg)	0.26
HC and VOC_{tot} (g/kg)	13
Heavy metals to air (g/kg) *	0.051
COD (g/kg)	2.6
BOD (g/kg)	0.69
Energy	
Non-renewable energy (MJ/kg)	34
Renewable energy (MJ/kg)	2.3
Natural raw materials	
- **	

* From fuels
** Basic raw material is by-product from other industry

4.14 Rye flour

The environmental profile of rye flour is based on reference [51] and data received from Suomen Vilja Oy. The systematics of the life cycle examination of the flours and data concerning the

[50] COST E1 working group is handling the matter. The recommendation concerning the allocation will probably be received during 1998. Pine crude oil is produced at sulfate cellulose plants approximately 5-8% of the amount of pulp production. It is worth 2% of the value of one ton of pulp.

environmental burdens due to the manufacture of fertilisers and pesticides are based on the above-mentioned reference. The data based on the Danish circumstances and concerning the quantities of fertilisers used, approximate crop etc. have been amended according to the data received from Suomen Vilja Oy so that they correspond to the Finnish circumstances.

The manufacturing process of rye flour on which this examination focuses includes grain growing, drying, milling and transports. The report covers the following phases of the manufacture of rye flour and necessary additives:

- manufacture of fertilisers,
- manufacture of pesticides,
- use of work machines in connection with grain growing,
- nutrient and pesticide emissions in connection with grain growing,
- drying and milling of grain, and
- transportation of grain and flour.

The estimate is based on the following assumptions:

- amount of nitrogen fertiliser used 126 kg N/hectare,
- amount of phosphorus fertiliser used 10 kg P/hectare,
- amount of potassium fertiliser used 24 kg K/hectare,
- amount of calcareous earth used 800 kg $CaCO_3$/hectare,
- amount of pesticides used approximately 0.95 kg (active components)/hectare,
- rye crop 2750 kg/hectare,
- nutrient emissions into water caused by grain growing (as far as nitrogen is concerned also from the evaporation of ammonia, etc.) 100 kg N/hectare and 0.5 kg P/hectare,
- pesticide emissions into the environment caused by grain growing 5 g/kg of pesticide (active components) and by the manufacture of pesticides 2.5 g/kg of pesticide,
- amount of seed-corn 5% of the grain, and
- material loss in the process from grain to flour 1% of the grain.

The environmental profile of rye flour is presented in Table 4.14.1.

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[51] Weidema, B.P., Pedersen, R.L. & Drivsholm, T.S. Life cycle screening of food products, two examples and some methodological proposals. Danish Academy of Technical Sciences. Group of cleaner technology, I. Kryger Consult A7S. Denmark 1995. 98 p. + attachments 95 p.

Table 4.14.1. Environmental profile of rye flour.

Emissions	
CO_2 (g/kg)	260
SO_2 (g/kg)	0.18
NO_x (g/kg)	1.6
NH_4 to air g/kg)	0.64
N_2O (g/kg)	0.79
Particles (g/kg)	0.091
CH_4 (g/kg)	0.45
VOC_{tot} (g/kg)	0.51
Heavy metals to air (g/kg) *	0.00042
N_{kok} to water (g/kg)	39
P_{kok} to water (g/kg)	0.18
F to water (g/kg)	0.86
COD (g/kg)	0.0027
Emissions of pesticides (g/kg)	0.00075
Energy	
Non-renewable energy (MJ/kg)	3.5
Renewable energy (MJ/kg)	0.044
Natural raw materials	
Rye flour	

* Based on fuels

4.15 Wood turpentine

The data concerning the manufacture of wood turpentine on which the estimate is based were received from Arizona Chemicals Oy. The process of making tall oil fatty acid by distilling crude tall oil gives energy raw material products containing 1% of crude turpentine as by-products. Crude turpentine is further distilled into wood turpentine. Wood turpentine is washed with hypochlorite solution and dried in a marine salt tower.

Life cycle assessment includes:
- energy content and transportation of crude tall oil,
- distilling of tall oil fatty acid,
- distilling of wood turpentine,
- washing with hypochlorite/water and
- transportation of wood turpentine.

The assessment does not take into consideration the acquisition, transportation and use of marine salt in the process of drying wood turpentine.

The environmental profile of wood turpentine is presented in Table 4.15.1.

Table 4.15.1. Environmental profile of wood turpentine.

Emissions	
CO_2 (g/kg)	170
SO_2 (g/kg)	7.6
NO_x (g/kg)	1.1
Particles (g/kg)	2.4
CH_4 (g/kg)	0.083
HC and VOC_{tot} (g/kg)	0.19
Heavy metals to air (g/kg) *	0.00024
COD (g/kg)	3.3
BOD (g/kg)	0.83
Cl^- (to water)	0.085
Energy	
Non-renewable energy (MJ/kg)	1.1
Renewable energy (MJ/kg) *	0.23
Natural raw materials	
- **	

* Based on fuels

** Basic raw materials is by-product of cellulose manufacturing

4.16 Other additives

In addition to the above-mentioned additives (chapters 4.1 to 4.15) the paints under examination also contain small amounts of other additives. The typical quantity of other additives in transparent wood stains and alkyd oil paints is approximately 2-4%. The environmental profiles of the additives were not detailed in this study. Table 4.16.1 presents a list of typical additives. The data were received from Tikkurila Oy. Of all the additives on the list, fungicides can be considered hazardous to the environment as such, if they or some of them end up in the environment during the life cycle of the paint.

Ferric sulphate received as a by-product of the production process of titanium dioxide is used as an additive of sludge paint. The environmental profile of ferric sulphate was calculated so that no environmental burdens of the production of ferric sulphate were allocated to it. The environmental burdens of ferric sulphate are thus caused merely by transportation. The environmental profile of ferric sulphate is presented in Table 4.16.2.

Table 4.16.1. Typical auxiliary agents and additives in transparent wood stains and alkyd oil paints.

Auxiliary substance or additive	**Quality**	**Content (% by weight)**	**Others**
Thickeners	Bentonite clay	0.5 - 1	
Drying agents	Co, Ca, Zr, Mn	<1	Octoates naphtenates
Fungicides	Diklofluanid	0.5 - 1	
Antiskinning agents	Methyl ethyl ketoksine	0.2 - 0.4	
Wetting agents	Soya lecithin	0.3	Also other types of agents are used, The same content

5 ENVIRONMENTAL BURDENS FROM MANUFACTURING AND TRANSPORTATION OF COATINGS

5.1 Model formulas

The paint manufacturers participating in the research designed formulations of priming oils, primers, undercoats and topcoats (Table 5.1). The coating recipes are based on linseed oil, tall oil alkyd and acrylic binders and also a recipe of Swedish red paint (Barn Red) with a binder of a mixture of cooked rye and linseed oil is included in the assessment.

The model formulations were based on average proportions of the coating constituents used in commercial products. Only the main components like binders, solvents or water (in emulsion coatings), pigments and extenders were included in the recipes. Additives were excluded, because a proportion of an individual additive is low, mostly under 1%. Environmental impacts of additives were thus considered to be insignificant compared to the main coating components. If an additive was evaluated to have toxic impacts on the environment, impacts were noted.

Table 5. 1. Model formulations. SB solvent-borne, WB water-borne.

Formulations	Solvent (mineral spirit or water)	Binder	Pigment	Extenders ($CaCO_3$)	Additives (fungicides, dryers, anti- skinning agents, etc.)
Alkyd (tall oil)					
1 SB priming oil	90%	10%			
2 SB undercoat	45%	25%	10% TiO_2	20%	
3 Factory primer	65% H_2O	10%	15% TiO_2	10%	
4 WB priming oil	90% H_2O	10%			
5 SB stain	77%	20%	3% iron oxide		
6 WB stain	77% H_2O	20%	3% iron oxide		
7 Opaque topcoat	20%	40%	20% TiO_2	20%	
Linseed oil					
8 Primer	20% (turpentine)	50%	30% ZnO		
9 Opaque topcoat		45%	15% TiO_2 15% ZnO	15% 10% talc	
10 Opaque topcoat		45%	30% yellow ochre 15% ZnO	10%	
Acrylic dispersion					
11 WB stain	77 - 82% H_2O	15 - 20% *	3% iron oxide		
12 Opaque topcoat	50% H2O	25%	15% TiO2	10%	
13 Swedish red paint	66% H2O	8% rye 6% linseed oil	16% Falu red pigment		4% iron sulphate

* The figure 17.5% was used in calculations

5.2 Manufacturing of coatings

The environmental burdens from production of coatings are mainly induced in production processes of coating components. In the actual coating production, environmental burdens are induced from use of electricity and fuels for heating of the production plant and production processes and from process emissions to air and water. Process emissions include for example volatile organic compounds. However, the amount of those is naturally much higher during coating than during production of solvent-borne coatings. Wastes from production process of paints are for example loss of materials.

The environmental burdens from manufacturing of coatings are based on the data received from Tikkurila, Teknos Winter, Akzo and Uula companies. The data was collected by means of a questionnaire presented in Appendix 2.

The environmental burdens could not be calculated according to coating types, because of inadequate information received. It was calculated that in the production process, the use of electrical energy is roughly 1 MJ/kg of paint and the consumption of energy (district heat) for heating of production spaces is also in average roughly 1 MJ/kg of paint. The solvent emissions during production process are low compared to those in situ during painting. The total amount of volatile organic emissions was assessed to be 2% of the amount of solvents used. The amount of problem wastes is in average 22 g/kg, solid matter to water 1 g/kg and other wastes roughly 20 g/kg.

The environmental burdens from the manufacturing of paints are presented in Table 5.2.

Table 5.2. Environmental burdens from the manufacturing of paints. SB = solvent-borne, WB = water-borne.

Emissions	**SB stain (solvent 90%)**	**Alkyd paint (solvent 20%)**	**WB paint**
CO_2 (g/kg)	160	160	160
SO_2 (g/kg)	0.30	0.30	0.30
NO_x (g/kg)	0.35	0.35	0.35
Particles (g/kg)	0.32	0.32	0.32
CH_4 (g/kg)	0.45	0.45	0.45
HC and VOC_{tot} (g/kg)	18	4.0	0.45
Heavy metals to air (g/kg)	-	-	-
COD (g/kg)	-	-	-
BOD (g/kg)	-	-	-
Energy			
Non-renewable energy (MJ/kg)	2.70	2.7	2.7
Renewable energy (MJ/kg)	0.42	0.42	0.42
Natural raw materials			
-			

5.3 Transportation of coatings

The environmental burdens from transportation of coating materials were assessed based on the reference [52].

The environmental burdens from lorry transportation come from consumption of diesel oil and the related energy consumption and causing emissions. The calculation is based on assumption that the average degree of fullness is 70%. In addition, the following values were applied for energy consumption (higher heating values):

- 0.00077 MJ/km in long distance transportation and
- 0.0013 MJ/km in local transportation

taking into account both the combustion and pre-combustion of the fuel.

The environmental profile of lorry transportation of paint products is presented in Table 5.3.

Table 5.3. Environmental burdens from the transportation of paints in relation to 100 km transportation distance.

Emissions	
CO_2 (g/kg)	5.3
SO_2 (g/kg)	0.0035
NO_x (g/kg)	0.073
Particles (g/kg)	0.0082
CH_4 (g/kg)	0.0039
VOC_{tot} (g/kg)	0.014
Heavy metals to air (g/kg)	0.060×10^{-6}
Energy	
Non-renewable energy (MJ/kg)	0.078
renewable energy (MJ/kg)	0.00

[52] Kronlöf, A. Environmental Loadings from Transport and energy use. VTT Building Technology, Internal Report 6/1994, RTE-IR-6/1994. 22 p. The up-dating of data by Kai Tattari VTT RTE 1996.

6 ENVIRONMENTAL BURDENS FROM COATING BASED ON SPREADING RATES

The environmental burdens from coating come from consumption of coating materials and inducing emissions as volatile organic compounds. The consumption of materials takes place both because of the painting itself and because of loss of materials.

Waste in brush application was evaluated to be 5% and in factory application (vacuum application of the factory primer) 10%. A thinner was evaluated to be used during and after the application in cleaning and washing 10 ml per functional unit of one painted square meter of exterior wooden cladding. VOC-emissions during painting were calculated based on the solvent content of paints under consideration. Spreading rates for one square meter are presented in Table 6.1.

Table 6.1. Spreading rate. SB = solvent-borne, WB = water-borne, (*) two coats.

Alkyd (tall oil)		
	priming oil (SB)	200 ml/m^2
	priming oil (WB)	200 ml/m^2
	primer (SB)	90 ml/m^2
	factory primer (WB)	125 ml/m^2
	stain (SB)	2 x 150 ml/m^2 (*)
	stain (WB)	2 x 150 ml/m^2 (*)
	opaque: (SB)	
	undercoat	70 ml/m^2 + 15 ml/m^2 mineral spirit
	topcoat	70 ml/m^2
Linseed oil		
	primer	40 ml/ m^2
	opaque:	
	undercoat	50 ml/m^2 + 15 ml/m^2 mineral spirit
	topcoat	50 ml/m
Acrylic dispersion		
	stain	2 x 150 ml/m^2 (*)
	opaque	2 x 125 ml/m^2 (*)
	Swedish red paint	2 x 200 ml/m^2 (*)

7 ENVIRONMENTAL BURDENS OF SAWN TIMBER

The environmental profile of sawn timber was assessed based on data received from Kymmene Ltd. The inventoried material and energy flow concerned the year 1992 [53]. However, the consumption of forest fertilisers are average Finnish values from years 1992 - 1994.

The examination includes:

- nursing of seedlings (energy consumption and emissions related),
- manufacturing of fertilisers,
- manufacturing and use of pesticides,
- harvesting of timber (energy consumption and emissions related, consumption of lubricants),
- transportation of timber,
- manufacturing of facade boards,
- manufacturing and transportation of packing materials,
- transportation of other auxiliary materials,
- transportation of products,
- assembling (consumption of timber, use of nails and corresponding environmental burdens, energy consumption related to assembling and emissions),
- the "potential energy" of timber and loss (as "negative" energy), and
- the bound carbon in timber products (as "negative" carbon dioxide).

The examination does not cover the manufacturing of lubricants, blue stain preservers and marking colours and corresponding environmental burdens. According to the inventory, the total consumption of these materials is roughly 1.5 g per one kilo of dry, assembled facade board. In addition, the examination does not take into consideration the nitrogen and phosphate emissions during forest growth.

The estimate is based on the following assumptions:

- The consumption of nitrogen fertilisers is 0.11 kg (N)/(log m^3), the consumption of phosphorous fertilisers is 0.01045 kg (P)/log m^3 and the consumption of potassium fertilisers is 0.003 kg (K)/log m^3 [54].
- The consumption of pesticides is 0.003 kg (active ingredients)/m^3 of log. Within the forest growth, the pesticide emissions are 0.5% of the amount of pesticides. The pesticide emissions within production processes of pesticides is 25 mg/kg of pesticide (active ingredients).
- The environmental burdens from manufacturing of fertilisers and pesticides are based on reference [55].
- During harvesting of timber, lubricants are used at 0.0895 l/ m^3 of log. 33% of these are based on vegetable materials. The energy content of lubricant materials is 40 MJ/kg.

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[53] Häkkinen, T. Environmental impact of building materials. VTT Research Notes 1590. Technical Research Centre of Finland. Espoo 1994.38 p.

[54] Suomen tilastollinen vuosikirja (1996). Metsälannoitteiden myynti 1992 - 1994. The statistical year book (1996). Sale of forest fertilizers 1992 - 1994 (In Finnish).

[55] Weidema, B.P., Pedersen, R.L. & Drivsholm, T.S. Life cycle screening of food products, two examples and some methodological proposals. Danish Academy of technical Sciences. Group of cleaner technology, I. Kryger Consult A7S. Denmark 1995. 98 p. + app. 95 p.

- The consumption of timber is 1.9 kg/kg of dry assembled facade board. The value includes the loss within manufacturing and assembling as well as the amounts of bark and sawdust when these are used as fuels in the manufacturing process of timber.
- The use of packing materials is 0.78 g of steel bands and 2.1 g of wrapping materials per one kilo of dry and assembled facade board.
- The use of nails is 7.2 g per one kilo of dry and assembled facade board.

The carbon dioxide released in combustion of sawdust and bark is not taken into account, because the corresponding quantity was bound into wood from the atmosphere during forest growth within a relatively short time scale. The environmental burdens from harvesting and transportation of logs are not allocated on sawn timber with respect to wood chips utilised in other industries. Also the environmental burdens from harvesting and transportation of logs are not allocated to sawn timber with respect to bark and sawdust if these are used to produce heat and electricity utilised elsewhere than within manufacturing of sawn timber. The value 450 kg/m^3 was used as the density of wood. The energy content of wood was assumed to be 20.5 MJ/kg (dry materials). The carbon content was assumed to be 50% from the dry wood material.

The environmental profile of facade boards is presented in Table 7.1.

Table 7.1 Environmental profile of facade board (calculated per 1 kg of dry and assembled timber).

Emissions	
CO_2 (g/kg)	110
CO_2 (g/kg), bound	- 1800
CO (g/kg)	5.4
SO_2 (g/kg)	0.17
NO_x (g/kg)	2.6
NH_4 to air (g/kg)	0.0061
N_2O (g/kg)	0.0061
Particles (g/kg)	0.13
CH_4 (g/kg)	0.35
VOC_{tot} (g/kg)	1.1
Heavy metals to air (g/kg) *	0.00041
N_{kok} to water (g/kg)	0.028
F to water (g/kg)	0.0098
COD (g/kg)	0.000010
Lubricant emissions, bio. (g/kg)	0.000049
Lubricant emissions, min. (g/kg)	0.000090
Pesticide emissions (g/kg)	0.000065
Energy	
Non-renewable energy (MJ/kg)	1.7
renewable energy (MJ/kg) **	39
Potential energy ***	26
Natural raw materials	
Wood (g/kg)	1900
Auxiliary materials ******	
Blue stain preservatives (g/kg)	0.31
Marking colours (g/kg)	0.013
Lubricants (g/kg)	1.1

* Estimated based on fuels
** Includes the energy content of product and loss
*** The energy content of product and loss
**** The environmental burdens from manufacturing of auxiliary materials are not included

8 ENVIRONMENTAL BURDENS FROM WASHING MOULD FROM CLADDING

8.1 Sodium hypochlorite

The environmental burdens from washing cladding were estimated in such a way that first the environmental profile of sodium hypochlorite was estimated.

The basic data was received from a Finnish producer. Sodium hypochlorite is manufactured by a membrane process. Vacuum salt, water and electricity are used in the manufacturing. Finally, the sodium hypochlorite is diluted in order to have 7.6% concentration.

The study includes:

- the transportation of vacuum salt from Europe,
- the production of sodium hyrdoxide and chlorine from vacuum salt,
- the production of sodium hypochlorite from sodium hydroxide, chlorine and water,
- the transportation of sodium hypochlorite to a paint factory.

The environmental profile of sodium hypochlorite is presented in table 8.1.

Table 8.1 Environmental profile of sodium hypochlorite.

Emissions	
CO_2 (g/kg)	140
SO_2 (g/kg)	0.23
NO_x (g/kg)	0.61
Particles (g/kg)	0.31
CH_4 (g/kg)	0.33
HC and VOC_{tot} (g/kg)	0.41
Heavy metals to air (g/kg)	0.000034
COD (g/kg)	0.00028
BOD (g/kg)	0.0000068
NaCl (to water)	1.3
Energy	
Non-renewable energy (MJ/kg)	3.4
Renewable energy (MJ/kg) *	0.64
Natural raw materials	
Salt (NaCl)	140
Water	

8.2 Facade washing

The total facade is not washed with hypochlorite, but is used only for areas having mould growth. The area was assumed to be 10% of the functional unit. The consumption of cleaning agent was thus assumed to be 20 ml/m^2. Table 8.2 shows the assessed environmental burdens from facade washed.

Table 8.2 Environmental profile of facade washing.

Emissions	
CO_2 (g/kg)	2.8
SO_2 (g/kg)	0.0046
NO_x (g/kg)	0.012
Particles (g/kg)	0.0062
CH_4 (g/kg)	0.0066
HC and VOC_{tot} (g/kg)	0.0082
Heavy metals to air (g/kg)	0.00000068
COD (g/kg)	0.0000056
BOD (g/kg)	0.00000014
NaCl (to water)	0.026
Energy	
Non-renewable energy (MJ/kg)	0.068
Renewable energy (MJ/kg) *	0.013
Natural raw materials	
Salt (NaCl)	2.8
Water	

9 ALTERNATIVE COATING SYSTEMS

9.1 Service life prediction

The new building guides and regulations pay increased attention to service life design. According to the building product directive of EU (see also chapter 6.2), building products must fulfil the essential requirements during the economically reasonable service life. The economically reasonable service life requires that all the costs of a product including those from design, assembling, care and maintenance and the removal from service are taken into account. In addition, the economically reasonable service life considers the environmental points of view. The increased durability and long service life of a product improve its total economy and environmental properties.

The service life design is most clearly emphasised in the Eurocode 1 56, according to which the constructions must be designed so they are suitable for use and can reliably withstand all loads and attacks that will likely take place during building and use. These designs should have acceptable probabilities and take into account the intended service life. This also means that durability should be taken into account within the design of safety and adaptations.

The methods for service life design and service life prediction have been developed in international co-operation for example within RILEM, CIB and ISO. The ISO standard of service life of buildings [57] is under work. The lack of data concerning the service life of building products is now a critical point of service life design. The adoption of service life design in design processes requires the predicted life of building products to be investigated and declared.

According to the ISO standard draft, design life (expected service life / intended service life, deprecated) corresponds to the service life defined by the designer in order to support the decision making of the client. Predicted service life is an evaluated service life of a building or building component based on experimental or empirical tests or computational reasoning.

The principle of service life design is to ensure that the predicted service life is longer than the design life. If this condition is not valid the designer must change the plan so that it will be fulfilled. The plan can be changed for instance by choosing another (more resistant) product, by changing the conditions or the level of maintenance (sheltering, protecting) or by accepting a shorter design life. A designer together with the owner of a building or the client defines the design life of the building and the design lives of building components. As guidance, the ISO standard proposal presents the recommended classes of design life of buildings and building components and gives examples of minimum design life classes of some parts and components of buildings (Table 9.1.1). A designer prepares a maintenance plan for a building. The predicted replacements, repairs and other necessary activities during the design life of a building are specified and scheduled in the maintenance plan as well as instructions for maintenance for each part of the building if necessary.

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[56] ENV 1991 - Eurocode 1: Basis if Design and Actions on Structures. Part 1: Basis of design. CEN/TC250. final project team document. 1993. 76 p.
[57] ISO/DIS 15686-1. Buildings - Service life planning - Part 1: General principles. ISO/TC59/SC 14. 1998-07-16 - 1999-01-16.

Service life predictions have not yet been fully released, with the exception of a few documents. The existing methods are basically suitable for exterior constructions and other constructions in restraining conditions. For a number of products the procedure of service life prediction is too difficult and time consuming. For those products suitable approach would be the service life assessment with reference to empirical quality criteria. This means that the criteria would be created for different products, the fulfilling of which is necessary in order to achieve the required service life. The criteria include not only the product itself, but also design details, assembling, service conditions and care.

Table 9.1.1 Recommended classes of design life for buildings and building components and examples of minimum design life classes.

Intended service life of building	**Load bearing constructions**	**Building parts the renewal of which is difficult or expensive**	**Renewable building parts**	**Surface assemblies**
Not limited	Not limited	100	40	25
150	150	100	40	25
100	100	100	40	25
60	60	60	40	25
25	25	25	25	25
15	15	15	15	15
10	10	10	10	10

9.2 Renewal of surface coating

9.2.1 Renewal periods

A criterion to maintenance coating was defined as incipient flaking and in the case of the wood stains as erosion. A coating used in maintenance was determined as one coat of the same topcoat as the previous coating. A maintenance interval of 10 or 15 years was taken as the starting values for the opaque coating systems.

A maintenance period for wood stains is shorter and was defined as 5 years for average maintenance, 3 years for southern and western cladding, and 7 years for northern and eastern cladding.

The above stated maintenance intervals were recommended values given by the producers. In the study they were taken as starting values, the significance of which was studied.

9.2.2 Maintenance of coating

Surface preparation prior to maintenance coating was defined as mechanical scraping of the paint film and as washing the coating surface showing mould growth with a hypochlorite solution, rinsing and drying. The hypochlorite treatment is not usually needed for the whole cladding but only locally for areas with mould growth. The area was assumed to be 10 % of the cladding and the spreading rate per the functional unit was calculated to be 20 ml.

9.2.3 Spreading rate in maintenance

The spreading rate was defined to be the same as one layer of topcoat in the first coating although it is known that the spreading rate decreases when coating layers increase due to the fact that the surface becomes smoother. On the other hand in repainting there may be uncoated wood surface due to scraping and then the spreading rate is higher than defined (Table 9.2.1).

Table 9.2.1 Spreading rates used in maintenance. SB = solvent-borne, WB = water-borne.

Alkyd (tall oil)		
	stain (SB)	150 ml/m^2
	stain (WB)	150 ml/m^2
	opaque (SB)	70 ml/m^2
Linseed oil		
	opaque	50 ml/m^2
Acrylic dispersion		
	stain	150 ml/m^2
	opaque	125 ml/m^2
	Swedish red paint	200 ml/m^2

9.3 Removal of the old paint and repainting

All paint layers should be removed when the total film thickness becomes so thick that internal stress of the film cause cracking and flaking. This was evaluated to occur once during 100 years of service life when maintenance interval of opaque coatings was 10 years (after the 6th repainting) excluding Swedish red paint, which does not form a continuous film.

In assessing impacts of the removal of old coating film, the following methods were taken into account:

- infrared method,
- sand blasting and
- new cladding.

9.3.1 Infrared method

The environmental profile of infrared(IR)-method is based on the data given by Renotiimi Oy concerning the consumption of electricity. The paint removal by IR-method is based on the effect of infrared radiation. The temperature of the coating is increased to 100 - 200 ^{o}C. After two minutes of heating the paint is warm enough and can be removed. The area of heating of the equipment is 0.15 m^2. The paint waste is collected.

The inventory excludes both the production of IR-equipment and transportation. As the coating is heated small quantities of decomposition compounds are formed (VOCs). These too are excluded in the inventory. Table 9.3.1 shows the environmental profile of the paint removal by IR-method.

Table 9.3.1 Environmental profile of the paint removal by IR-method.

Emissions *	
CO_2 (g/m^2)	260
SO_2 (g/ m^2)	0.44
NO_x (g/ m^2)	0.61
Particles (g/m^2)	7.50
CH_4 (g/m^2)	0.73
HC and VOC_{tot} (g/m^2)	0.75
Heavy metals to air (g/m^2)	-
COD (g/m^2)	-
BOD (g/m^2)	-
Energy *	
Non-renewable energy (MJ/m^2)	7.23
Renewable energy (MJ/m^2)	1.44
Natural raw materials	
-	

* Calculated on the basis of electricity consumption

9.3.2 Sandblasting

The environmental inventory of paint removal by sandblasting covers the acquisition of sand, transportation of sand and sandblasting itself. The estimation is based on data received from Hiekkapuhaltamo Kärkilogistiikka Oy.

The sandblasting of painted wooden cladding is usually carried out by means of the dry method. Sieved natural sand or sometimes recycled sand is dried. The grain size is normally below 0.2 mm, but it can also be up to 0.7 mm for some sand qualities. The consumption of sand in sandblasting is 20 kg/m^2 of cleaned surface. The environmental profile of paint removal by sandblasting is presented in Table 9.3.2.

Table 9.3.2 Environmental profile of paint removal by sandblasting.

Emissions	
CO_2 (g/m^2)	580
SO_2 (g/m^2)	0.97
NO_x (g/m^2)	1.4
Particles (g/m^2)	16
CH_4 (g/m^2)	1.6
HC and VOC_{tot} (g/m^2)	3.3
Heavy metals to air (g/m^2)*	0.048×10^{-6}
COD (g/m^2)	0.000042
BOD (g/m^2)	-
Energy	
Non-renewable energy (MJ/m^2)	16
Renewable energy (MJ/m^2) *	3.2
Natural raw materials	
Sand (kg/m^2)	20

* Calculated on the basis of electricity consumption

9.3.3 Renewal of surface cladding

The inventory includes the environmental burdens of wooden cladding calculated with regard to one square meter (comparison Chapter 7). Table 9.3.3 shows the environmental profile for the cladding renewal.

Table 9.3.3 Environmental profile of renewal of cladding.

Emissions	
CO_2 (g/m^2)	1100
SO_2 (g/m^2)	1.7
NO_x (g/m^2)	26
Particles (g/m^2)	1.3
CH_4 (g/m^2)	3.5
HC and VOC_{tot} (g/m^2)	11
Heavy metals to air (g/m^2) *	0.0041
COD (g/m^2)	0.000099
BOD (g/m^2)	-
Energy	
Non-renewable energy (MJ/m^2)	17
Renewable energy (MJ/m^2) *	390
Natural raw materials	
Wood	

* Calculated on the basis of electricity consumption.

10 RECYCLING AND FINAL DISPOSAL OF COATED WOODEN CLADDING

Environmental impacts of recycling or final disposal of coated wood were assessed by two alternatives:

- Combustion (power station or small scale combustion)
- land filling.

Reuse of the painted exterior wooden cladding was assumed not to happen. According to VTT Building Technology estimations, 51% of wooden waste in Finland is disposed in landfills, 46% is incinerated and 2% is reused (doors, windows,etc.) (Table 10.1).

Table 10.1 Recycling and final disposal of wooden building waste in Finland in 1995. Estimation, in tons.

Wooden building waste	Dumping	Combustion	Reuse
New construction sites	15 000 t	45 000 t	0
Building renovation sites	140 000 t	100 000 t	5 000 t
Building demolition sites (total buildings)	55 000 t	45 000 t	5 000 t
Total (1000 tons)	210 000 t	190 000 t *	10 000 t
Total (%)	51%	46%	2%

* 90% practical application, main part of which is small scale combustion

10.1 Final disposal

As final disposal in landfills is included in LCI of wooden exterior cladding, the emissions from the anaerobic decomposition of the products should be estimated. Very different estimations have been presented both concerning the amount of emitting gaseous carbon compounds from wood waste and the composition of these gases. Micales and Skog [58] have estimated that a maximum of only 0-3% of the carbon from wood is ever emitted as landfill gas. The remaining carbon stays in the landfill. Some of the carbon can be removed during leaching, but large part of it is stored permanently. Micales and Skog estimate that the mix of gases during methane production can be 60% methane and 40% carbon dioxide.

Decomposition of wooden products in landfill occurs in a series of stages by specific landfill bacteria. In the first stage of decomposition oxygen from the waste is removed by aerobic bacteria. In the second stage of the decomposition process three major groups of bacteria are assumed to be involved in methane production from waste [59]:

- The hydrolytic and fermentative bacteria, which convert biological polymers such as cellulose and hemicellulose to sugars which are then fermented to carboxylic acids, alcohols, carbon dioxide and hydrogen,
- the oblicate proton reducing acetogenic bacteria, which convert longer-chain carboxylic acids and alcohols to acetate, hydrogen and carbon dioxide,

[58] Micales, J. A., Skog K. E. The Decomposition of Forest Products in Landfills. International Biodeterioration & Biodegradation Vol. 39. No 2-3 (1997). 145 - 158.

[59] Barlaz, M.A. et al. Bacterial population development and chemical characteristics of refuse decomposition in a simulated sanitary landfill. Applied and Environmental Microbiology Vol. 55. No 1 (1989). 55 - 65.

- the methanogenic bacteria, which convert primarily acetate and hydrogen, to carbon dioxide and methane.

Landfills consist of very heterogeneous mixed waste. Different areas of a landfill can be in various stages in the decomposition process. Many factors impact the rate of decomposition in landfills. The most critical factor in landfill decomposition is the amount of moisture in the waste.

The environmental burdens from final disposal were studied in such a way that the significance of alternative pre-consumptions were investigated. The parameters included the degree of decomposition of wooden material and the composition of released gases.

10.2 Combustion

In combustion, wood is mainly transformed into carbon dioxide, which is released into the atmosphere. However, in the LCI of wooden claddings it was considered that combustion of the wood does not increase the carbon dioxide concentration in the atmosphere. This is because the released carbon is originally bound into wood material in growing trees during a relatively short time period (compared to that of fossil fuels). Carbon monoxide and hydrocarbon emissions are generated in the burning of all fuels when the combustion is incomplete. Most of the hydrocarbon emissions from wood burning are methane, which is primarily generated in the small-scale boiler. Especially hydrocarbon emissions from burning of wood in small boilers vary in a large range depending on the moisture content of the wood and the burning conditions. In this life cycle inventory of wooden exterior claddings it was estimated that in small scale boiler carbon monoxide emission are 5 times and methane emission 2 times bigger than on a power station scale.

11 ENVIRONMENTAL BURDENS OF THE SURFACE COATING OF WOOD

11.1 Environmental profiles of coatings

Tables 11.1.1 to 11.1.13 show the environmental profiles of the coatings studied. These tables also show the relative effects of various factors on the environmental burdens. The study includes:

- manufacturing of paints and paint components,
- transportation of materials and products, and
- application of paints.

In the tables 11.1.1 to 11.1.13 the following acronyms are used:

- MF for manufacturing,
- TRP for transportation,
- NRE for non-renewable energy,
- RE for renewable energy, and
- VOC_{app} for the VOCs released during application.

Different coatings are not fully comparable as being of similar composition, but the comparison must be based on equivalent functional units. The environmental burdens from individual coatings, however, are summarised according to the results as follows.

In all paints with calcium carbonate or talc as filler, ferric oxides or red or yellow ochres as pigments, or ferric sulphate as an additive, the environmental burdens are rather low with respect to these components. In addition, the relative significance of paint transportation (100 km) was minor (in most cases <1% from the total burdens).

In the priming oils and stains, in which the content of white spirit is high, the solvent is responsible for the main part of the environmental burdens. The environmental burdens (emissions and use of resources) are typically one third less in the corresponding water-borne products having alkyd as the binder. However, the emissions of VOCs are only 0.1 -0.2 percentages from the corresponding value of solvent-borne priming oils and stains.

The environmental burdens of acrylate stains are roughly double to those of water-borne alkyd stains.

In the coatings where the content of titanium dioxide or zinc oxide pigments is 10 - 30%, the environmental burdens of the paint is significant based on these pigments. Titanium dioxide is responsible for some tens of percentages and zinc oxide for roughly 10% of the different environmental burdens.

The opaque alkyd or acrylate topcoats have environmental burdens roughly in the same order of magnitude, independent of VOC emissions. However, the paints should only be compared based on equivalent functional units (compare section 11.2).

With regard to the linseed oil coatings, the main part of the environmental burdens (emissions and use of resources) come from the linseed oil the content of which is 45 -

50%. With regard to the Swedish red paint, linseed oil is roughly as much responsible for the different environmental burdens as red ochre.

The environmental burdens from the manufacturing of coatings were assumed to be the same, apart from VOC emissions. Thus the relative affect of manufacturing varies according to the magnitude of other environmental burdens. However, the significance of manufacturing was typically around 10% from the total individual components of burdens.

Table 11.1.1 The environmental profile of the solvent-borne priming oil (no 1 (Table 5.1.1), per 1 kg of coating.

Coating 1	Total	White spirit	Alkyd	MF	TRP
	g or MJ/kg	%	%	%	%
NRE	48	87	7.0	5.6	<1
RE	1.0	38	22	40	<1
CO_2	410	33	27	39	1.3
SO_2	1.5	18	61	20	<1
NO_x	1.5	42	30	23	4.9
Particles	0.97	19	48	33	<1
CH_4	0.66	27	3.9	68	<1
VOC	0.82	44	<1	55	1.7
VOC_{app}	900	100	<1	<1	<1

Table 11.1.2 The environmental profile of the solvent-borne undercoat (no 2) (Table 5.1.1), per 1 kg of coating.

Coating 2	Total	White spirit	Alkyd	$TiO_{2\ Sulf}$	$CaCO_3$	MF	TRP
	g or MJ/kg	%	%	%	%	%	%
NRE	40	54	22	18	<1	6.8	<1
RE	1.8	11	31	35	<1	23	<1
CO_2	1000	6.6	27	49	1.8	16	<1
SO_2	5.7	2.4	40	51	1.3	5.3	<1
NO_x	4.1	7.6	27	51	4.3	8.4	1.8
Particles	3.6	2.5	32	39	17	8.9	<1
CH_4	1.8	4.9	3.6	66	<1	25	<1
VOC	2.1	8.7	<1	68	1.3	22	<1
VOC_{app}	450	100	<1	<1	<1	<1	<1

Table 11.1.3 The environmental profile of the factory primer (no 3) (Table 5.1.1), per 1 kg of coating.

Coating 3	Total	Alkyd	$TiO_{2\ Sulf}$	$CaCO_3$	MF	TRP
	g or MJ/kg	%	%	%	%	%
NRE	17	20	62	<1	16	<1
RE	1.6	14	60	<1	26	<1
CO_2	1000	11	73	<1	16	<1
SO_2	5.6	16	78	<1	5.4	<1
NO_x	4.1	11	77	2.2	8.5	1.8
Particles	3.2	14	66	9.7	10	<1
CH_4	2.3	1.1	79	<1	20	<1
VOC	2.6	<1	82	<1	18	<1

Table 11.1.4 The environmental profile of the water-borne priming oil (no 4) (Table 5.1.1), per 1 kg of coating.

Coating 4	Total	Alkyd	MF	TRP
	g or MJ/kg	%	%	%
NRE	6.2	55	44	1.3
RE	<1	35	65	<1
CO_2	280	40	58	1.9
SO_2	1.2	75	25	<1
NO_x	<1	52	40	8.4
Particles	<1	58	41	1.0
CH_4	<1	5.4	94	<1
VOC	<1	<1	97	3.0

Table 11.1.5 The environmental profile of the solvent-borne stain (no 5) (Table 5.1.1), per 1 kg of coating.

Coating 5	Total	White spirit	Alkyd	Fe_2O_3	MF	TRP
	g or MJ/kg	%	%	%	%	%
NRE	46	79	15	<1	5.9	<1
RE	1.2	28	38	<1	35	<1
CO_2	500	23	44	<1	32	<1
SO_2	2.4	9.7	77	<1	13	<1
NO_x	1.9	29	48	1.6	19	3.9
Particles	1.4	11	66	<1	23	<1
CH_4	<1	23	7.8	<1	68	<1
VOC	<1	40	<1	<1	58	<1
VOC_{app}	770	100	<1	<1	<1	<1

Table 11.1.6 The environmental profile of the water-borne stain (no 6) (Table 5.1.1), per 1 kg of coating.

Coating 6	Total	Alkyd	Fe_2O_3	MF	TRP
	g or MJ/kg	%	%	%	%
NRE	9.7	71	<1	28	<1
RE	0.88	52	<1	48	<1
CO_2	390	57	<1	41	1.4
SO_2	2.1	85	<1	14	<1
NO_x	1.4	67	2.2	26	5.4
Particles	1.3	74	<1	26	<1
CH_4	<1	10	<1	88	<1
VOC	<1	<1	<1	96	3.0

Table 11.1.7 The environmental profile of the alkyd undercoat (no 7) (Table 5.1.1), per 1 kg of coating.

Coating 7	Total	White spirit	Alkyd	$TiO_{2\ Sulf}$	$CaCO_3$	MF	TRP
	g or MJ/kg	%	%	%	%	%	%
NRE	40	24	34	35	<1	6.8	<1
RE	2.7	3.2	34	48	<1	15	<1
CO_2	1700	1.8	27	61	1.1	9.7	<1
SO_2	9.9	<1	37	59	<1	3.0	<1
NO_x	6.7	2.1	27	62	2.7	5.2	1.1
Particles	5.6	<1	33	50	11	5.7	<1
CH_4	3.0	1.3	3.5	80	<1	15	<1
VOC	3.4	2.4	<1	83	<1	13	<1
VOC_{app}	200	100	<1	<1	<1	<1	<1

Table 11.1.8 The environmental profile of the undercoat with zinc oxide (no 8) (Table 5.1.1), per 1 kg of coating.

Coating 8	Total	Wood turpentine	Linseed oil	ZnO	MF	TRP
	g or MJ/kg	%	%	%	%	%
NRE	37	<1	80	11	7.4	<1
RE	26	<1	97	<1	1.6	<1
CO_2	810	4.2	46	29	20	<1
SO_2	3.0	50	35	5.4	9.9	<1
NO_x	7.0	3.2	86	4.7	5.0	1.0
Particles	1.4	36	30	8.4	24	<1
CH_4	<1	2.0	30	13	54	<1
VOC	1.2	3.3	43	13	39	1.2
VOC_{app}	200	100	<1	<1	<1	<1

Table 11.1.9 The environmental profile of the white linseed oil paint (no 9) (Table 5.1.1), per 1 kg of coating.

Coating 9	Total	Linseed oil	$TiO_{2\ Sulf}$	ZnO	$CaCO_3$	Talc	MF	TRP
	g or MJ/kg	%	%	%	%		%	%
NRE	43	62	24	4.9	<1	1.7	6.3	<1
RE	24	94	4.1	<1	<1	<1	1.7	<1
CO_2	1400	24	52	8.3	1.0	3.5	11	<1
SO_2	6.0	16	73	1.4	<1	3.9	5.0	<1
NO_x	9.4	57	33	1.7	1.4	1.8	3.7	<1
Particles	3.4	11	62	1.6	14	2.1	9.5	<1
CH_4	2.6	8.7	69	2.1	<1	2.0	17	<1
VOC	3.2	14	66	2.4	<1	1.9	14	<1

Table 11.1.10 The environmental profile of the yellow linseed oil paint (no 10) (Table 5.1.1), per 1 kg of coating.

Coating 10	Total	Linseed oil	Yellow ochre	ZnO	$CaCO_3$	MF	TRP
	g or MJ/kg	%	%	%	%	%	%
NRE	32	82	2.5	6.5	<1	8.3	<1
RE	23	98	<1	<1	<1	1.8	<1
CO_2	670	50	6.2	18	1.4	24	<1
SO_2	1.6	58	17	5.0	2.3	18	<1
NO_x	6.6	82	7.8	2.5	1.4	5.3	1.1
Particles	1.1	33	3.3	5.1	28	29	<1
CH_4	0.78	29	4.6	7.0	1.0	58	<1
VOC	1.1	42	6.7	7.0	1.2	42	1.3

Table 11.1.11 The environmental profile of the water-borne stain (no 11) (Table 5.1.1), per 1 kg of coating.

Coating 11	Total	Acrylate	Fe_2O_3	MF	TRP
	g or MJ/kg	%	%	%	%
NRE	20	86	<1	13	<1
RE	<1	27	<1	73	<1
CO_2	860	81	<1	19	<1
SO_2	3.7	91	<1	8.1	<1
NO_x	3.2	86	<1	11	2.3
Particles	<1	64	<1	35	<1
CH_4	2.3	80	<1	19	<1
VOC	4.4	89	<1	10	<1

Table 11.1.12 The environmental profile of the acrylate paint (no 12) (Table 5.1.1), per 1 kg of coating.

Coating 12	Total	Acrylate	$TiO_{2\ Sulf}$	$CaCO_3$	MF	TRP
	g or MJ/kg	%	%	%	%	%
NRE	39	66	26	<1	6.9	<1
RE	1.6	14	60	<1	26	<1
CO_2	1900	53	39	<1	8.2	<1
SO_2	9.7	52	45	<1	3.1	<1
NO_x	7.7	52	41	1.2	4.6	1.0
Particles	3.6	24	58	8.6	8.9	<1
CH_4	5.0	55	36	<1	9.0	<1
VOC	8.3	69	25	<1	5.4	<1

Table 11.1.13 The environmental profile of the swedish red paint (no 13) (Table 5.1.1), per 1 kg of coating.

Coating 13	Total	Linseed oil	Rye flour	Red ochre	Ferric sulphate	MF	TRP
	g or MJ/kg	%	%	%	%	%	%
NRE	10	35	2.8	35	<1	27	<1
RE	3.8	78	<1	12	<1	11	<1
CO_2	410	11	5.1	43	<1	39	1.3
SO_2	1.4	8.9	1.0	67	<1	21	<1
NO_x	1.6	46	8.2	16	<1	22	4.5
Particles	0.94	5.1	<1	60	<1	34	<1
CH_4	0.57	5.3	<1	14	<1	80	<1
VOC	0.59	10	<1	9.8	<1	77	2.4

11.2 Environmental burdens of coating systems

The environmental burdens of different coating systems were estimated and compared to each other. The chosen time period was 100 years. The studied coatings are shown in Table 11.2.1.

Table 11.2.1 Coating systems in functional units.

	Primer	Undercoat	Topcoat	Renewal period
1.		Swedish red paint	Swedish red paint	10
2.	Primer with ZnO pigment	Linseed oil undercoat	Linseed oil topcoat	10
3.	Primer with ZnO pigment	Linseed oil undercoat	Linseed oil topcoat	10
4.	SB priming oil	SB stain	SB stain	5
5.	WB priming oil	WB stain	WB stain	5
6.	SB priming oil	WB stain	WB stain	5
7.	SB priming oil	Alkyd opaque undercoat	Alkyd opaque topcoat	10
8.	Factory primer	Alkyd opaque undercoat	Alkyd opaque topcoat	10
9.	WB priming oil	WB acrylic stain	WB acrylic stain	5
10.	SB priming oil	WB acrylic stain	WB acrylic stain	5
11	SB priming oil	SB alkyd opaque undercoat	Acrylic opaque topcoat	10
12.	SB priming oil	Acrylic opaque topcoat	Acrylic opaque topcoat	10
13.	Factory primer	Acrylic opaque topcoat	Acrylic opaque topcoat	10
14.	WB priming oil	SB alkyd opaque undercoat	Acrylic opaque topcoat	10
15.	WB priming oil	Acrylic opaque topcoat	Acrylic opaque topcoat	10

The life cycle inventory of the coating systems includes:

- production processes of coating materials,
- manufacturing and assembling of wooden cladding,
- painting, repainting and paint removal when necessary.

Paint layers should be removed when the total film thickness becomes so thick that internal stress of the film cause cracking and flaking. This was evaluated to occur once during 100 years of service life when maintenance interval of opaque coatings was 10 years excluding Swedish red paint, which does not form a continuous film. The assembling of a new cladding was taken as the primary mean of paint removal. In addition, the effect of sand blasting and IR-method was studied.

Undercoating was assumed to be done before the assembling of boards except for Swedish red paint. This affects the spreading rate of the undercoats. Also the loss of materials was estimated and taken into account both with regard to the manufacturing process, assembling and painting. The environmental profiles of the coatings are presented in Table 11.2.2.

In the following the coatings are compared to each other on the basis of the pre-consumptions that:

- the renewal periods are according to Table 11.2.1, and
- the paint removal (when necessary) takes place by help of removal of whole cladding and assembling of a new one.

The comparison of the alternative coating systems is only made with reference to:

- the consumption of non-renewable energy,
- the CO_2, SO_2 and NO_x emissions to air, and
- VOC emissions to air.

Table 11.2.2. Environmental profiles of coatings. Energy consumption and emissions are presented as MJ/m^2 or g/m^2 during 100-year time period. The estimation includes the environmental burdens of wooden exterior wall. The estimation does not take into account the bound (”negative”) carbon in wood (compare section 11.3).

Coating system															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
NRE *	45	85	75	160	52	61	100	88	95	100	140	140	130	120	120
RE **	400	800	800	390	390	390	780	780	390	390	780	780	780	780	780
CO_2	2200	3800	3000	2600	2500	2500	4200	4500	4400	4400	6200	6600	6800	6200	6500
SO_2	5.6	10	5,6	8,8	9,4	9,4	14	16	16	16	23	25	27	23	25
NO_x	30	62	60	32	31	31	60	61	38	38	67	69	70	67	68
Part.	3.9	6.4	3.9	5.5	5.8	5.8	9.0	10	4.9	4.9	11	11	12	11	11
CH_4	5.0	9.8	7.9	5.5	5.4	5.4	10	11	12	12	17	18	19	17	18
VOC	13	25	23	13	13	13	26	27	27	27	38	40	41	38	40
VOC paint.	0	52	52	2400	0	200	630	230	0	200	520	400	0	120	0
HM ***	0.0042 ****	0.0093 ****	0.0089 ****	0.035 ****	0.041 ****	0.041 ****	0.032 ****	0.032 ****	0.0055 ****	0.0052 ****	0.015 ****	0.011 ****	0.011 ****	0.015 ****	0.012 ****
COD	<0.01	0.090	0.089	1.6	1.9	1.9	1.2	1.2	2.3	2.3	1.9	2.0	2.0	1.9	2.0
P_{tot}	1.0	3.3	3.4	0	0	0	0.45	0.45	0	0	0	0	0	0	0
N_{tot}	8.9	0.55	0.55	0.28	0.28	0.28	0.55	0.55	0.28	0.28	0.55	0.55	0.55	0.55	0.55
F_{tot}	0.29	0.19	0.19	0.097	0.097	0.097	0.19	0.19	0.097	0.097	0.19	0.19	0.19	0.19	0.19
SO_4^{2-}	0	40	0	0	0	0	51	68	0	0	75	81	97	75	81

* Non renewable energy

** Renewable energy

*** Heavy metals to air

**** Figures are not comparable because of lack of information with regard to several processes

From this table, the following conclusions are drawn:

During the 100 year time period, the lowest environmental burden (emissions and the use of energy) is induced by the Swedish red paint system.

The environmental burdens with roughly the same magnitude are also induced from water-borne alkyd stains 5 and 6. However, the VOC emissions of stain 6 are roughly ten folds compared to those of stain 5. This is because of the solvent-borne priming oil in stain 6.

The environmental burdens of the solvent-borne alkyd based stain 4 are otherwise of the same order of magnitude than those of water-borne stains 5 and 6. The only excepts are the use of NRE, which is roughly three fold and the VOC emissions roughly 200 or 10 fold.

The environmental burdens of acrylate stains 9 and 10 are roughly two folds compared to alkyd stains 5 and 6. However, the VOC emissions of stains 9 and 10 are not higher than those of stains 5 and 6.

Opaque alkyd coating 7 has environmental burdens that are roughly double compared to alkyd stains 5 and 6 except for VOC emissions, which are roughly 50 fold compared to stain 5 and 3 fold compared to stain 6.

Opaque acrylate coatings 11 to 15 have the highest environmental burdens irrespective of VOC emissions. The carbon dioxide and sulphur dioxide emissions of coating 15 are roughly 50% higher than those of opaque alkyd coating 7. On the other hand, the VOC emissions of system 15 are less than 10% from those of coating 7.

The environmental burdens of linseed oil coatings 2 and 3 are roughly half compared to those of coating 15 and roughly 25% less compared to coating 7. However, the VOC emissions of coatings 2 and 3 are significantly lower than those of opaque alkyd coating 7.

The loss of coating materials during application was assumed to be 5%. With reference to environmental burdens, the loss, naturally, represents the same magnitude.

Table 11.2.3 presents the environmental burdens of the six coating systems (1, 2, 6, 7, 9 and 15) excluding the timber cladding. The paint removal (when necessary) was assumed to be made by means of sand blasting.

Table 11.2.3 Environmental burdens of coating systems 1, 2, 6, 7 and 9 during 100 years time period per 1 m^2 of cladding excluding the timber cladding. The results of the estimation are given with the accuracy of one number, but with regard to CO_2 emissions with the accuracy of two numbers.

	1	2	6	7	9	15
NRE * (MJ/m^2 year)	30	70	40	90	80	100
RE ** (MJ/m^2 year)	10	30	3	10	2	7
CO_2 (g/m^2 year)	1100	2200	1400	2600	3300	4900
SO_2 (g/m^2 year)	4	8	8	10	10	20
NO_x (g/m^2 year)	4	10	5	10	10	20
Particles (g/m^2 year)	3	20	5	20	4	20
VOC_{tot} (g/m^2 year)	2	50	200	600	20	20

* Non-renewable energy
** Renewable energy

11.3 Study of alternative pre-consumptions

The environmental burdens of wooden exterior cladding were studied with respect to the following alternative pre-consumptions:

- the length of the renewal period (Table 11.3.1),
- the means of renewal of the surface coating (Table 11.3.2), and
- the alternative means of final disposal or recycling.

Table 11.3.1 Estimated environmental burdens (emissions and use of energy) of wooden exterior wall during 100 years time period with respect to alternative renewal periods of the surface coating (in g/m^2 or MJ/m^2). The portion of the wooden cladding from the total burdens is presented in parenthesis (in %). NRE = non-renewable energy.

Renewal period	**NRE**	**CO_2**	**SO_2**	**NO_x**	**VOC_{tot}**
Swedish red barn (1)					
7 years	55	2600	7.0	32	13
10 years	45 (37%)	2200 (49%)	5.6 (30%)	30 (86%)	13 (87%)
15 years	37	1900	4.5	29	12
Linseed oil based system (2)					
7 years	100	4300	12	66	78
10 years	85 (20%)	3800 (29%)	10 (17%)	62 (41%)	77 (14%)
15 years	57	2300	6.8	34	66
Water-borne alkyd based system (6)					
5 years	61 (28%)	2500 (43%)	9.4 (18%)	31 (84%)	210 (5%)
7 years	51	2100	7.2	29	210
Opaque alkyd based system (7)					
7 years	120	4800	18	63	740
10 years	100 (16%)	4200 (26%)	14 (12%)	60 (43%)	660 (1%)
15 years	74	2600	10	32	590
Opaque acrylate based system (15)					
7 years	150	7900	32	74	46
10 years	120 (28%)	6500 (33%)	25 (14%)	68 (75%)	40 (55%)
15 years	83	4400	18	38	24

Table 11.3.2 Environmental burdens of wooden exterior cladding. Method of paint removal is studied as parameter. NRE = non-renewable energy, RE = renewable energy.

Method of paint	**NRE (MJ/m^2)**	**RE (MJ/m^2)**	**CO_2 (g/m^2)**	**SO_2 (g/m^2)**	**NO_x (g/m^2)**	**Particles (g/m^2)**	**CH_4 (g/m^2)**	**VOC (g/m^2)**	**$VOC_{painting}$ (g/m^2)**
Coating system 2									
New claddings	85	800	3800	10	62	6	10	25	52
Sand blasting	84	420	3300	9	38	21	8	18	52
IR-method	76	420	3000	9	37	6	7	15	52
Coating system 7									
New claddings	100	780	4200	14	60	9	10	26	630
Sand blasting	100	400	3700	14	36	23	9	18	630
IR-method	93	390	3300	13	35	8	8	16	630
Coating system 12									
New claddings	140	780	6600	25	68	11	18	40	400
Sand blasting	140	390	6000	24	44	25	16	32	400
IR-method	130	390	5700	24	43	10	15	30	400
Coating system 15									
New claddings	120	780	6500	25	68	11	18	40	0
Sand blasting	120	390	6000	24	44	25	16	32	0
IR-method	110	390	5700	24	43	10	15	30	0

The significance of the renewal period, the means of paint removal and washing paint surface with regard to the environmental burdens of wooden exterior cladding is summarised as follows:

The variation of service life between 7, 10, and 15 years with opaque coatings and between 5 and 7 years with stains, affects the carbon dioxide emissions roughly by ±15% compared to the starting values. These starting values were calculated using 10 years as the starting value for opaque coatings and 5 years for stains. The corresponding effect on the use of non-renewable energy is roughly ±20%. The renewal period only slightly affects the quantity of VOC emissions, because the topcoats of the studied systems are water-borne. The significance of the renewal period is in most cases less than are the differences between the studied systems (section 11.2).

The share of wooden cladding itself from the use NRE and emissions of carbon and sulphur oxides is roughly 20 to 40%. The share of wooden cladding from VOC emissions and nitrogen oxide emissions is higher. However, the share of wooden cladding from VOC emissions is rather low with regard to those systems where solvent-borne coatings are applied.

The environmental burdens of the alternative means of paint removal differed significantly from each other only with regard to RE (renewable energy). In addition to RE, the studied environmental burdens included NRE and the emissions of CO_2, SO_2, NO_x and VOC to air. With regard to coatings 7 and 12, the consumption of RE was roughly two fold when using cladding renewal when compared to sand blasting or IR-method (Table 11.2.1). In addition, the quantity of wooden waste was two folds.

Washing wooden exterior cladding with sodium hypochloride has only a minor effect on the whole system's environmental burdens.

The alternative means of recycling or final disposal are the following (Table 11.3.3):

- disposal by combustion,
- utilisation by combustion, and
- final disposal on dumping areas.

When disassembled wooden boards are utilised as energy, the corresponding quantity of other fuels can be saved. The system of recycling or final disposal was enlarged so that the system also covers the saving of other fuels. The point of comparison is fuel oil having the same energy content as that of the wooden waste. The release of decomposition gases in damping areas are studied by using the following pre-consumptions (see section 10):

- the carbon bound in wood is released producing CO_2,
- the carbon bound in wood is released producing CH_4, and
- 3% of bound carbon is decomposed producing both methane (60%) and carbon dioxide (40%).

Table 11.3.3 The alternative means of recycling or final disposal and their effect on the final result. The study is made with respect to coating 7 (Table 11.2.1). The estimated use of energy and release of emissions are given in MJ or g/m^2 over 100 years. The "saved emissions" are assumed to be from "avoided use of fuel oil". The estimated values are given with accuracy of one figure.

	Coating materials	Wooden cladding	Combustion or decomposition	Saved burdens	Total
Disposal by combustion of waste					
NRE	70	30	-	-	100
RE	7	800	-	-	800
CO_2	2000	-20000+2000	20000	-	4000
CH_4	4	7	5	-	20
VOC_{tot}	600	20	10	-	700
Solid waste	-	-	100 *	-	100 *
Utilisation by combustion					
NRE	70	30	-	-200	-100
RE	7	800	-	-	800
CO_2	2000	-20000+2200	20000	-20000	-10000
CH_4	4	7	5	-10	5
VOC_{tot}	600	20	10	-10	700
Solid waste	-	-	100 *	-	100 *
Disposal on damping areas. All carbon to CO_2.					
NRE	70	30	-	-	100
RE	7	800	-	-	780
CO_2	2000	-20000+2000	20000	-	4000
CH_4	4	7	0	-	10
VOC_{tot}	600	20	9	-	700
Solid waste	-	-	10 000 **	-	10 000 **
Disposal on damping areas. All carbon to methane.					
NRE	70	30	-	-	100
RE	7	800	-	-	800
CO_2	2000	-20000+2000	0	-	10000
CH_4	9	7	7000	-	7000
VOC_{tot}	600	22	7000	-	7000
Solid waste	-	-	10000 **	-	10000 **
Disposal on damping areas. 3% from wood bound carbon to either CO_2 (40%) or CH_4 (60%).					
NRE	70	30	-	-	100
RE	7	800	-	-	800
CO_2	2000	-20000+2000	200	-	-10000
CH_4	9	7	10	-	30
VOC_{tot}	600	20	10	-	700
Solid waste	-	-	10000	-	10000

* Combustion ash from wood
** Until the wooden material is decomposed

The significance of the alternative means of recycling or final disposal were studied with regard to the use of energy and release of greenhouse gases, VOC emissions and solid waste. The following results were determined.

If dismantled wooden cladding is utilised as energy so that fossil fuels are saved at the same time, NRE is saved roughly 2 fold and CO_2 emissions are saved roughly 4 fold compared to the corresponding burdens from the manufacturing and use of the wooden exterior cladding. Also the mere disposal of wooden waste through combustion is more beneficial than the disposal on damping areas, if the carbon bound by wood is gradually released as CO_2. However, this is probably not to happen, but a significant share of wooden waste remains non-decomposed and on the other hand a significant part of the wood bound carbon is released as methane as the wooden material decomposes. If a major share of wooden material decomposes and a major share of carbon is released as methane, the disposal on damping areas becomes very disadvantageous. This is because the climate change potential of methane has been assessed to be remarkably higher than that of carbon dioxide. However, if a major share of wooden waste remains non-decomposed, the damping is beneficial because of lower net burdens of CO_2 but disadvantageous because of greater quantities of solid waste.

11.4 Significance of results and needs of further studies

The environmental burdens of wooden exterior wall depend primarily on:
- the coating system, the selection of undercoat and topcoat,
- the composition of the coating, especially the content of acrylate, alkyd and linseed oil and the content of titanium dioxide and zinc oxide used as pigments,
- the durability of surface coating and the length of necessary renewal periods, and
- the manufacturing process of the coatings (in some degrees).

On the other hand these factors interact with each other. For example, the composition of the coatings affect the length of the renewal period. Improving the environmental properties of coating systems means the optimisation of the factors mentioned above.

The significance of other additives than the previous mentioned binders, intermediate agents and pigments is rather low especially with regard to the use of energy, the release of related emissions and also with regard to VOC emissions.

The life cycle inventories of the coatings and the components are mainly based on the data received from the producers. This data consists of the energy and materials flows of the systems. Some of the inventories were based on literature. In most cases the data thus concerns the European averages calculated on the bases of input and output values given by the European producers. With respect to the data quality, the poorest results are the environmental profiles of synthetic ferric oxide and linseed oil varnish. With respect to the final result, the quality of data is very important concerning acrylate and alkyd binders, white spirit, titanium dioxide and zinc oxide. The environmental profiles of these components were assessed in co-operation with the producers. However, the environmental profile of acrylate binder is based on:
- the European average of polymethyl methacrylate, which is calculated based on the information received from the producers,
- the estimation derived together with the producer concerning the mixture ration of co-polymers in acrylate binder, and
- the data concerning the environmental burdens of butyl acrylate, which was received from literature (section 4.12).

With regard to the environmental burdens, the data concerning energy contents and emissions of carbon dioxide is the most reliable. Also the data concerning emissions of sulphur dioxides and nitrogen oxides and total quantities of VOCs can be taken as tolerably reliable. They are mainly generated because of the use of fuels and because of some known processes, like the

VOCs coming from the evaporation of solvents. If average specific environmental profiles of fuels and electricity are accepted as the starting point, life cycle inventories give comparable results with respect to those parameters which are primarily related with the consumption of fuels and electricity. The consumption of fuels and electricity is normally easy to trace because of their economic significance.

However, comparable results are not achieved from separate life cycle inventories if differing and non-justified specific values for fuels and electricity are applied and also if non-justified different system boundaries are used (for example if the procurement of fuels and electricity is either included or excluded). This means that the detailed documentation of the calculation and handling principles of energy is a necessary precondition in order to compare results from separate life cycle inventories. In those cases where literature data was used in this study, the informed dealing principles of energy were the same as applied in this study.

The estimations on emissions of heavy metals and particles were based either on mere energy data or also considering the process emissions. Thus the results are not comparable with regard to heavy metals and particles. The study includes such mineral processes like production of red ochre and synthetic ferric oxide pigments that probably also induce emissions of heavy metals. However, these are not taken into account because of lack of information. The study could be complemented with respect to these parameters in order to give a better basis for the environmental development of the manufacturing processes and selection of aditives. The complementing of the study by data concerning heavy metals and particles would require receiving this information from all mineral processes involved. Also the results concerning the emissions to water are not comparable with each other. The supplementing of results would also require data on measured emissions to water.

Specifying the data concerning the hydrocarbon emissions and VOCs of the polymer industry would be very useful for the paint industry using of the polymer products in manufacturing processes. The environmental profiles of the polymer products which have been published as European averages are highly valuable basic data in the life cycle inventories of many other products which include additives from the polymer industry. Adaptability would be even better if the hydrocarbons typical or having high environmental potential could be specified in the eco-profiles. These especially include methane because of its greenhouse potential and also PAH compounds and benzene because their health effects.

The alternative means of recycling or final disposal were dealt with in this report as parameters having an effect on the environmental burdens of coated wooden exterior cladding. However, the result must be viewed as a preliminary study. In order to carry out further studies, basic information on the long term behaviour of organic materials in final disposal site should be available.

12 SUMMARY

The target of this study was to create a system for evaluating the environmental impact of coated exterior cladding considering the service life and care of the surface. The object was that the paint industry could utilise the results when assessing the environmental burdens of coatings and when developing tools for environmental product development.

The inventory covers production of coating components and surface coating materials, all transportation, application, care and renewal of the coating during the 100 years, recycling and final disposal. The functional unit in the life cycle inventory (LCI) is one square meter of coated exterior cladding during 100 years service life in restraining outdoor exposure in Finland.

The environmental properties of the systems were assessed making use of life cycle methodology. LCI is generally understood as an evaluation of the environmental burdens associated with a product system by identifying and quantitatively or qualitatively describing the energy and materials used and emissions and wastes released into the environment. Life cycle includes all the phases of the studied systems from the acquisition of raw materials until the final disposal of wastes resulting from demolition of the products in the studied system. The data in LCI mainly consists of material and energy input and output values of the whole product system. Inputs and outputs deal with the raw materials and energy raw materials used, products and by-products produced, emissions and wastes induced. The use of natural resources and the release of hazardous emissions are dealt with as environmental burdens.

This study includes only inventory analyses of the product systems. The coatings and the parameters were studied on the basis of their effect on the use of natural resources and release of hazardous emissions to air.

The deterioration mechanisms of coatings are influenced by the binders and the composition of the coating. The opacity especially affects the durability in such a way that renewal periods can be significantly longer with paints than stains. On the other hand, the service life of wooden exterior cladding is remarkably affected by other factors than the quality of coating materials. These factors include the quality of wooden cladding itself, outdoor conditions during application, construction and maintenance. This is why individual renewal periods could not been defined, but 5 year intervals were used for the stains and 10 or 15 year time intervals were used for the opaque coatings. These values were taken as typical values. A criterion for renewal of opaque coatings (except for Swedish red paint) was defined as incipient flaking. This affects not only weakening the protective ability but also aesthetic properties of the paint. In the case of the wood stains and Swedish red paint erosion was defined as the criteria for coat renewal. If the maintenance interval can be lengthened, it directly decreases the environmental burdens of the coating. This can be influenced e.g. by constructional means, by selection of good-quality timber and by assuring that the application conditions are suitable. The coatings differ from each other with regard to durability. In developing weather-resistant products, also the environmental properties of coatings can be improved.

The product system was one square meter of coated wooden exterior cladding during a 100-year time period. It includes roughly 10 kg of wood. During the 100-year life time, roughly 1 kg of coating materials are also consumed. As the material inputs of the system are low, typically also the environmental burdens due to manufacturing, transportation, use and final disposal are minor. Thus the environmental impact of the coatings are small compared to for example those of the whole building or compared to those due to the heating of building during the 100 year period. From the viewpoint of a private consumer, the changes in the consumption of heating energy, household electricity or use of vehicles are normally significantly more important with regard to the environmental burdens than the selection of building products. However, from the point of view of the paint producer, comparing coatings to the heating of building is not relevant, unless the heating energy consumed could be affected by coatings.

Although the environmental burdens of 1 kg of paint are rather low the adoption of eco-based product development methodologies, not only in paint industry but in all industry, is nationally and economically necessary. This is critical when the total energy consumption and related emissions are to be controlled or decreased. In Finland the industry sector is responsible for roughly 40% of the total energy consumption. The heating of buildings is responsible for roughly 25% and traffic for roughly 10% of the total energy consumption [60]. The main part of the emissions of carbon dioxide, sulphur dioxide and nitrogen oxides come from the use of fossil energy, but a significant part of the emissions of heavy metals, particles and VOCs are induced also in industrial processes. The effect of coatings on the total man-made NMVOC [61] emissions have been estimated to be 12% [62] [63]. This means that the reduction of emissions of photochemical oxidants should still be one of the primary environmental interests of the paint industry.

The emissions of volatile organic compounds will be limited by the European Union directives. The last date for the adaptation of the regulations will 2007 for existing manufacturing plants. The most important meaning of the directive is to limit the solvent emissions, but alternatively national guides can be created. The emission limits are defined as content of organic compounds in flue gases, which are not to be exceeded in normal production. If the emission limits are not determined, it will be calculated on the basis of the content of total carbon or the content of total organic compounds per the volume of total flue gases in constant conditions. In those plants where the VOC emissions are 15 to 20 tons/year, the emissions limit for paint spreading and drying is 100 mg C/m^3 . If the emissions are more than 25 tons/year, the emission limit is 75 mg C/m^3 for application line and 50 mg C/m^3 for the drying zone.

Life cycle assessment is a method for comparison of equal functional units from the environmental point of view. One should not compare for example transportation units with coating but for instance coatings having the same functional properties are compared with each other. Each systems includes the necessary phases of transportation and heating of spaces. The method is suitable for assisting product development and product design. However, the method can also be used in setting goals and targets when environmental management systems are created. The results of life cycle assessment also give basic data for environmental declarations of products. The data received by help of life cycle assessment is not suitable as such to be used in consumers' decision making. This is because of the large quantity of

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[60] Energy statistics 1997. Tilastokeskus. Energia 1997:1. Helsinki 1997. 130 p.
[61] Non Methane Volatile Organic Compounds
[62] NMVOC = Non Methane Volatile Organic Compounds
[63] Arnold, M., Kuusisto, S. & Mroueh, U.-M. Haihtuvien orgaanisten yhdisteiden (VOC) päästöt vuonna 1996. Espoo 1998. VTT Tiedotteita 1921. (The emmissions of volatile organic compounds in Finland in 1996, Research Notes #1921, in Finnish)

information and issues that should be taken into account. However, the results from life cycle assessment should be utilised when creating environmental labelling criteria for products.

This report deals with the environmental properties of wooden exterior cladding on the basis of life cycle analyses. The analyses is mainly founded on data concerning the use of energy and inducing related emissions during the life cycle of coating systems and data concerning the emissions of volatile organic compounds. The primary objective of the research project has been to create a framework for environmental assessment of coatings including the introduction of necessary elements to be considered. With respect to all elements, it is listed all assumptions and data sources so that the results can later be utilised and further focused within the paint industry. This is important when the paint industry creates systems and tools for product development in order to account for environmental points of view.