Indoor air quality as an impact category in life cycle assessment of building materials—the case study of indoor paints

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ABSTRACT
Building environmental performance evaluation should make use of a life cycle assessment (LCA) approach, by considering all building process phases: raw material acquisition, manufacture, transportation, construction, use or operation, decommissioning, disposal and re-use. Such an approach is intended to measure, not only impacts on natural and non-natural resources but also building indoor environmental quality (IEQ). In many cases, building 'running' phase, that is maintenance operations, is strongly related to health, safety and well-being standards and requirements, which assure minimum IEQ levels. This category includes indoor walls maintenance and the related painting results of extension phase.

This paper deals with a procedure for the calculation of material and energy flows related to seven selected indoor paints and varnishes; the calculation takes into account the environmental impact of both production and usage phases. It includes the supposed increased ventilation rates effective in reducing indoor air pollutants from paints and varnishes, the degree of increase depending on the exposure reduction necessary for the most toxic of the pollutants. The increased energy consumption produces an environmental impact that will flow on from using higher ventilation rates.

The aim of the paper is to outline a methodology that could be assumed as a guideline in a LCA easily to be updated whenever new information and database will be available. What will be described in the paper are partial results of building environmental and energetic performance system (BEEPS) programme, carried out by University La Sapienza of Rome in cooperation with Italian Environmental Ministry.

INDEX TERMS
Life cycle assessment; Material emissions; Building maintenance; Paint; Ventilation

INTRODUCTION
Life cycle assessment (LCA) is frequently used as a tool for environmental assessment of buildings and building products. Traditionally, the main focus of LCA is the impact on the local and global external environment. However, there are important environmental problems related to buildings, which arise locally in connection with the indoor air quality (IAQ) such as effects on comfort and human health.

This traditional separation of life cycle environmental assessment from IAQ analysis has limited the influence and relevance of LCA for decision-making, and left uncharacterized the important relationships and trade-offs between the IAQ and life cycle environmental performance of alternative product design scenarios.

The possibility of including indoor emissions from building material in building-related LCA is investigated within of the procedure of ISO 14040 (ISO, 1997) by means of adding a section related to IAQ. IAQ is generally affected by different parameters:

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- those related to human activity or presence;
- those from combustion processes for heating and cooking;
- those from construction materials and furnishings emissions.

Concentrations of pollutants in the first two categories tend to vary with time. Those in the third are, in a long run, likely to be more constant, provided that air exchange rates remain constant. Thus, control strategies for these three categories have to be different.

Control of pollutant emissions from source materials is considered to be the optimum strategy for the control of indoor air pollution. This approach allows the identification and control of the major sources of target pollutants, where these sources are shown to lead to unacceptable toxic pollutant exposures. However, pollutant emission control requires that these materials be selected according to the type, quantity and persistence of toxic air pollutants, with this measurement being predictive of low-polluting performance in buildings, as well as an understanding of the risks presented from exposure to the pollutants, and how control strategies (voluntary labels, regulations) can be implemented.

Among the pollutants widely existing in an indoor environment, this paper—as a first proposal and related to the case study here presented—focuses on total volatile organic compounds (TVOCs). These compounds are deeply studied in the field of emission from building materials (WHO, 1999; FiSIAQ, 2001). A number of IAQ codes apply to a wide range of product types (wall and ceiling panels, floor coverings, insulations, paints, glues), which are assessed in a standard chamber for emission factors at 28 days after manufacture.

METHODOLOGY

According to ISO 14040 procedure (ISO, 1997), one of the general categories of environmental impact (the others are ecosystem quality and resources) is human health, which is sufficiently affected by IAQ. Generally, indoor effects from products on users (typically of IAQ) are presently not considered in LCA. LCA addresses the potential effects of various environmental loads, including emissions from building materials during the use phase.

In order to use a proper set of data, it is necessary to get information on substances emitted from materials in terms of time and surfaces. The choice to use TVOC emissions to be suitable for input data in LCA has been already presented (Asa Jönsson, 2000).

A poor indoor climate may lead to comfort and health effects and as an example of such a relationship related to TVOC, data from Mølhave's toxicological work on mucous membrane irritation can be assumed (Mølhave, 1990). Target values can be assumed from Classification of Indoor Climate (FiSIAQ, 2001).

To control the material emission from materials during the life cycle of a building mainly leads to consideration of surfaces indoor emissions due to maintenance and repainting (Levin, 1992; Tähtinen *et al*., 1996).

Three approaches are possible to reduce indoor air pollutant exposures (Gunnarsen *et al.*, 1993):

- increased building ventilation;
- inclusion of air-cleaning devices in buildings;
- reduction of pollutant emissions from the source materials.

Increased ventilation rates will be effective in reducing all indoor air pollutants, whatever their sources (Brown, 2001). However, ventilation code requirements have been historically set at minimum levels to remove pollutants and moisture from occupants, in order to prevent building air being perceived as 'stuffy'. These minimum levels can be increased, but the degree of increase needed will depend on the exposure reduction necessary for the most toxic of the pollutants, not only an unknown factor, but often requiring impractical ventilation rates to achieve an acceptable reduction. An added problem with this approach is the increased energy consumption (and related environmental impacts) that will flow on from using higher ventilation rates.

To include IAQ aspects in LCA, the paper proposes the following procedure:

1. The knowledge of TVOC content in the paint used: Information comes from European Ecolabel. (European Ecolabel, 1993). The ecolabelling criteria based on the life cycle inventory of some indoor decorative paints gives information about input data for paint extension phase. AFNOR certification as revision of Commission Decision 99/10/EC is also available for establishing the ecological criteria for the award of the Community Ecolabel to indoor paints and varnishes (Biointelligence Service, 2001).
2. The knowledge of the comfort value for the TVOC indoor concentration from European Standards or Codes: In Finland, the Ministry of Environment operates a voluntary scheme called 'Classification of Indoor Climate, Construction, and Finishing Materials' (http://www.rts.fi/M1classified.htm) to supplement the building code. It applies to a wide range of product types (wall and ceiling panels, floor coverings, insulations, paints, glues), which must not exceed the following limits: TVOC < 200 μg/m^3. Other information for Germany (http://www.blauer-engel.de), Denmark and Norway, (http://www.uk.teknologisk.dk/1689), and USA (http://www.ul.com/eph/iaq/index.htm and http://www.carpet-rug.com) are also available.
3. The decision to define a maintenance strategy as repainting frequency: from 15 to 20, all along the 50 years of building life (Di Giulio, 1999).
4. The calculation of the CO_2 production from the energy consumptions of the HVAC system able to guarantee the appropriate TVOC indoor concentration. It depends on climate and period of maintenance strategy. The case study refers to an office room ($6 \times 5 \times 3.3$ m^3) located in Rome, Italy with maintenance repainting occurring during the winter period. Seven different paints have been considered in the case study.
5. The insertion of CO_2 in production phase and in extension phase in the LCA of the paint analysed, as damage category output: air emission.

The following hypotheses have been considered:

- Paints are categorized as 'wet products'; they emit most of the pollutants in a few hours or days after installation (Levin, 1992; Tähtinen *et al.*, 1996).
- A first-order emission decay occurs to the following source model:

$$EF_t = k_1 M_0 \exp(-k_1 t)$$

where EF_t is the emission factor at time t, k_1 the first-order rate constant for emission decay; and M_0 the mass of pollutant in the source at time $t = 0$. Thus, this model is fully defined by the parameters k_1 and M_0. Interestingly, this model has been found to be applicable for the emission decays of many materials, especially wet and semi-dry materials. The total amount of fresh air to supply to the room to limit the TVOC concentrations appears to be weekly affected by k_1 variations.

TVOC emissions from building materials alone are not enough to predict the contribution from building materials to indoor air VOCs because factors such as chemical reactions in the air, sink effects and the temperature of the air also affect these emissions (Berglund and

Johansson, 1996). The difficulties to adopt a value for TVOC comfort concentrations, deals with the assumption that TVOC cannot be used for normal regulatory Risk Assessment which aims at predicting the probability of adverse effects on human health, ecological health and so on. TVOC should only be associated with sensory irritation and only if there are substantial indications that VOC is a problem (Mølhave, 2003). Moreover, there is no standardized procedure yet to calculate a TVOC value. As a rule, in the aggregation of VOCs into TVOCs, differences in potential health effects between the VOCs are not considered (Åsa Jönsson, 2000).

THE CASE STUDY

The seven selected products are white decorative indoors paints for walls and ceilings, according to European Ecolabel for Paints and Varnishes, December 1993.

They are manufactured by multinational companies in Europe, and these products are representative of the European market. Due to confidentiality reasons, the paints are mentioned with letters (A, B, C, D, E, H, I), so that the name of the companies and the commercial name of the products are kept secret. The main characteristics of the seven products are presented in the Table 1 (according to European Ecolabel for Paints and Varnishes, December 1993):

Table 1 Paints characteristics

Paint	Aspect	Vehicle	Resin	Solvent	Q (l/20 m^2)
A	Mat	Water	Styrene–acrylic	–	2.47
B	Gloss	Water	Styrene–acrylic	–	2.08
C	Semigloss	Solvent	Alkyd	White spirit <5%	1.9
D	Gloss	Solvent	Alkyd	Isoparaffinic	1.96
E	Mat	Solvent	Styrene–acrylic	Isoparaffinic	2.99
H	Mat	Solvent	Limed oil	Isoparaffinic	3.13
I	Mat	Water	Limed oil	–	2.94

The last column refers to the functional unit used for analysing the inventories of the paints, that is the amount of paint necessary to cover 20 m^2 with an opacity of 98% (Q).

Paints A and B are conventional water-borne paints, representative of the European market of the styrene–acrylic paints. Paint C is conventional alkyd paint with less than 5% aromatics white spirit. Paint D is sold with a view to being more ‘environmentally friendly’ than conventional alkyd paints because either they contain less aromatics with less than 1% aromatics white spirit or they contain odourless isoparaffinic solvent. Paint E contains an acrylic resin in an isoparaffinic solvent. The name ‘natural paint’ is given to the paint I by its producer characterized by zero-VOC emissions.

LCA results for the paints expressed as consumptions and emissions values are reported in Tables 2 and 3, respectively (where CO_2 emissions of production phase and the content of TVOC are reported). LCA results in terms of CO_2 emitted during the use phase are reported in Table 4 where CO_2 emissions per mass unit of paint, per functional unit and the total amount after 50 years of building life are reported.

Table 2 Energy consumptions in production phase (per functional unit)

	A	B	C	D	E	H	I
Petroleum (kg)	0.75	0.67	1.8	1.9	3.1	2.9	0.23
Coal (kg)	0.93	0.69	1	1	1	1.7	0.68
Gas (kg)	1.3	1.2	1.3	1.6	3.2	3.4	0.93
Water (l)	210	180	240	260	230	450	130
Electric (MJ)	13	14	15	14	15	22	14
Thermal (MJ)	65	62	120	140	250	230	49
Prim. en. (MJ)	110	92	170	180	310	310	68
Water disc (l)	210	170	240	250	210	440	120

Table 3 Emission figures (per functional unit)

	A	B	C	D	E	H	I
PM (g)	14	11	14	15	15	29	5
SO_x (g)	33	28	38	37	59	55	27
CO_2 (kg)	5100	4100	5900	6100	9200	11 000	3600
Hydrocarbons (kg)	45	37	51	53	30	96	33
TVOC (g)	133	180	744	790	1438	1627	0,01
Waste (kg)	4.7	3.6	4.3	4.4	4.6	8.1	2.9
Q (l/20 m^2)	2.47	2.08	1.9	1.96	2.99	3.13	2.94
M_0 (mg/m^2)	6600	9000	37 000	38 000	70 000	80 000	0.001
k_1	0.13	0.15	0.3	0.38	0.11	2.3	—

Table 4 CO_2 emissions in use phase (seven re-paintings in 50 years)

	A	B	C	D	E	H	I
CO_2 per mass unit of paint (ton/l)	0.65	1.06	4.83	4.81	5.81	6.35	0.01
CO_2 per functional unit (ton/20 m^2)	1.61	2.21	9.18	9.43	17.36	18.99	0.03
CO_2 after 50 years building life (ton)	164	224.84	932.96	958.72	1764.28	2020.90	2.80

Final results are also reported in Figures 1 and 2.

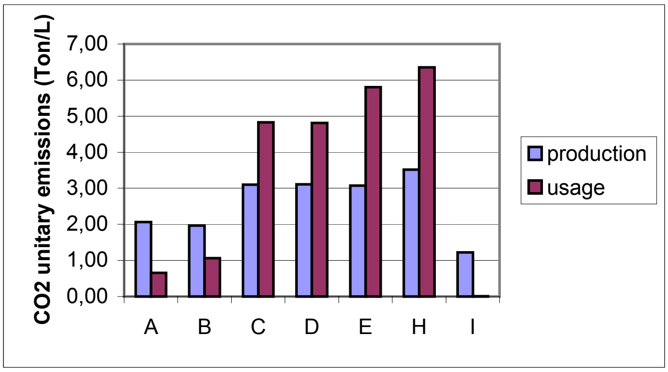

Figure 1 CO_2 unitary emissions in production and use phases (ton CO_2/l).

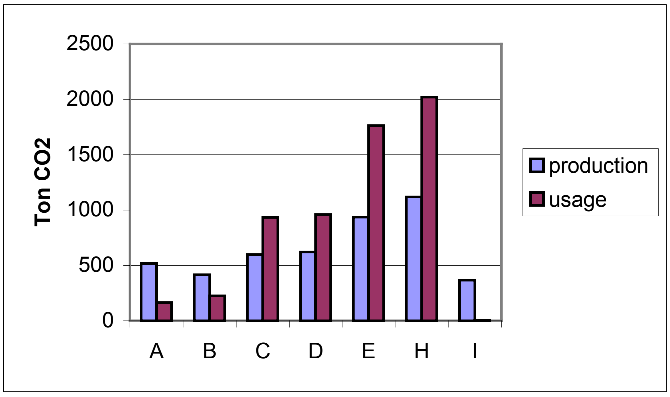

Figure 2 CO_2 emissions in production and use phases (after seven re-paintings in 50 years of building life).

CONCLUSIONS

The advantages of including IAQ as an impact category in assessment of the environmental life-cycle impact of building materials with potential effects on the IAQ might not be neglected. The presented procedure proposes the calculation of CO_2 environmental emissions during the paint use phase and its comparison with the CO_2 emissions during the paint production phase. CO_2 emissions during the paint use are related to the energy consumption of an HVAC system able to guarantee a defined level of TVOC concentration in indoor air during the painting of the indoor surfaces. An air change rate due to people comfort has been always considered as minimum level of ventilation in the room. This procedure has considered only TVOC emissions from paints, without any other surfaces emission.

CO_2 emissions during the paint production phase grow with the increase of energy needed to produce the paint; CO_2 emissions during the paint extension phase grow with the presence of TVOC content in the paint. CO_2 emissions both in production and use phase have to be correctly referred to the functional unit, that is, the amount of paint necessary to cover a surface of 20 m^2 with an opacity of 98% (Q), in order to take into account such a quantity in the maintenance operation.

Paint A's consumption is 1.3 times higher than paint C consumption, but its environmental impact is quite lower. Paint B is characterized by an higher value of the environmental impact during the use phase (expressed as CO_2 emissions in atmosphere) than that of paint A but the its total impact after 50 years of building life (seven wall re-paintings) is lower due to the combination of a lower value of Q and a marked lower level of CO_2 emissions during the production phase. The higher value all along the building life of the presented case study is related to paint H and the lower (up to 20%) is related to paint B.

CO_2 emissions in production and use phases as percentage of total amount, after seven re-paintings in 50 years of building life, can be different during the production phase (up to 80% for paint A) and during the use phase (30–35% for paints E and H).

Nevertheless, Figure 1 shows few differences between the behaviour of paints D and E, the actual result from Figure 2 shows a significantly wider difference. The impact of zero-VOC emission paint I has to be calculated considering other substances emitted (such as PMs, SO_x, etc.) and a deeper ecobalance is necessary to identify the actual impact on environment of this 'natural paint'.

Further studies will be developed in BEEPS LCA Module (www.beeps.it).

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