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ORIGINAL PAPER

VOC emission reduction and energy efficiency in the flexible packaging printing processes: analysis and implementation

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Abstract

Volatile organic compound (VOC) emissions into the atmosphere are among the primary environmental problems caused by flexible packaging printing plants. Since 1999, VOC emissions from the use of solvents in various technological processes have been limited by the volatile organic compounds solvents emissions directive, and by directive 2010/75/EU on industrial emissions since 2010. Thus, flexible packaging plants require processing technologies or other solutions to ensure compliance with these requirements. In this paper, combined VOC pollution prevention and treatment alternatives were suggested and were evaluated for their technical, environmental, and economic feasibility. A flexible plastic packaging company that produces over 1920 t/year of plastic packaging for the food industry was selected for detailed analysis. The material and energy flow analysis shows that VOC emissions from the main technological processes reached 112.2 kg/t of production, and a considerable amount of energy (up to 771.6 kWh/t of production) was used. Three integrated pollution prevention and control (IPPC) alternatives of the five analysed in this study were selected and implemented within the company to reduce its VOC emissions and energy consumption. The results indicate that after the implementation of the three suggested economically reasonable IPPC alternatives (replacement of solvent-based with water-based inks; modernisation of the ventilation and lighting system), the VOC emissions decreased to 8.4 kg/t (92.5%) and the total energy consumption for the production of 1 t of flexible packaging decreased to 605.6 kWh/t (21.5%). This study shows that IPPC methods not only significantly reduces VOC emissions from flexible packaging printing processes, but also saves energy and raw materials, and reduces costs.

Keywords Volatile organic compounds · Emissions · Cleaner Production · Environmental performance · Water-based flexography · Packaging

List of symbols

$EI_{(i)}$	Relative environmental indicator for input or output flow i
$X_{(i)}$	Amount of input or output flow i per year
P	Production volume
X_{VOC}	VOC emissions
M	Volume of chemical materials
K	Percentage composition of volatile substances [according to the material safety data sheet (MSDS)]
$E_{pollutant}$	Emissions of GHG (CO_2), air emissions (such as CO, NO_x)
$AR_{fuel\ consumption}$	Amount of fuel combusted
$EF_{fuel\ pollutant}$	Emission factor of combusted fuel
$W(t)$	Environmental performance indicator (effect) in a certain environmental area
P	Payback period
I	Total project investments
S	Savings
Q	Heat energy losses
C	Specific heat capacity of air
V	Air volume
ρ	Air density
t_2	Temperature of exhaust air (°C)
t_1	Average air temperature in the country during the heating period

Abbreviations

VOC	Volatile organic compounds
IPPC	Integrated pollution prevention and control
CP	Cleaner Production

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BAT	Best available techniques
EI	Environmental indicators
MSDS	Material safety data sheet

Introduction

Printed plastic flexible packaging is one of the fastest growing segments of the packaging industry as it is used for delivering a broad array of products to the food and beverage, personal care product, and pharmaceutical industries (Cristea and Cristea 2017). Plastic is suitable as packaging material because it is inexpensive, lightweight, flexible, and suitable for printing. This is why it is currently replacing other packaging materials (World Economic Forum 2016). However, the abundance of printed plastic packaging goods creates serious environmental problems. The life cycle of printed plastic packaging production begins with the extraction and acquisition of raw materials, along with the production of plastic packaging and printing materials, printing and lamination, distribution, use, and disposal (Viluksela 2008). Considerable amounts of energy are required, waste is produced, and pollutants are released throughout the plastic packaging life cycle. The process of plastic packaging printing causes environmental problems ranging from the consumption of energy and raw material resources to waste and pollution emissions, particularly those of volatile organic compounds (VOC). VOCs are generated from the use of different solvents in technological processes such as packaging gravure, flexography, lamination, and varnishing (Andrade et al. 2012; BAT 2007).

Most of the VOC content is emitted from solvent evaporation during the ink drying process and can be managed. Other VOCs, referred to as fugitive emissions, are emitted by diffused sources and are often difficult to control (Viluksela 2008). Cleaning solvents and thinners with different evaporation rates are used to wash painting dishes and clean machine parts, which leads to fugitive VOC emissions.

Since 1999, the VOC solvents emissions directive has limited VOC emissions from various technological processes (VOC 1999). In addition, the European directive 2010/75/EU on industrial emissions established more stringent limitations on VOC emissions from the use of solvents. These limits range from 20 to 150 mgC/Nm^3, depending on industrial activities, the volume of solvent used, and the types of VOC. For example, the concentration limit for total organic carbon emissions from organised sources of flexography printing if solvents are used is over 15 t/year–100 mgC/Nm^3 (IED 2010). Thus, the flexographic industry requires processing technologies that are compliant with the directive regulating VOC emissions.

The reference document on the best available techniques (BAT) for surface treatment using organic solvents (BAT 2007) presents a series of solutions for reducing VOC levels in exhaust gas ranging from VOC treatment to prevention. The most important methods of treating printing industry emissions include physical adsorption, thermolysis, catalytic conversion, and treatment by biofilters or scrubbers. If a treatment method is used efficiently, a VOC treatment efficiency of over 90% can be achieved (BAT 2007). Biotechnologies, including biofilters, bioscrubbers, and biotrickling filters are used as advanced alternatives to conventional VOC emission treatment methods (Lafita et al. 2012; Sempere et al. 2008).

The BAT on surface treatment using organic solvents also suggested well-known VOC pollution prevention methods directed towards input substitution by less hazardous materials (BAT 2007). In many cases, substances that have a lower impact on the environment and human health can replace organic solvents that emit VOCs. For example, solvent-based inks can be substituted with water-based, and organic cleaning solvents can be replaced by almost non-volatile plant-based cleaning products. Water-based inks use water as a carrier, replacing most of the organic solvents, reducing VOC emissions. For example, an average of 1.55 kg VOC per kg of purchased ink input is released by the production and auxiliary processes during flexography solvent-based printing. The range in this example is 1.09–1.84 kg VOC per kg of purchased ink input. In the case of water-based flexography, an average of 0.17 kg VOC per kg purchased ink input is released, with is 89% lower than that of solvent-based technologies (BAT 2007). The greatest advantage of water-based paints lies in the substantially reduced solvent emissions; however, the drying time of water-based paints is higher and there are difficulties related to the high surface tension of water (Miller 2008).

Despite this, reducing the environmental impact of a single process can reduce impacts in other areas. For example, replacing solvent-based paints will not only reduce VOC emissions into the atmosphere, but also energy consumption and costs. Using water-based paints, air recirculation in the dryer can significantly reduce the energy demand by increasing the inlet air temperature (EPA 2002). Material substitution can eliminate other problems, such as contamination from leaking storage tanks, exposure of workers to the original solvent, contamination of packaged products, and the flammability risk (Ma and Xia 2009).

Despite the VOC pollution prevention methods and their advantages proposed in the BAT documents, most companies, especially in new EU member states, select "end-of-pipe" VOC treatment methods, such as absorption by carbon tubes or regenerative carbon adsorption. The usage of such methods is not generally sustainable; it leads to additional costs and transfers environmental burdens to other stages of the life cycle. The strategic documents of the European Union promote a resource-efficient economy and Cleaner Production (CP) concept, which is based on the sustainable use of resources, waste minimisation, and pollution prevention at the source. The sustainable use of energy and materials provides significant economic opportunities, increases productivity, reduces costs, increases competitiveness, and, most importantly, reduces environmental impacts and pollution (European Commission 2011; UNEP 2010).

To the best of our knowledge, there is little research or few case studies in which prevention and treatment were analysed as an integrated approach when managing VOC pollution in the flexible packaging printing processes (Bravo et al. 2017; Xiao et al. 2017).

This study aims to demonstrate that Integrated pollution prevention and control methods not only significantly reduces VOC emissions in the flexible packaging printing processes, but also saves energy and raw materials, reduces costs, and increases competitiveness. The primary goal of this research is to evaluate the possibilities of decreasing VOC emissions and increasing energy efficiency in flexible packaging printing processes by integrating pollution prevention with treatment techniques. To reach this goal, the objectives are as follows:

- to perform an initial environmental assessment of printed plastic flexible packaging production to identify leading environmental problems and causes related to VOC emissions and energy use;
- to offer integrated pollution prevention and control (IPPC) alternatives for sustainably using resources and decreasing pollution;
- to evaluate the environmental and economic benefits of the suggested IPPC alternatives;
- to evaluate the company's environmental performance after the implementation of the chosen IPPC measures.

Methodology

A standard flexible plastic packaging company producing over 1920 t/year of plastic packaging for the food industry was selected for a detailed analysis. The three main stages and methods used for evaluating the possibilities to increase the environmental and economic benefits of the company chosen for this study are presented in Fig. 1.

The main principles of the CP methodology were applied to identify environmental problems, their causes, and feasibility analysis of alternatives. The main goal of IPPC was selected for decision-making. IPPC means that emissions in air, water, and land, in addition to a range of other environmental effects, must be considered together; pollution that cannot be avoided by primary (preventive) methods should be treated by secondary methods, and all methods must be based on the BAT for a certain industry. IPPC regulations apply an integrated approach to the environmental regulation of certain industrial activities (IPPC 1996, 2008; Staniskis et al. 2010).

Initial environmental assessment

The first stage of the study is the initial environmental assessment. The aim of this stage was to evaluate the

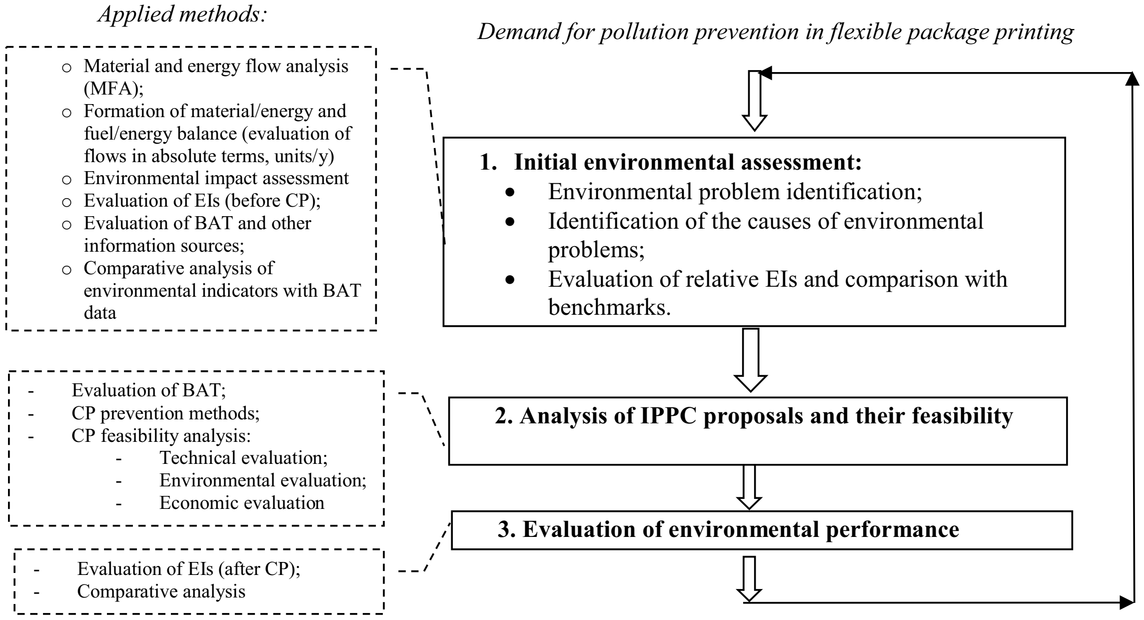

Fig. 1 Primary stages in the evaluation of possibilities to increase the environmental performance of flexible package printing

current situation of the company, i.e., to identify the leading environmental problems and causes related to atmospheric emissions and energy use. During the initial environmental assessment, the company's IPPC permit and its environment monitoring reports were analysed, and the material and energy flows of all technological processes were quantitatively identified (from accounting, environmental reports, or evaluations, following environmental impact assessment methods). The material/energy and fuel/energy balances were determined for the entire company and used for the evaluation of relative environmental indicators (EI).

Relative EI were comparatively compared for evaluating environmental problems and improvements. Relative EI, such as the concentrations of some VOC emissions (ethanol and isopropyl alcohol) from stationary sources (mg/Nm^3), were obtained from the IPPC report on direct measurements taken from the plant in 2016. Other relative EI were calculated using Eq. (1) (Malinauskienė et al. 2016; Staniskis et al. 2010):

$$\mathrm{EI}_{(i)} = \frac{X_{(i)}}{P} \tag{1}$$

where i is the input or output flow; $X_{(\mathrm{t})}$ is the absolute amount of consumed raw materials, energy, or water, or the amount of generated waste or pollution per year [t/year, m^3/year, kWh/year, (t/year)]; and $P_{(\mathrm{t})}$ is the production volume during the analysis period (t/year).

VOC emissions (t/year) were calculated using Eq. (2):

$$X_{\mathrm{VOC}} = M \times K \times 10^2 \tag{2}$$

where M is the volume of chemical materials (solvents, paints, printing inks; t/year) and K is the percentage composition of volatile substances (according to the material safety data sheet (MSDS) presented by the company's technologist).

The concentration of total gaseous organic carbon in the flue gases was measured using a continuous flame ionisation detector manufactured by a licensed company. This method is presented in the CEN EN 13526 standard for stationary source emissions (CEN EN 13526 2001). This standard is suitable for measuring emissions up to 500 mg/Nm^3 from one stationary source. VOC emissions were estimated following guidelines for the estimation and measurement of volatile organic compound emissions No. ECE/EB.AIR/WG.5/2016/4 (UN ESC 2016).

The method for evaluating CO_2 was taken from volume 2 "Energy" of the Intergovernmental Panel on Climate Change (IPCC) guidelines for national greenhouse gas inventories (IPPC 1996). Air emissions from any combustion source were evaluated following the method presented in EEA/EEA 2016 part B Sect. 1.A. combustion (EMEP/EEA 2016). The volume of CO_2 or air emissions during the combustion process was calculated according to Eq. (3):

$$E_{\mathrm{pollutant}} = \mathrm{AR}_{\mathrm{fuel\ consumption}} \times \mathrm{EF}_{\mathrm{fuel,\ pollutant}} \tag{3}$$

where $E_{\mathrm{pollutant}}$ is the GHG (CO_2) or air emissions (such as CO or NO_x; t/year); $\mathrm{AR}_{\mathrm{fuel\ consumption}}$ is the activity rate, such as the amount of combusted fuel (in TJ) (in the case of natural gas consumption: 1000 nm$^3 \equiv 0.03379$ TJ); and $\mathrm{EF}_{\mathrm{fuel,\ pollutant}}$ is the emission factor, kg/TJ of combusted fuel. If gaseous fuel is combusted in a small combustion plant in the manufacturing industry: $\mathrm{EF}_{\mathrm{NO}x}$-0.046–0.103 t NO_x/TJ; $\mathrm{EF}_{\mathrm{CO}}$-0.021–0.048 kg CO/TJ (EMEP/EEA 2016); and default $\mathrm{EF}_{\mathrm{CO2}}$-56.1 t CO_2/TJ (IPCC 2006).

NO_x and CO emissions were identified during the measurement of air emissions and an inventory of the company's stationary sources, which was conducted by a licensed company. One part of the NO_x and CO emissions is emitted through the stationary sources of water-heating boilers (WHB; see Fig. 2, No 001; 007–009) and the other is emitted by the burning of natural gas in the burners of one of the printing machines (see Fig. 2, No 003).

IPPC proposals and their feasibility analysis

Based on the reference document on the best availed techniques on surface treatment using organic solvents, several IPPC alternatives were suggested to reduce VOC emissions and energy consumption (BAT 2007; IPPC 2008). Feasibility analysis, including technical, environmental, and economic evaluations of all alternatives, was conducted to select the optimal decisions for increasing environmental performance during flexible package printing by economically reasonable methods.

Technical evaluation is the first important step in the feasibility analysis of the suggested alternatives. For this reason, a technical specialist must be involved in the evaluation (Malinauskienė et al. 2016). The alternatives were initially screened based on the technical criteria provided. In the next step, the feasible alternatives were environmentally and economically evaluated. Environmental evaluation of the selected alternatives' criteria involved the calculation of relative EIs (Eq. 1) after the implementation of the IPPC option and a comparison of this with the relative EIs before the option was implemented. The payback period of the investment required for the IPPC option was the main result of the economic evaluation of the suggested alternative (Malinauskienė et al. 2016):

$$P = \frac{I}{S} \tag{4}$$

where I is the total project investments (EUR) and S is the savings due to the minimisation of annual direct process costs and incomes after project implementation (EUR/year).

To consider the implementation of the IPPC option, P must be less than 3 years.

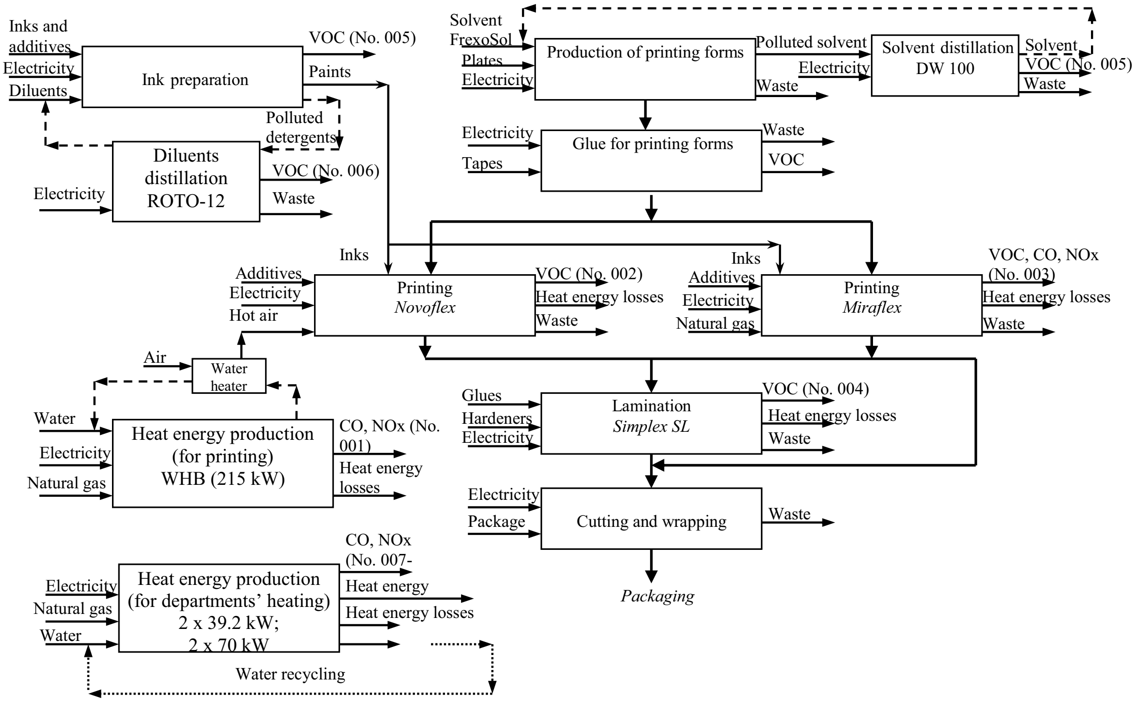

Fig. 2 Flowchart of the flexible package production processes

Evaluation of environmental performance

The indicators of environmental performance [$W(t)$] in a certain environmental area for the situation after the implementation of the selected option (−s) were calculated using Eq. (5) (Malinauskienė et al. 2016).

$$W_t = \mathrm{EI}_{(t-1)} - \mathrm{EI}_{(t)} \tag{5}$$

where $\mathrm{EI}_{(t-1)}$ and $\mathrm{EI}_{(t)}$ are the relative environmental indicators before and after the implementation of an option (−s), for example, kWh/t, kg/t.

Heat energy losses (MWh/h) from exhaust air were calculated using the equation of heat transfer (6):

$$Q = C \times q \times V \times \left(t_2 - t_1\right) \times 10^{-9} \times 0.28 \tag{6}$$

where C is the specific heat capacity of air, 1040 J/kg °C; V is the air volume, m^3/h; ρ is the air density, 1.2 kg/m^3; t_2 is the temperature of exhaust air, °C; t_1 is the average air temperature in the country during the heating period (for example, −5 °C); and 1 GJ ≡ 0.28 MW.

Results and discussion

Company description

The company selected for this study is a standard flexible packaging plant that produces packaging materials for the food industry (dairies, bakeries, confectionaries, meat and meat products, fish, frozen pre-cooked products, and so on) from polyethene (PE) and polypropylene (PP) film. The production capacity of the company exceeds 1920 t/year. The main production processes are presented in Fig. 2. Printing inks (paints) are prepared in closed containers with automatic process control following the required code, using white paint, various colour concentrates, organic additives, diluents (thinners), and solvents. Inks are injected into the rocket camera device and then transmitted onto raster paint rollers.

The rotating shaft transmits inks to the shaft, on which a photopolymer printing form is sealed. From this shaft, the inks are transferred onto a polyethene film and applied to various posters and prints. Shafts pass a polyethene film with a graphic stamp through the drying chambers, and the solvents are evaporated from the inks.

Heat energy for the drying chamber of the "Novoflex" printing equipment is produced by a water-heating boiler (WHB, 215 kW) that burns natural gas. The produced hot water heats the air supplied in the coil. Heated air is then blown into the drying zone, and VOCs from the drying process are released into the atmosphere through stationary air emissions source No. 002 (Fig. 2).

Two natural gas burners with capacities of 26 and 75 kW are installed in the drying chamber of the "Miraflex" printing equipment. Air with solvent vapours is supplied to the burners for heating and is then moved to the drying zone. One part of this air is recycled to the burners, while the other is released into the atmosphere with combustion products through stationary source No. 003 (see Fig. 2).

Glue and hardener are supplied into the chamber of the "Simplex SL" lamination equipment, where the adhesive mixture is transferred to an overlay shaft with rotating shafts. A polyethene film scrolls through the shaft and is coated with this adhesive. This film is then pressed against another transparent film or the printed film by the two laminating rollers at the end of the device. The "Morchem" glue and hardener do not contain solvents; therefore, there are direct VOC emissions from lamination. Hot air from lamination contains a small amount of VOCs from the production department and is released into the atmosphere through stationary source No. 004 (see Fig. 2).

Used and polluted solvents from the "Cyrel" printing equipment are collected and distilled in the "DW 100" solvent distillation machine. Treated and distilled solvents are recycled into the printing form production process. Solvent vapours are released into the atmosphere through the ventilation system (stationary source No. 005). In addition, VOC emissions from the paint production department are removed through the same stationary source No. 005 (see Fig. 2).

Painting machines are periodically treated (washed) with diluents in a closed system. A polluted detergent is collected and distilled in the "ROTO-12" diluent distillation machine. VOC emissions from this department are released into the atmosphere through the ventilation system (stationary source No. 006). Hazardous waste from the distillation machines is collected in special tanks and then passed over to the waste-management company.

Initial environmental assessment: identification of leading environmental problems and causes

The leading environmental problems were determined by analysing the current situation, which are presented as a flowchart (Fig. 2), through creating materials/energy and fuel/energy balances, evaluating relative EI (Table 1), and analysing environmental protection laws and the BAT of certain industrial activities. Several CP projects have been successfully implemented in recent years, which has reduced the generation of plastic shavings and offcuts by over 90%; thus, the consumption of raw materials has decreased by 5.9%. Despite all efforts to modernise the company's flexography process, the results of controlling VOC emissions show that their concentration exceeded the limit by eight times. VOC emissions from the main technological processes

Table 1 Relative environmental indicators of the analysed flexible packaging printing company (current situation)

Inputs	Units	$EI_{(t)}$	Outputs	Units	$EI_{(t)}$
PE and PP film	t/t	0.95	Production	t/t	1
Inks (paints) and pigment concentrates	kg/t	93.75	Heat energy losses during energy production	kWh/t	5.25
Varnishes	kg/t	1.56	Air emissions, including	kg/t	113.43
Technical mediums	kg/t	0.52	VOC emissions	kg/t	112.19
Primer	kg/t	3.13	CO, NO_x	kg/t	1.25
Diluents	kg/t	59.90	GHG emissions (direct)	kg/t	29.61
Solvents	kg/t	1.56	Wastewater (municipal)	m^3/t	0.42
Glues	kg/t	18.23	Waste, including:	kg/t	50.15
Hardener	kg/t	10.42	Plastic shavings and offcuts	kg/t	5.21
Packaging materials	kg/t	11.98	Hazardous (organic solvents, still bottoms, washing liquids, etc.)	kg/t	13.54
Water (municipal)	m^3/t	0.42	Hazardous (fluorescent lamps)	kg/t	0.15
Electricity	kWh/t	625.00	Packaging waste	kg/t	8.33
Natural gas (for heat energy production)	nm^3/t (kWh/t)	15.62 (146.61)	Other non-hazardous waste	kg/t	9.38
Fluorescent lamps	Units/t	0.05	Municipal waste	kg/t	13.54

Production volume for EI evaluation: $P = 1920$ t/year

Table 2 Causes of VOC emissions: consumption of solvent-based chemical materials

Processes	Used chemical materials	Solvent-containing components[a]	Consumption[b] (t/year)	$\mathrm{EI}^{c}_{\text{chemicals consumption}}$ (kg/t)
Flexography (film printing)	Printing inks (Brightstar, flexistar, flexilam, flexiprint MV, nitrobase clear)	Ethanol, ethyl acetate, methoxy propanol, isopropyl alcohol, *n*-propanol, titanium-chelate, polypropylene glycol, methoxy propanol acetate	150	78
	Pigment concentrates (nitrobase WZ64)	Ethanol	30	16
	Varnishes (protection/gloss lacquer)	Ethanol, ethyl acetate, methoxy propanol, heptane.	3	2
	Ink thinners (FFL)	Ethanol, isopropyl alcohol, *n*-propyl acetate, ethoxypropanol, 3-methoxy butanol	108	56
	Additives for printing: "Precoat Fmet" primers, promoters	Isopropyl alcohol, ethyl acetate, methoxy propanol, ethanol, propyl acetate, *n*-propanol	7	4
Washing of dyeing machines	"FFL" diluents	Ethanol, isopropyl alcohol	7	4
Production of printing forms	"FrexoSol" solvent	Decahydronaphthalene, hydrocarbons C11–C14, benzyl alcohol, 2-ethylhexane	3	2
Film lamination	"Morchem PL 275A" glue, "Morchem CF-75" hardener	–	55	29
Total			363	189

Information sources: [a]MSDS, [b]IPPC permit, [c]Production volume for $\mathrm{EI}_{\text{chemicals consumption}}$: $P=1920$ t/year

Table 3 VOC emissions emitted from the company's stationary sources

Processes	VOC emissions[a]			Stationary source (Fig. 2)
	Name	t/year	EI[c] (kg/t)	
Flexography (Novoflex)	Ethanol[b]	39.00	20.31	002
	Ethyl acetate	6.900	3.59	
	Isopropyl alcohol[b]	26.375	13.74	
	Other VOCs	30.193	1573	
Flexography (Miraflex)	Ethanol[b]	39.00	20.31	003
	Ethyl acetate	6.900	3.59	
	Isopropyl alcohol[b]	26.375	13.74	
	Other VOCs	30.193	15.73	
Lamination (simplex SL)	VOCs	0.462	0.24	004
Solvent distillation (DW 100) and paint preparation	Benzyl alcohol	0.675	0.35	005
	Ethanol[b]	0.826	0.43	
	Isopropyl alcohol[b]	0.185	0.10	
	Other VOCs	2.325	1.21	
Diluent distillation (ROTO-12/18)	Ethanol[b]	2.674	1.39	006
	Isopropyl alcohol[b]	3.315	1.73	
Total		215.398	112.19	

[a]VOC volume was calculated using Eq. (2)

[b]Concentrations of ethanol and isopropyl alcohol from stationary sources were measured by a licensed company

[c]Production volume for $\mathrm{EI}_{\text{VOC emissions}}$: $P=1920$ t/year

reached 112.19 kg/t of production, and the concentration of total organic carbon reached 836.8 mgC/Nm^3 (the limit is 100 mgC/Nm^3); a considerable amount of energy (reaching 771.61 kWh/t of production) was also used.

All the solvent-based chemical materials and preparations used were analysed using the material safety data sheet (MSDS; Table 2). These materials are used in all technological processes by major companies and for the distillation of solvents and diluents. The total concentration of solvents in the inks ranged from 17 to 70% in additives, and from 30 to 85% in diluents.

The results of the VOC evaluation are presented in Table 3. VOC is emitted into the atmosphere through five stationary sources without any treatment. Over 95% of VOCs are emitted from flexography during film printing due to the use solvent-based inks, ink thinners, and other additional materials.

Heat energy for technological and heating purposes is produced by burning non-renewable resources such as natural gas (up to 29.990 thousand nm^3 per year). A total of this volume, 60% is used for hot air preparation in the drying chambers of the flexography printing equipment; the remainder is combusted in WHB with a high efficiency (91–95%) for department heating and hot water preparation. In addition, a heater with 15/30 kW of installed electrical capacity is used for extra heating in the production department during the heating season from 15 to 18–20 °C. Thus, additional energy consumption for heating purposes amounted to approximately 16.2 MWh/year.

The results of evaluating the physical specifications of all stationary air emission sources (indicators of exhaust air: flow rate, temperature, volume flow) were as follows:

- 1.52 Nm^3/s of exhaust air with a maximum temperature of 36 °C is released into the atmosphere from stationary source No. 002 (flexography in Novoflex) (heat energy losses—up to 0.059 MWh/h);
- 1.99 Nm^3/s of exhaust air with a maximum temperature of 54 °C is released into the atmosphere from stationary source No. 003 (flexography in Miraflex) (heat energy losses—up to 0.122 MWh/h);
- 0.55 Nm^3/s of exhaust air with a maximum temperature of 58 °C is released into the atmosphere from stationary source No. 004 (lamination department) (heat energy losses—up to 0.036 MWh/h).

The average amount of heat energy lost through the company's building ventilation systems was 0.217 MWh/h.

IPPC proposals and their feasibility analysis

Guided by the suggested VOC minimisation methods for flexography presented in the reference document on BAT on surface treatment using organic solvents (BAT 2007), five IPPC alternatives were suggested during investigation:

- to reduce VOC concentrations in exhaust air:
- (option 1) replace organic solvent-based with water-based inks;
- (option 2) VOC treatment by adsorption on activated carbon;
- (option 3) catalytic VOC combustion (catalytic converters used for oxidising VOCs);
- to reduce energy intensity within the company:
- (option 4) modernising the company's ventilation system by implementing heat recovery;
- (option 5) modernising the company's lighting system by implementing new-generation LED lamps.

Three options (1, 4, and 5) were selected for implementation. This paper now presents the detailed results of a feasibility analysis of the two main options (1 and 4). Other options (2, 3, 4, and 5) are also mentioned in the results and discussion.

Option 1: replacing solvent-based with water-based inks

The primary positive aspects of a water-based ink system (BAT 2007; Johnson Polymer 2005; PNEAC 2006) are as follows:

- water-based ink and thinners contain only approximately 5% of solvents; thus, the volume of VOC emissions decreases considerably;
- the consumption of these materials is considerably reduced: 20–60% less ink is used, and 70–90% less thinner is used (EPA 2002; Piluso et al. 2009);
- implementation allows the diluents' distillation process to be bypassed;
- electricity consumption in flexography decreases by 10–30%;
- elimination of risks to workers' health.

The primary negative aspects of a water-based ink system (BAT 2007; Johnson Polymer 2005) are the following:

- water-based inks are at least 20% more expensive than solvent-based inks;
- water evaporation requires more energy than solvent evaporation; thus, the drying process consumes 20–30% more heat energy (it is technically feasible in the company);
- the wastewater volume is approximately 2–3 m^3/t of used inks.

The following steps for implementation are suggested in this option:

1. Replacement of solvent-based printing inks, thinners, pigments, improvers, varnishes, primers, and cleaning agents by water-based products;
2. Modification of the flexography printing presses and their functional components (PNEAC 2006): The fountain and anilox rollers must be replaced with new ones adapted to water-based inks;
    - The drying system must be rebuilt and equipped with better air movement (with a higher exhaust rate). Airflow must be adequate; otherwise, production on a high-speed press will be limited (from 25 to 30%). The use of scrubbing equipment for removing amines and water with a high velocity to remove the water vapours is the best solution;
    - Installation of new ink pumps;
    - Installation of post-treatment units (at the press) to increase surface tension during printing;
    - Printing plates may need to be changed to different rubber or photopolymer-based materials with surface tensions that can accept and transfer inks more effectively.
3. Implementation of a wastewater treatment system.

Treatments such as coagulation and flocculation are the most commonly applied. Using these methods, the adsorbable organic halides (AOX), hydrocarbons, and chemical oxygen demand (COD) concentrations of wastewater can be decreased from 1500 to 1, 1000/5000 to 10, and 1000 to 200 mg/L, respectively (BAT 2007).

Environmental and economic benefits of Option 1

The volume of solvents and non-volatile parts of the solvent- and water-based inks, thinners, and other materials used in flexible package printing was evaluated based on the composition of these materials from the material safety data sheet (MSDS) and other technical documents presented by the company.

The results of evaluating the volume of all necessary materials for water-based flexography and the expected VOC volume are presented in Table 4. Replacing solvent-based with water-based inks in the flexible packaging plant will achieve the following environmental benefits:

- saving over 126 t/year of inks, thinners, and other chemicals;
- reducing VOC emissions by over 199 t/year;
- reducing electricity consumption by over 231 kWh/year.

In addition, harmful effects to the workers' health are likely to be reduced.

Due to the notable reduction in VOC emissions (up to 92.5%), improved air movement, and elimination of stationary source No. 006, it is recommended to pass all exhaust air from the printing and lamination processes through the new one-extraction system (see Option 4).

If this option is selected, it will not be necessary to implement a treatment system for VOC emissions as the concentration of total organic carbon emissions from the sources in flexography printing will most probably meet the requirements of the VOC solvents emissions directive, and directive 2010/75/EU on industrial emissions (IED 2010; VOC 1999). An important aspect of Option 1 is that approximately 270 m^3/year of wastewater will be generated by water-based flexography. Flexographic wastewater treatment requires several steps (hydroflo technologies): emulsion breaking (reducing the pH to 2.5 with acid), precipitation and coagulation [increasing pH to 8.5 with caustic and adding a coagulant (iron or aluminium salts)], flocculation (adding a polymer flocculent; maximising flocculent dispersion throughout the coagulated wastewater), clarifying (the settling particles are moved into the sludge chamber from treated water to sewerage), and sludge handling and dewatering by a filter press (BAT 2007). Approximately 2.5 t/year of dewatered sludge will be transferred as a non-hazardous waste and managed by a waste-management company. Notably, this sludge would be considered as non-hazardous waste.

The implementation of this option will save approximately 135 thousand EUR per year. The total investment required for the modification of printing machines and their functional components, and the implementation of a wastewater treatment system will be approximately 440 thousand EUR (including designing works and 21% VAT). The payback period of this option is 3.3 years. The company may receive subsidies (up to 200 thousand EUR or 80% of the eligible costs) from the LAAIF (Lithuanian environment fund), according to one of the programme's priorities: the financing of prevention projects (LAAIF). In this case, the payback period of the company's own investments will decrease to 1.8 years.

Options 2 and 3: VOC treatment by adsorption on activated carbon and catalytic combustion

The results of the feasibility analysis of the other two alternatives for minimising VOC emissions from flexography printing are as follows; VOC emissions treatment by adsorption on activated carbon without replacing solvent-based printing inks with water-based ones will reduce VOC emissions by 80–90% (BAT 2007). However, the company will obtain no economic advantage, as there will

Table 4 Results of evaluating the environmental effects and economic savings due to the implementation of Option 1 for a production volume of 1920 t/year

Input and output flows at process level	Units/year	Situation before implementing Option 1	Expected situation after implementing Option 1	Savings	
		Units/year	Units/year	Units/year	Thousand EUR/year[i]
Inks[a]	t	150	108.33	41.67	−116.50
Thinners for inks[b]	t	108	38.4	69.60	226.30
Pigment concentrates[c]	t	30	25.83	4.17	−35.00
Improver[d]	t	1	0.56	0.44	0.60
Varnish[e]	t	3	1.08	1.92	7.30
Cleaning agent[f]	t	7	2.00	5.00	22.40
Primer[g]	t	6	2.70	3.30	2.3
Solvent for printing from production	t	3	3	0	0.00
Glue and hardener	t	55	55	0	0.00
VOC emissions from all stationary sources:	t	215.398	16.175	199.223	1.00
Ethanol		81.50	13.46	68.04	
Ethyl acetate		17.30	0.00	17.30	
Isopropyl alcohol		52.75	0.00	52.75	
Other VOCs		63.173	2.04	61.133	
Benzyl alcohol		0.675	0.675	0.00	
Electricity consumption within production processes	MWh	1156.529	925.223	231.406	29.30
Natural gas consumption for drying process (in printing machine Miraflex and WHB (215 kW)	nm^3 (MWh)	18,030 (169.23)	22,537.5 (211.54)	−4507.5 (−42.31)	−1.50
Air emissions from burning natural gas (CO, NO$_x$) (No 001, 003)	t	2.290	2.863	−0.573	0.00
GHG (CO$_2$) (direct)	t	34.18	42.72	−8.54	0.00
Hazardous (organic solvents, still bottoms, washing liquids)	t	26.00	16.97	9.03	5.40
Wastewater treatment and sewerage[h]	m^3		270	−270	−6.20
Waste (sludge)	t		2.5	−1.5	−0.40
Total amount					135.00

[a] Replacement of solvent-based printing inks (Brightstar, flexistar, flexilam, flexiprint MV) with 62.5% of the average volume of solvents with water-based printing inks; for example, Resino (Revalux 168 or 161), with 7% solvent content

[b] Substitution of water-based thinners, for example, water/ethanol (10:1), with thinners for solvent-based inks (FFL), with 95–99.5% of solvent content

[c] Replacement of pigment concentrates for solvent-based inks with 25% solvent content with pigments for water-based inks; for example, resino (RECON 105)

[d] Replacement of improver for solvent-based inks (nitrobase WZ64) with 75% solvent content with an improver for water-based inks; for example, resino (Promotor 9700)

[e] Substitution of water-based varnish, for example, resino (Revalux 153), with a solvent-based varnish (gloss lacquer) with 82.3% VOC content

[f] Replacement of cleaning agent for solvent-based inks with 95% of VOC with a water-based agent; for example, resino (Redivers), concentrated alkaline cleaning fluids, or pasta

[g] Substitution of water-based primer, for example, Aquatack 141, with solvent-based Precoat Fmet with 77.5% VOC content

[h] Annual expenses of wastewater treatment by coagulation and flocculation in treatment plants ranges from 2400 to 4800 EUR/year, without VAT, and depends on the plant size; investments: from 25 to 50 thousand EUR (Johnson Polymer 2005)

[i] Incl. VAT (21%)

be a moderate increase in the electricity consumption and hazardous waste generation by the treatment plant (used filters loaded with emissions).

The catalytic VOC combustion system will reduce VOC emissions by 90–98% (depending on the emissions; BAT 2007); in addition, natural gas consumption for flexography printing will decrease by 10,000 m^3/year due to heat energy recovery by the VOC destruction process. Thus, the company will save up to 4.4 thousand EUR/year. The payback period of this alternative will be over 20 years.

Option 4: modernisation of the ventilation system by implementing heat recovery

To reduce heat energy losses in exhaust air through stationary sources No. 002–004 and thus reduce energy intensity within the company, a new ventilation system with heat recovery must be installed.

The printing and lamination equipment work together. In addition, to increase the production volume, VOC emission treatment methods must be implemented. Thus, all exhaust air flows from equipment (up to 14,620 m^3/h with an average temperature of 47 °C) should be supplied to a single extraction system connected to an indirect vertical energy recovery system (for example, ventus). Heat energy that accumulates in the steam of the exhaust air (~ 0.217 MWh/h), will transfer to fresh air and will be supplied to the production departments (V-6800 m^3). In accordance with work-safety requirements, indoor air must be changed up to two-times per h, and the temperature of the production department during the winter must not be below 18 °C. Therefore, the supplying/exhaust system must have an airflow of 13,600 m^3/h. The evaluated heat energy demand ranges from 0.04 to 0.16 MWh/h.

The technical characteristics of the suggested equipment are as follows: airflow of the ventilation system-up to 14,000 m^3/h; plate cross-flow recuperator with minimum heat-recovery efficiency-75% [heat recovery at very high flow separation (up to 99.9%)] (see Fig. 3); automatic process control; type of ventilator-PLUG fan with a direct drive; for example, VS-120 (two units, 1440 rpm, T-up to 60 °C); type of filter-bag filter G4/F5 (two units; minimum filtration ratio, 90%).

Environmental and economic benefits of Option 4

The implementation of a heat-recovery system will achieve the following environmental benefits for the company (see Table 5):

- reduction of natural gas consumption for heat energy production by a maximum of 11,960 nm^3/year;
- reduction of heat energy losses during heat energy production in WHB and throughout the company's ventilation system by a maximum of 128 MWh/year;
- reduction of air pollution and GHG emissions by a maximum of 22.67 t/year;
- reduction of electricity consumption by a maximum of 7.9 MWh/year.

Implementing this option will allow savings of over 4635 EUR/year. Investment for this option consists of design work, the ventilation and heat recuperation systems (see Fig. 3), and installation works, amounting to approximately 60 thousand EUR, including VAT. The maximum payback period for this option is 12.9 years. Currently, the company can receive subsidies (up to 55% of eligible costs) according to the cogeneration for industry LT program. Thus, the payback period of its own funds will be reduced by a maximum of 7 years.

Option 5: modernisation of company's lighting system by the implementation of new-generation LED lamps

Feasibility analysis of Option 5 showed that the company could expect to save up to 9.4 MWh/year (or approximately 36% of all electricity used for lighting) and minimise the volume of hazardous waste (fluorescent lamps) by 0.3 t/year. Detailed feasibility analysis of the implementation of new-generation LED lamps was not presented here.

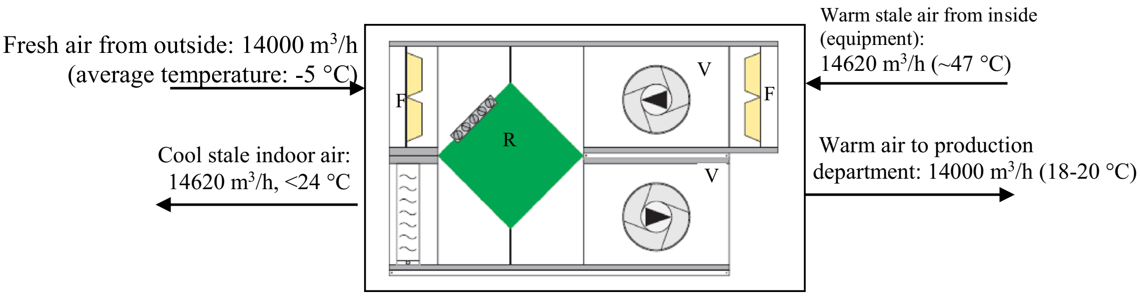

Fig. 3 Principal scheme of the recuperation system (main system elements: R—plate cross-flow regenerator, F—bag filter, V—ventilator)

Table 5 Environmental benefits and economic savings from the implementation of Option 4 for a production volume of 1920 t/year

Input and output flows at process level	Situation before implementing Option 4	Expected situation after implementing Option 4	Savings	
	Units/year	Units/year	Units/year	EUR/year[a]
Heat energy (for department heating)	(104 + 16.2) MWh (WHBs + heater)	120.2 MWh (heat-recovery system)		
Natural gas consumption	11,960 nm^3 (112.26 MWh)	–	11,960 nm^3 (112.26 MWh)	4008.55
Air emissions (No 007–009):				
CO	0.081 t	–	0.081 t	0.32
NO$_x$	0.025 t	–	0.025 t	4.90
GHG emissions				
CO$_2$	22.67 t	–	22.67 t	–
Heat energy losses (in WHW)	8.22 MWh	–	8.22 MWh	–
Electricity consumption	17,344 kWh	9450 kWh	7894 kWh	999.86
Bag filters (G4/F5)	–	4 units	−4 units	−104.00
Hazardous waste (used filters)	–	~ 180 kg	−180 kg	−274.43
Total amount				4635.20

[a] incl. VAT (21%)

Environmental performance of implemented options

Three IPPC options were selected for implementation. Two were analysed and presented in detail [replacement of organic solvent-based inks with water-based inks (Option 1), and the modernisation of the company's ventilation system by the implementation of heat recovery (Option 4)]. A third modernisation of the company's lighting system by the implementation of new-generation LED lamps (Option 5) was also included in the environmental performance calculations.

The environmental performance planning indicators *W* for the expected situations after the implementation of these three IPPC options were calculated using Eq. (5), and the results are presented in Table 6.

Increased environmental performance is expected for all the company's analysed environmental areas. The energy consumption required to produce 1 t of flexible packaging will decrease by 165.96 kWh/t; the environmental performance in this area will increase by 21.5%, including 25.3% due to the elimination of natural gas usage by the heating production department; thus, GHG emissions will decrease by 24.6%. The consumption of solvent-based materials will decrease by 65.68 kg/t due to the substitution of solvent-based with water-based inks; the environmental performance will increase by 34.74%. VOC emissions will decrease by 103.77 kg/t due to input substitution and the reduction of material consumption, and the environmental performance in the VOC emissions area will increase by 92.5%. The suggested three options were implemented by the company. The concentration of total gaseous organic carbon in flue

Table 6 Environmental performance indicators before and after the options are implemented

Environmental indicator	Units	EI$_{before}$	EI$_{after}$	W, (EI$_{before}$–EI$_{after}$)	Savings due to Option 1	Savings due to Option 4	Savings due to Option 5
Inks, thinners, solvents, and other materials	kg/t	189.06	123.39	65.67 (35%)	65.67	0	0
Total energy consumption	kWh/t	771.61	605.65	165.96 (21.5%)	98.49	62.58	4.9
Natural gas consumption	nm^3/t	15.62	11.74	3.88 (25%)	−2.35	6.23	0
	kWh/t	146.61	110.18	36.43	−22.04	58.47	0
VOC emissions	kg/t	112.19	8.42	103.77 (92.5%)	103.76	0	0
	mgC/Nm^3	836.8	97	740	–	–	–
Total air emissions (CO, NO$_x$, VOC)	kg/t	113.43	9.92	103.51 (91%)	103.46	0.06	0
GHG (CO$_2$) (direct)	kg/t	29.61	22.25	7.6 (26%)	−4.45	11.81	0
Total waste production, incl. hazardous	kg/t	36.61	32.65	3.96 (11%)	3.92	−0.09	0.14

gases after the implementation of Option 1 was measured at stationary sources No 002–006. The results show that the total concentration reached 97 mgC/Nm^3, which meets the environmental requirements < 100 mgC/Nm^3.

Conclusions

The results of the initial environmental evaluation of the company showed that VOC emissions from the main technological processes, such as solvent-based flexography printing, reached 112.2 kg/t of production, and a considerable amount of energy (reaching 771.61 kWh/t of production) was used. A non-renewable resource—natural gas (up to 15.62 m^3/t of manufactured production)—was used to produce heat energy (for ink drying and department heating). Heat energy losses through the company's ventilation system were 0.217 MWh/h.

Five IPPC alternatives to reduce VOC emissions and energy consumption were evaluated in this study. Three [replacement of solvent-based with water-based inks (Option 1); modernisation of the ventilation system (Option 2), and modernisation of the lighting system by adopting new-generation LED lamps (Option 3)] were proposed for implementation by the flexible packaging company.

The results show that the environmental performance of the flexible packaging company would increase in all the target environmental areas after the implementation of the three suggested IPPC options. The environmental performance in the VOC emission area will increase by 92%, mainly due to the 93% reduction in VOC emissions (from 112.2 to 8.4 kg/t of production). In the energy consumption area, the environmental performance will increase by 21.5% (from 771.6 to 605.6 kWh/t of production). In addition, GHG emissions (CO_2) will decrease by approximately 25% due to the reduction in natural gas consumption for generating heat energy. In the chemical material consumption area, the environmental performance will increase by approximately 35%. The best results from the feasibility analysis were obtained by the input substitution method (Option 1): VOC emissions will decrease by 92.5% without any treatment; the company will save approximately 130,000 EUR/year due to the reduced consumption of chemical materials; and investments will be recouped in 3.3 years. The concentration of total gaseous organic carbon in flue gases after the implementation of Option 1 was measured at stationary sources No 002–006, and the results show that the total concentration reaches 97 mgC/Nm^3, which is within the environmental requirements < 100 mgC/Nm^3.

The three suggested options were implemented by the company. The study shows that IPPC methods increases the environmental performance and ensures economic benefits (reducing direct process costs).

The environmental assessment aspect of this study is restricted to reducing air emissions and energy use. Therefore, further research, including a broader environmental impact assessment, would be beneficial. A suggestion for future work is to conduct the environmental aspect of the assessment by including different environmental impact categories, such as water footprint or global warming potential, especially for the solvent-based and water-based ink substitution solution.

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