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Article

Feasibility Analysis of Sustainability-Based Measures to Reduce VOC Emissions in Office Partition Manufacturing

Frank S. Luisser and Marc A. Rosen *

Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, 2000 Simcoe Street North, Oshawa, Ontario, L1H 7K4, Canada; E-Mail: fluisser@yahoo.com

* Author to whom correspondence should be addressed; E-mail: marc.rosen@uoit.ca; Tel.: +1-905-721-8668; Fax: +1-905-721-3370.

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Abstract: A feasibility analysis is reported of reduction opportunities for volatile organic compound (VOC) emissions in manufacturing office furniture partitions, aimed at contributing to efforts to improve the sustainability of the process. A pollution prevention methodology is utilized. The purpose is to provide practical options for VOC emissions reductions during the manufacturing of office furniture partitions, but the concepts can be generally applied to the wood furniture industry. Baseline VOC emissions for a typical plant are estimated using a mass balance approach. The feasibility analysis expands on a preliminary screening to identify viable pollution prevention options using realistic criteria and weightings, and is based on technical, environmental and economic considerations. The measures deemed feasible include the implementation of several best management practices, ceasing the painting of non-visible parts, switching to hot melt backwrapping glue, application of solvent recycling and modification of the mechanical clip attachment. Implementation, measurement and control plans are discussed for the measures considered feasible, which can enhance the sustainability of the manufacturing of office furniture partitions. Reducing VOC emissions using the measures identified can, in conjunction with other measures, improve the sustainability of the manufacturing process.

Keywords: sustainability; volatile organic compound; VOC; manufacturing; office furniture; pollution prevention; emissions

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1. Introduction

Canada's furniture industry, the second largest exporter in the world according to Industry Canada [1], generates wastes during manufacturing that impact land, air and water. The U.S. Environmental Protection Agency points out that the most significant environmental impact of the wood furniture industry is its emissions of volatile organic compounds (VOCs), especially toluene, methanol and xylene [2]. VOCs are carbon containing substances that evaporate rapidly, and contribute to acid rain and the greenhouse effect and react with oxides of nitrogen in the presence of sunlight to form low-level ozone, a component of smog. Smog can impact health and property [3]. The U.S. wood furniture industry emits about 60,000 tons of VOCs annually [2], but Canada and the US have since the 1990s significantly reduced VOC emissions [4]. VOC emissions normally represent the majority of air pollutant releases in manufacturing office furniture partitions, a segment of the wood furniture industry.

As part of an investigation to identify strategies for improving the sustainability of the manufacturing of office partitions by reducing VOC emissions in the manufacturing operations and processes, a preliminary screening of emission reduction options was carried out by the present authors [5]. That investigation utilized the pollution prevention methodology defined by the Ontario Ministry of the Environment. In the screening, baseline VOC emissions for a typical plant were estimated using a mass balance approach, and pollution prevention measures were identified and screened using realistic criteria and weightings. Several measures were deemed viable, including implementing several best management practices, ceasing painting of non-visible parts, switching gluing processes, recycling solvent and modifying attachments.

Subsequently, a preliminary feasibility analysis was carried out of reduction opportunities for volatile organic compound emissions in manufacturing office furniture partitions [6]. In this article, more comprehensive feasibility analyses based on technical, environmental and economic considerations are performed for selected measures (based on the results of the preliminary screening of options) for reducing VOC emission levels in typical manufacturing operations for office furniture partitions. Also, factors affecting the implementation of feasible measures are considered and metrics for tracking and evaluating their impact are developed. This feasibility analysis extends the preliminary one reported earlier, in part by focusing on sustainability [6]. The objective is to identify reasonable strategies for reducing VOC emissions in the manufacturing of office furniture partitions, and thereby to contribute to enhancing the sustainability of the industry by balancing many of the competing factors.

Several important points about this investigation are noted:

- Reducing VOC emissions for the manufacturing process considered, while accounting for technical and economic factors, is but one step in improving its sustainability. Although the present study consequently provides an important step in enhancing the sustainability of the process, this measure needs to be accompanied by other sustainability efforts to ultimately make the process sustainable from all perspectives.
- The scope of this article is in line with a case study, rather than a scholarly investigation of new methods, and the results reported are consequently oriented towards the application considered.

- The investigation adopts in large part an engineering approach, aimed at developing feasible options for reducing VOC emissions for the manufacturing process, from the perspective of an industrial company. This approach is taken because options that do not focus on industry needs and instead dwell only on other factors are likely not to be successful.

Challenges to achieving sustainable development in the manufacturing enterprise have been discussed by Sutherland *et al.* [7], and many efforts have been expended to enhance the sustainability of manufacturing processes and technologies used in industry, from several perspectives including design. For instance, the achievement of greener manufacturing and operations through designing for energy efficiency and selection has been investigated by the present author [8]. Also, Jovane *et al.* [9] have investigated pathways towards competitive and sustainable high-adding-value manufacturing, while global technological and industrial revolution for competitive sustainable manufacturing has been described [10]. Furthermore, guidelines for design for remanufacturing to support sustainable manufacturing have been proposed by Ijomah *et al.* [11]. This study contributes to these and other efforts.

2. Background

Many investigations of VOCs, their effects on people and their control have been reported. Many of these relate to industrial operations like manufacturing.

A study of indoor sources that contribute to occupant exposure to VOCs was carried out for homes in Quebec City, Canada in winter, based on continuous measurements of concentrations of 26 VOCs for 7 days in 96 homes [12]. In that study, correlations to housing characteristics were investigated. Also, workplace exposure to 26 VOCs has been evaluated using environmental and biological monitoring for four different types of workers: house painters, varnishing workers, car painters and petrol station workers [13].

The impact on indoor air quality of chemical reaction products from building materials and furnishings has recently been reviewed [14]. Studies have been carried out of room VOC concentrations from wooden furniture [15], and methods to determine formaldehyde and total VOC emissions from wood-based composites (e.g., medium density fiberboard, particleboard and laminate flooring) [16] and adhesives for building materials [17]. Also, VOC emissions have been examined for several non- or low-emitting building materials and compared to those for traditional building materials [18]. Additionally, formaldehyde and other VOC emissions have been investigated in temporary housing of the U.S. Federal Emergency Management Administration [19], with the results suggesting that the extensive use of composite wood products, sealants and vinyl coverings, combined with the low air exchange rates relative to material surface areas, likely cause high concentrations of some VOCs and formaldehyde.

Methods to control VOC emissions in furniture manufacturing have been developed. For example, the performance of a biotrickling filter for VOC emissions control has been assessed over one year in manual and automated painting operations of a furniture manufacturing facility [20]. The system performance was altered based on test results to ensure it achieves air quality in compliance with legal constraints. Also, the control in various manufacturing processes has been investigated of formaldehyde and total VOC emissions from wood-based flooring composites that are bonded by urea-formaldehyde resin, focusing on the emission variations for different surface finishing materials [21]. Further, an investigation has been reported of the potential and challenges of biological treatment of indoor air for VOC removal, indicating the need for technical innovations, specific testing protocols and better understanding of both microbial activities and the mechanisms of substrate uptake at trace concentrations [22]. An investigation of the potential of biofiltration for VOCs emission control demonstrated that its investment and operation costs are lower and performances are comparable with other abatement systems [23]. Furthermore, the potential improvement in indoor air quality has been investigated *via* the reduction of formaldehyde and total VOC emissions from furniture materials and wood-based composites through the addition of volcanic pozzolan as a scavenger to urea formaldehyde resin [24].

The promotion of environmentally sound furniture by green public procurement has been examined, including the use of eco-design strategies by furniture manufacturers [25]. More generally, the use of industrial ecology and sustainable engineering in industrial operations has been described [26].

The U.S. Environmental Protection Agency (EPA) has been actively engaged for over a decade in ensuring VOC emissions are adequately managed. A guideline for the control of VOC emissions from wood furniture manufacturing operations was developed in 1996 by the EPA's Office of Air Quality Planning and Standards [27]. That document outlines emission control techniques, the development of model plants and associated emission estimates, and the environmental and cost impacts of the implementation of reasonably available control technology for control of VOC emissions for the wood furniture industry. An EPA report was issued in 1997 on utilizing low volatile organic content exterior coatings for wood furniture [28]. Also, wood furniture coatings with low VOC and hazardous air pollutant (HAP) emissions were examined in 2000 by the Air Pollution Prevention and Control Division of the U.S. EPA's National Risk Management Research Laboratory [29]. In that investigation, case studies were presented of wood furniture manufacturing facilities that had converted to low-VOC/HAP wood furniture coatings, demonstrating that low-VOC/HAP coatings are used successfully by some wood furniture manufacturing facilities, and that other wood furniture manufacturing facilities could achieve similar results. An EPA implementation document for National Emissions Standards for Hazardous Air Pollutants (NESHAP) was published in 2004 for wood furniture manufacturing operations [30]. Much of the information developed by the U.S. EPA provides guidelines and motivation for the research reported herein.

3. Preliminary Feasibility Assessment

In a typical manufacturing operation for panels, medium density fibreboard is milled to specific shapes (trims). Veneer is applied to the trims using a hot melt adhesive. The trims are coated with primer and paint or with stain, sealer and lacquer. The coating material is solvent-based and is applied manually or automatically in ventilated booths. The parts are air-dried on heating racks or in an air tunnel or by baking in an industrial oven. Sheets of acoustical fibreglass are cut and fitted with metal clips, which are attached to the panels using a polyester resin. The product is sprayed with an adhesive, and moved to an assembly area where fabric is applied. Aluminium frames are assembled and the trims and panels are applied to the frames.

The main processes that contribute to VOC emissions are surface coating, adhesive application and cleaning. Surface coating material typically consists of solutions of organic resins, organic and inorganic colour pigments, stabilizers and extenders, according to Rafson [31]. The organic solvent is used for transporting the components and for giving the liquid properties necessary for consistent application of coating layers [31]. Adhesives are used in such operations as applying metal clips to fibreglass, veneer to medium density fibreboard, fabric to fibreglass and polyvinyl chloride, and solid wood end caps to medium density fibreboard. Industrial solvents are used to clean the piping in finishing application equipment, manufacturing booths and glue application equipment, and to remove coating from non-conforming parts [2].

Baseline emission rates are estimated using a mass balance approach, following the method and steps outlined elsewhere [32]. This approach, which is a widely accepted and cost-effective method of estimating VOC emissions [4], is used here to calculate emissions because VOC and material usage data are often available. In the present investigation, the main VOC sources are coatings and adhesives, which consist of resins, pigments, additives, solvents, diluents and thinners. Resins, pigments and additives are the solid (non-volatile) portion of the coating or adhesive, while solvents, diluents and thinners are the volatile portion, which evaporate during the mixing, application and curing of the coating or adhesive [32]. Table 1 summarizes annual VOC emissions by material type and plant area for a typical plant (based on examinations of several plants). The typical facility is assumed to produce 200,000 panels annually, and to have a total floor area of approximately 15,000 m^2.

Table 1. Annual VOC emissions (in tonnes) by area.

Area	**Source**			
	Surface coating	**Adhesive**	**Cleaning**	**Total**
Trims	20.0	0.0	5.5	25.5
Upholstery	0.0	14.0	1.5	15.5
Total	20.0	14.0	7.0	41.0

It is useful to understand the regulatory limits for VOC emission levels in air for the type of facility considered in this article. The maximum VOC contents for categories of coating products, as applied, are provided by the Canadian Council of Ministers of the Environment [4] for wood furniture, kitchen cabinets and caskets. The VOC content limit (in g/L) is listed as 730 for wash coat, 760 for semi-transparent stains, 780 for non-grain-raising stains, 760 for glazes, 480 for fillers, 670 for clear sealers, 600 for pigmented coatings, 670 for clear topcoats, 780 for lacquer topcoats and 780 for all other coatings. The limits are calculated using the methods described in Referrence [4], which adjust for the amount of volatiles that are not considered VOCs (*i.e.*, exempted solvents and water). To determine compliance, the VOC content of the product is calculated after all reducers and components are incorporated into the product according to the coating product manufacturer’s specifications.

In order to meet the goals outlined in Referrence [4], Product and Operating Standards can be used. The Product Standard describes VOC content limits for coatings products. The Operating Standard has three components: (1) an application equipment standard; (2) a Code of good practices (including record keeping and reporting requirements); and (3) an operating standard for new and expanded facilities. Alternatively, wood furniture manufacturing facilities may achieve VOC emission reductions using pollution control (abatement) technologies. Although not typical in this industry, this approach is an option at facilities. But facilities choosing this method of reducing VOC emissions must demonstrate to appropriate authorities that the level of capture and control meets or exceeds the level of VOC emission reduction that would be achieved by complying with the Product and Operating Standards [4]. Given the nature of this industry, abatement technologies are not considered extensively in this article.

In an earlier effort to improve sustainability, the pollution prevention alternatives were screened according to criteria deemed most relevant for the present manufacturing operation by several manufacturers: internal and external VOC emissions, capital and operating costs such as for raw material and waste disposal, employee health and safety, product quality, implementation time and resources required. The weighted-sum method was used for screening and rating pollution prevention measures, as suggested by the Ontario Ministry of the Environment [33]. Each screening criterion is weighted based on its perceived importance, ranging from 1 for a high negative impact to 5 for a high positive impact.

The initial screening considered best management practices (e.g., standard operating procedures, preventative maintenance, employee training and involvement, production scheduling, inventory management, scrap reduction), paint equipment modifications (e.g., high volume, low pressure spray guns, spray pattern optimization, air purge of paint lines), production process modifications (e.g., water-based surface coatings, hot melt backwrapping adhesive), product redesign (e.g., mechanical clip attachment, cease painting non-visible parts), recycling and reuse (e.g., solvent recycling), and abatement technologies (e.g., oxidation, biological abatement).

It is noted that other methods to assess and compare measures for reductions of VOC emissions in industrial facilities have been investigated and applied [34-38], and some of these have the potential for use in extensions of the research reported here.

4. Approach: Detailed Feasibility Analysis of Preferred Measures

The sustainability measures selected for detailed feasibility analyses based on the preliminary screening are best management practices, air purge of paint lines, water-based finishes, hot melt backwrapping, cease painting non-visible parts, mechanical clip attachment, and solvent recycling. The detailed feasibility analysis determines which measures are technically, environmentally and economically feasible. A measure is considered feasible if the end result is considered to be acceptable using typical considerations applied in industry. The acceptability considerations used here were developed based on examinations of several manufacturers. Each measure is considered on its own merit. Although alternative methods for assessing feasibility exist, they are not considered here.

The technical evaluation determines whether a pollution prevention measure is likely to work in a given application. A careful assessment is needed where the measure requires changes to the production methods or input materials. A measure is discarded if it appears impractical or significantly reduces product quality.

The evaluation weighs the environmental advantages and disadvantages of a measure. The environmental factors considered are the number and toxicity of waste streams, risk transfer to other media, environmental impact of alternate input materials, and energy consumption [33]. VOC emission reductions are estimated when possible. Most measures are not mutually exclusive and the predicted VOC emission reductions for each measure are not cumulative. After a measure is implemented, therefore, emission reductions must be re-evaluated for other measures based on the lower emission levels. VOC emissions are based on annual production data for a typical plant.

The economic evaluation weighs the financial costs and benefits of pollution prevention measures. If a measure involves little capital cost, economic profitability can be judged based on reduced operating costs and/or VOC emissions. A more detailed analysis is required for capital-intensive measures. Intangible benefits such as improved public perception and worker morale, compliance with future regulations and reduced liability are not considered directly, but are identified and described for completeness.

5. Relevant Sustainability Measures

The feasibility is assessed in this section of several best management practices that can help reduce VOC emissions and enhance sustainability, including the application of standard operating procedures, preventative maintenance, employee training and involvement, production scheduling, inventory management and scrap reduction methods.

5.1. Standard Operating Procedures

Technical: Implementing standard operating procedures is a simple, low-cost method for reducing VOC emissions for processes. The development of standard operating procedures for a typical company's significant environmental impacts is normally consistent with the requirements of its environmental management objectives.

Environmental: The implementation of standard operating procedures does not change the toxicity of the waste streams or transfer waste to other media. Standard operating procedures reduce energy consumption and solvent use. VOC emission reductions are not calculated for best management practices due to the inherent difficulty in predicting how improved operations impact air pollution releases. For example, standard operating procedures and preventative maintenance can decrease the chance of a spill. Quantifying how this relates to potential emission reductions is challenging. One approach uses probabilistic risk assessment based on the likelihood of failures of system components, but this evaluation is beyond the scope of this investigation.

Economic: Implementing standard operating procedures typically has low expenses and operating cost usually increases slightly. Compared to the other measures and the technology considered here, it is estimated that no capital is required and operating costs do not increase due to the implementation of standard operating procedures.

5.2. Preventative Maintenance

Technical: Preventative maintenance of process and pollution control equipment is another simple, low-cost method of reducing the risk of leakages and spills causing VOC emissions. Software such as Maximo (MRO Software, Bedford, Mass.) can control plant-wide maintenance activities. Maximo keeps records of maintenance activities. In addition, environmental inspections can be performed that go beyond existing equipment preventative maintenance such as regular checking of spray guns, pumps and fluid lines.

Environmental: The implementation of environmental preventative maintenance does change the toxicity of the waste stream or transfer waste to other media. Preventative maintenance likely reduces energy consumption and solvent use.

Economic: No capital costs are required for the implementation of preventative maintenance. Operating cost may increase slightly since equipment is inspected and serviced more frequently.

5.3. Employee Training and Involvement

Technical: Involving employees in waste reduction initiatives and keeping employee training current is an effective method of emission reductions. Employee training and involvement is also consistent with the requirements of the environmental management system in many companies.

Environmental: The implementation of employee training and involvement does not change the toxicity of the waste stream, but should reduce energy consumption and solvent use.

Economic: No capital and minimal expenses are required to implement employee-training programs.

5.4. Production Scheduling

Production scheduling to reduce waste generation is usually more challenging than the aforementioned best management practices. To remain competitive, there is continual pressure to reduce inventories and product lead times. A reduction in lead time and inventory is generally obtained through reducing changeover times and batch sizes. Reducing batch sizes leads to more frequent cleaning, which increases VOC emissions. Since these company objectives conflict, production scheduling as a method of VOC emissions is not pursued further.

5.5. Inventory Management

Inventory is normally managed electronically through a material resource planning system in most companies. A first-in/first-out policy is usually used for managing chemical usage in the plant. Although opportunities exist for improving inventory management, this option is not pursued further because the initial screening and subsequent assessments suggest that resources are better spent on other VOC reduction methods.

5.6. Scrap Reduction

Technical: Defect reduction is an ongoing issue for many manufacturing process for office partitions, where typical defect rates of approximately 5% are common. The reduction of scrap and rework reduces resource needs (labour, materials, transportation). Several methodologies for reducing scrap and defects exist. For example, the Six Sigma data-driven approach, which aims to reduce process variation and improve process capability, has been applied successfully in numerous companies to reduce defects. To achieve Six Sigma success, a process must have no more than 3.4 defects per million opportunities. Here, a less stringent target is applied involving a more easily achievable 10% decrease in defects (*i.e.*, reducing the defect rate from a typical value of 5% to 4.5%).

Environmental: Reducing the defect rate does not alter waste toxicity or transfer wastes to other media, but does reduce energy and solvent use by avoiding the need to re-make parts. VOC annual emissions from decreasing scrap and rework are predicted to decrease by just over 200 kg (see first section of Table 2).

Economic: Minimal capital and expenses are required for this pollution prevention measure.

Table 2. VOC emissions predicted before and after implementation of several reduction measures.

Measure	Material	Current VOC emissions (tonnes/yr)	Proposed reduction in VOC use (%)	Predicted VOC emissions (tonnes/yr)
Reduce scrap and rework	Surface coatings (paints, stains, sealers, top coats)	20.0	0.5	19.9
	Adhesives	14.0	0.5	13.9
	Cleaning solvents	7.0	0.5	7.0
	Total	41.0	0.5	40.8
Implement water-based finishes	Surface coatings (paints, stains, sealers, top coats)	13.5	Specific to coating	5.5
	Cleaning solvents (for finishing equipment only)	5.5	40	3.3
	Total	19.0	-	8.8
Implement mechanical clip attachment	Adhesive (polyester resin in styrene)	13.0	90	1.3
	Catalyst (cadox)	0.4	90	0.04
	Cleaning solvent (acetone)	1.5	90	0.15
	Total	14.9	-	1.5
Above measures	Overall total	74.9	-	51.1

6. Feasibility Assessment of Equipment Modifications

The feasibility is assessed in this section of the sole equipment modification that was considered to be realistically able to help reduce VOC emissions and enhance sustainability while being deemed acceptable from an industry perspective. The modification involved adding air purge into the paint lines.

6.1. Air Purge of Paint Lines

Many manufacturers use a closed-loop finishing system, so such a system is considered here. In such a system, compressed air forces unused finishing material into a pail for reuse during a colour changeover. When the finishing line is empty, dirty recycled solvent is pumped through the material line for initial cleaning followed by clean recycled solvent for final cleaning. All material is captured for reuse or disposal. An air purge system is therefore not pursued further because it would be redundant.

7. Feasibility Assessment of Production Process Modifications

The feasibility is assessed in this section of several modifications to the production process that can help reduce VOC emissions and improve sustainability, including the utilization of water-based coatings and hot melt backwrapping adhesive.

7.1. Water-Based Coatings

Technical: Conversion to water-based coating material for panel trims can be beneficial. One approach involves retaining current solvent-based stains, but applying a new solvent-based sealer and water-based topcoat, primer and paint. Such a change does not require extensive capital investment and can meet or exceeded most product requirements (although minor chemical resistance problems may remain). This approach is considered here.

Environmental: The implementation of a water-based finish decreases the toxicity of wastes by reducing solvent use and does not transfer wastes to other media. This measure does not impact energy usage. The resulting VOC annual emissions reduction is found in Table 2 (second section) to be 10,200 kg. It is assumed that pumps and hoses dedicated to water-based operations are cleaned using water, reducing solvent demand for cleaning [39]. Since paints, primers and topcoats represent 40% of the product, cleaning solvent consumption is estimated to decrease proportionally.

Economic: The spray equipment and pumps need to be replaced for this measure because, although typical equipment is capable of spraying water-based finishing product, it will corrode over time and the guns tend to clog. The capital cost to replace the spray equipment and pumps is approximately $40,000, plus $3,000 for installation and $2,000 for a pre-start safety review. Regarding operating costs (for the typical annual production levels considered here), water-based coatings cost an additional $120,000 and hazardous waste disposal costs are reduced by $20,000. A cost-benefit analysis is presented in Table 3 (first section). The significant increase in operating costs precludes this measure from being pursued in this study. The significant reductions it can yield in VOC emissions may make it more attractive in the future if VOC regulations become more stringent.

An economic comparison between the increasing operating cost of implementing water-based finishes and the cost of the VOC abatement for the same amount of VOC avoidance using air pollution control technologies (e.g., incineration, biological treatment). The authors may carry out such investigations in the future, based on methods described elsewhere [34-38].

Table 3. Cost-benefit analysis for selected measures for reducing VOC emissions.

Financial parameter	Item	Value	Notes
Measure: Implementing water-based finishes			
Capital cost ($)	Equipment	40,000	Quote: pumps, spray guns
	Installation	5,000	Estimate
	Engineering	2,000	Estimate: Pre-start safety review
	Total	47,000	
Operating cost rise ($/yr)	Disposal	–20,000	Reduced hazardous waste disposal
	Raw material	120,000	Quote: water based coatings
	Labour	0	
	Energy	0	
	Net increase	100,000	
Payback period (months)		-	Measure increases operating costs
Measure: Implementing hot-melt backwrapping glue			
Capital cost ($)	Equipment	50,000	Quote: 2 melter units, 4 spray guns
	Installation	10,000	Estimate
	Engineering	0	
	Total	60,000	
Operating cost rise ($/yr)	Material	–16,000	Spray booth filter savings
	Labour	30,000	Additional labour (1 operator)
	Energy	–20,000	Natural gas and fan electrical use
	Non-billable orders	–25,000	Edge yellowing field defect
	Net increase	–31,000	
	Material	–16,000	Spray booth filter savings
Payback period (months)		23	
Measure: Implementing a mechanical clip attachment			
Capital cost ($)	Metal-related equipment & tooling	130,000	Estimates: tile divider dies, frame punching and notching machines
	Panel-related equipment & tooling	20,000	Estimates: modify frame assembly fixtures, clip insertion tables
	Vendor equipment & tooling	100,000	Estimates: metal tile clip dies, plastic tile divider clip dies
	Total	250,000	
Operating cost rise ($/yr)	Raw material	70,000	Increased cost of clips, tile connector & tile connector clips less cost of resin, center post & U-clips
	Labour	–200,000	New panel clip application method (4 operator reduction) & removal of U-clip application (3 operator reduction)
	Energy		No change
	Net increase	–130,000	
Payback period (months)		23	

Table 3. *Cont.*

Financial parameter	Item	Value	Notes
Measure: Recycling dirty solvent			
Capital cost ($)	Equipment	25,000	Quote: solvent recycler, ventilation booth
	Installation	4,000	Quote: compressed air & electrical connection
	Engineering	3,000	Quote: pre-start safety review
	Total	32,000	
Operating cost rise ($/yr)	Disposal	–9,000	Less hazardous waste generation
	Raw material	–11,000	Reduced solvent purchases
	Energy	1,000	Increased energy consumption
	Net increase	–19,000	
Payback period (months)		20	

7.2. Hot Melt Backwrapping Adhesive

Technical: Hot melts are used throughout the furniture industry for similar applications as considered here. In the proposed system, a melter unit (consisting of a tank, pump, filter, manifold and temperature controller) heats the adhesive to the application temperature. The glue is then pumped through a heated hose to a spray gun, which utilizes controlled fiberization (Nordson Corporation, Norcross, Georgia) technology to dispense the glue. Controlled fiberization uses high velocity air jets to draw the adhesive into a fine fibre. The directed air jets rotate the monofilament into a spiral pattern for application to the substrate, according to Nordson [40]. Switching to a hot melt adhesive improves product quality since hot melt adhesives create a stronger bond than the adhesive typically used and do not discolour when subjected to ultraviolet radiation.

Environmental: The implementation of a hot melt backwrapping process does not change the toxicity of wastes or transfer wastes to other media. Hot melt glue is solid and the process has no emissions, eliminating the need for ventilation booths and reducing energy consumption to draw and heat air from outside the plant. VOC annual emissions the typical annual production levels considered here are predicted to decrease by 550 kg *via* hot melt backwrapping. It is noted on a broader scale that the gluing techniques compared here are not necessarily the ultimate sustainable solutions since gluing makes it difficult to apply other sustainability efforts like recycling and remanufacturing. For instance, other attachment methods, like the metal clips used elsewhere in the process and discussed previously, can be more sustainable. Hence, alternative attachment methods may prove preferable in the future. In the present investigation, the gluing process was for adhering fabric to a fibreglass substrate, and a company requirement was that the final appearance of the "tile" remained the same. This requirement significantly restricted potential cost effective fastening options (and precluded the use clips, staples or sewing). Nonetheless, in terms of recycling and remanufacturing, hot melt glues are reversible so the fabric could possibly be removed for recycling by applying heat.

Economic: The capital cost to purchase the two melter units and four spray guns required for current production is $40,000. In addition, four gun balancers costing $10,000 are needed to improve the ergonomics of the operation. Disassembly of the existing spray booths and installation of the new system is estimated to cost $10,000. Regarding operating costs (for production levels for the typical year considered), removing the spray booths reduces costs by $20,000 annually in energy for heating and moving make-up air, $16,000 for spray booth filters and $25,000 for reduced tile edge yellowing warranty claims. The application rates are slower so an additional operator is needed to meet demand, increasing annual labour costs by $30,000. The payback period is 23 months (see second section of Table 3), which is within the two-year payback period required to receive funding for capital projects that is typical of many industries..

8. Feasibility Assessment of Product Redesign

The feasibility is assessed of several redesign options for the product that can help reduce VOC emissions and improve sustainability, including the utilization of a mechanical clip attachment in place of the present attachment method and ceasing the painting of non-visible parts.

8.1. Mechanical Clip Attachment

Technical: A mechanical clip attachment method is currently used in some panel manufacturing facilities. The implementation of this measure normally requires engineering redesign of the profile of the frames and design of new clips and tile dividers. A separate benefit is that mechanical clip attachment allows panels to be individually removed and replaced, which may improve market share.

Environmental: The mechanical clip attachment does not change the toxicity of the wastes or transfer wastes to other media or change energy consumption, but does reduce solvent use. It is estimated that the mechanical clip will eliminate 90% of the demand for polyester resin, cadox and acetone. VOC annual emissions (for production levels for the typical year considered) are predicted to decrease by 13,410 kg *via* converting to a mechanical clip attachment method (see third section of Table 2).

Economic: The capital costs are of three types and are described here for production levels for the typical year considered. The metal-related costs are $70,000 for modification of frame punching machines, $30,000 for a vertical end notching machine and $30,000 for tile divider dies. The panel-related costs are $15,000 for modifications to frame bolting fixtures and $5,000 for tables and ergonomic floor matting for the clip insertion process. The cost for vendor tooling to fabricate metal tile clips and plastic tile divider clips is estimated as $100,000. Regarding operating costs, such a panel design eliminates the need for polyester resin to apply the clips and frame U-clips to connect the tiles to the frame, resulting in annual savings of $160,000 and $80,000 respectively. In addition, the tile connector is more rigid than typical connectors, eliminating the need for the center reinforcing post currently used on many larger panels (wider than 42 inches) and saving $70,000 annually. The new mechanical clip is more expensive and increases annual operating costs by about $130,000. The new tile connector is also more expensive and requires a bracket to connect to the frame, increasing annual material costs by about $250,000. The insertion of the new tile clip requires fewer operators, reducing annual labour costs by approximately $110,000, and eliminates the U-clip insertion process and its operators, saving $80,000. The payback period is 23 months (see third section of Table 3), meeting financial project requirements for many companies.

8.2. Cease Painting of Non-Visible Parts

Technical: All parts that are coated by most manufacturers are visible to the customer. However, some aluminium components, often coated by external suppliers, such as the upper frame horizontal, frame verticals and corner posts are not visible to the customer. Ceasing painting operations on these parts can be implemented quickly.

Environmental: Leaving parts uncoated does not reduce manufacturer VOC emissions directly since external suppliers coat horizontals, verticals and the center post. Due to the inherent difficulties in acquiring process data from external suppliers, the VOC emissions reductions are not evaluated.

Economic: No capital is required for this change. Purchasing unpainted vertical frames, top horizontal frames and corner posts is estimated to reduce the overall annual cost of the components by $175,000. The payback period is instantaneous.

9. Feasibility Assessment of Recycling and Reuse

The feasibility is assessed in this section of the sole measure involving recycling and reuse that is considered realistically able to reduce VOC emissions and enhance sustainability while being deemed acceptable from an industry perspective. The modification involved instituting solvent recycling.

Solvent Recycling

Technical: Solvent recyclers use distillation to extract clean solvent from waste paint. The distilled solvent can be used for cleaning or returned to the process. The remaining waste paint is collected for hazardous waste disposal. The major technical restriction on solvent recyclers is Ontario's stringent regulatory requirements pertaining to the processing, handling and storage of flammable liquids (Ontario Fire Code—Part 4, Ontario Ministry of Labour—Engineered Data Sheet 4–16: Solvent Recovery Equipment). A ventilation system is needed to control the release of flammable vapours.

Environmental: A solvent recycler decreases the toxicity of the waste stream by removing most of the hazardous solvent prior to disposal. Waste is not transferred to another medium. Energy consumption increases since the unit requires compressed air and electricity to operate and electricity is required to run the exhaust fan. Recycling spent solvent significantly reduces external VOC emissions by reducing the demand to manufacture virgin solvent and the quantity of waste solvent for disposal. External VOC reductions are not quantified because they are specific to the processes of suppliers. However, it is noted that external VOC reductions could perhaps be estimated from solvent recycling based on the reduction of raw material usage, and this approach may be used in future research into enhancing the sustainability of the operation.

Economic: The cost of a solvent distillation unit to meet the waste demand of the trims-related processes is estimated to be $8,000 (based on 25 L per 4 hours). The ventilation booth and exhaust fan cost about $17,000. Installation and engineering costs are estimated as $4,000 and $3,000 respectively. Regarding operating costs, reductions in waste disposal costs and raw material usage respectively save $9,000 and $11,000 annually, while increased electrical demand for the solvent recycler and the exhaust fan cost $1,000 annually. The payback period is 20 months (see fourth section of Table 3), meeting the financial project requirements of most companies.

10. Summary of Results and Implementing Capital Measures

Table 4 summarizes the potential economic and environmental benefits that can be realized by implementation of pollution prevention measures for production levels for the typical year considered, and that meet the objectives of typical companies.

Table 4. Summary of potential benefits of implementing selected pollution prevention measures.

Measure	Cost savings ($/yr)	Payback period (months)	VOC emissions reduction (tonnes/yr)
Non-Capital Measures			
Implement standard operating procedures	Not evaluated	Not evaluated	Not evaluated
Implement preventative maintenance	Not evaluated	Not evaluated	Not evaluated
Employee training and involvement	Not evaluated	Not evaluated	Not evaluated
Improve scrap reduction	Not evaluated	Not evaluated	0.21
Cease painting non-visible parts	175,000	0	External*
Capital Measures			
Switch to hot melt backwrapping glue	31,000	23	0.55
Recycle solvent	19,000	20	External*
Modify mechanical clip attachment	130,000	23	13.4

* VOC emissions are reduced through these measures, but are not quantified because they are specific to the processes of external suppliers.

Of the measures having the greatest potential for pollution prevention (see Table 4), the capital measures require a significant investment. Possible implementation times for the capital measures have been estimated based on typical equipment and tool-build lead times and past experience in similar processes. The estimated times to complete the hot melt backwrapping, mechanical clip attachment and solvent recycling measures are approximately 8, 13 and 8 months, respectively. As in any forecasting exercise, there is a margin of error due to the uncertainty of future events. Also, timing depends on the resources allocated to each measure.

11. Measurement and Control

It is necessary to monitor and measure the progress of VOC emission reduction measures, to determine if the pollution prevention, production and economic goals are met.

The quantity of VOC emissions are normally tracked using a mass balance approach. These data are corrected to ensure that factors, such as batch size or overall production volume, not related to pollution prevention do not influence the results. For instance, batch size influences VOC emissions, with smaller batches leading to more frequent changeovers. Increased changeovers increase solvent consumption thereby increasing emissions. If batch size in decreased to meet alternate goals, such as a reduction in lead time, the overall emissions must be corrected accordingly when measuring pollution prevention progress.

11.1. Trims-Related Measures

The volume of finishing material purchased annually is analysed. The total length of trims processed is used to normalize this value. Also, average batch size is calculated as the total pieces processed per day divided by the total number of colours scheduled. A company's material resource planning system can normally be used to retrieve required data.

11.2. Upholstery-Related Measures

For the mechanical clip application, the volume of material purchased annually is determined (acetone, polyester resin and catalyst). The total area of panels manufactured is used to normalize the data, as panel size is roughly proportional to the amount of resin applied for clip applications.

For the backwrapping measure, the volume of backwrapping glue purchased annually is determined. The sum of the total circumferences of all the panels manufactured is used to normalize the data because the backwrapping glue is only applied around the edge of the underside of the panel.

12. Benefits

The direct environmental, economic and technical benefits, as well as the indirect benefits, derived from the measures evaluated in this feasibility study, and their contributions to enhanced sustainability, are discussed.

12.1. Environmental Benefits

The pollution prevention measures considered are evaluated environmentally for VOC emissions, by assessing flows of wastes and inputs. The data allow a determination of the benefits of each measure, and in total exceed 14 tonnes annually.

12.2. Economic Benefits

Pollution prevention measures are evaluated economically similar to other process changes or capital investments. Capital and operating costs for each measure are compared with revenues and other benefits to determine the financial return. The data are tracked and assessed, and then used to determine the return on investment for each measure.

12.3. Indirect Benefits

Even when financial performance indicators are included in the analysis, all potential sources of cost reduction or revenue may not be identified or properly accounted for [33]. Only direct operating costs such as labour, material, waste disposal and energy are included in the cost-benefit analysis performed here. Intangible and indirect benefits resulting from pollution prevention measures need to be accounted for and, where possible, quantified to facilitate better decision making. These intangible and indirect benefits can include those listed below.

12.3.1. Improved employee morale

Employees are likely to be more productive when they believe their company in committed to improving working conditions and acts responsibly in the community [33].

12.3.2. Reduced risk of workers compensation claims

Work related accidents and illnesses can be decreased by reducing the quantity of hazardous materials used and produced in a facility.

12.3.3. Tax incentives

Governments offer tax incentives for investment in the development and application of clean technology. For example, the federal Scientific Research and Experiential Development Program offers up to a 35% refundable investment tax credit for expenditures in research and development that lead to new or improved products or processes [41].

12.3.4. Reduced risk of liability

Reducing the quantity and toxicity of hazardous material in a facility decreases the risk of civil and criminal liability. A successful pollution prevention program may be evidence of “due diligence”.

12.3.5. Potential to exploit environmental legislation

Environmental legislation is becoming stricter over time. Pollution prevention activities undertaken today may generate revenue by permitting the sale of emissions credits in the future. For instance, Ontario’s Clean Air Plan proposes to reduce smog and acid rain by further regulating emissions and including industrial emitters in emissions trading programs [42]. Although the plan focuses on nitrogen oxides (NOx) and sulphur dioxide (SO_2), VOC emissions may eventually be included in emissions trading.

12.3.6. Reduced risk of need for environmental remediation

A pollution prevention program can reduce the risk of hazardous waste accumulation on-site requiring costly remediation during decommissioning.

12.3.7. Improved company image

Publicizing environmental successes can improve the perception of a company by the community and customers [33], potentially increasing sales revenue.

12.4. Sustainability Benefits

By improving the environmental performance of the manufacturing of office furniture partitions, while providing economic, technical and other indirect benefits, the overall sustainability of the industrial operation is enhanced. Of course, reducing VOC emissions is but one of many necessary steps for improving the sustainability of this manufacturing operation; other sustainability measures are also needed to provide a more comprehensive approach.

13. Conclusions

It would likely be advantageous in terms of sustainability and other criteria for manufacturers of office panels to undertake several pollution prevention measures aimed at reducing VOC emissions. The specific measures depend on the particular circumstance, but the present study suggests that the measures likely to be found to be beneficial include the implementation of standard operating procedures, preventative maintenance and employee training programs, and the improvement of scrap reduction efforts. In addition, several process modifications, product redesigns and recycling initiatives are likely worthwhile. Specifically, the mechanical panel clip attachment, solvent recycler and hot melt backwrapping measures can provide both VOC emissions reductions and cost savings. Note that, although the measure involving conversion to a water-based finish can significantly reduce VOC emissions, the measure is difficult to justify financially at present because it involves a large increase in material costs. However, this measure is likely to prove beneficial in the future as the conversion to a water-based topcoat may improve customer perception and limit risk if VOC emission regulations change. To improve the analysis, intangible and indirect benefits resulting from the pollution prevention measures need to be quantified better. In addition, companies should consider lengthening the payback requirement they apply for projects (typically no more than two years) for pollution prevention measures because of the longer times required to realize their benefits. Such a change may allow more pollution prevention measures to be justified, benefiting companies and their communities in the long term through better sustainability. Of course, reducing VOC emissions needs to be viewed as but one step in more comprehensive efforts to improve the sustainability of office panel manufacturing.

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