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A method to estimate the total VOC emission of furniture products

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Abstract

In the last decade, the environmental sustainability has become an important issue that drives more and more the consumer decisions. Consequently, industrial companies are called to meet the growing demand for more sustainable products. Especially in the furniture sector, customers pay serious attention to the emissions that negatively affect human health and so they request products with low volatile organic compounds (VOCs) emissions. This represents a big challenge because it requires the strictly control of each component provided by all the supply chain actors through expensive laboratory tests. For this aim, the present paper proposes a method to estimate the total VOCs emissions of furniture products starting from the characteristics of all semi-finished products (e.g., geometric features, product composition, process information and functionality) and through the definition of an appropriate impact scale based on historical data. It allows making the supply chain (SC) more sustainable, limiting costly chamber tests.

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Keywords: Sustainable Manufacturing; Indoor air quality; Furniture products; Product declaration; VOC emissions;

1. Introduction

Nowadays, more people spend most of their daily life at indoor environments, especially in industrialized countries. This exposes them to a vast range of building materials and consumer products, that emanate volatile organic compounds (VOCs), contributing considerably to the deterioration of Indoor Environmental Quality (IEQ) [1]. A few

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examples of VOCs are formaldehyde, benzene, hexanal, and phenol. These indoor air contaminants can contribute to the onset of Sick Building Syndrome, a medical condition where people in a building suffer from symptoms of illness or feel unwell for no apparent reason [2]. In detail, short-term exposure to VOCs may cause decreased worker productiveness [3,4] and acute health effects such as eye and respiratory irritations, headaches, fatigue, and asthmatic symptoms [5,6]. Long-term exposure may cause cancers [7,8] with benzene and formaldehyde classified as "known human carcinogens" [9]. Additionally, while outdoor air and working environments are controlled by legislation aimed at reducing exposure to pollutants, air quality of private buildings is not regulated by laws, but only recommendations (e.g. WHO guidelines for indoor air quality [10]).

In this context, furnishing products are a key element in determining the quality of indoor air. Indeed, they are essentially assembling products, which employs several raw materials that range from wood to metals, from plastics to textile. Adhesive, paints, solvents, treated wood, urethane coatings are also used in their production. These wood-based products are known to contain and emit VOCs, especially if they are recently installed [11,12]. The majority of these products is bonded with urea-formaldehyde adhesive, which leads to off gassing of formaldehyde due to chemical reactions during their service lives [13].

The purpose of this study was to develop a method to estimate the total VOCs emissions of furniture products starting from the characteristics of all semi-finished products (e.g., geometric features, product composition, process information and functionality) and through the definition of an appropriate impact scale based on historical data. The method will be useful for the designer to know in advance the emissions impact of the furnishing product during the use phase, limiting costly chamber tests. At the same time, it involves the entire Supply Chain (SC). Indeed, the collaboration with suppliers is fundamental to identify and eliminate substances or components that impact more. As well, this method could be used to help the consumer in the correct evaluation of the product. In fact, in the furniture sector there are no certifications of finished products: the certifications are often only on the individual components such as, for example, particleboard panels [14, 15].

Methods and regulations mainly used for assessing the sustainability and safety of a product and the state of art of VOCs emissions are detailed in Section 2. Section 3 describes a new model for the calculation of impact for a furniture product. This model includes the estimation of three important parameters that allow to consider the material, surface and the contribution to the total VOCs emissions. Section 4 presents a case study in which this new method is applied. The results obtained are compared with those obtained experimentally through emission chamber testing. The paper concludes with a discussion of the strong and weak points of this new method.

2. Research background

The control and mitigation of the volatile organic compounds is one of the most important indices affecting sustainable development of furniture industry [16]. It is due to the large use of synthetic resins, varnishes, adhesives and other substances that are detrimental for human health and environment. In particular, VOCs encapsulated in this kind of products can be a major emission source in the use phase. Therefore, the selection of products with low emission rates is essential to improve the IEQ in which they are used. New regulations have been introduced in some European countries and in America (e.g., LEED, BREEAM, French Regulations on VOC etc.). However, these norms regard buildings and construction products installed indoors (e.g., floor and wall coverings, paints and lacquers) and they do not consider furniture products.

In addition to the regulatory requirements and incentives related to the use of building materials without pollutant emissions, labelling programs should be promoted to support designers in the selection of a low-VOC alternative. Parikka et al. also suggest Green Public Procurement (GPP) as a method to promote environmentally sound product design and motivate manufacturers to make furniture with reduced environmental impacts [17]. In order to comply with these requirements, the emissions of VOCs have to be characterized and assessed by industries, which often use environmental chamber equipment and procedures [18]. As demonstrated by literature, many efforts have been dedicated by researchers to the study of methods for the analysis of formaldehyde and VOCs from wood-based panel materials for furniture and building interiors, highlighting how they affect indoor air quality [19, 20, 21]. Other researchers adapted a complex model which describes VOC emissions from building materials and subsequent removal by ventilation [22]. However, these research works offer rather complex methods to determine the VOC emission and only a small number of models, not yet validated, are able to predict them in in the absence of experimental data [23]. Furthermore, most of them have been developed for a specific condition (e.g. formaldehyde emissions from particleboard and other engineered wood or biocide emissions from treated wood) and do not allow calculating the emission of a complete furniture product.

The LCA studies and other materials (e.g. Environmental Product Declaration - EPD) available in the literature can represent important sources of information for addressing the assessment and improvement of the sustainability of products. However, these methods provide only data on emissions occurring during the production and disposal phases of commonly used indoor wood products and do not contain information on pollutants emitted by these products during their use phase [24].

Moreover, the consideration of sustainability aspects in product development is still immature and poorly implemented compared to other aspects, such as product performance and manufacturability [25].

Therefore, it still emerges the needs of a simplified approach that supports designers in a preliminary evaluation of VOC emission of complex products. It should be also taken into account the consumers' mistrust regarding the non-observable environmental impact of wood products, which is a purchase barriers concerning eco-friendly products. Indeed, current studies have shown that eco-labels may be perceived mostly as a marketing tool, while providing product information based on traceability systems increases consumers' product acceptance of environmentally friendly goods and purchase intentions [26]. In order guarantee a complete traceability and improve the environmental performances it is important to involve the entire SC [27, 28, 29]. Upstream supply chain activities play an important role in determining the product environmental sustainability [30].

This paper aims to overcome the current lack by proposing a method to estimate the total VOCs emissions of furniture products starting from the characteristics of its components and the analysis of the SC, and using historical data. It allows designers to compare several materials and components and to preliminary estimate the impact of final product during the use phase.

3. The method

The proposed method for the estimation of the total impact of a complex industrial product, based on its VOCs emissions, is characterized by four main steps, which are described in the following paragraphs:

- Collection of information about all materials and parts of the product;
- Estimation of an impact score for each material of the product;
- Estimation of contribution of each material to the total VOCs emissions of the product;
- Estimation of the total impact of the product.

3.1. Collection of all information about all materials and parts of the product

This step aims to identify all the components of the product and to determine the emissive surfaces (visible or not) and the materials that characterize each of them. This implies the analysis of the product, in order to acquire all information about the geometry of its parts (surface, thickness, etc.), their relations within sub-assemblies and assemblies (e.g., parts glued / mounted, visible parts, parts not in view, etc.) and their materials. In general, the majority of such information can be easily retrieved from the Bill of Material (BOM) of the product. However, the approach is not limited to the final product, but considers all the elaboration processes it undergone. In this case, the BOM usually does not hold information about all the materials of product components (e.g., the glue used for the veneer of a shutter, or the type of paint used to finish it). For this aim, each step of the supply chain needs to be identified and characterized in order to collect information about all raw materials, semi-finished components, and processes that contribute to the product impact in terms of VOCs emissions. The active involvement of suppliers plays a key role in this phase.

3.2. Estimation of the impact factor for each material of the product

The retrieval of information about the materials begins with a careful analysis of SC. Through the involvement of all SC actors, it will be possible to achieve all the information concerning raw materials and semi-finished components. All chamber tests and other analysis conducted by suppliers on their own products are collected (e.g., the results of formaldehyde analysis for chipboard panels). The relationship with suppliers is no longer limited to the compliance with specific requirements, but is based on data sharing to improve the product performance in terms of sustainability. Only in this way, an acceptable level of accuracy in the estimation of final product VOCs emissions can be reached.

Instead, for the materials of which there are no information about the emissions during the use phase, the method uses an internal database developed in collaboration with specialists of a center for wooden furniture companies. The database collects, for each material, all the information about already made analysis (historic of chamber tests) and the information derived from scientific literature. Based on this information, three experts in VOCs, working for at least 10 years in accredited labs for product certification, are asked to assess product materials, by using the 0-10 Impact Scale defined in Table 1. Such scale allows the assessment of material/product based on both the level of emission and the dangerousness to health of released substances.

The Impact Score $Is(M)$ is assigned considering four emission levels, defined according to the French Regulations on VOCs emissions from construction products (i.e., very low: <1000 μg·m^3, low: <1500 μg·m^3, moderate: <2000 μg·m^3 and high: >2000 μg·m^3) [31] and three levels of danger of released substances (i.e., substances not present in the ECHA Candidate List, substances presented in the ECHA Candidate List with suspected toxicity/carcinogenicity/dangerous for the environment, substances presented in the ECHA Candidate List with assessed toxicity/carcinogenicity/dangerous for the environment) [32]. For each material, the resulted impact factor is determined as the medians of experts' judgments.

Table 1. The proposed product classification based on VOC emission estimation

Impact Score (Is)	*Classification*	*Total VOC emissions*	*Characterization of emitted substances*
	No-emissive		
0	Low/moderate emissions not dangerous to health	very low (<1000 μg·m^3)	no substances from the candidate list ECHA
1		low (<1500 μg·m^3)	no substances from the candidate list ECHA
2		moderate (<2000 μg·m^3)	no substances from the candidate list ECHA
3	High emissions not dangerous to health / Low emissions dangerous to health	high (>2000 μg·m^3)	no substances from the candidate list ECHA
4		very low (<1000 μg·m^3)	presence of substances belonging to the ECHA candidate list with suspected toxicity / carcinogenicity / dangerous for the environment
5		low (<1500 μg·m^3)	presence of substances belonging to the ECHA candidate list with suspected toxicity / carcinogenicity / dangerous for the environment
6		very low (<1000 μg·m^3)	presence of substances in the candidate list of ECHA with assessed toxicity / carcinogenicity / dangerous for the environment
7		moderate (<2000 μg·m^3)	presence of substances belonging to the ECHA candidate list with suspected toxicity / carcinogenicity / dangerous for the environment
8	High emission dangerous to health	low (<1500 μg·m^3)	presence of substances in the candidate list of ECHA with assessed toxicity / carcinogenicity / dangerous for the environment
9		high (>2000 μg·m^3)	presence of substances belonging to the ECHA candidate list with suspected toxicity / carcinogenicity / dangerous for the environment
10		moderate (<2000 μg·m^3)	presence of substances in the candidate list of ECHA with assessed toxicity / carcinogenicity / dangerous for the environment

3.3. Estimation of contribution of each material to the total VOCs emissions

Once specified the geometry of the product and the materials used, the contribution of each material to the total VOCs emissions calculated in percentage of the total emissive surface has been established. The percentage of emission due to each material can be then computed by using the following formula:

$$E\,(M) = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m} S_{ij\,(M)}\,\theta_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{m} S_{ij}\,\theta_{ij}}$$

where $S_{ij\,(M)}$ represent the j^{th} surface of the i^{th} product component, characterized by the M material, and θ_{ij} is the coefficient of orientation of j^{th} surface of the i^{th} component. The calculation of the orientation coefficient is performed by considering the position of the surface with respect to the geometry of the finished product distinguishing those which are in contact with the environment and those partially or completely occluded. It is reasonable to assume that the total VOC emission is determined primarily by the contacting surfaces, while in general the contribution of those completely occluded is very poor. In order to estimate total emissive surfaces of furniture, we consider $\theta_{ij} = 1$ for the external surfaces of the furniture, $\theta_{ij} = 0.1$ for the internal surfaces and $\theta_{ij} = 0.01$ for glued/covered to/by other parts.

3.4. Estimation of the total impact of the product

In order to estimate the total impact of the product, it is necessary to estimate its total VOCs emission (TVOC). To this purpose, TVOC is then estimated by the following formula:

$$TVOC = \sum_{M=1}^{n} E(M) \cdot Is(M)$$

where $E(M)$ is the percentage contribution of each material to the total emission of the product and $Is(M)$ is the emission of each material. Once estimated the total product emissions, the product impact class can be determined by using the Table 2.

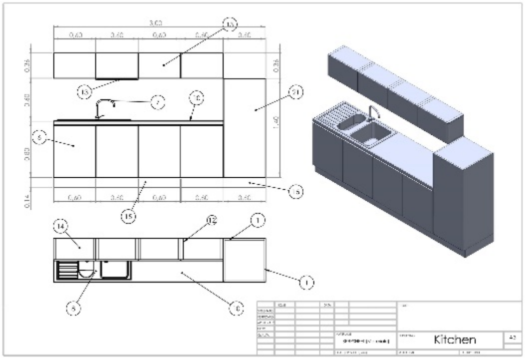
Table 2. The proposed classification for furniture products

Class	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
TVOC score	< 0,75	< 1,5	< 2,5	< 3,5	< 4,5	< 6,0	< 7,5	> 9

4. Case study

The proposed method has been applied on the kitchens sector and the obtained outcomes have been then compared with the emission chamber testing results.

In detail, two kitchen models with the same dimensions but different finishes and materials have been analyzed. The upstream SC has been involved to retrieve the necessary data. The most used materials and finishes in the production of kitchens have been considered: for the first kitchen model, structure in E1 chipboard [14] and doors in medium density fiberboard (MDF) painted with acrylic finish; for the second model, F4star chipboard [15] for the structure panels and doors in F4star chipboard painted with polyester paints. The definition of impact score of each material have allowed obtaining the TVOC and the corresponding emission class of the whole kitchens (Figure 1). Subsequently, the same two kitchen models have been analyzed by chamber tests according to EN ISO 16000.



	VOC (K_1)	**VOC** (K_2)
Wood-effect melamine-coated wood particle board panel (E1 quality)	0,981	
ABS edging glued on using a thermosetting polyurethane adhesive	0,236	0,236
MDF panels painted with acrylic finish	1,472	
Aluminium	0,000	0,000
Melamine faced wood particle board panels (F****)		0,436
F4star panels painted with polyester paints		0,654
Pvc	0,061	0,061
Wood particle board coated with high pressure laminate	0,779	0,779
Laminate with thermosetting polyurethane adhesive	0,042	0,042
TOTAL VOC	3,573	2,209

Fig. 1. Kitchen layout (left) and an extract of the TVOC Calculation for each kitchen model (right).

Through the application of the method, it emerged how the two kitchen models differ from the emissive point of view. The two models obtained different TVOC scores and therefore different emission classes (i.e. E for the first model and C for the second). The difference of total emissions of the two models has also been confirmed by chamber tests (Table 3). In this way, during the design or the purchase phase, it is possible to estimate the impact that the choice of a material or a finishing has on the final product.

Table 3. Total VOC emissions of two kitchen models.

		Kitchen Model 1	**Kitchen Model 2**
TVOC	*Calculated by our method*	Class E	Class C
	Tested by EN ISO 16000	0,47 $\mu g \cdot m^3$	0,27 $\mu g \cdot m^3$

5. Discussion

The proposed method allows estimating the total VOCs emissions of a complex furniture product through the study of the materials and the SC. At this early stage of research, the method has been tested only for the kitchen industry. It was applied to the kitchen industry because it allows offering an exemplifying overview of the furniture sector. A kitchen, indeed, is made by several components combined on the needs of the final customer, in order to both create a unique instance of the product and, more relevantly, to fit the furniture dimensions with the specific measures of the room where it is placed. Another common feature is the possibility to choose the type of material and finish. Additionally, the proposed method is generic and can be easily extended to other product groups as the necessary data become available, and, hence, enable a standard assessment of indoor emissions.

It estimates only the total value of the emissions and it does not make distinctions between the several kinds of emitted substances. This is because the method aims to provide an indication of the overall emissions of the finished product. Indeed, through it will be possible to develop a kind of "labeling" of the product that allows differentiating a more impactful produced by one less.

Moreover, this method could be implemented in the existing sustainability analysis tools. In fact, in the furniture sector, customers pay serious attention to the emissions that negatively affect human health and so they request sustainable products with low VOCs emissions. The health impact factors would be so listed side by side with environmental impact of LCA and EPD analyses. Thus, the consumer will have a better awareness of the product through the indication of the amount of total VOC emissions and environmental impact. At the same time, for the furniture company the method is useful to incorporate human health considerations (together with the sustainability of product) in the supply chain alongside the conventional criteria of price and quality. By applying this approach, the company shifts part of the liability of being sustainable and safe for human health to suppliers, in order to meet the customers demand of green and safe products.

Finally, the evaluation of the emission from the study of the materials used in the furniture production and the SC may be helpful to both the designer and the consumer. Indeed, in the design phase of a new product, it could help the designer in the definition of finishes and materials safe for human health, limiting costly chamber tests. It may also be useful in the selection of suppliers and it allows making the SC more sustainable. Finally, the method makes the consumer more aware in the choice of the finish and materials of a furniture product, estimating their impact during the use phase.

6. Conclusion

A method to estimate the total VOCs emissions of furniture products starting from the characteristics of all semi-finished products (e.g., geometric features, product composition, process information and functionality) and through the definition of an appropriate impact scale based on historical data has been developed. The method is useful for the designer to know in advance the emissions impact of the furnishing product. As well, it can be used to help the consumer in the correct evaluation of the product.

The method has been tested for kitchen furniture because it is difficult to determine in advance the emissive impact of the final product due to the heterogeneity of the elements and it allows offering an exemplifying overview of the furniture sector. In detail, the proposed approach is based on the emission tests of materials and on the knowledge gained through SC. The calculated emissions were then compared with the experimental results of the chamber tests.

The method aims to provide an indication of the overall emissions of the finished product and it is also compatible with the methods already used in EPD/LCA. Through it, a kind of "labeling" of the furniture product that allows differentiating a more impactful produced by one less has been developed through the method. Future activities will be focus on the generalization of the method: it will be tested on other furniture products and extended to all industrial products.

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