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# Systematic design analysis and risk management on engineered nanoparticles occupational exposure

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**ABSTRACT**
The production of nanotechnology-based products is increasing, along with the conscience of the possible harmful effects of some nanomaterials. The "safety-by-design" approaches are getting attention as helpful tools to develop safer products and production processes. The Systematic Design Analysis Approach could help to identify the solutions to control the workplace risks by defining the emission and exposure scenarios and the possible barriers to interrupt them. By applying this approach in a photocatalytic ceramic tiles development project it was possible to identify relevant nanoparticles emission scenarios and related barriers, and defining possible ways to reduce it.

**Keywords:** emission scenarios; exposure scenarios; safety-by-design; bow-tie model; ceramics

## 1. INTRODUCTION
Photocatalytic ceramic tiles containing nano-sized titanium dioxide have self-clean characteristics and are also able to transform some air pollutants, like nitrogen oxides, contributing to a cleaner ambient air, and reveal anti-bacterial properties (Chen & Poon, 2009).
In general, the in-vitro and in-vivo tests done with micronized and nano-sized titanium dioxide demonstrates potential for harmful health effects in humans, (NIOSH, 2011)
Some authors have been defending the need for methodologies that deal with the risks related with nanotechnologies based on the processes or products design (Amyotte, 2011; Fleury et al, 2011; Schulte et al., 2010).
The aim of this paper is to present the work carried out to establish a safer production process resulting from a development project. The research questions underlying this analysis are:

- Does a design approach of the production line of photocatalytic ceramic tiles generate relevant emission scenarios and related barriers?
- What are the possibilities of Systematic Design Analysis Approach (SYDAA) on reducing emission scenarios during photocatalytic ceramic tiles production?

## 2. METHODOLOGY

### 2.1. Framework
The work presented in this paper was performed during the development project of photocatalytic ceramic tiles, using titanium dioxide (anatase) and made by common ceramics production processes, which was part of a funded research project. The multidisciplinary project team discuss on the health and safety aspects during the project meetings. These discussions were complemented by observation and information collection during the laboratory and semi-industrial tests performed during the project.

### 2.2. Systematic design analysis approach
Although occupational safety and hygiene research pays more attention to risk analysis (Swuste, 1996), several authors in this domain have done research in the safety by design field, especially at the Safety Science Group of Delft University of Technology (e.g., Stoop, 1990; Schupp et al., 2006; Hale et al, 2007). Swuste (1996), for example, proposed a systematic approach towards solutions based on three complementary elements:

- Hazard process model;
- Design analysis;
- Problem-solving cycle.

### 2.3. Design analysis
The design analysis methodology allows studying and understanding the workplace conditions. In design analysis the production process is split into three levels of decision, described below:

- **Production function**: is the highest level and divides the production process into his core activities, similar to unit operations;
- **Production principle**: identifies the general process, motive power and operational control methods by which the production function can be achieved;
- **Production form**: is the lowest level and specifies the detailed design by which the production principle will be accomplished.

If there is a large number of production processes, the type of functions (or unit operations in rigor) in which each process can be broke down is relative small. In the ceramic tiles industry some examples of processing production functions or unit operations are milling, conformation, drying, glazing, firing and sorting, among others.

### 2.3. Hazard process model - Bow-tie

The bow-tie model is used in the safety science field as a tool to prevent the occurrence of accidents (Visser, 1998). Its adaptation to the occupational hygiene field helps to establish the necessary barriers to control the risks arising from different workplace exposure scenarios (Silva et al, 2013).

## 3. RESULTS AND DISCUSSION

### 3.1 Production process and the design analysis

After the preliminary tests the planned photocatalytic ceramic tiles production process was defined and proposed the use of already existing equipment in the ceramic production plant. Then, the first step was to detail the production process, dividing in its functions, principles and forms. This work was performed during the project meetings, by getting contributions from all the project team members.

During the project meetings, it was possible to define alternative production principles and alternative forms for the production process. The possible options were the automation of the sack empting operation, ultrasound agitation for raw materials mixing and a few non-spraying techniques to apply the $TiO_2$ aqueous suspension in the ceramic tiles (e.g. roll printing, serigraphy or ink-jet).

Considering the bow-tie model together with the design analysis, it is possible to identify the emission scenarios and the barriers for each production function, and related principles and forms. The scenarios and barriers are defined for the normal functioning situations, process disturbances, facilities cleaning and equipment maintenance (Table 1).

Table 1 - Emission scenarios and related barriers related with possible options of production principle

| Production function | Production principle | Normally functioning | | Process disturbances | | Cleaning | | Maintenance | |
|---|---|---|---|---|---|---|---|---|---|
| | | Emission scenario | Emission barrier | Emission scenario | Emission barrier | Emission scenario | Emission barrier | Emission scenario | Emission barrier |
| **Pouring raw materials** | Manual operation | Dust release | | Powder spills | | Cleaning powder spills | | Intervention on dirty equipment | |
| | Automatic process | Dust release | Closed cabinet | Powder spills | Closed cabinet | Cleaning powder spills | Vacuum-cleaner | Intervention on dirty equipment | |
| **Pre-prepared slurry** | | | | Slurry spills | Closed containers | Cleaning dried slurry spills | | | |
| **Mixing raw materials** | Mechanical stirring | | | Slurry spills | | Cleaning dried slurry spills | | Intervention on dirty equipment | |
| | Ultrasound agitation | | | Slurry spills | | Cleaning dried slurry spills | | Intervention on dirty equipment | |
| **Surface coating** | Spraying, automatic | Spraying (aerosol release) | Closed cabin with LEV | Slurry spills, spray gun clog | | Cleaning dried spills | | Intervention on dirty equipment | |
| | All non-spraying technics, automatic | | | Slurry spills | | Cleaning dried spills | | Intervention on dirty equipment | |

### 3.2 Discussion

The SYDAA creates a cooperative environment between process engineers, safety practitioners and other people involved on the development of the process, facilitating the communication and understanding inside the multidisciplinary team. With this approach it is possible to really involve the designers and engineers in occupational risk management.

The production functions and production principles are crucial to design solutions, since emission is directly related to the applied production functions. These functions will limit the number of possible principles, and consequently the number of forms. The actual emission, resulting in exposure, always becomes visible at the production form. Conventional occupational hygiene control measures, such as local exhaust ventilation (LEV), enclosure, etc., will act upon the production form.

However, when the emission (and the related exposure) is too excessive, or the contaminants are too dangerous, (re)design approaches will be the only option left to reduce or eliminate emission (apart from cancelling the whole production). (Re)design consist on changing production-principles under an unchanged production function, or changing or eliminating production functions. This last option is very effective, because the corresponding principles and forms will be also eliminated. Using pre-mixed slurries instead of mixing powdered raw materials is an example where all functions related to raw materials processing are eliminated. When a company introduces these changes, it is reducing substantially the sources of emission and exposure at the initial phase of the production process. Obviously, other companies will need to perform these production-functions, but when volumes are big enough, also these companies can modify their production methods, for example, by changing their mode of operation from manual to automatic.

Accordingly, the use of the supply chain with OSH purposes is one question raised with SYDAA. The design analysis performed along the supply-chain helps at identifying opportunities to transfer higher risk operations to facilities prepared to deal with it, allowing others to focus on the core process operations, which will ultimately result in safer workplaces by implementing cost-effective solutions.

## 4. CONCLUSIONS

The use of the SYDAA helps on finding solutions to reduce the workers' exposure during the work with engineered nanomaterials. As shown in the current case, it seems that there is an advantage in applying during the project development, or by other words, during the project phase, before the final process design being set.

With this approach it was possible to generate emission scenarios resulting from the photocatalytic ceramic tiles production process operations, being the bow tie a helpful concept model to achieve this.

Following the emission scenarios identification, it was also possible to define emission reduction barriers. In the particular case of the production of photocatalytic ceramic tiles it was possible to identify opportunities to reduce emission of nanoparticles, resulting in the proposal of an intrinsically safer production process.

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