Particle number concentrations and size distributions of nanoparticles during the use of hand-tools in refurbishment activities

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ABSTRACT

Hand-tools, such as sledgehammer, are widely used in refurbishment activities, nonetheless there is very little knowledge on nanoparticle generation. We measured particle number size distributions (PSD) and concentrations (PNC) in the 10–420 nm using a NanoScan Scanning Mobility Particle Sizer (SMPS) during the use of hand-tools (i.e., sanding and removal of wall) in a real indoor refurbishment environment. Results indicated that refurbishment activities from removal of wall increased average PNCs by ~6 times over the background, while was ~1.5 times higher than sanding. Highest total PNC was 1.9×10^5 particles cm^{-3} , that corresponded to removal of wall activities. For sanding activities, PNC was lower as the

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coat of the plaster was probably slightly wet. Moreover, comparison between the two principal activities showed a similar peak in the accumulation mode (~65 nm), with a monomodal pattern. Results suggest that removal of wall activities emitted nanoparticles with a 59% of contribution in the Aitken mode. According to these data, can be inferred that the application of hand-tools in refurbishment activities generates lower total PNC than using electromechanical equipment. This study may contribute to our understanding of nanoparticle generation in refurbishment activities.

Keywords: nanoparticles, refurbishment, particle number concentration, particle size distribution

1. Introduction

Over the past 50 years, the urban population has grown worldwide and it is estimated to reach 8.5 billion by 2030 (Parrish et al. 2011). Development of urban infrastructure is an inevitable consequence of the population growth, which means the need for new construction and, at the same time, the demolition and/or refurbishment of the older ones (Kumar et al. 2012b, 2014). With the introduction of nanotechnology, primarily, the improvements in the civil construction materials, such as mortars, concretes, ceramics, acrylic masses, and others, have brought great advantages in terms of workability, durability, and strength. However, one of the disadvantages of actual civil construction industry (construction, demolition, refurbishment) is their effects on surrounding environments (Kumar et al. 2012a; Azarmi et al. 2015a; Azarmi and Kumar 2016). For example, the construction industry alone consumes

more raw materials (about 3000 Mt/year, almost 50% by weight) than any other economic activity and still focus on the mechanical properties of construction materials, needing more concern regarding environmental considerations (Pacheco-Torgal and Labrincha 2013).

Moreover, workers handle materials such as cement, sand, water, additives, and other materials during construction, demolition, or refurbishment activities, which constitute a continuous mechanical application of these materials. Furthermore, there are very few or no studies that have analyzed the applications of acrylic surface coating that is used during the refurbishment process. These mechanical applications may emit submicron and nanoparticles of different sizes and concentrations (Jabbour et al. 2017a). Nanoparticles emission, is a crucial concern to human health, as these particles are subject to inhalation and may cause respiratory allergies and trigger the immune system (Kazzaz et al. 2017). In the indoor environment, air currents near the floor surface can keep the particles suspended for a long time. Moreover, sources and forces induced by human construction activity are not well studied, and experiments are recommended to quantify the real particle adhesion force with surfaces in indoor environment, even though resuspension forces are generally smaller for nanoparticles (Hu et al. 2008).

Even though some research work has been conducted in demolition or construction activities, few studies have analyzed the generation of nanoparticles in refurbishment activities. Currently, most studies focus on the cement industry and airborne mass measurements, principally PM_{10} and $PM_{2.5}$ (Cuccia et al. 2010; Azarmi et al. 2016). Demolition and refurbishment has the potential to release nano-sized particles of a range of potentially reactive aluminosilicates (Kumar et al. 2012b). This is of some concern as currently there is little knowledge about the generation of refurbishment nanoparticles and their impact on

work environment (Brouwer et al. 2009; Azarmi et al. 2016; Jabbour et al. 2017b). There have been few empirical investigations with regard to the associated emissions of nanoparticles, their exposure levels, potential effects on air quality, and health risks, despite the increasing demand of refurbishment activities (Kumar et al. 2012a). Nanoparticles incorporated in concrete may cause airborne problems during demolition, which has not yet adequately assessed for risk factors (Bystrzejewska-Piotrowska et al. 2009). Building materials may contain toxins or cancer agents in paints, varnishes, and concrete blocks (radioactivity), among others (Torgal and Jalali 2011). Construction materials for finishing the interior are now used, together with adhesives or other materials rather than they are used alone. Consequently, composite material have different characteristics in emission from construction materials (Kim et al. 2005). Therefore, the sustainable development and pollution-free production should be the primary objective of industries (Hens et al. 2017).

Few studies have already been done with other size ranges, although, especially for mass particle concentrations (Kumar et al. 2012b; Azarmi et al. 2014; Azarmi and Kumar 2016) in different environments. Given the scarceness of studies in this subject, the objective of this study was to measure the size distribution and the number concentration of nanoparticles generated during real refurbishment activities in an indoor environment using hand-tools. This is a unique study, carried out in typical construction indoor environment of Latin American cities, providing new insights to number concentration and size distribution of nanoparticles, generated during refurbishment activities using hand-tools, a typical practice used in developing countries, such as removal of indoor walls and sanding.

2. Materials and methods

2.1. Description of site and activities

In developing countries, such as Brazil, all minor refurbishment (removal of walls, sanding and others) activity are performed using hand tools. In this study, a removal of wall and a sanding activity were evaluated. Two workers performed the refurbishment activities. Apartment was located in a small city, i.e., Nova Santa Rita, of South Brazil, in the metropolitan area of the capital of Rio Grande do Sul state. During the refurbishment mean temperature and relative humidity were 23.45 °C and 78.50%, respectively. Activities were done with natural ventilation, with windows open and prevailing wind direction SE, mean wind velocity 3.12 m/s. More information about the meteorological conditions of the Region may be consulted in Landim (2018).

For “removal of wall” activity, a sledgehammer (steel head dimensions 225.0 mm height × 95.0 mm width and 9.0 kg weight; wood handle of 915.0 mm height) was used for collapsing the wall. Also, a hammer (steel head dimensions 123.0 mm height × 50.0 mm width and 2.0 kg weight; wood handle of 280.0 mm height) and a chisel (steel body dimensions 200 mm height, 30.0 mm head width, 19.0 mm handle width and 0.40 kg weight) were used for completing small debris removal from wall collapse and kitchen tiles. Removed wall was composed of ceramic bricks, with a layer of cement Portland plaster and an additional paint layer. During the cleaning of the location, the larger debris was manually collected, while smaller debris and dust were collected using broom and shovel. During the cracking, the waste was stored in bags and transported to the east window of the apartment (see figure S1 in Supporting Information). At the end of the activities, the bags were removed through the window by using a slider associated with a special dump container.

For the sanding activity, a flint sandpaper of 150 grit size was used. Sanding was performed in a cement wall coated with plaster (BASF, 2018). As explained above, during the cleaning, dust was collected using broom and shovel. However, sometimes the plaster was employed at the same time as cleaning activity.

2.2. Data collection

A NanoScan Scanning Mobility Particle Sizer (SMPS; model 3910, TSI Inc.) was used every 60 s with a 0.75 L min⁻¹ inlet flow and a 0.25 L min⁻¹ CPC flow to measure the atmospheric nanoparticles (Schneider et al. 2015). The SMPS used isopropyl alcohol as condensation liquid and considered particles of sizes 10 – 420 nm distributed across 13 channels. Sampling of nanoparticles using the SMPS was carried out at a fixed location near the living room window (see SI Figure S1).

This study was conducted to analyze the impact of removal of wall and sanding activities on the generation of nanoparticles during refurbishment activities. Following the approach of Azarmi et al. (2015), we organized all data collected in four main groups to estimating the impact of removal of wall activities, which they based on the process/activities that originated the particles: background, activity (removal of wall), non-activity (break intervals and lunchtime), and cleaning/dumping of waste material.

In the same way, sanding activities data were partitioned into five main groups: sanding, non-activity, plastering, cleaning and plastering, and the final cleaning of waste materials. Sanding was manually performed using a sandpaper, while in some moments the two workers stopped for short periods. During sanding breakouts, occasionally a worker performed the

plaster application, while another one cleaned the location; whereas in other occasions the application of product was carried out. Therefore, the plaster may present certain humidity during sanding.

3. Results and discussion

3.1. Breaking wall activities

Figure 1 shows the average PSDs of all groups for the removal of wall activities. Background PNC sampling was measured before starting the removal of wall activity, showing different PSD and total PNC with other activities groups, which is a striking result. For instance, the highest total PNC was 1.9×10^5 particles cm^{-3} that corresponded to removal of wall activities (see SI Figure S2); it was 11-times higher than background PNC peak. Moreover, background PSD showed a bimodal pattern with low concentrations: one in the nucleation mode (~ 28 nm) and the other in the accumulation mode (~ 154 nm). Removal of wall PSD presented a monomodal pattern and the peak value obtained was 6.02×10^4 in the Aitken mode (~ 65 nm). Whereas non-activity PSD (lunch-time) presented a bimodal pattern similar to background PSD and peak value was 3.85×10^4 (Figure 1) at ~ 20 nm and another lower peak at ~ 115 nm. This finding differs from the previous studies (Azarmi et al. 2014, 2015b) where the obtained peaks principally corresponded to the nucleation mode. Possibly, because hand-tools, unlike electric tools, are not used continuously over a long period of time. Therefore, their measured results are averages of moments of stops and use, continuously. In addition, because of its use in various places on the same wall depending on each worker.

Comparing activity (removal of wall) and non-activity average peak with background PSD, peak PSD values were 5.6 and 3.6-times higher, respectively. On the other hand, as a consequence of the emission of a wide range of particles sizes, cleaning and dumping PSD showed a smooth curve, with no significant apparent peaks, where its highest value was 2.4 times higher than the background.

Figure 1. Average PSDs of removal of wall activities: background, removal of wall, non-activity (lunch time), and cleaning/loading of waste materials.

Figure 2 presents the average PNC of removal of wall activities. Removal of wall PNC was ~6 times higher than background concentrations, whereas non-activity PNC (lunch-time) and cleaning/loading activities PNC were ~4 and ~2 times higher, respectively. It is also observed that by far the greatest PNC was generated during activity (breaking wall). One of the possible causes of the generation of nanoparticles is due to the removal of the wall caused by the impact of the chisel and the hammer. Wall was built with the use of cement-based materials, where the removal of wall activity generated a large number of particles in a wide range of sizes and types of materials, with the presence in general of elements based on

calcium and silicon (Kukadia et al. 2003). Moreover, cleaning/loading PNC had greater values than non-activity (lunch-time) and background, although lower than removal of wall PNC. The possible cause for this difference needs more studies. Levels observed in this investigation are far below than those observed by Azarmi and Kumar (Azarmi and Kumar 2016) and Kumar (Kumar et al. 2012b). According to these data, we can infer that using hand-tools in refurbishment activities generates less PNC than using electromechanical equipment.

Figure 2. Average PNC of removal of wall activities: background, removal of wall, non-activity (lunch time), and cleaning/loading during demolition.

Figure 3 presents the proportion of PSD for all removal of wall activities for nucleation mode (10-30 nm), Aitken mode (30-100 nm) and accumulation mode (100-420 nm). Results suggest that removal of wall activities emitted nanoparticles with a 59% of contribution in the Aitken mode. Background and non-activity PSD expressed predominance over the

nucleation mode with 42% and 52% of the contribution, respectively. On the other hand, for cleaning and loading PSD, the accumulation mode had a slight dominance with a 40% of contribution. However, a balance between the three modes may be deduced. Alternatively, the non-activity period had a 52% contribution of nucleation mode and just 26% for the Aitken mode. Cleaning/loading PSD released in the nucleation, Aitken, and accumulation modes constituted 31%, 29%, and 40% proportion, respectively. These observations clearly suggest the presence of nanoparticles in all modes.

Figure 3. Proportion of PSD of removal of wall activities: background, removal of wall, non-activity (lunch time), and cleaning/loading during demolition.

These findings for the background nanoparticle concentration (PSD and PNC) must doubtless be much scrutinized, but there are some immediately dependable conclusions. For instance, the local site chosen for this study, the metropolitan area of the capital of Rio Grande

do Sul State (Porto Alegre), was a small municipality not highly impacted by local pollution sources. Particles formed during nucleation have short-time life periods, though their presence may be due to organic vapors and high SO₂ that may attribute to mechanisms such as sulfuric acid–water binary nucleation, sulfuric acid–ammonia–water ternary nucleation, the nucleation of organic vapors, ion-induced nucleation, and halogen oxide nucleation (Seinfeld and Pandis 2006). These pollutants are typical of the study area where the measurements were carried out (Teixeira et al. 2013; Agudelo–Castaneda et al. 2014; Agudelo-Castañeda et al. 2016). In the nucleation mode, the particles may grow by the condensation of sulfuric acid, organic species, and heterogeneous reactions. Then, aerosol particles may come into contact due to coagulation processes and increasing concentration in the accumulation mode. On the contrary, sulfur aerosols originated from mobile sources may increase the concentration of nanoparticles due to the closeness of the sampling site with roadways (Whitey 1977). Moreover, the presence of nonvolatile vapor, such as sulfuric acid and some organic compounds, all formed by oxidation reactions, involve suitable precursor gases (sulfur dioxide and volatile organic compounds) that affect atmospheric nucleation (Kulmala et al. 2004a). Consequently, the proportions of the background PSD present on Figure 3 were similar in all modes (nucleation: 42%; Aitken: 32%; accumulation: 26%), although different from removal of wall activities. This proportion is typical of the aged aerosol of rural and natural levels in the study area (Agudelo-Castañeda et al. 2018).

3.2. Sanding activities

Figure 4 shows the average PSDs for all activities. Interestingly, sanding PSD showed a monomodal curve with a peak of 3.4×10^4 in the Aitken mode (~65 nm), whereas cleaning

and plastering had a bimodal curve where their highest peak of 2.5×10^4 occurred at ~ 36 nm. Final cleaning and non-activity PSD showed a bimodal curve, with their highest peaks at ~ 3 nm, too, with values of 4.4×10^4 and 1.2×10^4 , respectively. Plastering PSD showed a smooth curve, probably due to the emission of different size particles, with no significant peaks.

Figure 4. Average PSDs of sanding activities: sanding, non-activity (lunch time), plastering, cleaning + plastering and final cleaning of waste materials.

Figure 5 compares the average PNC for each sanding activities. Final cleaning showed the highest PNC of 4.4×10^4 , whereas sanding was just 3.0×10^4 . Consequently, final cleaning PNC was ~ 1.5 times higher than sanding PNC. For sanding activities, PNC was lower as the coat of the plaster was probably slightly wet. Non-activity PNC had the lowest value (1.2×10^4), followed by plastering (1.3×10^4). As expected, cleaning and plastering PNC had intermediate values between plastering and final cleaning (2.3×10^4). Some authors recommends using different finishes/systems from sanding plasterboard fitted with dust suppression/collection equipment (HSE 2013). The problem with the use of collection

equipment for hand-tools is evident but must be addressed. Moreover, several control guides suggest using water sprays to minimize dust and local exhaust ventilation when possible (Kukadia et al. 2003). In the current study, local natural ventilation was used. final cleaning PNC showed the highest value. Similar results were obtained during the cleaning in the removal of wall activities, as explained before.

Figure 5. Total average PNC of sanding activities sanding, non-activity (lunch time), plastering, cleaning + plastering and final cleaning during sanding.

Figure 6 presents the proportion of PSDs for the five groups for sanding activities. In general, the Aitken mode predominated. Sanding and final cleaning PSD showed predominance over the Aitken mode with 52% and 45%, respectively, while non-activity expressed dominance over the nucleation mode with 39%. These findings confirmed a similar distribution of the proportion of modes between sanding and final cleaning, which confirms the previously explained results.

Figure 6. Proportion of PSD of sanding activities: sanding, non-activity (lunch time), plastering, cleaning + plastering and final cleaning during sanding.

3.3 Removal of wall and sanding comparison

Removal of wall PNC was ~1.5 times higher than sanding PNC, indicating that this activity generated more nanoparticles as it was performed dry and probably escaped to the environment during the usual construction activities, because of the mechanical application on the building materials (Kumar et al. 2013). On the contrary, sanding was performed using

the plaster presenting a slight moisture and hence it showed lower PNC. In the current study, several differences were obtained between peak modes for removal of wall and sanding activities. In the accumulation mode, the comparison between removal of wall and sanding showed a similar peak at ~65 nm. Moreover, during non-activity, the peak modes appeared at ~20 nm for removal of wall, whereas for sanding peak modes appeared at ~15 nm, ~36 nm, and ~115 nm. For the final cleaning during removal of wall, peak modes appeared at ~15 nm, ~36 nm, and ~154 nm, and for sanding peak modes appeared at ~15 nm and ~40 nm.

PSD proportions were estimated to be similar for removal of wall and sanding, although the latter showed more accumulation mode proportion (27%). It was observed that particles in this mode were generated due to the growth or the coagulation of nucleation particles as well as the production of large numbers of primary sources (Kulmala et al. 2004b). In addition, comparisons showed little difference in the Aitken and accumulation modes proportions. Removal of wall had greater PSD proportion in the Aitken mode (59%) than sanding (52%), whereas the latter (i.e., sanding) generated a higher average PSD proportion in the accumulation mode (27%). These results indicate that, probably, removal of wall and sanding may be generating nanoparticles, as emissions sources. Expected or possible chemical nanoparticle composition produced from the removal of wall include silica (SiO_2) and alumina (Al_2O_3) from ceramic bricks and cement Portland plaster; lime (CaO) and iron oxide (Fe_2O_3) from cement Portland plaster. Moreover, nanoparticle from paint containing titanium dioxide (TiO_2) and silver (Ag), may be present (NIOSH, 2009; 2011), while from sanding the plaster may be composed of mainly copolymer styrene acrylic (BASF, 2018).

The uniqueness of the study is that is the first one which addresses nanoparticle emission from refurbishment activities. Consequently, the comparison of PNC with other research

studies is rather complicated. Mostly all researches focus more on nanoparticles generated from engineered nanomaterials rather than from construction activities or incidental ones. A great difference between these two focuses lies in the distinction, a worker may be exposed during the manufacture to an engineered nanomaterial, a potential hazard NIOSH have well studied to know the measures that can be taken to minimize workplace exposures (NIOSH, 2009). Although some researches done by the NanoRelease project (initiated in partnership with US Environmental Protection Agency and the American Chemistry Council) investigated release from paint containing nanoparticles in response to sanding (Froggett et al. 2014). Consequently, more studies about the physicochemical composition in activities of demolition/refurbishment in the civil construction and their health impacts are necessary.

5. Conclusion

The objective of this study was to investigate the nanoparticles emitted from hand-tools released during a typical refurbishment activity. A NanoScan SMPS was used to measure the number concentration and distributions of particles in the range of 10–420 nm released during refurbishment activities, such as removal of wall and sanding, including cleaning/dumping waste.

According to these data, can be inferred that the application of hand-tools in refurbishment activities generates lower total PNC than using electromechanical equipment. Was observed that PSD proportions between removal of wall and sanding were similar, principally for the nucleation mode, with ~20% of contribution. Moreover, removal of wall generated more

average PSD proportion in the Aitken mode (59%) as compared to sanding (52%).

Furthermore, removal of wall emitted more PNC than sanding.

In addition, particle emission originated from hand-tools use in the activities of removal of wall, sanding, plastering, cleaning, and dumping of construction waste was compared to other studies. Was verified that the simulation performed in the laboratory under climatic conditions and the application of electromechanical tools can differ from what is evidently performed in practice.

Finally, it was concluded that a detailed study of the generation of nanoparticles particles and their physicochemical composition in activities of demolition/refurbishment in the civil construction is necessary to assess the extent of emissions and their health impacts.

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Conflict of Interest

The authors declare that they have no conflict of interest.

References

Agudelo-Castañeda DM, Teixeira EC, Braga M, et al (2018) Cluster analysis of urban ultrafine particles size distributions. Atmos Pollut Res 0–1. doi: 10.1016/j.apr.2018.06.006

Agudelo-Castañeda DM, Teixeira EC, Schneider IL, et al (2016) Potential utilization for

341 the evaluation of particulate and gaseous pollutants at an urban site near a major
 342 highway. *Sci Total Environ* 543:161–170. doi: 10.1016/j.scitotenv.2015.11.030

343 Agudelo–Castaneda DM, Teixeira EC, Pereira FN (2014) Time–series analysis of surface
 344 ozone and nitrogen oxides concentrations in an urban area at Brazil. *Atmos Pollut Res*
 345 5:411–420. doi: 10.5094/APR.2014.048

346 Azarmi F, Kumar P (2016) Ambient exposure to coarse and fine particle emissions from
 347 building demolition. *Atmos Environ* 137:62–79. doi: 10.1016/j.atmosenv.2016.04.029

348 Azarmi F, Kumar P, Marsh D, Fuller G (2016) Assessment of the long-term impacts of PM
 349 10 and PM 2.5 particles from construction works on surrounding areas. *Environ Sci*
 350 *Process Impacts* 00:1–14. doi: 10.1039/C5EM00549C

351 Azarmi F, Kumar P, Mulheron M, et al (2015a) Physicochemical characteristics and
 352 occupational exposure to coarse , fine and ultrafine particles during building
 353 refurbishment activities. *J Nanoparticle Res* 17:1–19. doi: 10.1007/s11051-015-3141-z

354 Azarmi F, Kumar P, Mulheron M (2014) The exposure to coarse, fine and ultrafine particle
 355 emissions from concrete mixing, drilling and cutting activities. *J Hazard Mater*
 356 279:268–279. doi: 10.1016/j.jhazmat.2014.07.003

357 Azarmi F, Kumar P, Mulheron M, et al (2015b) Physicochemical characteristics and
 358 occupational exposure to coarse , fine and ultrafine particles during building
 359 refurbishment activities. *J Nanoparticle Res* 17:1–19. doi: 10.1007/s11051-015-3141-z

360 BASF. 2018. Technical report information. Suvinil Massa Corrida.
 361 [https://www.suvinil.com.br/upload/ffa3fa64-0cdd-43a7-a124-52751733c69b-suvinil-](https://www.suvinil.com.br/upload/ffa3fa64-0cdd-43a7-a124-52751733c69b-suvinil-massa-corridamaio2018pt.pdf)
 362 [massa-corridamaio2018pt.pdf](https://www.suvinil.com.br/upload/ffa3fa64-0cdd-43a7-a124-52751733c69b-suvinil-massa-corridamaio2018pt.pdf)

363 Brouwer D, Van Duuren-Stuurman B, Berges M, et al (2009) From workplace air
 364 measurement results toward estimates of exposure? Development of a strategy to
 365 assess exposure to manufactured nano-objects. *J Nanoparticle Res* 11:1867–1881. doi:
 366 10.1007/s11051-009-9772-1

367 Bystrzejewska-Piotrowska G, Golimowski J, Urban PL (2009) Nanoparticles: Their
 368 potential toxicity, waste and environmental management. *Waste Manag* 29:2587–

369 2595. doi: 10.1016/j.wasman.2009.04.001

370 Cuccia E, Bernardoni V, Massabò D, et al (2010) An alternative way to determine the size
371 distribution of airborne particulate matter. *Atmos Environ* 44:3304–3313. doi:
372 10.1016/j.atmosenv.2010.05.045

373 Froggett SJ, Clancy SF, Boverhof DR, Canady RA (2014) A review and perspective of
374 existing research on the release of nanomaterials from solid nanocomposites. Part
375 *Fibre Toxicol* 11:1–28. doi: 10.1186/1743-8977-11-17

376 Hens L, Cabello-Eras JJ, Sagastume-Gutiérrez A, et al (2017) University–industry
377 interaction on cleaner production. The case of the Cleaner Production Center at the
378 University of Cienfuegos in Cuba, a country in transition. *J Clean Prod* 142:63–68.
379 doi: 10.1016/j.jclepro.2015.10.105

380 HSE “Health and Safety Executive.” (2013) Construction dust, HSE information sheet.

381 Hu B, Freihaut JD, Bahnfleth W, et al (2008) Literature review and parametric study:
382 indoor particle resuspension by human activity. *Environ Monit Assess* 176:1–7

383 Jabbour N, Rohan Jayaratne E, Johnson GR, et al (2017a) A mechanism for the production
384 of ultrafine particles from concrete fracture. *Environ Pollut* 1–7. doi:
385 10.1016/j.envpol.2016.12.059

386 Jabbour N, Rohan Jayaratne E, Johnson GR, et al (2017b) A mechanism for the production
387 of ultrafine particles from concrete fracture. *Environ Pollut* 1–7. doi:
388 10.1016/j.envpol.2016.12.059

389 Kazzaz M, Habchi C, Ghali K, et al (2017) Micro-particle indoor resuspension under
390 periodic airflows: A numerical-analytical study and experimentations. *Build Environ*
391 123:299–314. doi: 10.1016/j.buildenv.2017.07.011

392 Kim H, Choi I, Oh M, et al (2005) 2 Pollutants and Pollution Sources. In: *Journal of Indoor*
393 *Air*. pp 69–139

394 Kukadia V, Upton S, Hall D (2003) Control of dust from construction and demolition
395 activities. BRE Bookshop, Watford, London

396 Kulmala M, Vehkamäki H, Petäjä T, et al (2004a) Formation and growth rates of ultrafine
397 atmospheric particles: A review of observations. *J Aerosol Sci* 35:143–176. doi:
398 10.1016/j.jaerosci.2003.10.003

399 Kulmala M, Vehkamäki H, Petäjä T, et al (2004b) Formation and growth rates of ultrafine
400 atmospheric particles: a review of observations. *J Aerosol Sci* 35:143–176. doi:
401 10.1016/j.jaerosci.2003.10.003

402 Kumar P, Morawska L, Birmili W, et al (2014) Ultrafine particles in cities. *Environ Int*
403 66:1–10. doi: 10.1016/j.envint.2014.01.013

404 Kumar P, Mulheron M, Fisher B, Harrison RM (2012a) New Directions: Airborne ultrafine
405 particle dust from building activities - A source in need of quantification. *Atmos*
406 *Environ* 56:262–264. doi: 10.1016/j.atmosenv.2012.04.028

407 Kumar P, Mulheron M, Som C (2012b) Release of ultrafine particles from three simulated
408 building processes. *J Nanoparticle Res* 14:. doi: 10.1007/s11051-012-0771-2

409 Kumar P, Pirjola L, Ketzel M, Harrison RM (2013) Nanoparticle emissions from 11 non-
410 vehicle exhaust sources – A review. *Atmos Environ* 67:252–277. doi:
411 10.1016/j.atmosenv.2012.11.011

412 Landim AA, Teixeira EC, Agudelo–Castañeda D, et al (2018) Spatio-temporal variations of
413 sulfur dioxide concentrations in industrial and urban area via a new statistical
414 approach. *Air Qual Atmos Heal* 11:801–813

415 NIOSH (2009). Approaches to Safe Nanotechnology Managing the Health and Safety
416 Concerns Associated with Engineered Nanomaterials. Cincinnati, OH: U.S.
417 Department of Health and Human Services, Public Health Service, Centers for Disease
418 Control and Prevention, National Institute for Occupational Safety and Health, DHHS
419 (NIOSH) Publication No. 2009–125. [https://www.cdc.gov/niosh/docs/2009-](https://www.cdc.gov/niosh/docs/2009-125/pdfs/2009-125.pdf)
420 [125/pdfs/2009-125.pdf](https://www.cdc.gov/niosh/docs/2009-125/pdfs/2009-125.pdf).

421 NIOSH (2011). Current intelligence bulletin 63: Occupational Exposure to Titanium
422 Dioxide. Cincinnati, OH: U.S. Department of Health and Human Services, Public
423 Health Service, Centers for Disease Control and Prevention, National Institute for

424 Occupational Safety and Health, DHHS (NIOSH) Publication No. 2011–160.
 425 <https://www.cdc.gov/niosh/docs/2011-160/pdfs/2011-160.pdf>. Pacheco-Torgal F,
 426 Labrincha JA (2013) The future of construction materials research and the seventh un
 427 Millennium Development Goal: A few insights. *Constr Build Mater* 40:729–737. doi:
 428 10.1016/j.conbuildmat.2012.11.007

429 Parrish DD, Singh HB, Molina L, Madronich S (2011) Air quality progress in North
 430 American megacities: A review. *Atmos Environ* 45:7015–7025. doi:
 431 10.1016/j.atmosenv.2011.09.039

432 Schneider I, Teixeira E, Silva L, Wiegand F (2015) Atmospheric particle number
 433 concentration and size distribution in a traffic–impacted area. *Atmos Pollut Res*. doi:
 434 10.5094/APR.2015.097

435 Seinfeld JH, Pandis SN (2006) *Atmospheric Chemistry and Physics: From Air Pollution to*
 436 *Climate Change.*, 2nd edn. John Wiley & Sons, Hoboken, New Jersey

437 Teixeira EC, Mattiuzzi CDP, Agudelo-Castañeda DM, et al (2013) Polycyclic aromatic
 438 hydrocarbons study in atmospheric fine and coarse particles using diagnostic ratios
 439 and receptor model in urban/industrial region. *Environ Monit Assess* 185:9587–9602.
 440 doi: 10.1007/s10661-013-3276-2

441 Torgal FP, Jalali S (2011) Toxicity of building materials: a key issue in sustainable
 442 construction. *Int J Sustain Eng* 4:281–287. doi: 10.1080/19397038.2011.569583

443 Whitey KT (1977) The physical characteristics of sulfur aerosols. *Atmos Environ* 12:135–
 444 159. doi: 10.1016/j.atmosenv.2007.10.057

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Supporting Information (SI)

For

Particle number concentrations and size distributions of nanoparticles during the use of hand-tools in refurbishment activities

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This file includes:

Figure S1 to S5

Tables S1 and S2

Supplementary text section S1 and S2

Figure S1 - Diagram of experimental conditions and location of SMPS and dump container

Figure S2 - Total PNC of removal of wall activities (particles/cm³).

Figure S3 – Average PSDs and proportion of PNCs for each range size mode (nucleation, Aitken and accumulation) for all the moments in removal of wall activities.

Figure S4 - Total PNC of sanding activities (particles/cm³).

Figure S5 – Average PSDs and proportion of PNCs for each range size mode (nucleation, Aitken and accumulation) for all the moments in sanding activity.

Table S1.- Remarks of nanoparticles behavior during removal of wall.

Moment	Hour	Remark
Start	8:53	Beginning of sampling near the window in the living room.
1	8:53 – 10:45	Equipment starts sampling at a fixed location near the living room window. Low concentration.
2	10:46 – 11:15	Concentration increases 5 minutes after opening the window and then concentration decreased.
3	11:16 – 12:00	Lunch time. Characterized for a non-activity period.
4	12:01 – 12:54	Return time from lunch. Another peak, possibly due to resuspension or return to work activities.
5	12:55 – 13:15	Concentration increases probably to intensification of removal of wall activities and resuspension of particles. At this moment, takes place the maximum peak of particle number concentration.
6	13:16 – 13:30	Cleaning of the place. Constant low concentration. Workers started sweeping the place.
7	13:31 – 13:40	Concentration increases, a very fast and short peak of 1 minute appears, possibly by a gust of wind. Workers continued sweeping the place.
8	13:41 – 14:04	Constant low concentration. Remodeling processes carried out until now continues.
9	14:05 – 15:16	Workers continued sweeping the place and collected wastes are placed in bags and located near the window.
10	15:17 – 15:32	Dumping process. Dump bucket is parked in front of the building, just below the window and workers start throwing bags with construction debris.
End	15:32	End of sampling.

Table S2 - Remarks of nanoparticles behavior during sanding.

Moment	Hour	Remark
Start	8:31	Beginning of sampling near the window in the living room
1	8:31 – 9:00	Equipment starts sampling at a fixed location near the living room window. Sanding start.
2	9:01 – 10:22	Gypsum plaster application.
3	10:23 – 10:45	Returning to sanding activity.
4	10:46 – 11:40	Cleaning and plastering.
5	11:41 – 12:05	Returning to sanding activity.
6	12:06 – 13:25	Lunch time. Characterized for a non-activity period.
7	13:26 – 13:44	Returning to sanding activity.
Error	13:46 – 14:45	
9	14:46 – 15:15	Cleaning and plastering were being taken place.
10	15:16 – 15:33	Gypsum plaster application.
11	15:34 – 15:45	Only sanding activity was being taken place.
12	15:46 – 17:00	Gypsum plaster was being applied.
13	17:01 – 17:30	Only sanding activity was being taken place.
14	17:31-18:30	Cleaning activity (work finishing).
15	18:31-20:00	Without activity.
End	20:00	End of sampling.

S1. NANOPARTICLES BEHAVIOR DURING REMOVAL OF WALL OF REFURBISHMENT ACTIVITIES

Figure S2 shows the total particle number concentration measured during removal of wall. Several peaks may be observed probably due to the performance of activities and/or the cleaning/dumping of waste. The initial concentrations were found to be $\sim 1 \times 10^4$ particles cm^{-3} , and after ~ 120 min the values were found to be constant or low and designated as *Moment 1*. These results support the idea of the presence of naturally occurred nanoparticles produced by the evaporation of liquid droplets, gas-to-particle reactions, or through homogenous nucleation, which may increase the total PNC in the work environments (Hill 2006). The overall average PNC during activity period was $3.51 \pm 2.27 \times 10^4$ particles cm^{-3} , while the background levels (*moment 1*) were $0.79 \pm 0.29 \times 10^4$ particles cm^{-3} . In Table S1, some additional *moments* are labeled and described, explaining the observed remarks of nanoparticle behavior during the refurbishment. During these activities, the total PNC showed a maximum value and a mean value of 6.6×10^4 and 3.7×10^4 particles cm^{-3} , respectively. All peaks presented in these moments were mostly $\sim 1.0 \times 10^5$ particles cm^{-3} , where the peak at *moment 5* was the highest with a value of 1.9×10^5 particles cm^{-3} . *Moment 2* corresponded to the beginning of refurbishment activities. The PNC increased for 5 min with a maximum value of 9.7×10^4 particles cm^{-3} . The initial refurbishment activities, probably, generated nanoparticles and afterward wind dispersion and particle deposition decreased the initial concentration. The total PNC of *moment 3* (mean value 2.38×10^4 particles cm^{-3}) remained constant until the beginning of *moment 4*. It may be observed that two principal peaks occur due to the restart of refurbishment activities, which caused the PNC to be increased over time. The highest peak occurred in *moment 5*. Subsequently,

moment 6 was characterized by a period of low concentrations of approximately 15 min. A similar pattern was presented by *moments* 7 and 8. Moreover, it may be observed that *moment* 9 showed a steady PNC for almost one hour during the cleaning of the location. The final *moment* (number 10) corresponded to the loading of refurbishment waste. One interesting aspect, shown in Figure S3, was observed in *moment* 3, where workers were out for lunch, which is explained in later sections.

Moreover, in order to establish the possible impact of the emitted nanoparticles, the particle size number distribution (PSD) and the proportion of PNCs were analyzed. Figure S3 shows the average PSDs and the proportion of PNCs for each range size of the mode (nucleation <30 nm, Aitken 30–100 nm, and accumulation 100–420 nm) for the moments in removal of wall activity. *Moments* 1 and 3 showed that the proportion of PNCs for the nucleation mode was 42% and 52%, respectively, i.e., the highest values for all moments. *Moments* 4, 5, and 2 showed the highest proportions for the Aitken mode with values of 59%, 58%, and 58%, respectively. *Moments* 7, 8, and 9 showed the highest values for the accumulation mode with values of 55%, 45%, and 42%, respectively.

The “background” mean minimum and maximum concentrations for all sizes were in 0.06×10^4 and 1.07×10^4 particles cm^{-3} , respectively (*moment* 1), before the initial activities. PSDs presented low concentrations compared to all moments, with a proportion of 42% for the nucleation mode, 32% for the Aitken mode, and 26% for the accumulation mode. At that point, PNC increased in the beginning of activities (*moment* 2). The values were increased primarily for the Aitken mode (58%), indicating that, probably, activities generated nanoparticles in this mode and the principal mechanism was condensation for polluted environments. Moreover, *moment* 3 was characterized by a nonactivity period, where an

increase in the nucleation mode (52%) and the accumulation mode (22%) proportion was presented. The same behavior was observed for *moment* 1; nevertheless, the total PNC measured for nonactivity was ~ 4 times the background concentration. For *moment* 4 (return time from lunch), the PSD curve was similar to *moment* 2. A growth in the Aitken mode (59%) and a reduction in the nucleation mode (52–19%) were observed. The maximum total particle concentration occurred for *moment* 5 that was almost 2×10^5 of the total PNC. *Moments* 6–10 were related to cleaning and loading activities, respectively. In general, the production of PSD curves presented in this period was similar, where the accumulation mode (42–55%) was predominant. *Moments* 6 and 10 were different from *moments* 7–9. *Moment* 6 (cleaning start) was characterized by the majority of the Aitken mode (40%) and an equilibrium between the nucleation and accumulation modes, with 29% and 31%, respectively. The nucleation and Aitken modes were more visible in *moment* 10 with values of 33% and 46%, respectively.

S2. NANOPARTICLE BEHAVIOUR DURING SANDING ACTIVITIES OF REFURBISHMENT

Figure S4 shows the total particle number concentration measured during sanding activities. Several peaks that originated during sanding activities may be detected. In order to analyze different activities during sanding, several *moments* were divided (see SI). The total PNC showed a maximum value of $\sim 2.54 \times 10^5$ particles cm^{-3} and a mean value of $\sim 2.07 \times 10^4$ particles cm^{-3} . The maximum value was presented in the final cleaning (*moment* 14), whereas other peaks were observed during sanding, i.e., in *moments* 1, 3, 5, 7, 11 and 13. The initial activities corresponded to the sanding of the wall, and afterward, the gypsum plaster

application was carried out (*moment 2*). In *moment 3*, workers resumed sanding activities, whereas in *moment 4* they initiated mixed activities, such as cleaning and plastering. In *moment 5*, workers returned to sanding activities until lunch time (*moment 6*). *Moment 7* corresponded to returning to sanding activities, and in *moment 8* a battery problem occurred (error). The activities of *moment 9* were similar to *moment 7*, cleaning and plastering, whereas in *moment 10* just plastering was carried out. Successively, *moments 11, 12, and 13* represented a similar kind of activity only, i.e., cleaning, plastering, and sanding, respectively. *Moment 14* showed a cleaning finishing activity after all the work was completed, and *moment 15* showed no activity.

Figure S5 shows the average PSDs and the proportion of PNCs for each range size of the modes (nucleation, Aitken, and accumulation) for the moments in sanding activity. As shown in the figure, and as explained above, *moments 1, 3, 5, 7, 11, and 13* showed similar patterns, and were found to be Aitken mode predominated, i.e., particles with a diameter between 30 and 100 nm, corresponding to sanding activities. The highest proportion for the Aitken mode was 59% and the lowest proportion was 40%. For plastering activities (*moments 2, 10, and 12*), Aitken mode predominated too with a slight variation (43–46%). For cleaning and plastering (*moments 4 and 9*) activities, different patterns were observed due to mixed activities. In *moment 4*, the nucleation mode predominated (41%), followed by the Aitken mode (37%). In *moment 9*, the Aitken mode predominated (44%), followed by the accumulation mode (29%) and the nucleation mode (27%).

NANOPARTICLES
FROM
REFURBISHMENT

Removal
of wall

Sanding