Cleaning strategies for Fresnel Linear Concentrator Mirrors in Solar Heating plants

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Abstract

A deep investigation on mirror dust deposition for a Fresnel Linear Concentrator System has been developed in order to elaborate an optimized cleaning strategy to be used in several conditions. The model was built on the accurate expected production of the solar system and enables the choice of required cleaning interventions per year, based on their specific cost compared to improved production. A rain-cleaning model based on historical precipitation data for specific location was developed and optimized intervention date has been defined.

Keywords: Fresnel Linear Concentrator, Solar Heating, Mirror Cleaning

1. Introduction

The present work concerns the determination of several cleaning strategies on full scale Fresnel Linear Concentrator Mirrors (FLCM) using both an analytical predictive model and experimental data. The aim of the work is the determination of an optimized strategy based on specific plant, environmental conditions, cleaning cost (Fernández-García et al., 2014) and technical specification of collectors including number of cleaning per year as well as best days during the year.

The model is based on solar system expected hourly production along the year determined through the assessment of FLCM in accordance with EN ISO 9806 (European Code EN ISO 9806, 2013). Reduction of cleanliness due to dust accumulation on mirrors should be measured in specific location since it shows a different time drop due to typical environment. Experimental data have been collected in Lucca (central area of Italy, with coordinates 43.82° north, 10.56° east) where an industrial FLCM system coupled with solar-cooling and a peak thermal power of 125 kW is installed.

Two different cleaning strategies have been defined in order to consider a wider range of plant management. First approach (Case 1) enables the determination of optimized number of cleanings per year and specific execution date for a plant whose cleanliness curve has been estimated without rain polish effect (i.e. mirrors are always in protection mode during precipitation). Optimized intervention number is a direct function of cleaning cost compared to relative expected production improvement, based on historical data. This approach can be profitable in every case where no direct monitoring of the optical performances is applicable (i.e. small scale process heating solar thermal systems). In the second approach (Case 2) cleaning effect due to rain precipitation has been added assuming a reference value of improved cleanliness. Such model can be applied in those systems with no protection position or with specific devices for the recognition of rain, hail and snow.

2. Cleaning operation description

The cleaning operation and cleanliness drop assessment have been carried out on FLCM coupled with Solar Heating and Cooling for office facilities located in Lucca, Italy. The Solar Plant is provided by the company Glayx srl, that proposes a proprietary technology based on solar concentration through linear Fresnel mirrors for the industrial heat, solar cooling and power generation. In Fig. 1 a view of FLCM Solar Plant is shown.

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Fig. 1: FLCM Solar Plant in Lucca, Italy.

The main features of the Solar Plant are summarized in Tab. 1.

Tab. 1: FLCM Solar Plant main features

FLCM Solar Plant in Lucca (Italy)	
Peak Power	125 kWt
Net reflective surface	187.5 m^2
Gross Area	287 m^2
Heat Transfer Fluid	Water
Outlet temperature	<90° C

The company has developed a proprietary technology for automatic cleaning of primary reflector mirror surface. The system has been designed to minimize water consumption and make it easy to use in several kind of installations, both on land and on the building, directly by the plant operator. The cleaning robot, based on rover kinematics (rover with articulated suspension linkage (Tarokh and McDermott, 2005)), can drive the whole line of the solar field unmanned, preserving the reflecting surface from any damage. Due to the high degree of automation and low power consumption, the system requires limited labor intensity by the operator with a consequent reduction of the operating costs. Driving, cleaning, dust removal, sensors and alarms are managed by a dedicated integrated control system. The cleaning operation is carried out through spraying water and rubber blade sliding. At the end of each single mirror line the machine is moved on the adjacent line or on the nearest plant row. In Fig. 2 a view of the Cleaning Robot is shown.

Fig. 2: Cleaning Robot provided by Glayx

The main features of the Cleaning Robot are summarized in Tab. 2.

Tab. 2: Cleaning robot main features

Cleaning Robot	
Dimension	80 cm length, 50 cm large, 21 cm height
Weight	17 kg (empty tank, including battery)
Water consumption	0.21 l/m^2
Cruise speed	80 mm/s
Duration of the battery	50 min at operative full load
Water tank capacity	6 l

3. Cleaning cost operation

The cleaning cost operation strictly depends on the specific site installation and plant scale. The whole operation cost is given from the sum of manpower, depreciation charge of Cleaning Robot and water cost. The transfer cost of operator, water and equipment on site is not considered.

The overall cleaning operation involves the following step: water and machine stowing on site installation, machine preparation and setting, single row cleaning, line replacing. The stowing operation strictly depends on the site installation. In rooftop installation with complicated accessibility (i.e. rooftop installation with vertical ladder) the stowing time (for both water and machine) may be significant and remarkable respect to overall operation. The cleaning time of single row depends on the dust accumulation for the specific location, given multiple cleaning for highly soiled surfaces. Since every plant row is composed by different mirror line, at the end of each line the Cleaning Robot must be moved on to the adjacent line, at end of the plant row the machine must be moved to the close row. For small scale plant (with short rows) or improper aspect ratio (high number of rows respect to total length) the replacing time may affect considerably the overall time. The refill time and the battery change are strictly proportional to the plant net surface.

Considering only manpower and water cost, the trend of intervention cost is shown in Fig. 3. Each dot of the graph represents a specific plant design with a given aspect ratio (number of mirror lines and mirror line length). So, the trend is not perfectly a straight line.

The plant considered in the present work is a small scale plant (single row with 10 mirror lines) and a rooftop installation with an easy access through metal staircase. For small scale Solar Plant the stowing time has a great impact on overall cost, especially for a rooftop with hard accessibility. In Solar Plant smaller than 300 m^2, the cleaning cost might be double respect to ground installation.

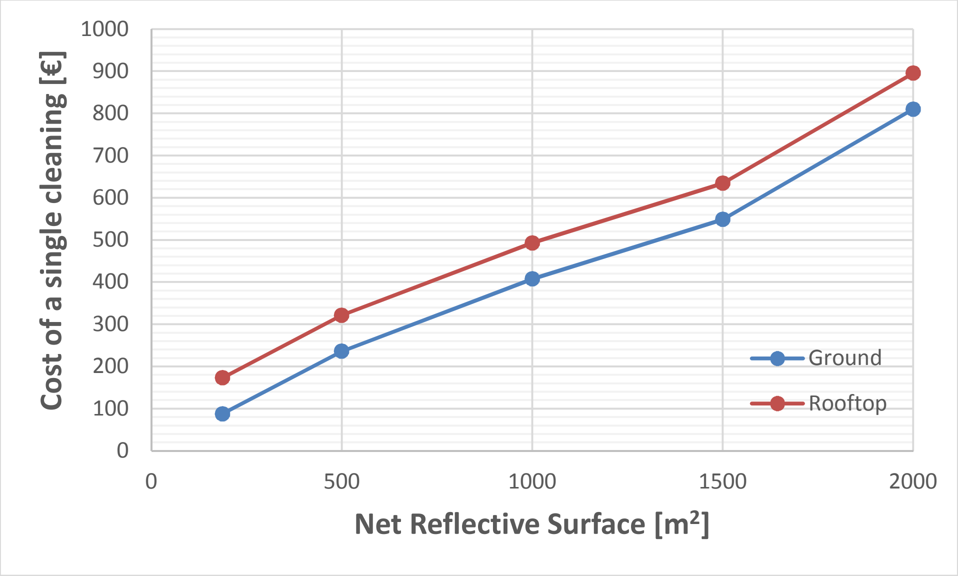


Fig. 3: Cleaning cost vs Net Reflective Surface using Cleaning Robot

4. Model description and experimental tests

The computational model has been developed based on EN ISO 9806 (European Code EN ISO 9806, 2013) efficiency curve experimentally determined for the specific Fresnel Linear Concentrator Mirror system and expressed in the following form:

$$\eta = IAM_L \cdot IAM_T \cdot \eta_0 + a_1 \frac{T_m - T_a}{G_b} + a_2 \frac{(T_m - T_a)^2}{G_b} \qquad \text{(eq. 1)}$$

where $T_m = \frac{T_i + T_e}{2}$ and IAM_L and IAM_T stand for solar system Incidence Angle Modifier on longitudinal and transversal direction, η_0 is optical efficiency with clean mirrors, G_b is Direct Normal Irradiance (beam), T_i, T_e, T_a are temperatures at inlet, outlet and ambient, a_1, a_2 are efficiency curve parameters defined according to EN ISO 9806 (European Code EN ISO 9806, 2013).

Dust deposition upon mirror surface yields reduction on reflectivity that can be immediately associated with lower η_0. In particular, the parameter used to measure the effect of dust on reflecting surfaces is called cleanliness and defined as:

$$Cl = \frac{\rho_d}{\rho_c} = \frac{\eta_{0,Cl}}{\eta_0} \qquad \text{(eq. 2)}$$

where ρ_d and ρ_c are mirrors reflectivity in dusty and clean condition respectively and $\eta_{0,Cl}$ is the optical efficiency associated to dusty condition.

Mirror cleanliness behavior has been assumed as shown in Figure 4: starting from hypothetic clean condition (mirror immediately after cleaning) *Cl* drops with constant time rate achieving baseline value (Guan et al., 2015; Alami et al., 2015; Bouaddi et al., 2018). This model is representative for solar system without direct rain exposure (blue line in Figure 3) because in these operating conditions rain cleaning effect cannot be considered. Such systems activate safety positioning on rainfall to prevent any damage to reflective surfaces. Otherwise, several FLCM are exposed to precipitation effects and related cleaning effects can be considered proportional to water amount; in particular, the amount of rain precipitation *R* in [mm] has been associated to an increase of *Cl* value based on direct measure on site, assuming that maximum *Cl* achievable with rain polishment cannot overcome 0.9 due to customary impurity content. An estimated behavior of yearly based cleanliness value is shown in Figure 3 in red line.

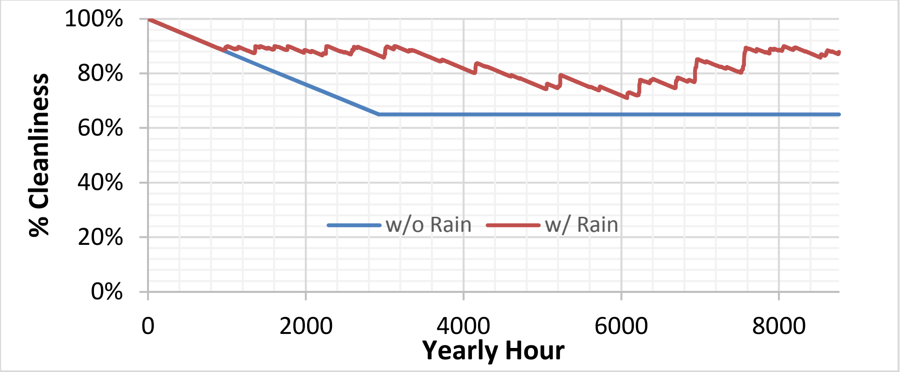


Fig. 4: Cleanliness curves with and without the polish effect of the rain (maximum effectiveness of the rain cleaning equal to 90% of the initial cleanliness, Cl baseline 65%)

Experimental tests are required to determine Cleanliness baseline in each plant since it can be affected by specific environmental condition. The value can be determined by managing dedicated tests according to EN ISO 9806 (European Code EN ISO 9806, 2013) where the inlet and outlet temperatures, DNI, and mass flow are accurately measured during steady state condition (i.e. at least ±0,1 K variation on T_i, T_e and maximum ±5% DNI variation along the test). It can be assumed that Cleanliness baseline doesn't change across time for the single site and is determined once after installation.

Every test execution provides a value of measured efficiency η_m defined as:

$$\eta_m = IAM_L \cdot IAM_T \cdot \eta_0 \cdot Cl + a_1 \frac{T_m - T_a}{G_b} + a_2 \frac{(T_m - T_a)^2}{G_b} \qquad \text{(eq. 3)}$$

Thus enabling determination of Cleanliness. Figure 5 shows test results achieved for FLCM in Lucca site during several performance tests developed along three different days, each during morning and afternoon (for a total of 6 performance tests). Average cleanliness value in this case resulted to be equal to 77%.

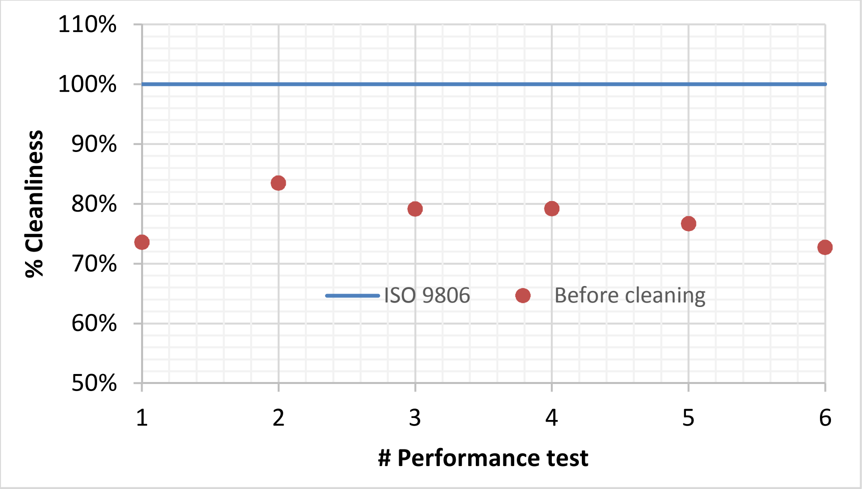


Fig. 5: Cleanliness points from performance tests before cleaning action

Model validation has been obtained repeating performance test in the hours immediately after completion of full mirror cleaning using the robot. In this case, five performance points have been found out and the results are shown in Figure 6. Average cleanliness after cleaning resulted equal to 99%, thus confirming the value of efficiency curve determined according to EN ISO 9806 (European Code EN ISO 9806, 2013) in order to estimate dust effects. The resulting yearly cleanliness curve for the specific site is shown in Figure 7.

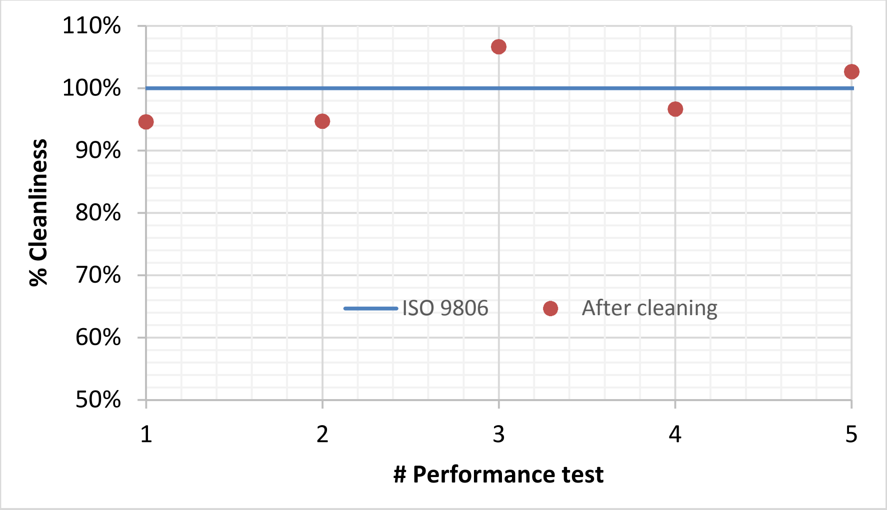


Fig. 6: Cleanliness points from performance tests after cleaning action

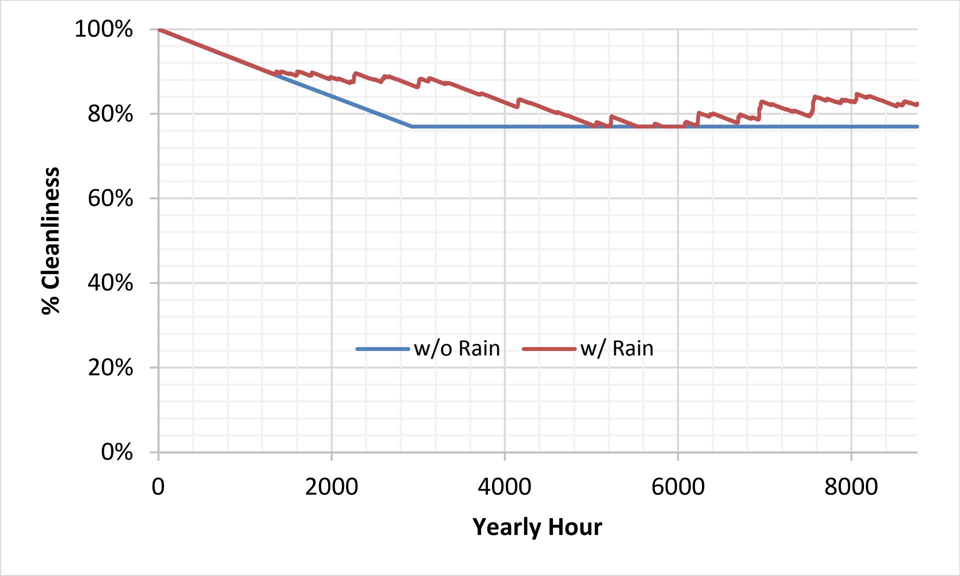
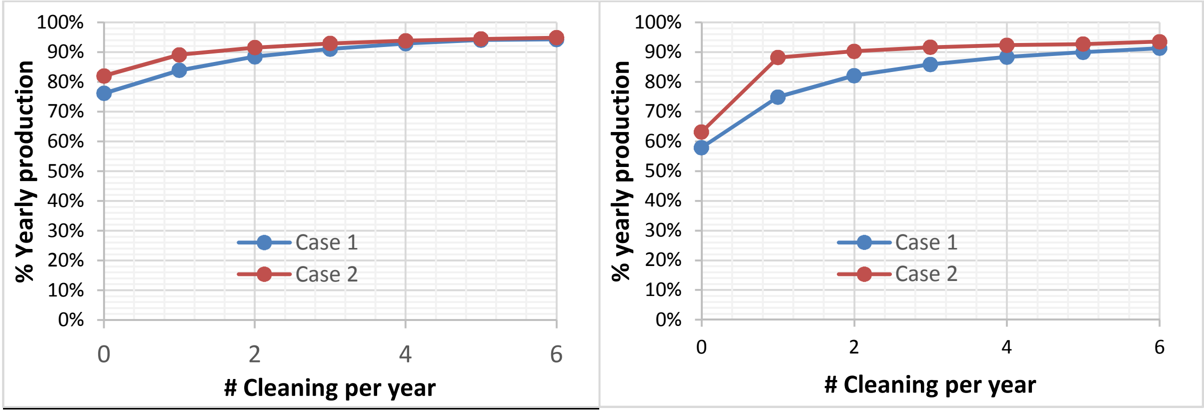


Fig. 7: Cleanliness curves with and without the polish effect of the rain (maximum effectiveness of the rain cleaning equal to 90% of the initial cleanliness, Cl baseline 77%)

Once cleanliness baseline has been determined for the single system, an optimization study can be developed in order to determine the number of the cleaning interventions and their distribution across the whole year.

In particular, expected production based on efficiency determined at Eq.1, DNI hourly values for the site and operating temperature can be combined within an hourly based simulation code with decreasing cleanliness both in Case 1 (without any rain effect) and in Case 2 (considering rain cleaning effect based on average measured precipitation).

Such computation has been coupled with a self-built genetic algorithm (Goldberg, 1989) to determine optimized number of cleaning per year and distribution in order to maximize the yearly production. The evolution starts from a population of 100 randomly generated combinations of yearly days of cleaning (a combination of n number between 1 and 365, where n is the cleaning number). In each generation, the fitness of every individual in the population is evaluated basically on expected yearly production; the combination showing major fitness are stochastically selected from the current population and each is modified through recombination and randomly mutated to form a new generation. The new generation of candidate solutions has been then used in the next iteration of the algorithm. The algorithm automatically stops when no improvement on best available combination has been found over 30 following generations. A mutation rate (probability) equal to 0.075 has been added, thus at each generation stage a small amount of day number has been redefined randomly. For each solution, the algorithm has been run twice in order to verify numerical convergence. Figure 8 shows the effect of increasing cleanings on total yearly energy production. Of course number of interventions must be established comparing specific economical value of FLCM production (heat, cooling or power) with increase in expected production.



(a) (b)

Fig. 8: Effect of cleaning intervention on yearly production with Cl baseline 77% (a) and 65% (b)

Once the optimized number of intervention is determined, a fixed time plan must be applied to achieve the expected results. As shown in Figure 9, cleaning intervention are usually optimized before the periods of greatest yearly irradiation.

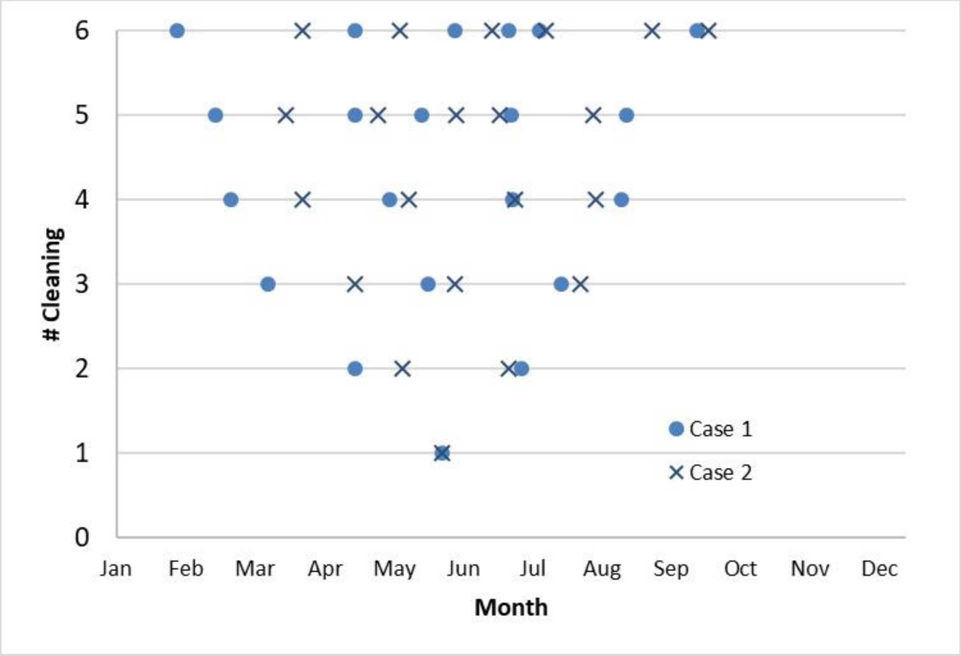


Fig. 9: Optimized days of execution for reference site in Case 1 and Case 2

5. Conclusions

The present work is addressed to find out a computational model enabling a technical and economical evaluation of dust effects on FLCM systems production. Looking at results achieved during performance tests, a relevant effect of the dust deposition on mirrors has been confirmed considering the difference between efficiency obtained before and after mirror cleaning. Besides, it has been assumed that efficiency drop does not overtake baseline value reached approximately within four months of dust exposition (without rain effect).

In addition, it should be considered that the weight of efficiency drop must be determined case by case since site exposition is relevant on value of final baseline. For this reason, an effective cleaning strategy should be based upon performance tests directly developed on single site for the determination of key parameter.

After the technical assessment has been achieved, economical matter should be considered within the whole strategy: as shown in Figure 10, the effect of an increasing number of cleaning interventions is different for Case 1 and Case 2 and depends on assumed baseline. Production benefits due to each intervention must be compared with their economic value on one side and specific intervention cost on the other side.

Optimized number of cleanings is then determined comparing yearly production increase associated to addictive cleaning intervention. Once determined optimized intervention number, time distribution is relevant to match expected production increase. As shown in Figure 9, independently on the total number, mirror cleanings should be concentrated preferably in summer season.

In case the solar plant is fully equipped for performance monitor, the proposed methodology can be applied dynamically through continuous monitoring of the optical efficiency. As a consequence, cleanliness values can be continuously updated.

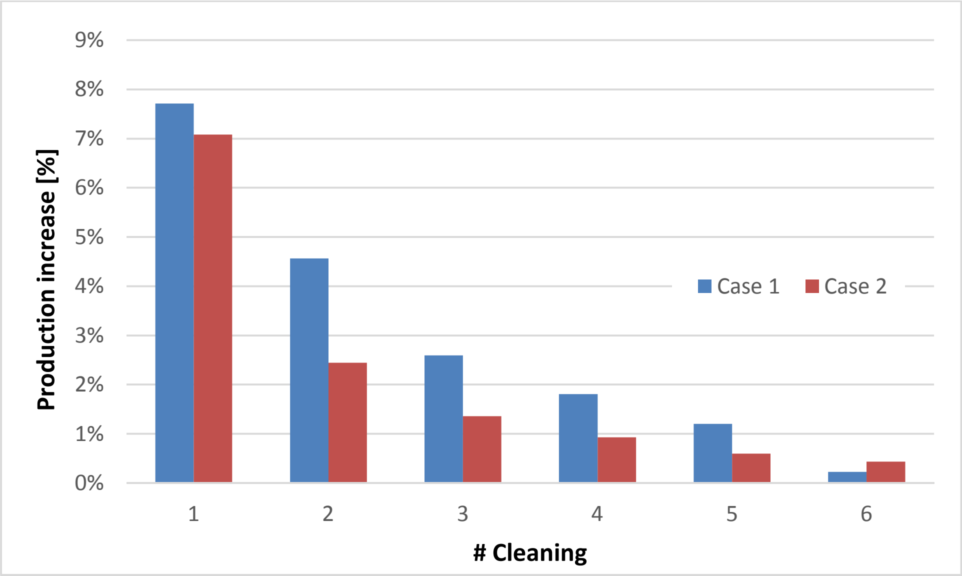


Fig. 10: % increase on yearly production for each cleaning intervention

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