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Corrosion Avoidance in the Metal Gate Industry Considering Sustainability

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Coating not cleaned up leads to massive emission worldwide, causing cancer and asthma. Coating gates to avoid corrosion needs to take place in nature. As a result, vast amounts of coating get sprayed out into nature, causing a significant sustainability issue. The industrial coating sector does not use protective equipment to save nature. The study aims to present a case study to minimise environmental pollution without increasing the cost of corrosion protection. The global cost related to corrosion has a significant burden on economies around the world – it costs approximately $2.5x10^{12}$ USD/y. It can be as high as 3.4 % of the GDP (2013). This cost has a significant impact on the efficiency of industries such as the automotive industry, industrial coatings and corrosion protection. Global demand for polyurethane coating materials will increase by 280 kt in 2022 (predictably). The volume of the solvent-based industrial coating consumption will grow significantly worldwide in the y 2021, predictably 1,400 Mt. In more detail, half of the coating is wasted, it drips onto the ground, gets into the air, so it causes pollution everywhere. The VOC (Volatile Organic Compounds) of the industrial coating pollutes the air, the living organism, and it can cause cancer, asthma and many other yet unknown health problems. The aim of this study is not only to introduce (based on data analysis) but to call attention to the environmental load originating from the industrial coating. In this study, the sustainability aspects of corrosion have been examined – especially in respect of the treatment of metal structures.

1. Introduction

Corrosion protection is a significant global government and corporation problem. It is a multi-variant challenge and cannot be approached by only considering environmental aspects. Half of the coat is wasted, released into nature, causing significant environmental disasters. The companies in the industrial coating sector do not use any protective equipment to shield nature (grass, flowers, rivers, etc.) until the corrosion avoiding process in nature. The global cost related to corrosion has a significant burden on economies around the world – it costs approximately $2.5x10^{12}$ USD/y (Koch et al. 2002). It can be as high as 3.4 % of the GDP (2013). This cost has a significant impact on the efficiency of industries such as the automotive industry, industrial coatings and corrosion protection (Koch, 2017). Approaching the topic from the corporate aspect, efficiency, cost-saving, and sustainable corrosion protection should be taken care of. This mindset considers environmental awareness and is reflected in the official corporate regulations. The cost of corrosion in China was approximately $3.1x10^{12}$ USD/y, representing about 3.34 % of gross domestic product (Hou et al., 2017.). Environmental protection and the interest of citizens should be considered at the same time as corporate interests making the economy function (Ouyang et.al.2021.). The above-mentioned parties have to cooperate in this outlined, complex, subtle interest system for sustainability. The present study is meant to introduce a case study-based analysis on the financial and environmental burden of industrial coating and finishing operations. Development of study and primary results the literature had been used from various greenhouse gases (CO_2, VOC, NOx, SOx, O_3, CH_4) especially focusing on CO_2 and VOC (Volatile Organic Compounds) pollution. The aim of this study is not only to introduce (based on data analysis) but to call attention to the environmental load originating from the industrial coating. Industrial coating has two options: it either takes place outdoors (e.g., maintenance or local operation) or in an enclosed space. In both cases, it can be said that as much as half of the coating material goes to waste – by adding the coating calculation process (Wang et al., 2018). In the present study, to demonstrate the

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previously mentioned issue, the case study is presented (Jacobson, 2016). The case study presents a multiple materials gate (carbon steel and stainless steel) have been used. This study is meant to analyse a given case where the object is made of a corrosion protective material, and by bearing in mind the sustainability aspects, it examines the environmental load and the ecological footprint directly connected to the creation of the object (Long et al. 2020.). The selected greenhouse gases are applied to global and corporate sustainability calculations. The present example is different since the materials and methods used during the coating process require a strict order and technique, it generally shows the calculation methods of corrosion protection (Kim et al., 2010.). Ecological footprint calculation literature considers three aspects: (i) direct pollution, (ii) pollution in relation to purchased energy, and (iii) other indirect pollutions. This study focuses on the latter aspect taking wide and holistic approaches.

2. Concept and literature review of corrosion and sustainability.

Greenhouse gases are responsible for global warming. These gases (CO_2, VOC, NOx, SOx, O_3, CH_4) are coming from different industrial sectors, especially the coating industry. The case study represents the effect of two main polluting greenhouse gases: CO_2 and VOC (Dovì et al., 2009). The fundamental question of the research is: what material and corrosion removal procedures are suitable for the objects? The goal of this study is to call attention to the environmentally damaging effects and long-term costs of industrial coating. Plenty of studies were performed previously on the topic, such as the one by Saif et al., undertaken to calculate the carbon emissions footprint of the coating industry. In order to find out the greenhouse gas pollution released by the industry, the carbon footprint of the industry was calculated according to the greenhouse gas (GHG’s) protocol guidelines (Saif et al., 2015.). Du et al. (2018) represent an experimental procedure to analyse different corrosion conditions in the corrosion process. Since half of the coat used during industrial coating is gone to waste, it is easy to acknowledge that the procedure does not meet the sustainability requirements. During the clarification of definitions, two types of materials and the procedures used will be introduced. The research question is whether carbon steel or a stainless-steel material-based object is the most suitable choice for sustainability criteria – as long as the object comes with a 100 y warranty featuring a corrosion protection clause. Carbon steel: An alloy of two components is made up of iron and carbon, while other elements occur in minimal traces, not influencing the alloy’s attributes. Alloying elements can be manganese (max. 1.65 %), silicone (max. 0.60 %) and copper (max. 0.60 %). In the case of carbon steel, corrosion protection could only be reached by coating. In the case of stainless steel: It is incorrodible due to the oxide layer content in chrome (at least 13 %), it is developed in a natural way, it is the standard state of stainless steels, and it is a passive state. It is quite a special self-medicating surface; in case of damage, it quickly regenerates itself provided there is enough oxygen in the environment. Generally speaking, there is no need for coating or corrosion protection. The weight should comprise at least 10.5 % chrome and no more than 1.2 % carbon. Corrosion could take place if the passive layer breaks and the surface becomes active. These areas are the oxygen lacking states where there are mechanical connections, narrow arches and low-quality welding joints. Gap corrosion and cavity corrosion – surface maintenance procedures applicable for stainless steel materials: (1) Descaling: Removal of a thick, visible dark-grey oxide layer. It is performed in the steel rolling mill. (2) Burnishing: Removal of the thin metal layer with nitric or fluoric acid. Discolored layers that arose during the welding process are removed this way. (3) Passivation: The passive layer of stainless-steel material oxidation by heating the steel. During the heating process, the thickness of the natural, transparent passive layer increases, and a discolored area appears due to the high temperature, and finally creating a grey colored oxide layer. Although this passivation process spontaneously takes place under normal conditions, oxidation-friendly conditions can serve as helping factors for the development of chrome rich oxide layer. It is important that before the acidic passivation treatment, the surface of the steel should be: (3a) free of hards (by removal of the hards), (3. b) metal-pure, oxide or discolored layers should be removed by burnishing. (3c) must be clean (from organic stains, lubricants, oils and greases). In terms of sustainability, the following four criteria must be met (Krotscheck and Narodoslawsky, 1996). Anthropogenic fluxes should not exceed the assimilation capacity of the hey and should be less than the natural fluctuations of the eogenous fluxes. Geogenic fluxes: heavy metal content of Ni, Co, Cr, As. Pollution should not compromise evolutionary potential. Faced with limiting resources rather than limiting pollution, anthropogenic fluxes (climate change, biodiversity reduction, impact on the hydrosphere) should not change the quality and quantity of global flux cycles. Carbon, nitrogen and water cycles: The extent of exploitation and recharge of natural resources and the associated changes in the quality of materials (i.e., use of other materials) need to be reconsidered. In this context, the most important thing is to keep the concentration of carbon roughly constant at a global level. If the reserves are contaminated, future resources are at risk. Renewable resources can only be extracted at a rate that does not exhaust local productivity. This requirement defines the input processes of the industrial systems. To meet this requirement, a locally adapted agricultural framework that guarantees the long-term preservation of the fertility of the land is needed. Erosion, soil contamination and salinisation must be stopped. A summary of the methodology for footprint-type calculations can be found in several studies: environmental footprints, carbon, water, ecological, energy footprint (Čuček et al., 2015). In the present study, CO_2 and VOC are quantified, the pollutions for a specific artefact. Rather, the natural diversity of species and landscapes should be maintained. It is proven that humans thrive in this system provided it is maintained in an appropriate natural environment. This can be seen from a very pragmatic point of view, as land and species are extremely important factors in a society striving for sustainable development. The irreversible degradation of these factors will hinder the chances of improving the quality of life and will deprive future generations of an important foundation for life. There is a large body of research on environmental indicator calculations related to manufacturing processes (Herva et al., 2011), but no uniform methodology has emerged so far. Čuček et al. (2012) describe in study a review of definitions and metrics that are related to environmental, social and economic footprints. These are important because the definitions of footprints vary and are often not clearly expressed (Yang et al. 2020).

3. Material and Methods

Below, the case study considers three aspects of sustainability: cost, CO_2 pollutions and VOC (Volatile Organic Compounds) pollution for this type of gate (Figure 1 a, b). “Emissions of CO_2, one of the key GHG emissions (Fózer et. al. 2020), accounts for two-thirds of GHG in 2014” (Wang et al., 2019). Wang et al. (2020) identify EU27 countries that contributed 1.4 Gt less CO_2 emissions compared to the rest of the world (Wang et al., 2021). This type of gate is small, and it is suitable for cost and pollution calculations. In the first step, a cost calculation of a naturally placed artefact made of carbon steel and stainless steel is performed. In the second step, the CO_2 pollutions of the artefact are calculated. By comparing these two factors, an anomaly between cost and sustainability is highlighted. To show the anomaly, a period of 100 y as the shelf life of stainless-steel artefacts has been added. Čuček (2015) uses a time span of 100 y to determine CO_2 pollution. Considering this research question, the solution is more sustainable in the long run – carbon steel or stainless steel. Similar research has been done by Soliman and Frangopol (2015), who determined indirect environmental, social, and economic impacts of maintenance. These data were computed to quantify the sustainability metrics associated regarding steel bridges during lifespan. There are many research studies that address questions on how to reduce CO_2 pollutions by using other materials or processes (Dovì et al., 2009). Stoeglehner and Narodoslawsky (2008) write about the application of ecological footprint metrics in corporate decision-making processes, but they note that it is a complex and multi-stakeholder process and that carrying out this type of analysis is a difficult and complex task.

(a)

(b)

Figure 1: A case study for avoiding corrosion of a gate on the Danube River close to the city Győr, front (a) and back (b) side

The cost calculation is based on the following factors: the cost of the raw material, the cost of the first coating process and the cost of maintenance over 100 y. For each of these steps, separate calculations are made in the workshop and in the field. The in-situ coating is not at all uncommon as some parts of the substructure may be damaged during the coating process, or other quality defects may be discovered on-site. The cost of coating outside is much higher (€480/t in the workshop, €960/t outside) than coating in a workshop. In the case of stainless steel, there is no coating involved, so the calculation does not include it. Overall, half of the coating used is wasted. Such waste either pollute the air in the workshop, or it is released naturally. Another aspect to consider from a sustainability point of view are CO_2 pollutions. CO_2 pollutions have to be considered during the production of raw materials and the coating process. The comparison is based on a sluice gate on a dead branch. The present calculation is generalisable because the cost of the materials used, the CO_2 pollutions, and the coating process are standardised. The example gives pseudo-analytical answers. Table 1 shows the amount of material needed to produce the gate, the cost of the raw materials and the CO_2 pollutions (Stainless Steel and CO_2). The basis of the calculation is in this case study, the gate material (t) in the type of gate Figure 1.

Table 1: Cost of raw materials (EUR) with the related CO_2 pollutions (t)

Gate material needs (t)	Unit cost (EUR/t)	Total cost carbon steel (EUR)	Unit cost stainless (EUR/t)	Total cost stainless (EUR)	CO_2 emissions carbon steel (1,4 t CO_2/t)	CO_2 emissions stainless (6 t CO_2/t, due to Chromium content)
68.20	1,388	94,661.60	5,500.00	375,100.00	95.48	409.20

The cost calculations presented in the Table 1 and Table 2 clearly show why companies are opting for the carbon steel version rather than the stainless-steel version. The final cost of the stainless-steel gate is 2.9 times higher than the cost of coating in a workshop and 2.3 times higher if coated in nature.

Table 2: Production and maintenance cost of the gate (EUR)

Cost comparison (EUR)	Carbon steel	Stainless steel
Quantity of raw material (t)	68.20	68.20
Total raw material cost (EUR)	94,661.60	375,100.00
Coating cost in workshop (480 EUR/t)	32,736.00	0.00
Coating cost in nature (960 EUR/t)	65,472.00	0.00
Coating cost in workshop (raw material and coating) (EUR)	127,397.60	375,100.00
Coating cost in nature (raw material and coating) (EUR)	160,133.60	375,100.00
Full maintenance cost (100 y 9 times in nature) (EUR)	589,248.00	375,100.00
Gate cost (100 y, full maintenance, first coating in a workshop) (EUR)	716,645.60	375,100.00
Gate cost (100 y, full maintenance, first coating in nature) (EUR)	749,381.60	375,100.00

Instead of considering only the costs, in the long run, it is wiser to make the gate from stainless steel. The corporation's way of planning does not always include long-term consequences and ignore sustainability because it is not profitable in the short run. When looked at the cost of such construction, companies prefer carbon steel. However, if we project the same plan out to 100 y, it's a different story. A carbon steel gate that is placed into the water has to be maintained every ten ys. The maintenance of a gate in water uses a coat that can protect the artefact from corrosion in aggressive industrial environments (Azizinamini et al., 2014), so the cost of maintenance adds significantly to the overall cost. Kabeb et al. (2019) suggest the development of a superior properties nanocomposite coating, evaluated by an adhesion tape test (Kabeb et al., 2019.). The cost of a gate made of carbon steel will be 1.9 times higher than that of stainless steel. Table 3 shows CO_2 pollutions. Focusing only on the CO_2 emissions of raw material production, the chromium content was considered in this study, being at least 13% for stainless steel, the CO_2 emissions of stainless-steel production are four times higher than those of carbon steel. The extent of chromium CO_2 emissions is most commonly studied in relation to leather products, and in these studies, the health impact is discussed (Herva and Roca, 2011). This is not investigated in this study but maybe an additional consideration in future studies. The CO_2 emissions of carbon steel are lower (159.2 t/100 y) than the CO_2 content of stainless-steel (409 t/100y), even after 10 y of coat.

Table 3: CO_2 emissions for the case study for carbon steel and stainless steel (t)

Comparison of CO_2 emissions (t)	Carbon steel	Stainless steel
CO_2 pollution of the raw material (t)	95.48	409.20
CO_2 pollution of coating based on the content of the dry matter (t)	5.84	0.00
Maintenance 100 y CO_2 pollution based on the content of the dry matter (t)	58.40	0.00
Sum CO_2 emission (t)	159.72	409.20

The VOC load is an indicator of the level of industrial coating emission. Solvents contribute to air pollution as volatile organic compounds (VOCs) when emitted during coating operations. VOCs have been the focus of environmental concern and regulated for two basic reasons: human health issues due to some VOCs being toxic and ozone formation through photochemical reactions with NOx (Kim, 2011) and sustainability issues (Kim et al. 2011). VOC content is an indicator of the number of aggressive substances that are particularly harmful to health. Overall, no environmental protection procedures are applied during on-site coating, and no care is taken to protect the natural environment. It is easy to see in the Table 4 that there is significant environmental pollution during on-site coating and that sustainability is not a relevant consideration.

Table 4: VOC pollution of the gate (t)

Quantity of VOC pollution (t)	Carbon steel	Stainless steel
Coating VOC pollution by the amount of coat applied (t)	0.61	0
Coating VOC pollution by the amount of coat applied 100 y (t)	6.10	0

4. Conclusions

Throughout this case study, the sustainability aspects were illustrated by cost calculation and by examining two types of greenhouse gases (GHG): CO_2 and VOC content. The greenhouse gas emission is higher than before, altering the climate, taking account into the global warming and causing health issues in humans. In terms of long-term sustainability, it is necessary to examine the greenhouse effect of artefacts maintained in nature, such as gates. Two different types of gates were considered: carbon steel and stainless steel. The coating environmental impact of carbon steel gates as a corrosion avoiding process was considered. In the long run (100 y), the stainless-steel gate is more cost-effective than the carbon one. The cost of the coated carbon steel gate is 749,382 EUR coated in nature. The stainless steel gate costs 375,100 EUR without coating. Considering the greenhouse effect (CO_2), the carbon steel gate is more sustainable than the stainless steel gate. The CO_2 pollution of the carbon steel gate (100 y) is 159 t, and the CO_2 pollution of the stainless steel gate (100 y) is 409 t. Considering the VOC pollutions, the stainless steel gate is more sustainable than the carbon steel one. The VOC pollutions of the stainless steel gate is 0.0 t for 100 y, but the VOC pollution of the carbon steel gate is 6 t for 100 y. VOC pollution is responsible for many issues. Air pollution can cause cancer, asthma or other fatal illnesses. The stainless steel gate is more cost-effective and more sustainable than the carbon steel gate. As for long-term sustainability, it can be concluded that the stainless steel gate protects the environment more than the carbon steel gate. An important aspect of full-size paper is to consider not only the release of the coating, but also the material of the gate.

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References

Azizinamini A., Power E.H., Myers G.F., Ozyildirim H.C., Kline E.S., Whitmore D.W., Mertz D.R., 2014. Design guide for bridges for service life (No. SHRP 2 Report S2-R19A-RW-2), doi: 10.17226/22617.
Čuček L., Klemeš J.J., Kravanja Z., 2012. A review of footprint analysis tools for monitoring impacts on sustainability. Journal of Cleaner Production, 34, 9-20, doi: 10.1016/j.jclepro.2012.02.036.
Čuček L., Klemeš J.J., Varbanov P.S., Kravanja Z., 2015. Significance of environmental footprints for evaluating sustainability and security of development. Clean Technologies and Environmental Policy, 17(8), 2125-2141, doi: 10.1016/j.proeng.2016.06.630.
Dovì V.G., Friedler F., Huisingh D., Klemeš J.J., 2009. Cleaner energy for sustainable future. Journal of Cleaner Production, 17(10), 889-895, doi: 10.1016/j.jclepro.2009.02.001.
Du H., Qi Y., He Y., Zhu H., Li Z., Yang Y., Meng S., 2018. Study on Stress Corrosion Characteristics of Different Grade H Sucker Rods. Chemical Engineering Transactions, 66, 145-150, doi: 10.3303/CET1866025.
Fózer D., Volanti M., Passarini F., Varbanov P.S., Klemeš J.J., Mizsey P., 2020, Bioenergy with carbon emissions capture and utilisation towards GHG neutrality: Power-to-Gas storage via hydrothermal gasification, Applied Energy, doi: 10.1016/j.apenergy.2020.115923.
Herva M., Álvarez A., Roca E., 2011. Sustainable and safe design of footwear integrating ecological footprint and risk criteria. Journal of Hazardous Materials, 192(3), 1876-1881, doi: 10.1016/j.jhazmat.2011.07.028.
Herva M., Franco A., Carrasco E.F., Roca E., 2011. Review of corporate environmental indicators. Journal of Cleaner Production, 19(15), 1687-1699, doi:10.1016/j.jclepro.2011.05.019.

Hou B., Li X., Ma X., Du C., Zhang D., Zheng M., Ma F., 2017. The cost of corrosion in China. Materials Degradation, 1(1), 1-10, doi: 10.1038/s41529-017-0005-2.
Jacobson G.A., 2016. NACE International’s IMPACT Study Breaks New Ground in Corrosion Management Research and Practice. The Bridge, 46(2), 30-38, <https://www.nae.edu/File.aspx?id=155268>, accessed 03/10/2021.
Kabeb S.M., Hassan A., Mohamad Z., Sharer Z., Mokhtar M., Ahmad F., 2019. Exploring the effects of nanofillers of epoxy nanocomposite coating for sustainable corrosion protection. Chemical Engineering Transactions, 72, 121-126, doi: 10.3303/CET1972021.
Kim B.R. ,2011. VOC pollutions from automotive coating and their control: a review. Environmental engineering research, 16(1), 1-9, doi: 10.4491/eer.2011.16.1.001.
Kim J., Park K., Hwang Y., Park I., 2010. Sustainable manufacturing: a case study of the forklift coating process. International Journal of Production Research, 48(10), 3061-3078. DOI: 10.1080/00207540902791785.
Kim Y.S., Lim H.K., Kim J.J., Hwang W.S., Park Y.S., 2011. Corrosion cost and corrosion map of Korea-Based on the data from 2005 to 2010. Corrosion Science and Technology, 10(2), 52-59, doi: 10.14773/cst.2011.10.2.052.
Koch G., 2017. Cost of corrosion. In: El-Sherik (Ed.), Trends in oil and gas corrosion research and technologies, Woodhead Publishing, Cambridge, UK, ISBN 9780081012192, 3-30.
Koch G.H., Brongers M.P., Thompson N.G., Virmani Y.P., Payer J.H., 2002. Corrosion cost and preventive strategies in the United States (No. FHWA-RD-01-156), <http://impact.nace.org/documents/ccsupp.pdf>, accessed 03/10/2021.
Krotscheck C., Narodoslawsky M., 1996. The Sustainable Process Index a new dimension in ecological evaluation. Ecological Engineering, 6(4), 241-258, doi: 10.1016/0925-8574(95)00060-7.
Long X., Yu H., Sun M., Wang X.C., Klemeš J.J., Xie W., Wang C., Li W., Wang Y., 2020. Sustainability evaluation based on the Three-dimensional Ecological Footprint and Human Development Index: A case study on the four island regions in China. Journal of Environmental Management, 265, 110509.
Ouyang X., Wei X., Li Y.G., Wang X.C., Klemeš J.J., 2021. Impacts of urban land morphology on PM2.5 concentration in the urban agglomerations of China. Journal of Environmental Management, 283, 112000, doi: 10.1016/j.jenvman.2021.112000.
Saif S., Feroz A., Khan M.A., Akhtar S., Mehmood A., 2015. Calculation and estimation of the carbon footprint of coat industry. Nature Environment and Pollution Technology, 14(3), 633.
Soliman M., Frangopol D.M., 2015. Life-cycle cost evaluation of conventional and corrosion-resistant steel for bridges. Journal of Bridge Engineering, 20(1), 06014005, doi: 10.1061/(ASCE)BE.1943-5592.0000647.
Stoeglehner G., Narodoslawsky M., 2008. Implementing ecological footprinting in decision-making processes. Land Use Policy, 25(3), 421-431, doi: 10.1016/j.landusepol.2007.10.002.
Wang L., Fan Y.V., Jiang P., Varbanov P.S., Klemeš J.J., 2021. Virtual water and CO_2 emission footprints embodied in power trade: EU-27, Energy Policy, 155, 112348, doi: 10.1016/j.enpol.2021.112348.
Wang M., Wang Z., Zhao X., 2018. Development and Application of Corrosion Monitoring and Management System for Chemical Equipment. Chemical Engineering Transactions, 66, 979-984. DOI: 10.3303/CET1866164.
Wang X.C., Klemeš J.J., Dong X., Fan W., Xu Z., Wang Y., Varbanov P.S., 2019. Air pollution terrain nexus: A review considering energy generation and consumption. Renewable and Sustainable Energy Reviews, 105, 71-85.
Wang X.C., Klemeš J.J., Wang Y., Foley A., Huisingh D., Guan D., Dong X., Varbanov P.S., 2020. Unsustainable Imbalances and Inequities in Carbon-Water-Energy Flows across the EU27. Renewable and Sustainable Energy Reviews. DOI: 10.1016/j.rser.2020.110550.
Yang L., Wang Y., Wang R., Klemeš J.J., Almeida C.M.V.B. de, Jin M., Zheng X., Qiao Y., 2020. Environmental-social-economic footprints of consumption and trade in the Asia-Pacific region. Nature Communications, 11, 4490, doi: 10.1038/s41467-020-18338-3.