LCC and LCA of Innovative Surface Coating Processes

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Abstract

The life cycle methodologies are a set of tools that support decision making, by considering the whole life cycle of a product. This set of methodologies is implemented in this work in order to study the economic and environmental performance of new coating alternatives, relatively to the conventional coating methods. The two alternatives are electroplating with nickel and silicon carbide and thermal spraying with tungsten carbide-titanium. These alternatives are proposed by a European project named PROCETS (PROtective composite Coatings via Electrodeposition & Thermal Spraying) and they aim to replace electroplating with chromium (VI) and thermal spraying with tungsten carbide-cobalt. The economic performance is calculated by the Life Cycle Cost methodology and the environmental performance is evaluated by using the Life Cycle Assessment methodology. The Life Cycle Cost methodology is implemented with the use of a Process-based Cost Model. Allowing to compute all the resources and operations required for each process and then link them with cost data. Since the mass and energy flows along with emissions are already computed by this model, they are uploaded into Life Cycle Assessment software in order to perform multiple analyses for each alternative, using different Life Cycle Impact Assessment tools. The use of these methodologies allows for the identification of the least environmentally burdensome coating, and to understand whether the coating alternatives are economically viable relatively to the conventional coating methods or not.

Keywords: Life Cycle Cost; Life Cycle Assessment; Process-based Cost Model; PROCETS; Electroplating; Thermal Spraying.

1. Introduction

The rapid growth in concern with the environment and human health has led to a multitude of attempts to replace hazardous processes with greener alternatives. The use of chromium (VI) (also known as hard chromium), in the production of coatings through electroplating presents a high risk to human health, caused by its carcinogenic emissions. Different coating procedures were created as an attempt to replace it, mainly electroplating with different formulations and thermal spraying with cermets (mainly Co-WC, tungsten carbide-cobalt). The use of this cermet still presents carcinogenic emissions and as such attempts to replace it were created as well.

Electroplated chromium is used because of the physical properties it confers to the coatings, without it, the service life of most chromium plated pieces would be significantly shorter since chromium plating provides protection to wear, corrosion, resistance to heat, hardness, etc. Chromium plating can be both used for decorative and functional applications. In order to accelerate this process organic- and double-catalyzed systems can be used, where the double-catalyzed systems provide the fastest plating times and the organic-catalyzed systems are well suited for functional applications. Sulfuric acid and sodium sulfate are the most commonly used sources of sulfate, these along with chromic acid (which provides chromium (VI), or hard chromium) are the basis of hard chromium baths (see table 1). Then, depending on the system, organic acids (such as alkene-sulfonic acid) are used [1].

The Co-WC coatings are produced by using the cold gas spray technology. This application produces coatings by accelerating particles in solid state to velocities ranging from 300 to 1200 m/s using gas-dynamics principles of converging/diverging flows to generate high-velocity gas streams and then project the powder into the surface [2]. If the impact velocity exceeds a given value the material will adhere to the surface, since this spraying application uses kinetic energy instead of thermal energy to produce coatings, undesired effects like tensile residual stresses, oxidation and chemical reactions can be avoided [2][3][4].

The alternatives currently at study attempt to replace these coating methods. Where electroplating with nickel and silicon carbide attempts to replace the use of chromium (VI), and thermal spray via cold gas spray with Ti-WC (tungsten carbide-titanium) powder attempts to replace the use of Co-WC powder. These alternatives were developed by companies working in a European research project called PROCETS (PROtective composite Coatings via Electrodeposition & Thermal Spraying). This work aims to compare the performance of these new alternatives with the conventional methods, by employing life cycle analysis methodologies. Namely, the LCC (life cycle costing) for the economic performance comparison and LCA (life cycle assessment) for the environmental performance. This work is the result of a collaboration between ISQ (which takes part in the project) and IST.

The LCA analysis was used in order to compare the environmental impacts of the alternatives with those of the conventional methods, to understand if the alternatives present better environmental performance and reduced carcinogenic emissions. Since the processes must be viable from an economic point of view, the LCC analysis is done to compare the cost performance of the alternatives with the conventional methods. The operations and resources required for each process are introduced in a PBCM (process-based cost model) that allows both the creation of an LCI (life cycle inventory) and to perform the LCC. The mass and energy flows, along with emissions of the processes are computed by the PBCM and are uploaded to the LCA software *SimaPro*, in order to perform the LCA. Where the LCIA (life cycle impact assessment) tool used is ReCiPe. A sensitivity analysis is performed for both the LCC and LCA. For the LCC results, the sensitivity analysis is done by the PBCM, where the production volume is changed. For the LCA results, the sensitivity analysis is done by performing LCA analyses using different LCIA tools, namely Impact2002+ and ILCD.

The results obtained allowed to identify which of the electroplating formulations and thermal spraying powders presents the best economic and environmental performance from a life cycle perspective. Making it possible to understand the feasibility of the alternatives as replacements to the conventional methods.

	Dilute Bath		Standard Bath		Concentrated Bath	
	$g\,L^{-1}$	Molarity	$g\,L^{-1}$	Molarity	$g\,L^{-1}$	Molarity
Chromic acid, CrO_3	100	1.0	250	2.5	400	4.0
Sulfate, SO_4^{2-}	1.0	0.001	2.5	0.026	4	0.042

Note: Ratio $CrO_3/SO_4 = 100$.

Table 1 Basic hexavalent chromium baths [1]

2. Technological Alternatives

The coating technological alternatives are electroplating and thermal spraying and are divided into the conventional formulations (hard chromium electroplating and thermal spraying with Co-WC) and the alternatives proposed by PROCETS in order to replace them (nickel with SiC electroplating and thermal spraying with Ti-WC, see figure 1). The companies that supplied the data for this study were *Artia Nano – Engineering & Consulting* which is a company based in Athens - Greece and a company that due to confidentiality issues doesn't wish to be identified and as such will be regarded as *Company A*. The former focuses on the study and implementation of the electroplating technology while the latter focuses on the study and implementation of the thermal spraying technology. The pieces being coated using electroplating are shock absorbers and the pieces coated using thermal spraying are laminating rollers (see figure 2).

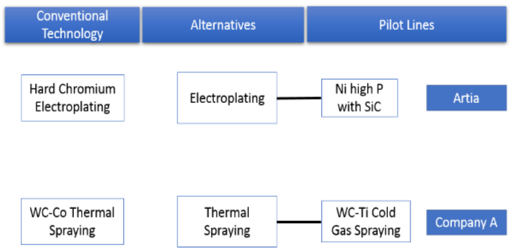

***Figure 1** Conventional and alternative technologies*

***Figure 2** Shock absorbers and laminating roller [5]*

3. LCA and LCC models

In order to perform both the LCC and LCA analysis, the scope and boundary conditions are established, where the life cycle stages of the processes are explained. Then, the data gathered for each technology is processed in order to create an LCI with all the inputs for each case. The data was gathered from the companies in the form of project deliverables for the alternative coating methods. The data used for the conventional coating methods is based on theoretical data coupled with data used in the alternative formulations. This data is introduced in a PBCM, that will be used to perform an economic evaluation on the technologies. Since the PBCM already calculates all the mass and energy flows along with emissions of the processes, the computed flows can be used in the environmental analysis. The PCBM will be providing the inventory data required to perform the LCA.

3.1. Scope and Boundary Conditions

The life cycle stages considered for these technologies are the raw material acquisition, which is the data regarding the materials used to produce the coatings, along with the materials used in both surface preparation and finish. The production stage consists of the coating lines along with their equipment data. Finally, the disposal is the data relevant to the waste treatment used for the leftover consumables that are not reused or recycled. The system boundaries along with the life cycle stages considered and their corresponding data are introduced in the PCBM. Allowing for the creation of an inventory that will then be used for the LCC and LCA analyses (see figure 3).

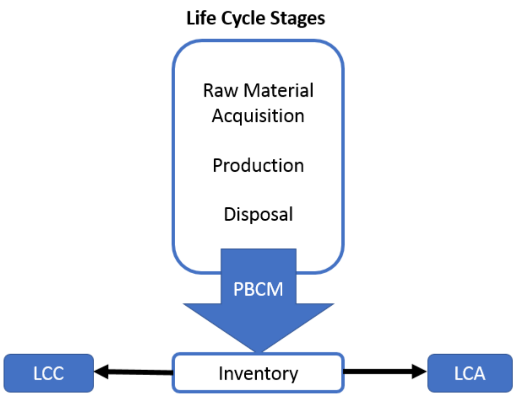

Figure 3 *Life cycle stages*

3.2. Process-based Cost Model

The PBCM is created by following a backwards approach, where every elementary process is decomposed into basic cost drivers that result from the required resources. The empirical and theoretical relations are then built in order to relate these cost drivers with the process requirements and operating conditions. Finally, a price factor is introduced to the consumption or use of the resources present in the process [6]. In this work, the PBCM calculates the annual costs of the process by using the expected annual production volume. The variable costs (material, labor and energy) are dependent on the production volume. Whereas, the fixed costs (i.e. overhead, building, equipment, tool and maintenance) are calculated by allocating an annual cost and are the result of previous or initial investments.

The mass and energy flows, along with the emissions, obtained in the PCBM are then uploaded in *SimaPro*, in order to perform the LCA. The coating methods will be regarded as electroplating - conventional, electroplating - alternative, thermal spray - conventional, thermal spray - alternative.

3.3. Economic Evaluation Methodology

The comparison of the conventional and alternative formulations focuses on key cost drivers. They are material, energy, labor and equipment costs. The material cost is broken down into consumables and solution cost. The energy cost is broken down in order to include a fixed energy cost. Finally, the equipment cost is broken down to include the tank cost along with the equipment cost. Cost drivers like building or fixed overhead are equal for both conventional and alternative cases because the line is considered the same. As such, they were not considered in this study. The cost drivers used are further explained below.

The material cost is comprised of consumables and solution cost. The consumables cost is the cost of expending materials to produce the coatings. As such, this cost is considered a variable cost. Because it is dependent on the expected annual production volume. The solution cost is the cost of all the solvents used in the solutions, along with the cost of the soluble used. Despite being a material cost, the solution cost is calculated as a fixed cost in the PBCM. This is caused by the solutions in the tanks not being dependent on the expected annual production volume (they are replaced periodically, independently of the production volume).

The energy cost is a variable cost that accounts for all the energy used in the process. This cost driver is dependent on the production volume. The existence of a fixed energy cost is caused by the use of a pump in the electroplating technologies that is always working, independently of the production volume. This is caused by the need to keep the powder used from depositing in the bottom of the tank.

The labor cost is a variable cost that accounts for the expenses with workers in the line.

The equipment cost is a fixed cost comprised of equipment and tank costs. The equipment cost accounts for the investment made with all the equipment used in these technologies. Additionally, the tank cost is the tank investment made in the electroplating processes.

With these cost drivers and the inventory data gathered, it is possible to find the total fabrication cost for each type of coating. This allows the use of the LCC methodology to perform the economic evaluation by coupling the results obtained with the disposal data gathered.

3.4. Environmental Evaluation Methodology

An LCA was produced for the environmental evaluation for each alternative and respective conventional technology by using the ReCiPe LCIA tool with the support of the LCA software *SimaPro*. ReCiPe was run by *SimaPro* using endpoint analysis with hierarchic weighting in order to obtain balanced results (not too conservative or too carefree).

In order to support the results obtained using ReCiPe, two other LCIA tools were used. Namely, impact2002+ and ILCD 2011 which were run by *Simapro* with no defined weighting and are directly comparable with ReCiPe 2008 as these LCIA tools provide a single score for the processes. Since ILCD can only be run using midpoint analysis, the results will be shown in impact categories that are similar to the three LCIA tools. Using the single score system, the results can be compared with the ones obtained for ReCiPe's impact categories. The single score is provided in eco indicator points (EI) and is the result of the weighting done by the LCIA tools to the results obtained for the impact and damage categories.

4. LCC and LCA results

4.1. LCC and sensitivity analysis results

The total fabrication costs for both alternative and conventional electroplating were obtained for a production volume of 2904 pieces coated per year, with 4 pieces coated per cycle and considering a dedicated production context.

The material cost is divided into consumables and solution costs in order to highlight the solution's contribution to the total fabrication costs. The main cost contributors to the total fabrication cost are the labor and equipment costs. The labor's cost contribution is caused by the need for an operator to follow the pieces being produced in a cycle, from its beginning to its end, which requires his continuous presence in the line. The contribution of the equipment cost is caused by the equipment's high acquisition costs and low life (very demanding working conditions – the equipment is submerged in a corrosive environment).
The results for both alternative electroplating and conventional electroplating are similar (see table 2). Presenting two major discrepancies in labor and solution costs caused by the existence of the particle preparation tank in the alternative electroplating. This operation (by being considered separated from the coating procedure) causes the increase in labor by adding the need of having an operator following an auxiliary process. Causing the increase in labor cost for the alternative electroplating. The solution cost in the alternative electroplating is also higher because of the particle preparation solution. This is caused by the acquisition costs of the solvents, mostly the SiC nanoparticles.

Cost Driver	Electroplating - alternative		Electroplating - conventional	
Consumables Cost	0.24 €	1.66%	0.24 €	2.17%
Energy Cost	0.75 €	5.18%	0.74 €	6.68%
Labor Cost	6.21 €	42.89%	5.17 €	46.66%
Solution Cost	2.24 €	15.47%	0.21 €	1.89%
Equipment Cost	5.04 €	34.80%	4.72 €	42.6%
Total Fabrication Cost	14.48 €	95.89%	11.08 €	94.7%
Cost of Disposal	0.62 €	4.11%	0.62 €	5.3%
Life Cycle Cost	15.10 €		11.70€	

Table 2 *Electroplating coatings' LCC results (in euros per piece coated)*

Regarding the thermal spraying results, the results were obtained for a production volume of 726 pieces coated per year, with 1 piece coated per cycle and a dedicated production context. Since the line and acquisition costs of both powders (Co-WC and Ti-WC) are the same (their acquisition cost data was provided by the producer during PROCETS project), the total fabrication costs will be equal (see table 3). This is caused by the use of the same technology as a potential replacement, where only the powder being sprayed has changed. This allows all the parameters of the surface preparation and surface finish along with the CGS to be the same (the CGS deposition efficiency is equal and is only dependent on the parameters of the gas used). As such, the analysis performed for the thermal spraying technologies allows to understand the contribution of each stage and is not focused on the comparison between both formulations. The material cost is the main contributor for this technology. This is caused by the low deposition efficiency of the CGS technology, that forces the use of higher quantities of powder to produce the coatings.

Cost Driver	Thermal Spray - alternative		Thermal Spray - conventional	
Material Cost	2955 €	93.96%	2955 €	93.96%
Energy Cost	96 €	3.05%	96 €	3.05%
Labor Cost	22 €	0.7%	22 €	0.7%
Equipment Cost	72 €	2.29%	72 €	2.29%
Total Fabrication Cost	3145 €	99.84%	3145 €	99.84%
Cost of Disposal	5 €	0.16%	5 €	0.16%
Life Cycle Cost	3150 €		3150 €	

Table 3 *Electroplating coatings' LCC results (in euros per piece coated)*

The variables chosen for the sensitivity analyses were the production volume, the cycle time, the equipment costs for a non-dedicated production context and the variation of the solution cost. The latter was done in order to determine the solution cost that the alternative electroplating requires to present the fabrication costs of the conventional electroplating. The LCC sensitivity analysis is only justified for the electroplating technologies, because the thermal spraying alternative and conventional applications present the same costs.

The fabrication costs of both electroplating formulations were calculated for an interval of production volumes of 100 to 10000 pieces coated per year (see figure 4). Where the production volume used for the LCC is marked. This will allow to see how the production volume variation affects the fabrication costs. For the given production volume interval, the graphic shows two cost spikes for the alternative electroplating and one for the conventional electroplating. These spikes are caused by the need to double the capacity of the line in order to achieve the desired production plan. They are evidence that the PBCM is working correctly as this behavior is expected for a PBCM of a dedicated line when the system capacity doubles. These cost spikes will reduce as the production volume increases, until the capacity of the line needs to be increased again.

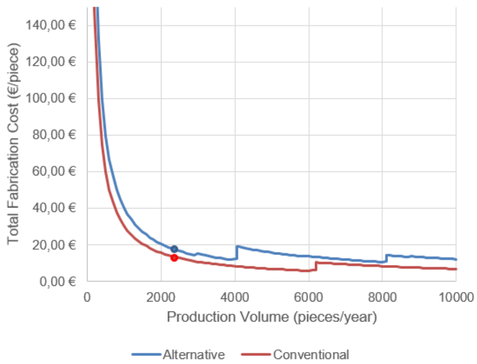

Figure 4 *Electroplating total fabrication cost variation with production volume*

From the production volume analysis, it is possible to conclude that, for pilot line production volumes of up to 4000 pieces per year (and 6000 to 8000 pieces per year) the fabrication costs of the alternative electroplating can be fairly competitive with the ones from the conventional electroplating. Despite this, the alternative electroplating will remain more expensive than the conventional electroplating.

A sensitivity analysis to the total fabrication costs variation with cycle time was made. By using the same production plan used for the LCC results (2904 pieces coated per year with 4 pieces being coated per cycle), it will be possible to understand how the different cycle times affect the cost of both formulations. By using a fixed production volume, the line occupation rate will decrease as the cycle time decreases, increasing the total fabrication costs of both formulations. The conventional electroplating presents a better overall economic performance for the cycle times selected (see figure 5). The cycle time interval selected was based on the data provided by *Artia* in the project deliverable. Despite the reduction of cycle time not allowing for a better economic performance than the conventional formulation, it still allows for an increased productive capacity, allowing to reduce the fabrication costs of the alternative by increasing the production volume.

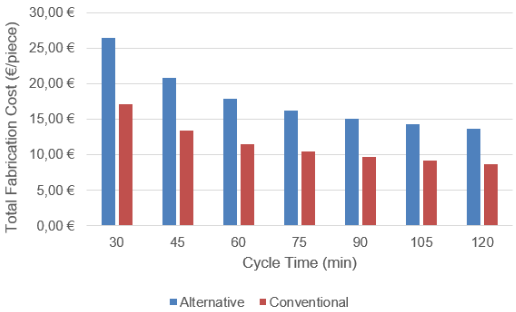

Figure 5 Total fabrication cost variation with cycle time

Then, a sensitivity analysis to the equipment costs was made. This analysis was made for the production volume defined in the LCC results and by changing the production context from dedicated to non-dedicated. This production context will allow to see the equipment occupation rate along with its costs for both formulations. In a non-dedicated production context, the costs per piece coated will remain constant as the line occupation rate increases with the increase in production volume (because only a percentage of the total costs of the line is allocated to this production volume). Since the production volume is fixed for this production context, the alternative electroplating presents an occupation rate of 72%, while the conventional electroplating presents an occupation rate of 47%. As such, their equipment costs are 3.46 €/piece and 2.23 €/piece respectively. The equipment costs of the alternative electroplating are higher than those of the conventional electroplating in a non-dedicated production context, this is caused by the additional equipment costs of the particle preparation operation and the conventional electroplating having a lower cycle time, which lowers its line occupation rate for this production volume.

Finally, an analysis to the alternative formulation solution cost was made. Despite the solution cost of the alternative formulation being higher (0.86 €/piece as opposed to 0.12 €/piece), its cost reduction is not enough to allow for the alternative electroplating to present the total fabrication cost of the conventional electroplating. This is caused by the particle preparation stage of the alternative electroplating, that increases its labor, equipment and solution costs. By creating a scenario where the particle preparation is not required and the SiC particles are directly used in the alternative electroplating solution, it is possible to determine the solution cost that the alternative requires to present the total fabrication costs of the conventional electroplating. The alternative electroplating would require a solution cost of 0.17 €/piece in order to achieve the economic performance of the conventional formulation. The higher solution cost of the alternative formulation (0.17 €/piece as opposed to 0.12 €/piece) is offset by the higher equipment cost of the conventional formulation, which as explained in the LCC results (chapter 5.1.1.) is caused by the difference in line occupation rate between formulations. This analysis shows that if the solution cost of the alternative formulation can be reduced to costs lower than 0.17 €/piece in a scenario where the particle preparation can be removed. The alternative electroplating can present a better overall economic performance than the conventional formulation.

4.2. LCA results

Regarding the electroplating LCA results, the most impactful operations are the plating operation, followed by the electro-cleaning and pickling pre-treatments (see table 4). These are the operations that contain the most hazardous baths along with highest energy consumptions in the line. Since the pre-treatment conditions are the same, the difference between the scores of alternative electroplating and conventional electroplating resides in the plating operations, along with the particle preparation tank for the alternative. Despite having one extra operation, the alternative electroplating presents a lower score. This is caused by the lower scoring in the plating operation, which shows that the coating formulation of the alternative is less hazardous than the conventional.

The main objective for the LCA analysis of these coatings is to try to determine, if the alternative electroplating reduces the risk to human health, by removing the carcinogenic emissions. The results obtained (using single score by operation) do not show how the alternative electroplating and conventional electroplating perform for the three damage categories of ReCiPe. The alternative formulation presents a similar performance for the three categories, only scoring worse for damage to human health (see figure 6). This is caused by the higher score in impact categories that lead to this damage category (i.e. particulate matter).

Operation Stage	Electroplating - alternative		Electroplating - conventional	
Degreasing (Pts)	0.33	0.49%	0.33	0.48%
Electro-cleaning (Pts)	12.27	18.26%	12.27	17.76%
Pickling (Pts)	12.04	17.92%	12.04	17.43%
Rinsing (Pts)	1.87	2.78%	1.87	2.71%
Plating (Pts)	39.24	58.39%	42.58	61.63%
Particle Preparation (Pts)	1.45	2.16%		
Total (Pts)	67.2		69.09	

Table 4 *Electroplating coatings' LCA results (ReCiPe endpoint analysis) by operations*

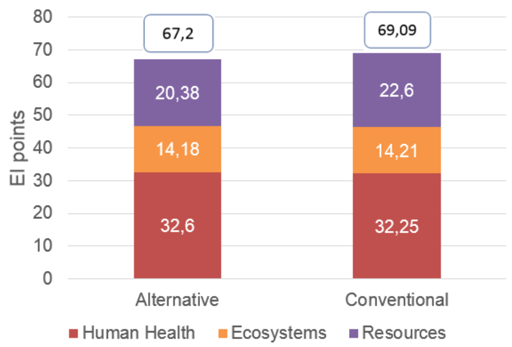

Figure 6 *Electroplating coatings' LCA results by damage categories (displayed in EI points)*

The results obtained for the impact categories show that the alternative electroplating scores negatively for human toxicity (the scores of the impact categories of ReCiPe are presented along with the score of Impact2002+ and ILCD in table 5). This means that the process presents less direct hazards to human health than the conventional electroplating. The main impact categories contributing to the alternative electroplating score are particulate matter formation and climate change. These impact categories also present similar values for the conventional method with the downside of the human toxicity also scoring higher which is caused by the use of Chromium VI.

The results obtained for the alternative electroplating show that it has a similar environmental performance to the conventional electroplating. The low human toxicity impact category is the main advantage for the alternative electroplating. Its difference in score between formulations is promising for the use of this technology as a replacement of the electroplating conventional. This advantage surpasses the drawbacks of having a higher particulate matter formation score (which is the main drawback of the alternative electroplating).

The total scores provided by Impact2002+ for the electroplating formulations differ from the results obtained using ReCiPe, and show that the environmental impact of the alternative electroplating is higher than the conventional electroplating. The total scores obtained with ILCD support the results obtained with ReCiPe and show that the alternative electroplating presents low carcinogenic emissions caused by the coating procedure. The difference in scores stems from the plating baths.

By studying the impact categories of Impact2002+ and ILCD, it is possible to understand how each impact category contributes to the total scores of both cases. From the impact categories of Impact2002+, it is possible to conclude that the major issue with the alternative electroplating is the particulate matter (caused by the use of the SiC nanoparticles). The results in the human toxicity impact categories of Impact2002+ reinforce the human toxicity results of ReCiPe and show a better performance of the alternative electroplating comparatively to the conventional electroplating.

The impact categories' scores obtained with ILCD show that the main impact category contributing for the conventional electroplating score is the cancer effects category. For this LCIA tool, the alternative electroplating presents a low score for all the impact categories. The impact categories that present different scores are the human toxicity categories and freshwater ecotoxicity, the latter is caused by the emissions of chromium (VI) to freshwater. The results obtained with ILCD show that, the overall environmental performance of the alternative electroplating is better than the performance of the conventional

Impact category	ReCiPe (Pts)		Impact2002+ (mPts)		ILCD (mPts)	
	Alternative	Conventional	Alternative	Conventional	Alternative	Conventional
Climate change. aggregated effects	36.41	36.26	79.2	78.86	7.58	7.56
Ozone depletion	0.0001	0.0001	0.00019	0.0003	0.0069	0.0011
Human toxicity. aggregated effects	-0.077	0.73	-0.29	0.92	7.83	2964.7
Human toxicity. non-cancer effects	NA	NA	-0.84	0.19	0.56	19.7
Human toxicity. cancer effects	NA	NA	0.55	0.73	7.27	2945
Particulate matter	10.38	9.31	102.54	93.73	10.05	9.13
Ionizing radiation. Human health	0.002	0.002	0.023	0.015	2	1.37
Photochemical ozone formation	0.001	0.001	NA	NA	2.74	2.57
Terrestrial acidification and eutrophication	0.09	0.08	1.02	0.93	13.49	11.85
Terrestrial ecotoxicity	0.013	0.012	1.61	1.27	NA	NA
Freshwater eutrophication	-0.0008	0.002	0	0	-0.082	0.17
Marine ecotoxicity	0.0003	0.0003	0.044	0.04	NA	NA
Freshwater ecotoxicity	0.001	0.0008			-5.36	103.05
Land use	-0.029	0.061	0.05	0.083	0.0025	0.0025
Mineral. fossil & renewables resource depletion	20.38	22.64	55.38	54.9	12.54	9.46
Total	67.2	69.09	239.58	230.75	50.8	3109.86

Table 5 *Electroplating impact categories results for ReCiPe, Impact2002+ and ILCD*

electroplating. The human toxicity scores obtained with ILCD are caused by this LCIA tool giving more weight to the mass flows of the processes instead of their energy flows. As such, the score of the cancer effects categories of the conventional electroplating is caused by the weight given by ILCD to the use of chromium (VI). Overshadowing the scores of the remaining impact categories for both cases. The results for the cancer effects of ILCD support the results obtained with ReCiPe and Impact2002+ for these categories and show that the cancer effects are mostly removed by using the alternative electroplating.

From these analyses, it is possible to conclude that the alternative electroplating is a suitable replacement for the conventional electroplating. Despite both formulations presenting similar total scores (the score difference is not high enough to state that one formulation performs better than the other), by looking at the different impact categories the difference in their scores is relevant. The human toxicity categories for the alternative electroplating present a better performance than the conventional electroplating for ReCiPe and Impact2002+ methodologies. This is greatly evidenced by the results obtained using ILCD, where the cancer effects of the conventional electroplating are 3 orders of magnitude greater than the scores of the alternative electroplating.

Regarding thermal spraying, the alternative thermal spray has a similar performance in the total scores to the conventional thermal spray (see table 6). Since the production lines are the same, the difference in results stems from the use of the different powders. The results obtained show that the cold gas spraying operation is the most hazardous, containing nearly the total of EI points for both processes. This is expected, since the other two operations are surface preparation with sand blasting and surface finishing with abrasive band. As such, they are not as impactful as thermal spray with cermets.

Despite scoring similarly to the conventional thermal spray, the alternative thermal spray presents higher scores for the three damage categories of ReCiPe (see figure 7). As such, the use of this powder as a replacement for the Co-WC can only be considered if the carcinogenic emissions are reduced.

Operation Stage	Thermal Spray - alternative		Thermal Spray - conventional	
Surface Preparation (Pts)	0.45	1.92%	0.45	2.26%
Cold Gas Spraying (Pts)	22.62	96.5%	19.07	95.88%
Surface Finish (Pts)	0.37	1.58%	0.37	1.86%
Total (Pts)	23.44		19.89	

Table 6 *Thermal spray coatings' LCA results (ReCiPe endpoint analysis) by operations*

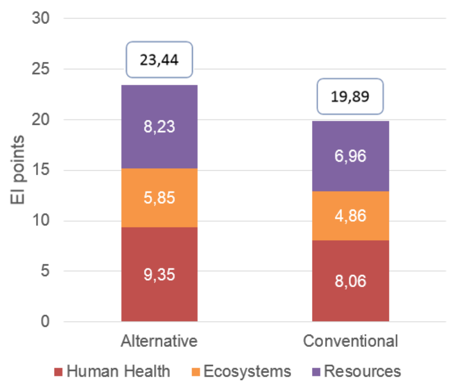

Figure 7 *Thermal spray coatings' LCA results by damage categories (displayed in EI points)*

The EI points indicate that the alternative thermal spray is more harmful than the conventional thermal spray. This however is not conclusive as to how both behave regarding the impact categories. The alternative has a slightly better performance in the human toxicity category of ReCiPe (lower score). At the same time, it presents a worse performance in the majority of the impact categories (the scores of the impact categories of ReCiPe are presented along with the score of Impact2002+ and ILCD in table 7).

The impact categories of Impact2002+ show that the main contributor for the higher environmental impact of the alternative are particulate matter, climate change and non-renewable energy categories. Supporting the results obtained using ReCiPe, as the impact categories of the latter also present higher scores for the climate change and particulate matter formation categories.

The results obtained using ILCD differ from the results obtained with the other LCIA tools. The alternative thermal spray scores worse than the conventional thermal spray in the cancer effects category. As such, the use of Ti-WC is considered more carcinogenic than the Co-WC powder (conventional powder) by ILCD. This is caused by the difference in characterization factors of the LCIA tools (as seen in electroplating where the use of chromium (VI) caused the cancer effects to be the major contributor for the score of conventional electroplating, when using ILCD).

From these results, it is possible to conclude that the alternative thermal spraying is not suitable to replace the conventional thermal spraying. Since the difference in total scores is low, they both present similar environmental performances (with the alternative scoring slightly worse). The alternative thermal spray presents higher score than conventional thermal spraying in carcinogenic emissions for ILCD and a lower score for Impact2002+ (for the latter, both scores are negative). Since the conventional thermal spray presents carcinogenic emissions, the cancer effects scores from Impact2002+ are disregarded.

5. Conclusions

The intended goal of this work was to compare new coating alternatives with the conventional coating methods already established, from an LCC and LCA perspective. The LCC and LCA analyses allowed to see, whether the alternatives presented better economic and environmental performance or not(with a special focus on the carcinogenic emissions).

The LCC methodology allowed the identification of the main cost drivers for the technologies studied (labor and equipment cost for electroplating and consumables for thermal spraying). The life cycle costs of the technologies were estimated considering the boundary conditions. Where the disposal costs of the alternatives were used for their respective conventional methods as well. As such, the economic performance focused

Impact category	ReCiPe (Pts)		Impact2002+ (mPts)		ILCD (mPts)	
	Alternative	Conventional	Alternative	Conventional	Alternative	Conventional
Climate change. aggregated effects	11.92	10.17	24.92	21.33	2.4	2.06
Ozone depletion	0.001	0.0005	0.002	0.0017	0.08	0.064
Human toxicity. aggregated effects	0.14	0.15	-6.66	-4.78	9.25	8.44
Human toxicity. non-cancer effects	NA	NA	-6.42	-4.62	-3.31	-1.18
Human toxicity. cancer effects	NA	NA	-0.24	-0.16	12.56	9.62
Particulate matter	1.9	1.67	19.37	17.07	1.44	1.22
Ionizing radiation. Human health	0.012	0.01	0.11	0.094	9.81	8.55
Photochemical ozone formation	0.0005	0.0005	NA	NA	0.96	0.88
Terrestrial acidification and eutrophication	0.015	0.013	0.28	0.26	2.72	2.39
Terrestrial ecotoxicity	0.016	0.012	1.14	1.56	NA	NA
Freshwater eutrophication	0.002	0.0015	0	0	0.21	0.16
Marine ecotoxicity	0.0003	0.0002	-0.055	-0.035	NA	NA
Freshwater ecotoxicity	0.0012	0.0001			13.44	10.84
Land use	1.2	0.9	0.49	0.38	0.0022	0.0019
Mineral. fossil & renewables resource depletion	8.23	6.96	27.84	24.08	15.23	18.91
Total	23.44	19.89	67.44	59.96	55.54	53.52

Table 7 *Thermal spraying impact categories results for ReCiPe, Impact2002+ and ILCD*

mainly on the production stages of the different formulations.

The LCA methodology allowed the assessment of the environmental impacts of the alternatives and conventional methods throughout their life cycle. The LCA was first performed using ReCiPe, in order to identify the main impact and damage categories for each method and to see the performance of the alternatives regarding human toxicity. Then, the use of Impact2002+ and ILCD tools allowed to complement the results obtained with ReCiPe. Some discrepancies were found (namely in the results obtained using Impact2002+) but are justified since these methods use different weighting systems and characterization factors.

The PBCM was created in order to have a parametric model capable of calculating the inventories of multiple production scenarios (sensitivity analysis) along with performing the LCC. With it, the data provided by the companies during the PROCETS project allowed the creation of an inventory for each process. The mass and energy flows along with the emissions were calculated and related with part description and operations. The flows calculated were also uploaded into *SimaPro* in order to perform the LCA. With the PBCM, various cost sensitivity analyses were made to the electroplating formulations by varying the production volumes, cycle times, production context and solution cost.

The results obtained with this work show that the alternative electroplating has higher fabrication costs than the conventional electroplating. This alternative presents similar costs with the conventional for a range of production volumes and cycle times as established in the sensitivity analyses, but will remain more expensive. The equipment cost is also higher for the alternative electroplating in a non-dedicated production context, due to the alternative electroplating having a higher cycle time and the existence of the particle preparation operation. Whereas the solution cost can be lowered and allow the alternative electroplating to present the economic performance of the conventional electroplating. This scenario is only possible if the particle preparation is not required. The environmental results for the electroplating formulations show that the alternative electroplating presents an overall similar environmental performance to the conventional electroplating, despite the existence of one extra operation (the particle preparation operation). In the impact categories, the alternative electroplating shows reduced human toxicity and cancer effects (for the three LCIA tools). The alternative electroplating presents similar damage scores to ecosystem and resources to those of conventional electroplating.

The results obtained for the thermal spraying lines show that both alternative thermal spray and conventional thermal spray present equal fabrication costs (the life cycle costs are the same since the same disposal cost is used for both cases). The environmental results for the thermal spraying lines show that the alternative thermal spray scores higher in all the damage categories of ReCiPe. It shares a similar value with the conventional thermal spray for human toxicity (for ReCiPe) and in ILCD it scores higher than the conventional thermal spray for cancer effects.

For these reasons, despite its lower economic performance, the alternative electroplating is a promising replacement to the conventional electroplating. Whereas, the alternative thermal spray is not a suitable replacement for the conventional thermal spray since it is more hazardous to the environment and human health.

5. References

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