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DEVELOPMENT OF ENVIRONMENTALLY-FRIENDLY TECHNOLOGIES BASED ON THE DOUBLE-ECO MODEL – AN EVALUATION PLATFORM

In recent years, the urgency to create environmentally-friendly technologies has dramatically increased. However, these technologies are usually not adopted due to their large cost and low profit. Previously the “Double-ECO model” has been proposed as a methodology that reconciles both “Economy” and “Ecology”, which relies on the exploration of technology alternatives that offer an improved mechanical performance. Here, as mechanical performance, cost and environmental impact were meant to be approached under the same degree of priority, this model was thought to offer the basis for a broader technology development framework. The current research initiates said framework by proposing an evaluation platform, which through a transition from a focus on environmental-friendliness towards an improved eco-efficiency definition lays groundwork for an automated evaluation. This was done by defining a dimensionless evaluation parameter based on existing methodologies and referred as the “DE Index”. This paper applied the proposed evaluation method into a machine tool lubrication technology example. It was concluded that, (1) the platform was able to effectively compare technologies under the proposed eco-efficiency parameter, (2) the developed technology possessed improvements in the environmental pollution output, mechanical performance and cost when compared to conventional technologies.

1. INTRODUCTION

Since the beginning of the 21st century, the importance to develop technologies and manufacture products in an environmentally-conscious way has been highlighted in efforts such as the Paris Agreement and the agenda of the WBCSE for the next half-century. In this regard, technologist, entrepreneurs and manufacturers not only need to conserve and utilize energy in an efficient way, but they also need to scrutinize in order to save resources and reduce emissions of environmentally-harmful pollutants [1,2]. Here, Japan is not the exception, the Japanese Diet is constantly engaged in enacting environmental protection bills and amendments that regulate emissions, taxation and energy usage [3]. Nevertheless,

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as stated on the third and fourth articles of the Paris Agreement, countries are singularly diverse and every country is bound by its own circumstances to achieve comprehensive development.

Consequently, countries have committed to join the global environmental protection efforts by abiding to goals defined by themselves under the FCCC [1]. The development of technologies and products should not be different; here, a flexible framework is required to generate environmentally-friendly technologies that can be applied to a wide range of applications without making significant compromises due to stringent standards or methodologies. As observed in the design process ecology-economy-equity fractal triangle presented by McDonough (2006), multiple approaches to develop such framework exist [4]. Most current methodologies that deal with the environmental-friendliness issue have been largely meant for the late stages of the technology development process or as countermeasures for existing technologies. Here, if an ecology-economy-performance fractal triangle is devised, it is possible to observe that most current technologies fall either on the ecology-performance or in the economy-performance categories. As a result, environmentally-friendly technologies are not usually adopted due to their large cost and low profit they represent.

During previous researches, it was observed that a competitive technologies can be achieved when approaching mechanical performance, economic and ecological parameters under the same degree of priority [5,6]. Subsequently, the “Double-ECO model” has been proposed as a methodology that reconciles both “Economy” and “Ecology”, which relies on the exploration of technology alternatives that offer an improved mechanical performance [7]. Here, based on current methodologies, a brief explanation regarding a “Double-ECO” based environmental-friendliness evaluation that relied on assigning specific weights to each of the aforementioned parameters was covered in previous researches [8,9]. The current research intended to initiate a flexible framework by proposing an evaluation platform, which through a transition from a focus on environmental-friendliness towards an improved eco-efficiency definition lays groundwork for an automated evaluation. This was done by defining a dimensionless evaluation parameter based on existing methodologies and referred as the “DE Index”. Finally, the platform was applied into a machine tool lubrication technology example.

2. LIFECYCLE ASSESSMENT

Lifecycle Assessment (LCA) was thought to be key in the development of a flexible evaluation platform as LCA is one of the major focuses of current literature and standards (i.e. ISO 14040) regarding environmental management [10,11]. In this regard, LCA refers to a “cradle-to-grave” perspective assessment that considers a technology lifespan from raw material acquisition to the manufacturing, usage and end-of-life [11,12]. Here, said perspective allows the identification of environmental impacts that might not be possible to observe when focusing on specific stages of the technology development process [11]. In Fig. 1, it can be observed that current specialized literature incorporates considerations from other fields such as supply chain management to improve the LCA at stages that are often neglected such as the end-of-life [10]. Here, a useful contribution from the LCA at the end-of-life was the concept of bioremediation that refers to what extent the generated waste can be processed back into nature [12]. Finally, it must be mentioned that the environmental focus of LCA usually does not take into account economic or social aspects but this research took a LCA perspective to define the categories that determined the cost parameter of the platform [11].

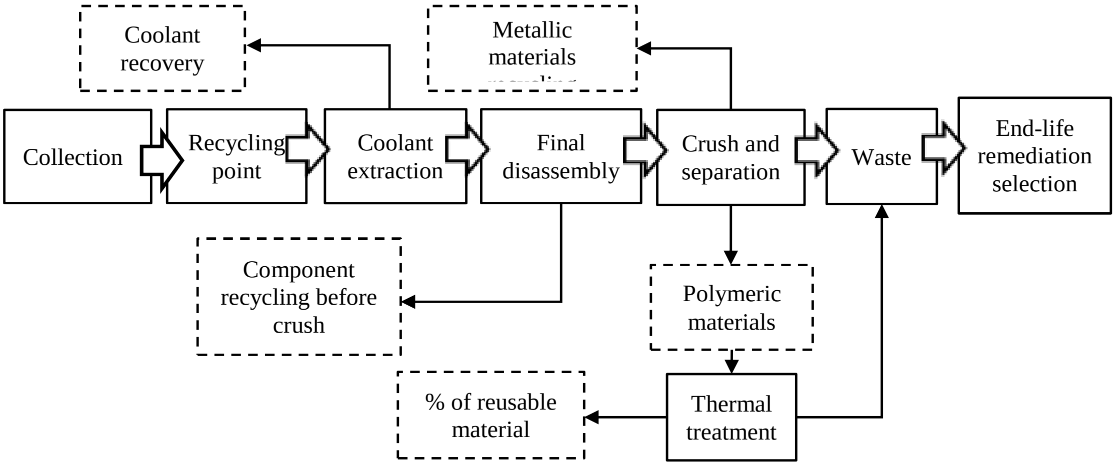


Fig. 1. Lifecycle of a refrigerator at its disposal stage [10]

3. DEFINITION OF THE EVALUATION AND ECO-EFFICIENCY

Currently, there are several definitions regarding eco-efficiency and they are usually plagued with ambiguity. Reinout Heijungs (2007) discusses in depth the lack of a “quantifiable and communicable term” that refers to eco-efficiency and raises the need for the development of one, while DeSimone (1997) adds that a life cycle perspective is necessary to measure eco-efficiency [13,14]. Here, Heijungs (2007) mentions that international consensus regarding a definition for eco-efficiency is leaning towards a meaning that refers to the ratio between environmental and economic variables; in addition, the author attempts to condensate the current generalization towards eco-efficiency into a productivity-based dimensionless indicator [13]. As competitive technologies can be achieved when approaching mechanical performance, economic and ecological parameters under the same degree of priority [5,6], an integration was deemed possible under a new eco-efficiency term referred as the Double-ECO area Index or “DE Index”. This index is also dimensionless but includes mechanical performance as an efficiency-determining parameter as shown in Fig. 2.

Subsequently, with the definition of this new term, the opportunity to quantify and automate eco-efficiency evaluations with currently available technology trends such as machine learning methods and big data analysis was deemed as highly relevant [15,16]. Particularly, said methods would avoid almost arbitrary weighting methods, such as the Eco-efficiency method of BASF, and detect what Schaltegger (1997) referred as “positive external effects” or synergistic effects that are present [8,13].

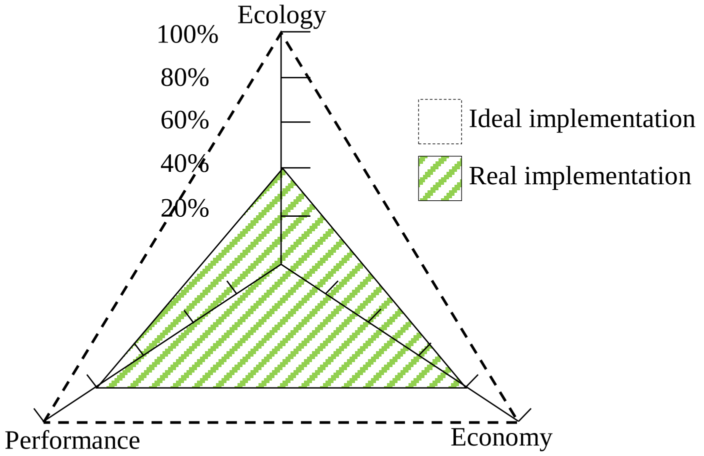


Fig. 2. Scheme of the double-ECO model principle

As shown in equation (1), the proposed term consists in a dimensionless index obtained from the comparison the proposed term consists in a dimensionless index obtained from the comparison between the real and the optimal implementation of a technology, which are areas generated through systematically defined ecology, economy and performance evaluation axes. Particularly, the index relies on comparing all the available similar technologies in a portfolio, which serves as input for the axes, and present which one is the best performing under the DE Index. This can be useful to compare a new line of products or technologies that do not have a direct comparison or competitor, but it can also be useful to compare a new technology to an existent technology. Thus, a flexible Double-ECO evaluation platform was thought to be possible.

$$\text{DE Index (\%)} = \frac{\text{Real implementation}}{\text{Ideal implementation}} \tag{1}$$

where: DE Index and the input data are non-dimensional parameters.

3.1. ENVIRONMENTAL FRIENDLINESS PARAMETER EVALUATION

As mentioned before, LCA is one of the main tools in the environmental management area and in this research it was used to define the main categories used to evaluate the environmental performance of a certain technology. In this regard, the main categories focused on three defined areas of the lifecycle of a technology. First, the categories that can be observed from the material supply to fabricate or generate the technology. Second, the categories that can be observed from the technology usage. Third, the categories that can be observed during the disposal of waste or the disposal of the technology itself. As shown in Fig. 3, the LCA diagram can depict these three main category areas. Moreover, the company BASF has developed an eco-efficiency method that relies on weighting based on polling, surveys and economic studies in order to define the importance of environmental parameters in a certain industry, region or country [8]. BASF was based on the standard ISO 14040 and their environmental finger print was constrained under the following categories: emissions, energy depletion, resource depletion, toxicity and risk potential [8]. Similarly, Bevilacqua (2012) has also documented the usage of weighting as a form of normalization to define environmental categories that are priority [10]. From this categorization it was possible to define the following ten categories in order to evaluate ecology performance. Here it must be considered that these categories will lack weighting and behave in a binary way (0 or 1) unless weighting is defined by the user or an automated system is used (e.g. big data). Non-binary answers rely on linear calculations among the compared technologies where 1 is the best performing technology and 0.1 is the worst performing (as 0 would mean non-performing).

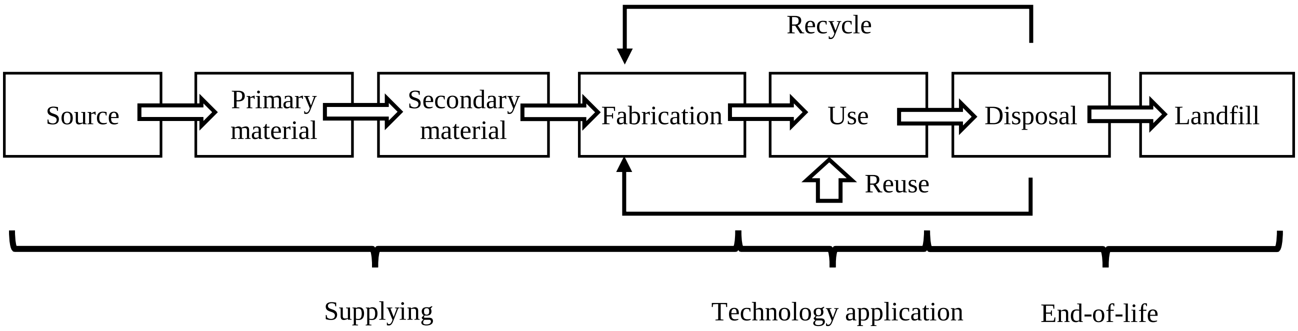


Fig. 3. Adapted LCA diagram with category divisions used in the current research [12]

Table 1. Chart describing the Double-ECO categories and definitions used for the ecology performance evaluation

Life Cycle Section	Double-ECO Category	Definition
Supplying	1. Locality	Favor local-to-local approach
Supplying	2. Renewability	Renewability the elements used or the product components
Technology Application	3. Durability	Frequency of repair
Technology Application	4. Energy efficiency	Least energy consuming technology
Technology Application	5. Emissions minimization	Least emitting technology
Technology Application	6. Noise / Vibrations	Absence of unintended effects
Technology Application	7. Waste minimization	Waste minimization (based on the total material requirement index)
End-of-life	8. By-product safety	Absence of waste that represent a health hazard
End-of-life	9. Recyclability	Recyclability of the elements used or the product components
End-of-life	10. End-life waste bioremediation	Industrial waste that can be treated with bioremediation

3.2. PERFORMANCE PARAMETER EVALUATION

The mechanical performance evaluation was determined through an existing method that could be used to analyze data of technologies that does not necessarily have a direct predecessor or competitor as a point of reference for performance evaluation. This method is the Mahalanobis Taguchi System, which is used to quantitatively make decisions based on a multivariate analysis. In this regard, extensive research has been done regarding the MTS and their application for pattern recognition [17,18]. The MTS employs Mahalanobis distances (MD) which are a distances that can be regarded as the measure of the divergence from the variables mean values of a certain population that constitute the Mahalanobis Space (MS) also known as the unit group (Fig. 4). As, the MD can be used as a measure to determine the similarity between sets of data this defined the performance. The MTS was applied using a MTS software and, thus, only two steps are considerably important on the Double-ECO performance evaluation section: 1. The creation of an appropriate Mahalanobis Space, 2. Validation of the Reference Space through abnormal data measurements.

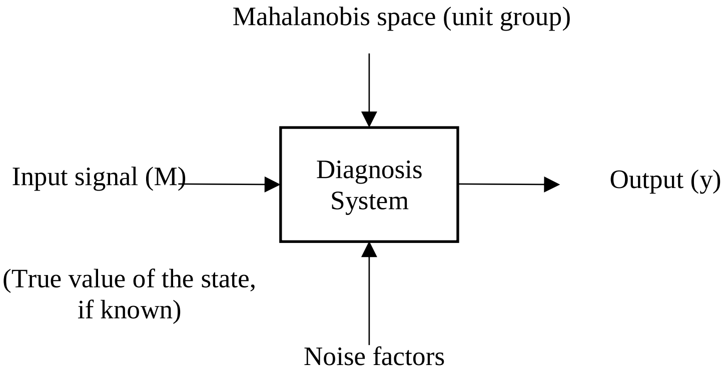


Fig. 4. Diagram depicting the MTS diagnosis system [17]

3.3. ECONOMY PARAMETER EVALUATION

The economy parameter evaluation consisted in three main categories: production cost, usage cost, disposal cost. This division was based on standard accounting calculations for product cost that rely on direct labor, direct materials and overhead [19] and machine tool cost calculations that relied on acquisition cost, usage cost and disposal cost [20,21]. In the case of non-production costs, research and development was also included as a non-production cost of the production category cost [19]. Additional considerations were that in the usage cost maintenance was replaced by monitoring and assessment as this is a WBCSD product development category could not be included in the ecology parameter section [4,14]. Here, monitoring and assessment was thought to include direct labor under a not-automated scenario, if automation happens then the direct labor would change into operation overhead. In the same way, as taxation is included in overhead costs, an environmental taxation sub-category was added [19]. Finally, disposal of waste and final disposal were thought to be as overhead costs that are not related to direct labor as their disposal costs often cover labor.

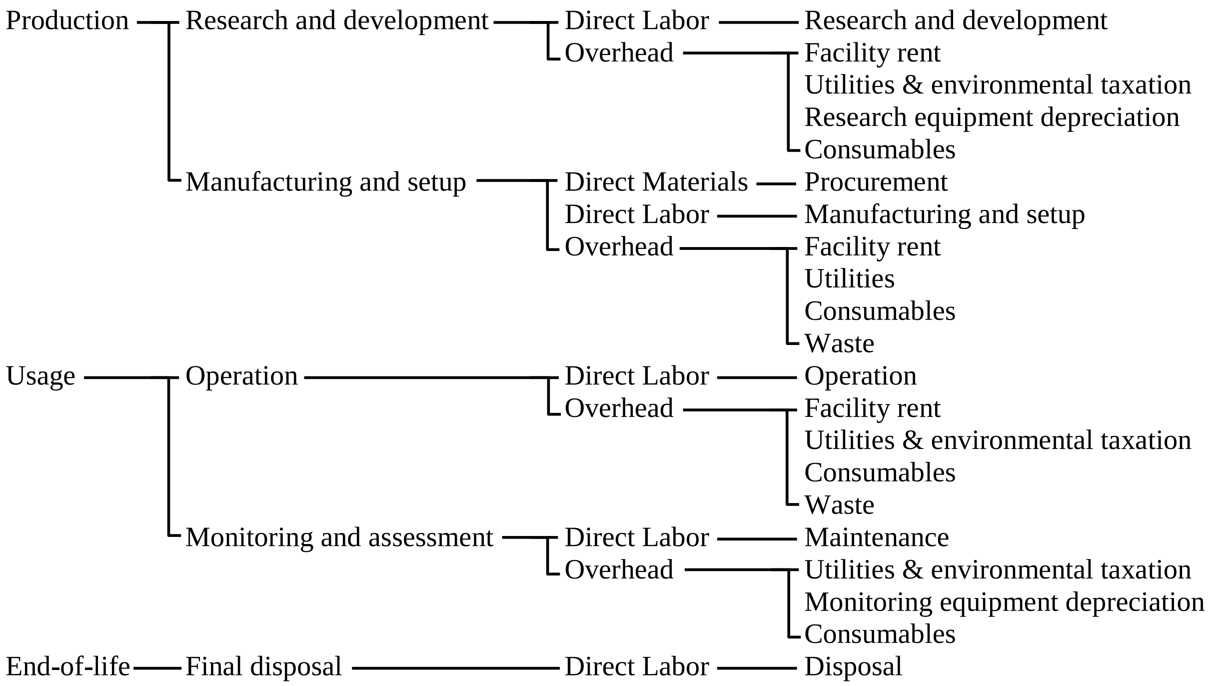


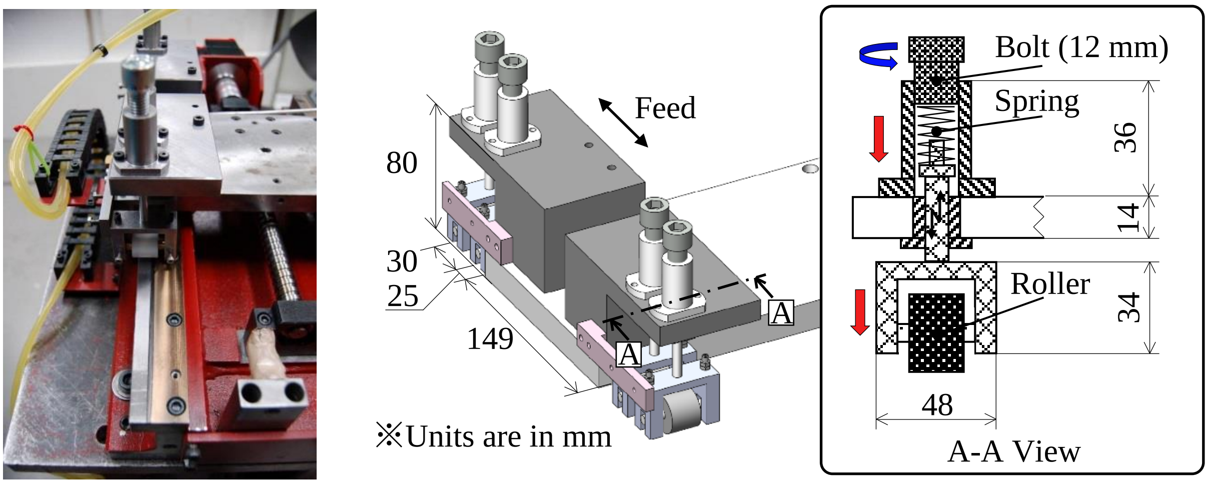
Fig. 5. Diagram describing the categories devised for the economy parameter evaluation

4. DOUBLE-ECO MODEL ON AN EXPERIMENTAL CASE

As mentioned before, previous researches have asserted that technological alternatives are necessary during the technology development process [7,9]. Nowadays, there are multiple tools that assist in the development of technology. For example, TRIZ and other innovation tools are being actively used to achieve sustainable ideas. Here, there is extensive literature regarding eco-design which is applicable to many examples and there are efforts to automate environmentally-friendly design [22]. In the case of the Double-ECO framework the application of such innovation tools for the development of an environmentally-friendly technologies framework could be possible when dealing with precise mechanical problems and will be explored in detail in further research. In this research, the experimental case deals with the development of a lubrication technology for machine tools. In this regard, it is known that there are many kinds of lubrication methods for machine tool guideways [23]. Oil pumps that periodically lubricate the machine tools are common [7]. In Table 2, it can be observed that the TRIZ 40 Principles themselves can yield opportunities to develop these kind of technologies. According to Table 2, machine tool lubrication relies on the amount of grease present, the absence of loss of grease, its adaptability to multiple installations and reliability.

Table 2. TRIZ Principles and characteristics to be improved when considering machine tool lubrication [24]

Characteristics to be improved	Principles	Definition
Amount of substance	Local quality	Transition from homogeneous to heterogeneous structure of an object or outside environment (action).
Loss of substance	Replace a mechanical system	Replace fields that are stationary with mobile
Adaptability	Self-service	An object must service itself and carry-out supplementary and repair operations.
Reliability	Extraction	Extract only the necessary part or property from an object.



(a) Photograph of the arrangement (b) Schematic view of the arrangement

Fig. 6. Double-roller arrangement for machine tool lubricant distribution (Outer rollers collect grease accumulated in the edges of the machine tool guideway and the inner rollers assure a uniform lubricant layer thickness)

Table 3. Arrangement specifications (roller specifications obtained using the Taguchi methods)

Transfer Machine		Control factors		Rollers (Best conditions)	Rollers (Worst conditions)
Feed	1000mm/min	Outside roller	Material	Felt	Polyurethane
Guideway length	360 mm		Diameter	φ20 mm	φ25 mm
Guideway width	10 mm		Load	2.5 N	0.0 N
Table weight	6.8 kg	Inside roller	Material	Polyacetal	Felt
Dimensions	360×740×130 mm		Diameter	φ20 mm	φ25 mm
Power	1.2 kW		Load	14.5 N	2.5 N

TRIZ points to the creation of a mechanical arrangement to distribute the grease, this arrangement could be of self-service nature and employ hybrid greases [24]. In Fig. 6, it is possible to observe the schematic of the whole mechanical arrangement and its assembly over a linear motor. In the case of the developed technology, a self-service mechanical system that distributes a hybrid grease was created [5-7]. In this case, the arrangement consisted of two rollers, with variable load using and arrangement of bolts and springs with different stiffness coefficients, that distributes the grease throughout the machine tool sliding parts. As shown in Table 3, the roller material was also considered and multiple combinations were devised to be used in the Taguchi Methods in order to find the best and worst combinations for the mechanical arrangement [6]. Particularly, the utilized hybrid grease was Multinoc (Nippon Oil Corporation) with a Polyisobutylene (PIB) concentration of 3 wt% due to its lubrication properties [5,25]. As shown on Table 4, the best and worst conditions for the roller mechanical arrangement were defined using the Taguchi Methods as done in a previous research [6]. Moreover, the experimentation was stopped upon reaching a lubrication thickness threshold of 5 μm (10 hours for conventional lubrication, 80 hours for rollers with worst conditions, and 1500 hours for rollers with best conditions). In the following Fig. 7, is possible to observe the different lubrication performances. Finally, it is worthwhile mentioning that existing technologies use automation to reduce oil pump usage which in return, along with this research, might have significant implications if sources such as big data are employed simultaneously [26].

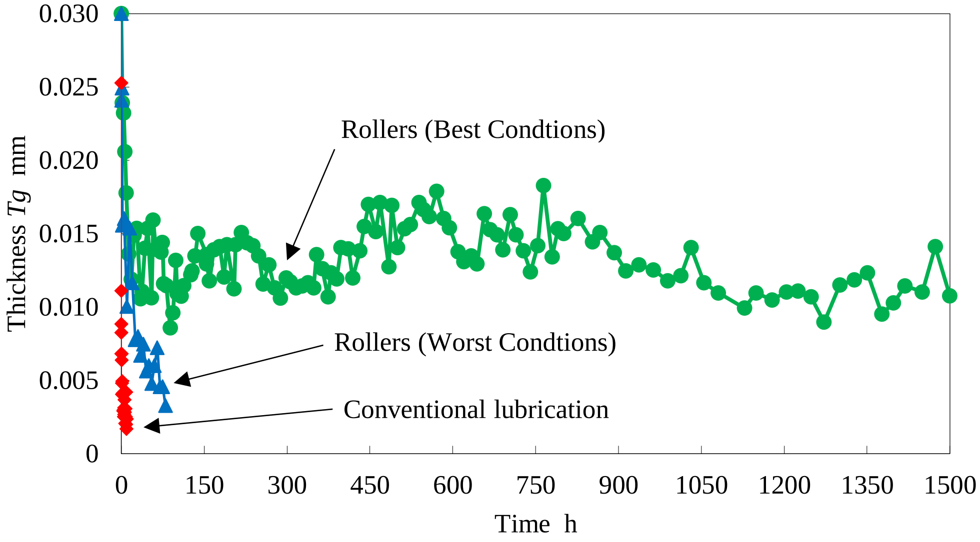


Fig. 7. Lubrication thickness *Tg* throughout time using different lubrication methods

5. EVALUATION PLATFORM ON EXPERIMENTAL CASE

5.1. ENVIRONMENTAL FRIENDLINESS PARAMETER EVALUATION

In this section, instead of weighting, the durability, emissions minimization, waste minimization and recyclability took certain considerations when assigning values. First, a year was defined as a 365-day period with 1 shift of 8 hours per day. In the case of durability, it referred to the times the lubrication needed to be changed per year (Best: 2, Worst: 37, Grease: 292), the emissions employed a Japanese emission coefficient calculation developed by the Ministry of Environment and explored in previous researches (Best: 0.01 g, Worst: 0.27 g, Grease: 1.81 g) [5,7]. In the case of waste minimization, it was calculated as the total amount of grease employed in a year (Best: 0.38 g, Worst: 7.10 g, Grease: 47.30 g). The aforementioned categories were compared to develop a scale (i.e. highest waste amount: 0.1, lowest waste amount: 1). Finally, the recyclability, renewability and end-life bioremediation was set to 0.5 as grease can be re-refined, repurposed or properly disposed [27].

Table 4. Assigned weighted values for each of the ecology categories in the machine tool lubrication case

Double-ECO Category	Units	Roller (Best Conditions)	Rollers (Worst Conditions)	Conventional Lubrication
1. Locality	(km)	1	1	1
2. Renewability	yes/no/partially	0.5	0.5	0.5
3. Durability	(times/year)	1	0.89	0
4. Energy efficiency	yes/no/partially	1	1	1
5. Emissions minimization CO_2	(kg/year)	1	0.87	0
6. Noise / Vibrations	yes/no/partially	1	1	1
7. Waste minimization	TMR (kg/year)	1	0.87	0
8. By-product safety	yes/no/partially	1	1	1
9. Recyclability	yes/no/partially	0.5	0.5	0.5
10. End-life waste bioremediation	yes/no/partially	0.5	0.5	0.5
	Total	8.5	8.13	5.50

5.2. PERFORMANCE PARAMETER EVALUATION

The performance evaluation section required an appropriate set of data to define a MS. In the same way, any technology that is being developed under the Double-ECO model platform must considerate about which variables define the performance of the technology being developed to make a proper selection. Experimentally, only three parameters were employed to describe the machine tool lubrication behavior in a MS. First, the lubrication thickness at the first 2 hours of the initial run Tg_{2h}. Second, the lubrication thickness when reaching the critical 5 μm threshold $T_{5\mu m}$ and the thickness change rate given by the slope of the lubrication graphs. On the other hand, as shown in Table 5, conventional lubrication data sets were the normal data used to create the MS (representative data set shown) and the roller lubrication data sets were the abnormal data. As a result, it was possible to run a confirmation run with abnormal conditions using the largest MD values and create a ranking.

Table 5. Mahalanobis-Taguchi System Input and Output data in terms of MD values for the experimental case

Input data				Confirmation run (Output data)	
Variables	Thickness after 2 h Tg_{2h} µm	Time at 5 µm thickness $T_{5\mu m}$ h	ΔTg µm/h	Technology	Largest MD Values
Conditions used to create the MS				Conventional Lubrication	0.001
Conventional Lubrication	4.95	1	-2.290	Rollers (Worst Conditions)	0.534
Abnormal conditions to validate the MS					
Rollers (Best Conditions)	23.92	1948	-0.013	Rollers (Best Conditions)	19.642
Rollers (Worst Conditions)	15.58	55	-0.334		

5.3. ECONOMY PARAMETER EVALUATION

In the case of the economy parameter evaluation there were a few considerations that were taken to adapt the evaluation procedure to this particular experiment. First, it was assumed that this would be the production cost plus a one-year usage cost calculation (365 days × 1 shift × 8 hours = 2920 hours) and, thus, not taking into account research and development cost nor disposal costs. Moreover, in Japan the environmental taxations come together with utilities cost [28]. Here, the electricity rate was counted to cost the highest rate of 0.15 USD/kWh [29] and the hourly wage of a technician as 23.6 USD [30]. Moreover, assembly was considered to last five hours, monitoring was assumed as 5 minutes per day, and waste disposal of grease was assumed to take 10 minutes. Procurement costs were the total cost of the assembly parts of the arrangement, utilities accounted for every hour in a year using the transfer machine and consumables were calculated using a 97% Multinoc grease and 3% Polyisobutylene mixture. From the total cost in USD it was possible to develop ranking within the technologies that are being compared.

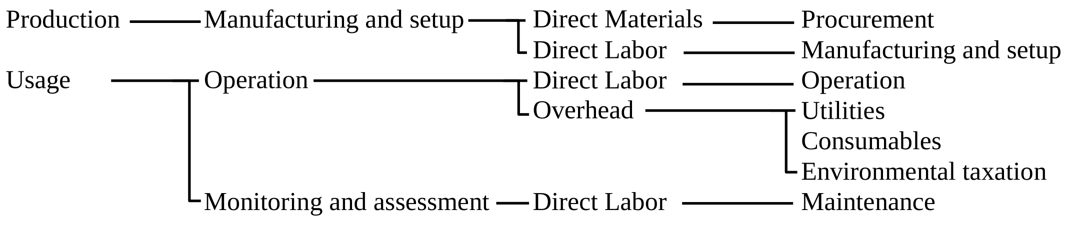


Fig. 8. Economy parameters selected for the machine tool lubrication case

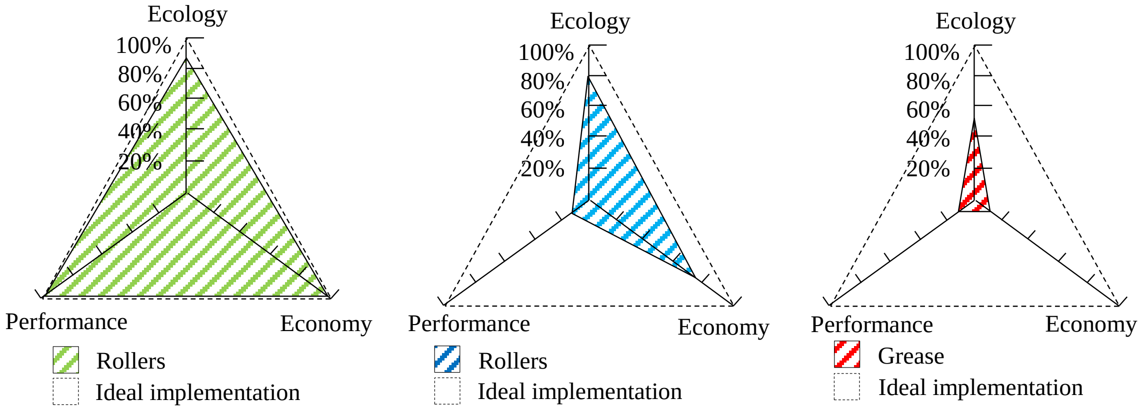
Table 6. Total annual cost for each technology in the experimental case

Cost categories	Rollers (Best Conditions)	Rollers (Worst Conditions)	Conventional Lubrication
Procurement	US$433.90	US$469.91	US$0
Manufacturing and setup	US$118.00	US$118.00	US$0
Operation	US$7.66	US$143.57	US$1148.53

Utilities	US$1621.81	US$1621.81	US$1621.81
Consumables	US$0.003	US$0.060	US$0.403
Maintenance	US$472.00	US$472.00	US$472.00
Total Cost	US$2653.37	US$2825.35	US$3242.74

6. COMPARISON OF DOUBLE-ECO TECHNOLOGIES EFFICIENCIES

The DE Index is a comparison between the ideal implementation of a technology or 100% of efficiency in all the three parameters considered and the real implementation of a determined technology. As observed in Fig. 9, it is clear that under the DE Index general evaluation the developed lubrication arrangement with the best conditions is the one with the best performance in the portfolio. Moreover, particular data of each of the sides of the colored areas is shown in Table 10. Here is possible to confirm that when comparing technologies, the conventional reaches about 4% of the DE Index as opposed to the 90% from the rollers.



(a) Best conditions (b) Worst conditions (c) Conventional lubrication

Fig. 9. Results of the Double-ECO evaluation for each technology in the experimental case

Table 7. DE Index of eco-efficiency for each technology in the machine tool lubrication case

	Double-ECO Parameters				
Technology	Performance (%)	Economy (%)	Ecology (%)	Calculated area (u^2)	DE Index (%)
DE Ideal implementation	100	100	100	14895.66	100
Conventional Lubrication	10	10	55	595.83	4.0
Rollers (Best Conditions)	100	100	85	13406.09	90.0
Rollers (Worst Conditions)	12.4	74	81	3932.51	26.4

7. CONCLUSIONS

1. The evaluation platform was able to effectively compare technologies under a Double-ECO Model eco-efficiency parameter known as "DE Index" (said parameter compiled multiple performance, ecology and cost evaluation tools). Thus, it was considered as an effective eco-efficiency platform to evaluate a group of technologies using their own characteristics, and a first step towards automation to avoid current arbitrary methods.
2. The developed lubrication technology had considerable improvements in: environmental pollution output, mechanical performance and cost parameters when compared with conventional methods (90% DE Index opposed to a 4%).

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