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Probabilistic Life Cycle Assessment of the Nano Membrane Toilet

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***Abstract*—**Developing countries are nowadays confronted with great challenges related to domestic sanitation services in view of the imminent water scarcity. Contemporary sanitation technologies established in these countries are likely to pose health risks unless waste management standards are followed properly. This paper provides a solution to sustainable sanitation with the development of an innovative toilet system, called Nano Membrane Toilet (NMT), which has been developed by Cranfield University and sponsored by the Bill & Melinda Gates Foundation. The particular technology converts human faeces into energy through gasification and provides treated wastewater from urine through membrane filtration. In order to evaluate the environmental profile of the NMT system, a deterministic life cycle assessment (LCA) has been conducted in SimaPro software employing the Ecoinvent v3.3 database. The particular study has determined the most contributory factors to the environmental footprint of the NMT system. However, as sensitivity analysis has identified certain critical operating parameters for the robustness of the LCA results, adopting a stochastic approach to the Life Cycle Inventory (LCI) will comprehensively capture the input data uncertainty and enhance the credibility of the LCA outcome. For that purpose, Monte Carlo simulations, in combination with an artificial neural network (ANN) model, have been conducted for the input parameters of raw material, produced electricity, NO_X emissions, amount of ash and transportation of fertilizer. The given analysis has provided the distribution and the confidence intervals of the selected impact categories and, in turn, more credible conclusions are drawn on the respective LCIA (Life Cycle Impact Assessment) profile of NMT system. Last but not least, the specific study will also yield essential insights into the methodological framework that can be adopted in the environmental impact assessment of other complex engineering systems subject to a high level of input data uncertainty.

***Keywords*—**Sanitation systems, nano membrane toilet, LCA, stochastic uncertainty analysis, Monte Carlo Simulations, artificial neural network.

I. Introduction

THE provision of sustainable sanitation has become nowadays a matter of increasing concern in view of the imminent water scarcity. By 2025, it is expected that two thirds of world population will experience water stress conditions [1]. The effect of such global trend seems to be adversely experienced in the developing countries which face already a limited access to clean potable water. Taking into consideration the inextricable relationship between water and sanitation, the toilet systems established in these countries have been designed in such a way to employ little to no water. However, though they facilitate people's daily needs, there are cases reported where improper use of those systems can lead to water contamination and, in turn, disease spread [2], [3]. Upon these facts, it seems imperative to orient the efforts towards the development of more sustainable sanitation technologies that will be less dependent on natural resources without compromising the basic hygiene standards.

A novel technology contributing towards that direction has been developed by Cranfield University in the framework of the Bill & Melinda Gates Foundation's ''Reinvent the Toilet Challenge''. The NMT system is established on the combustion of the human faeces with simultaneous energy recovery from the generated flue gas and the purification of the urine through a nanostructured membrane into treated wastewater [4]-[7]. As the given sanitation system is still under development, proceeding with an ex-ante LCA will yield important insights into to the areas that could be potentially improved and, thus, enhance its environmental performance.

The majority of the reported literature on the LCA studies carried out on different sanitation technologies follows a deterministic approach to the estimation of the environmental impacts [8]-[11]. To exemplify, Flores et al. [12] have evaluated the waterborne and waterless sanitation systems from a sustainability viewpoint- technological, economic, social and environmental criteria- in the context of a specific urban settlement in China. The environmental assessment has shown a better performance of the waterless system than that of the waterborne one for the indicators of eutrophication and water consumption by 71% and 88%, respectively. Moreover, enhanced performance of the former system has been demonstrated for the organic and nutrient recovery indicator over the latter one which showed no such potential. In addition to this study, another deterministic LCA has been presented by the sanitary ware company Kohler [13] on the manufacture of a toilet bowl with service life of 20 years. Results have exhibited, indicatively, a GWP and ODP value of 144 kg CO_2-Eq and 3.01E-05 kg CFC-11 Eq, respectively.

Although deterministic LCA studies provide important views into the factors influencing the environmental profile of the examined sanitation technologies, the impact of data uncertainty on the generated LCA profile seems not to have been fully reflected. There are only a few studies, incorporating a data uncertainty analysis into their LCA studies, mainly by employing Monte Carlo simulations and illustrating it either with the form of error bars on the LCA

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graphs or in tabular format [14], [15]. The present research study aims at providing a probabilistic analysis of the environmental profile of the novel sanitation system, the NMT, with the aid of Monte Carlo simulations coupled with an ANN.

II. Methodology

A. LCA Model

The LCA model of the NMT has been developed in SimaPro software employing the Ecoinvent. v3.3 dataset and the functional unit has been set to ''the provision of a sanitation service for the daily defecation of a 10-occupant household in South Africa'' [16]. The system has been evaluated against the ReCiPe impact assessment method adopting a hierarchist approach for the endpoint categories of Human Health, Ecosystems and Resources.

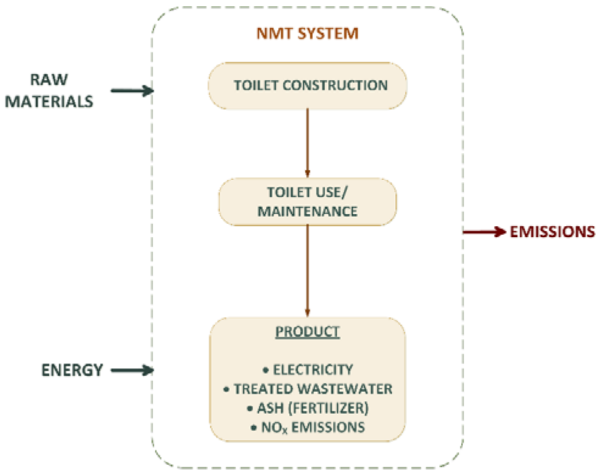

Fig. 1 System boundaries of Nano-membrane Toilet system

The system boundaries of the NMT system (Fig. 1) have been defined as such to include all energy and raw material extraction activities which are involved in the processes, starting from the construction of the toilet system up to the transportation of the valuable products to the selected location. Prior to proceeding with the specific unit processes included in the system boundaries of the NMT system, it is important to provide a brief overview of its operating principle.

The NMT system constitutes a waterless sanitation technology which has been developed at Cranfield University. Its operation is established upon the sedimentation of faeces from human excreta [4]. The separated faeces are directed through a screw conveyor to a combustor where they are converted to ash and flue gas. The latter product is used to dry the faeces prior to the combustion and preheat the urine which is filtered through a nanostructured membrane to a treated wastewater. Moreover, part of the waste heat from the flue gas is able to be recovered in a sterling engine for electricity generation [4].

Considering that the development of the NMT system is still in progress, certain assumptions have been implemented in the context of this LCA study. To elaborate, with respect to the manufacture phase of the NMT, plastic has been used as raw material for the toilet seat and cistern which undergo the industrial process of ''injection molding''. Ceramic has been considered for the toilet bowl, process which has been simulated with the in-built unit of "sanitary ceramics''. The material input has been adopted from literature [17] with the assumption of using 20% more material so as to offset the extra space required for the membrane, combustor and screw. In terms of the combustor and the screw, steel has been employed as raw material, whereas the membrane has been assumed to be produced by glass fibre. Moreover, the toilet system has been assumed to be located at 920 km away from the sanitary ware factory. Transportation for the given distance has also been included considering freight transport by lorry. The material input of this life cycle stage has been normalized against the lifetime of the NMT system, 7 years, so as to reflect the respective environmental impact on the basis of daily use of the particular sanitation system.

As far as the use phase is concerned, human faeces and urine, at the respective amount of 2 kg and 14.2 kg, are treated by the NMT system for the final production of ash, NOx gases, electricity and treated wastewater, for which data have been extracted from process simulations conducted for the given sanitation system. The maintenance of the toilet system involves the replacement of the membrane every two months which has been incorporated in the LCA model by the amount of glass fibre required for its production and corresponding to the daily use of the NMT system. Besides that, environmental credits have been also allocated in this LCA study to the generated products, except for the NOx gases, by applying the concept of ''avoided burden'' [18]. More precisely, the ash has been considered as a potential fertilizer substitute with its phosphorus (P) and potassium (K) content being estimated as 13.7% and 15.1% of its total amount [7]. In addition to that, transportation of ash to a local field at an approximate distance of 34 km has been taken into account. Fertilizer substitution of commercial synthetic fertilizers has been implemented in this LCA study based on the amount of the mineralized P and K, which has been estimated as 95% and 100%, respectively, of the initial nutrient content [19]. The treated wastewater has been assumed to replace tap water for small-scale irrigation purposes at a distance close to the location of the toilet system, so that its transportation can be practically neglected and excluded from the system boundaries. In terms of the environmental credits assigned to the system for the production of electricity, the unit process of generating medium voltage electricity has been employed. The detailed inventory and material/energy input data used in the LCA simulations are provided in Tables I and II, respectively.

B. Probabilistic Analysis

1) Stochastic Variables

The stochastic variables required for the probabilistic analysis, which has been realized though Monte Carlo simulations, have been chosen based on the deterministic LCA results which will be presented in Section III. More precisely, the impact of certain material and energy flows involved in the system boundaries of the NMT system on the values of the impact categories has been assessed and based on the magnitude of their contribution the selection of the most critical process parameters has been made.

TABLE I
INVENTORY DATA OF LCA MODEL

Polystyrene, general purpose {RoW}| production | Alloc Def, S
Sanitary ceramics {RoW}| production | Alloc Def, S
Steel, low-alloyed {RoW}| steel production, converter, low-alloyed | Alloc Def, S
Injection moulding {RoW}| processing | Alloc Def, S
Glass fibre reinforced plastic, polyamide, injection moulded {RoW}| production | Alloc Def, S
Tap water {RoW}| tap water production, conventional treatment | Alloc Def, S
Electricity, medium voltage {RoW}| market for | Alloc Def, S
Nitrogen oxides; low. pop., long-term
Phosphate fertiliser, as P {GLO}| market for | Alloc Def, S
Potassium fertiliser, as K {GLO}| market for | Alloc Def, S

TABLE II
MATERIAL AND ENERGY INPUT DATA FOR THE LCA MODEL (EXPRESSED PER FUNCTIONAL UNIT) [16]

Material/Energy Input	Amount	Unit
Toilet Construction		
Polystyrene - toilet seat	9.39E-04[1]	kg
Polystyrene - cistern	1.64E-03[1]	kg
Glass fibre -membrane	1.45E-05[2]	kg
Alloy steel-combustor	3.32E-04[2]	kg
Alloy steel – screw	4.20E-04[2]	kg
Injection molding	3.33E-03	kg
Sanitary ceramics - toilet bowl	8.45E-03[1]	kg
Transportation	1.11E-02	t-km
Toilet Use/Maintenance		
Faeces	2.00E+00[3]	kg
Urine	1.42E+01[4]	kg
Glass fibre	6.17E-04	kg
Ash	8.00E-02[3]	kg
P	1.10E-02[5]	kg
K	1.21E-02[5]	kg
NOx-emissions	1.10E-02[3]	kg
Product		
Transportation	2.72E-03	t-km
P-Fertilizer	1.04E-02	kg
K-Fertilizer	1.21E-02	kg
Electricity	4.62E-02[3]	kWh
Treated wastewater	9.56E+00[3]	kg

[1][17]; [2]NMT Project estimations; [3][4]; [4][20] for a urine density of 1.002 g/cm^3; [5][7].

In the context of this LCA study, the raw material required in the manufacture phase, the generated electricity, the amount of the potential fertilizer produced as a function of the mass of ash and the NO_X emissions have been identified as important factors affecting the performance of the NMT. Furthermore, although the transportation of the fertilizer in terms of distance has not shown a considerable effect on the LCA results, it has been selected as a stochastic variable due to the arbitrary choice of its value. The specific parameters have been stochastically modeled with a normal distribution and a standard deviation of 10% for the first two aforementioned variables and 5% for the remained ones.

2) Probabilistic Model

In order to determine a mathematical relationship between the input variables- material and energy input- of the LCA model and the impact categories of human health, ecosystems and resources, an ANN technique has been employed. As far as the operation of the ANN is concerned, an artificial neuron (AN) can be considered as a node whose main role is to dispatch and receive signals to and from the environment or other neurons [21]. In the case of a signal received by an external source, its transmission by the neuron to all other connected nodes is taking place.

The connections between ANs are characterized and defined by a critical parameter termed as weight, which establishes the dynamic relationship between inputs and outputs (Fig. 2). The strength of a signal being sent or received depends on a function that controls the operation, the activation function. Each neuron gathers all received signals and creates a net input signal which is a function of the respective weights. A typical ANN comprises an input layer, a hidden layer and an output layer. Input layer consists of datasets that are subject to training at the hidden layer. Upon completion of the training process whose performance depends on the minimization of the mean squared error, the output layer provides the approximation results [22].

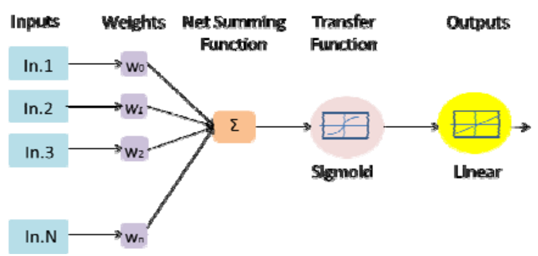

Fig. 2 The architecture of a typical ANN

In this case study, function fitting has been performed by the use of the Neural Fitting App embedded in the MATLAB software. A feed-forward ANN with 100 neurons in the hidden layer has been employed and network training has been implemented based on the Bayesian regularization algorithm. Among training data, 50%, 25% and 25% of them have been used for training, validation and testing purposes, respectively. The generated outputs of the ANN model have been incorporated as input in the Monte Carlo simulations which have been conducted for 1,000,000 iterations in MATLAB software.

III. RESULTS

In this section the LCA results based on a deterministic approach will be first discussed so as to justify the selection of the stochastic variables. The probabilistic results will then be presented in the form of probability density function (PDF) plots.

A. Deterministic LCA Results

In Fig. 3 the normalized profile of the resources, ecosystems and human health impact categories for the NMT system is depicted with respect to the individual contribution of the major processes involved in the given system. More precisely, as it can be deduced from the graph the resources impact category is mainly dominated by the cumulative impact of the raw materials and manufacture phases accounting for 35%. The second most contributory factor is the credits linked to the electricity generation and P fertilizer whose both share is 23%.

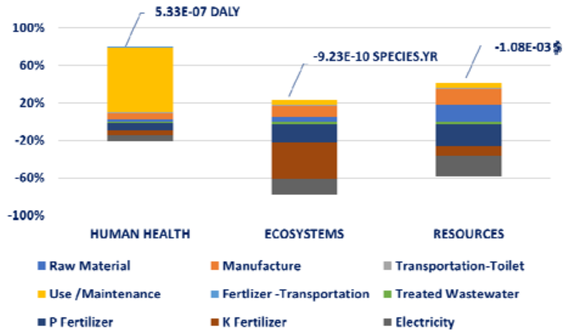

Fig. 3 Normalized (percentage) profile of life cycle impact categories of the NMT system

The ecosystems profile demonstrates a different impact distribution than that of the aforementioned category. The fertilizer production and generated electricity dictate the profile by 75%. On the other hand, the human health impact category is highly controlled by the use/maintenance phase with a share of 69%. This is primarily attributed to the NOx gases as it is the only material output from the particular life cycle stage.

B. Probabilistic LCA Results

According to the probability plot, shown in Fig. 4, the mean value of the human health impact category is 5.50E-7 DALY with a standard deviation of 18%. As compared to the deterministic LCA results, the mean value demonstrates a difference of 3% which indicates the good predictability of the model for the given impact category. Moreover, there is a high likelihood (95% confidence) that the NMT system will exhibit a value of the human health category in the range of 3.55E-07 and 7.45E-07 DALY per functional unit.

In terms of the ecosystems impact category, which is illustrated in Fig. 5, the deviation of the mean value, -0.92E-9 species.yr, from that estimated by the deterministic LCA model is 1%. Considering that the standard deviation of the probability distribution is 19%, it seems that there is a good agreement between the two types of LCA analyses. Within a confidence interval of 95%, the ecosystems category is predicted to be in the range of -1.27E-09 and -0.56E-09 species.yr.

The mean value of the PDF of the resources impact category, shown in Fig. 6, is -0.925E-3 $ with a standard deviation of 65%. The difference of the mean value of the PDF and the respective deterministic value is 15%, which demonstrates in this case a less efficient predictive performance as compared to the other two impact categories. The high standard deviation indicates that the input data uncertainty of the examined variables influences greatly the value of the specific impact category. This can be clearly demonstrated by the probability distribution, which for a confidence interval of 95% it gives the likelihood of the value of the resources impact category to be within a wider interval, with a lower limit of -2.12E-03$ and an upper limit of 0.28E-3$.

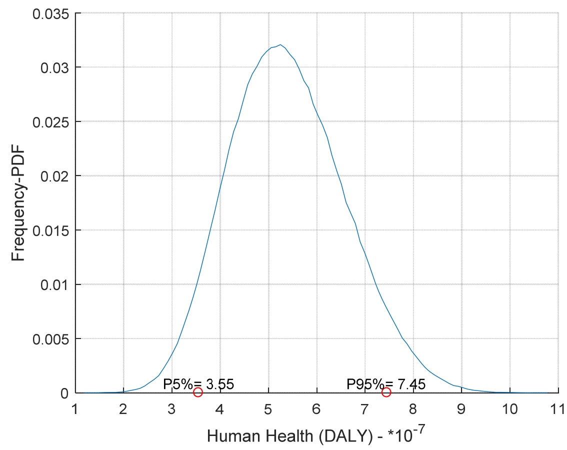

Fig. 4 PDF of the human health impact category

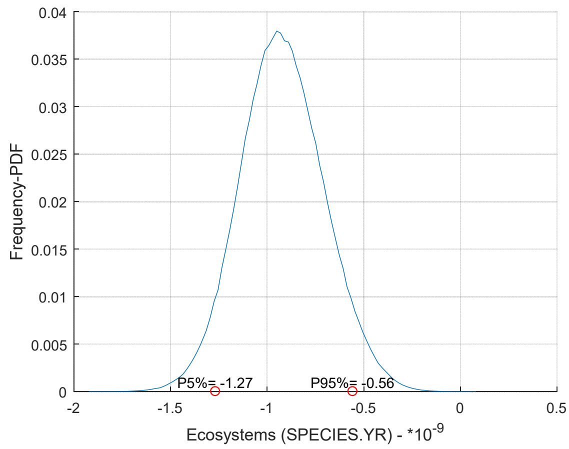

Fig. 5 PDF of the ecosystem impact category

IV. Conclusions

A probabilistic LCA study has been conducted for the NMT considering the data uncertainty of specific input energy and material flows. More precisely, the impact of uncertainty related to the input values of the raw material, the generated electricity, the amount of produced ash, the NOx emissions and the distance involved in the fertilizer transportation, on the three selected impact categories - human health, ecosystems and resources- has been evaluated with the aid of Monte Carlo simulations based on an ANN model.

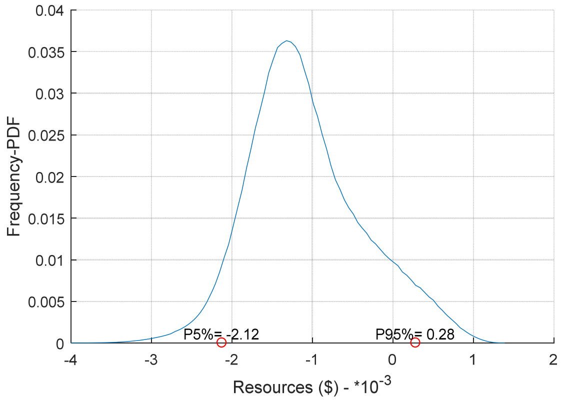

Fig. 6 PDF of the resources impact category

Probabilistic analysis has exhibited a good predictability of the of the NMT performance against the human health and the ecosystem impact categories. This is clearly observed by the low deviation of the mean values of their respective PDF from the deterministic ones, which accounts for 3% and 1%, correspondingly. However, a lower predictability is illustrated in the case of the resources impact category, as a deviation of 15% is observed between the mean value of its probabilistic distribution and the deterministic value. In terms of the effect of the uncertainty of the stochastic variables on the three impact categories, the resources impact category seems to be affected more than the remained two categories. This is manifested by the standard deviation of the probability distribution which for the resources impact category is 65%. Based on the aforementioned results, probabilistic analysis has provided important insights into the way input parameters affect the LCA profile of the NMT system and, in turn, the importance of optimizing them for an enhanced environmental performance.

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