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Exploring product lifecycle using Markov chain

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Abstract

This paper applies the Markov chain to model a product's lifecycle. Given the initial condition, the model is used to predict important information about the behavior of the product throughout its lifecycle. The predictions include the number of visits made by the product to a lifecycle stage, expected quantity of products that visit a lifecycle stage, product's mean duration of stay in a lifecycle stage, probability and the expected quantity of products being discarded, and the average total environmental impact caused by the products. The model is validated by applying it to analyze the lifecycle of plastic produced in 2015.

Keywords: Model; lifecycle; Markov chain

1. Introduction

Lifecycle assessment (LCA) is an analytical tool used to assess the environmental impact and resources used over the lifecycle of a product or service [1,2]. Models, software, databases, and tools have been developed to support the modeling, inventory analysis, and the interpretation of the LCA results [2,3]. Currently, three approaches in LCA can be used to assess the environmental impact of a product, process-based LCA, Economic Input-Output (EIO) LCA, and the combination of the two called hybrid LCA.

In an LCA analysis, there are two types of information that are often a concern. They are hotspots and trip numbers [4]. A hotspot is a lifecycle stage or an activity that has the highest contribution to the overall environmental impact of the product. A trip number is a number stating how many times a product visits a particular lifecycle stage before ends at its grave. If the number of trips is known, the average quantity of products that visit a specific lifecycle stage and how long the products stay there can be determined. The information is beneficial for the promotion of reuse, recycling, and remanufacture. Other information that may also be very useful is, among all products that are produced or used today, how many of them will be reused, recycled, or disposed of in nature in the future. A well-established concept in probability theory called the Markov chain is seen to have the ability to model and predict the aforementioned information.

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The objectives of this paper are to model the lifecycle of a product using the Markov chain and manipulate the chain to predict the behavior of the product throughout its lifecycle. The model is expected to have the ability to predict the number of visits made by a product to a lifecycle stage, the expected quantity of products that visit a lifecycle stage, the mean duration of stay of a product in a lifecycle stage, the probability and expected quantity of products being absorbed (discarded or incinerated), and the average total environmental impact caused by the product. Note that the model presented in this paper is only applicable for products having monolithic product structure (no components and modules), such as clothing, paper, plastic, plastic bag, drinking cup (ceramic, glass, polystyrene, paper, foam), and steel. To show the applicability of the model, a simplified flow of plastic at the global level is taken as a case study.

2. Markov chain

If the occurrence of a state in the future only depends on the immediate preceding state, it is called a Markov chain [5,6,7]. Following Feldman and Valdez [5], a set of random variables $X = \{X_n;\ n = 0, 1, \ldots\}$ with a set of state space $S = \{x_0, x_1, \ldots, x_n, x_{n+1}\}$ is a Markov chain if the following holds,

$$\Pr\{X_{n+1}=x_{n+1}\mid X_0=x_0, X_1=x_1, \cdots, X_n=x_n\}=\Pr\{X_{n+1}=x_{n+1}\mid X_n=x_n\} \tag{1}$$

If a Markov chain has a stationary transition probability, the following must be satisfied,

$$\Pr\{X_1=x_1\mid X_0=x_0\}=\Pr\{X_{n+1}=x_{n+1}\mid X_n=x_n\}$$

From Eq. (1), the probability of moving from x_n to x_{n+1} only depends on x_n. In a stationary Markov chain, the one-step transition probability does not alter as time progresses. By definition, the one-step transition probability must hold the followings,

$$p_{ij} \geq 0$$

$$\sum_j p_{ij} = 1$$

The one-step probabilities are conveniently presented as a one-step transition matrix **P**,

$$\mathbf{P}=\begin{pmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ p_{n1} & p_{n2} & \cdots & p_{nn} \end{pmatrix}$$

There is limited research in the literature applying the Markov chain to material flow analysis and lifecycle assessment. Paras and Pal [4] presented a model quantifying the number of trips that a clothing product made to the use stage over its lifetime. The developed model was based on the well-established Markov chain and probability models. Eckelman et al. [8] applied the Markov chain concept to explore visits made by nickel to each stage of its lifecycle. The authors showed that the Markov chain is a useful tool in analyzing the flow of materials over its lifecycle. Yamada et al. [9] developed a Markov chain based methodology that can estimate the mean number of times of a material being used over its lifecycle. In Matsuno et al. [10], the model developed by Yamada et al. [9] was then applied to a real-life case study. The authors estimated how many times steel is used in Japan. Combining these results with steel production environmental impact, the authors calculated the amount of CO_2 generated by the one-time use of steel.

Based on the literature, it can be concluded that previous studies only focused on the use phase when applying the Markov chain in lifecycle analysis. They used the model to predict the number of visits made by a product to the use phase. In this paper, the application of the Markov chain model is expanded so that other relevant information can be predicted and explored. Besides the number of visits made by the product to the use stage, the model developed in this paper can predict the average quantity of products that visit a specific life cycle stage, how long the product stays in the specified lifecycle stage, the estimated quantity of products that will be reused, recycled, or disposed of in nature, and the expected total environmental impact of the product over its lifecycle. Furthermore, from the methodological point of view, this study models the lifecycle of a product using absorbing Markov chain analysis technique while the previous studies used a non-absorbing chain analysis technique.

3. Method

The lifecycle of a product can be modeled as a Markov chain because the occurrence of a future lifecycle stage only depends on the immediately preceding lifecycle stage. For example, the occurrence of an end-of-life stage (recycling, disposal, or incineration) only depends on the use stage, and the occurrence of the use stage depends on the production or recycling stage (use of the recycled products). Predictions made using the Markov chain are accurate when the flow of the products is stable. Therefore, in modeling the lifecycle of products as a Markov chain, this paper assumes that the flow of the products is constant over a long period of time.

In a Markov chain, processes that terminate after some period are modeled as absorbing states. If the flow of products throughout their lifetime is seen as a random process, several lifecycle phases can be categorized as absorbing states, such as disposal and incineration, because after entering the states the products stay there forever. Other lifecycle phases, such as production, use, and recycling, can be modeled as transient states because after leaving the phases the products never come back to those phases. For example, after plastic bags are being used, they are recycled and come back to the use phase, but once they are incinerated, they never come back to the use phase.

To model the lifecycle as a Markov chain, let's denote the lifecycle phases as a set of state space $S = \{1, 2, \dots, m, m+1, \dots, m+n\}$, where m and n are the number of transient and absorbing states, respectively. Fig.1, called a transition diagram, is an example of a product's flow over its lifecycle. In the figure $S = \{1, 2, 3, .., 10\}$. States 8 and 10 are absorbing, states 1, 2, 3, 4, 5, 6, 7 and 9 are transient. In other words, $m = 8$ and $n = 2$. In the modeling process, the size of S depends on how detailed the information to be obtained.

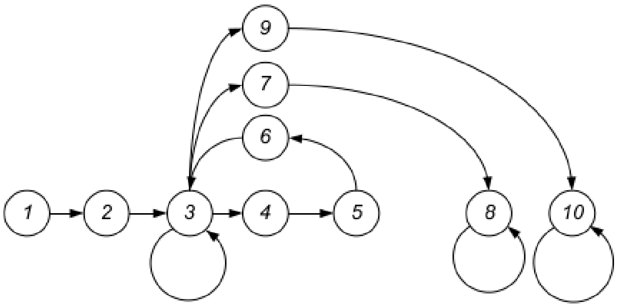

Fig. 1 An example of a transition diagram representing the lifecycle of a product.
1 = production, 2 = transportation from production to use, 3 = use, 4= transportation from use to recycling, 5 = recycling, 6 = transportation from recycling to use, 7 = transportation from use to discard, 8 = discard, 9 = transportation from use to incineration, 10 = incineration

The next step is to form a transition matrix **P**, Eq. (2), where all absorbing states are located in the southeast corner of **P** [6,7]. The element of the matrix p_{ij} indicates the probability of moving from state i to state j. If one defines 1 as the products are in the production phase and 2 as the products are in the transportation phase (transportation from production to use), p_{12} means the probability of products moving from the production phase to the transportation phase (transportation from production to use).

Based on Feldman and Valdez [5], Ravindran [6], and Taha [7], by manipulating **Q** and **R**, several useful estimations can be made. The first estimation is the expected amount of time spent by the products in state j starting in state i, represented by l_{ij} and given by Eq. (3). $\mathbf{I}$ is an identity matrix, and d_j is the mean amount of time spent by the products in state j.

$$\mathbf{P}=\begin{pmatrix} p_{11} & p_{12} & \cdots & | & p_{1m+1} & \cdots & \cdots & p_{1m+n} \\ p_{21} & p_{22} & \cdots & | & p_{2m+1} & \cdots & \cdots & p_{2m+n} \\ \cdots & \cdots & \cdots & | & \cdots & \cdots & \cdots & \cdots \\ p_{m1} & \cdots & p_{mm} & | & p_{mm+1} & \cdots & \cdots & p_{mm+n} \\ - & - & - & | & - & - & - & - \\ 0 & \cdots & 0 & | & 1 & 0 & \cdots & 0 \\ 0 & \cdots & 0 & | & 0 & 1 & \cdots & 0 \\ \vdots & \cdots & \vdots & | & \vdots & \cdots & \ddots & 0 \\ 0 & \cdots & 0 & | & 0 & 0 & \cdots & 1 \end{pmatrix}=\begin{pmatrix} \mathbf{Q} & | & \mathbf{R} \\ - & | & - \\ \mathbf{0} & | & \mathbf{I} \end{pmatrix} \tag{2}$$

$$l_{ij}=\text{element }(i,j)\text{ of }(\mathbf{I}-\mathbf{Q})^{-1}\times d_j \tag{3}$$

The absorption probabilities can also be calculated. From the lifecycle perspective, absorption probabilities can be interpreted as the probability of products being discarded or incinerated given their current states, such as in the production, use, or recycling phase. The absorption probabilities matrix $\mathbf{A}$ is calculated using Eq. (4). If the initial condition is known, such as the number of products currently being produced or used, the number of products being absorbed (discarded or incinerated) and the mean amount of products visiting a particular state can be estimated. These estimates are calculated using Eqs. (5) and (6). In the equations, $\mathbf{U}$, $\mathbf{W}$, and $\mathbf{p}^{(0)}$ are row vectors denoting the average amount of products being absorbed, the expected amount of products that visits a particular state, and the initial condition, respectively.

$$\mathbf{A}=(\mathbf{I}-\mathbf{Q})^{-1}\mathbf{R} \tag{4}$$

$$\mathbf{U}=\mathbf{p}^{(0)}\mathbf{A} \tag{5}$$

$$\mathbf{W}=\mathbf{p}^{(0)}(\mathbf{I}-\mathbf{Q})^{-1} \tag{6}$$

Now let **Et** and **Ea** be column vectors denoting environmental impact per unit when the products are in the transient and absorbing states, respectively. Then, the expected total ecological impact of products throughout their lifecycle, denoted as v, is,

$$v=\mathbf{W}\mathbf{E}_t+\mathbf{U}\mathbf{E}_a=\mathbf{p}^{(0)}(\mathbf{I}-\mathbf{Q})^{-1}(\mathbf{E}_t+\mathbf{R}\mathbf{E}_a) \tag{7}$$

4. Case study

In this case study, the flow of plastic is analyzed by modeling it as a Markov chain. It is a simplified case study and due to the lack of data, the transportation and logistics operations behind the transition are not considered. According to Geyer et al. [11], at the global level, from 1950 to 2015, 8300 million metric tons (Mt) plastic had been produced, 2600 Mt was in used (both primary and secondary), 600 Mt was recycled, 4900 Mt was discarded, and 800 Mt was incinerated. Now let's define that 1 = production, 2 = use, 3 = recycling, 4 = discard, and 5 = incineration. Therefore the state space is $S = \{1, 2, 3, 4, 5\}$.

Here there are three transient states $\{1, 2, 3\}$ and two absorbing states $\{4, 5\}$. Based on the data provided by Geyer et al. [11], the transition matrix $\mathbf{P}$ is formed. The matrix $\mathbf{P}$ can also be modeled as a diagram called a transition diagram, presented in Fig. 2.

$$\mathbf{P} = \left(\begin{array}{ccc|cc} 0 & 1 & 0 & 0 & 0 \\ 0 & 0.29 & 0.07 & 0.55 & 0.09 \\ 0 & 1 & 0 & 0 & 0 \\ - & - & - & - & - \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{array}\right)$$

In 2015 there was 407 Mt plastic produced [11] meaning that for the year of 2015, $\mathbf{p}^{(0)} = (407, 0, 0)$. The initial quantities for the use and recycling stages are zeros because the focus is to see what will happen to the 407 Mt plastic only.

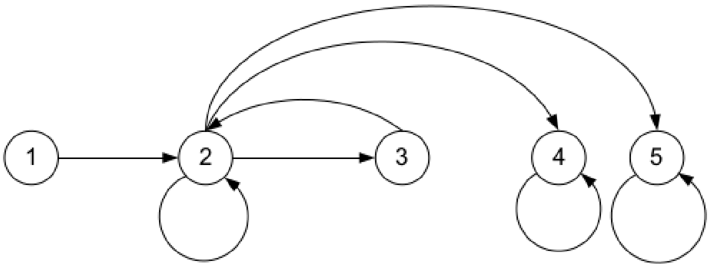

Fig. 2. A transition diagram representing a simplified lifecycle of plastic

Now let's manipulate the chain to obtain relevant information. It starts with calculating $(\mathbf{I} - \mathbf{Q})^{-1}$,

$$(\mathbf{I} - \mathbf{Q})^{-1} = \begin{pmatrix} 1 & 1.56 & 0.11 \\ 0 & 1.56 & 0.11 \\ 0 & 1.56 & 1.11 \end{pmatrix}$$

The first row of $(\mathbf{I} - \mathbf{Q})^{-1}$ indicates the expected number of visits made by the plastic starting at the production stage. On average, the production stage is visited once, use stage is visited 1.56 times, and the recycling stage is visited 0.11 times. The number of visits at the use stage is more than one because the plastic is recycled and reused. The second row indicates that, if the plastic is at the use stage now, then it will visit the recycling stage 0.11 times. In the third row, if the plastic is currently at the recycling stage, it will be reused 1.56 times. The reused plastic will be recycled again, which will make its average number of visits to the recycling stage 1.11 times.

By utilizing Eq. (5), from 407 Mt plastic produced in 2015, the quantity of the plastics that visit the production, use, and recycling stages is estimated. By using Eq. (6), from the 407 Mt plastic produced in 2015, a prediction on the quantity of plastic which will be discarded and incinerated is made. The results are presented in Table 1.

Table 1. The average quantity of plastic visiting each lifecycle stage, given the initial condition of 407 Mt plastic produced in 2015.

Lifecycle stage	Average quantity (Mt)
Production	407.00
Use	635.49
Recycling	42.84
Discard	349.88
Incineration	57.12

By using Eq. (3) together with the information in Table 2, the average duration of stay of plastic from each market sector at the use phase can be obtained. The duration of the stay of plastic from the packaging market sector at the use stage is 0.5 × element (1,2) of $(\mathbf{I} - \mathbf{Q})^{-1}$= 0.78 years. Table 3 gives the complete results. Utilizing the above results together with the 2015 percentages of the primary production, the overall average duration of stay of plastic at the use stage is 35.87% × 0.78 + 6.63% × 20.30 + … + 11.55% × 7.81 = 13.65 years.

Table 2. Market sectors using plastic and their mean usage periods in 2015 [11].

Market sector	2015 primary production (%)	Mean lifetime (years)
Packaging	35.87	0.5
Transportation	6.63	13
Building and Construction	15.97	35
Electrical/ Electronic	4.42	8
Consumer & Institutional Products	10.32	3
Industrial Machinery	0.74	20
Textiles	14.50	5
Other	11.55	5

Table 3. Plastic's average duration of stay at the use stage according to the market sector.

Market sector	Average duration of stay at the use stage (years)
Packaging	0.78
Transportation	20.30
Building and Construction	54.65
Electrical/ Electronic	12.49
Consumer & Institutional Products	4.68
Industrial Machinery	31.23
Textiles	7.81
Other	7.81

Energy consumption over the lifecycle of polyethylene (PET) is analyzed to show the application of Eq. (7). The total quantity of PET produced in 2015 was 33E+03 kg [11]. The production of PET requires 3 MJ/kg of energy [12], PET recycling needs energy that equals to 7.97 MJ/kg [13], and the combustion of PET recovers 27 MJ/kg energy [13]. Assuming that the use and disposal of PET do not consume or recover energy, then the average total energy consumption for the production, use, and end-of-life of PET in 2015 was,

$$v(\text{production, use, discard, incineration}) = (33\text{E}{+}03, 0, 0)\begin{pmatrix} 1 & 1.56 & 0.11 \\ 0 & 1.56 & 0.11 \\ 0 & 1.56 & 1.11 \end{pmatrix}\left(\begin{pmatrix} 3 \\ 0 \\ 7.97 \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ 0.55 & 0.09 \\ 0 & 0 \end{pmatrix}\begin{pmatrix} 0 \\ -27 \end{pmatrix}\right) = 1632.63\ \text{MJ}$$

It means that on average, during the production, use, and end-of-life stages of PET, the energy consumption level of PET in 2015 was about 0.05 MJ/kg.

5. Discussion

The Markov chain model is similar to the EIO LCA in terms of their construction and assumptions [8]. They both use a matrix-based operation. The difference is, EIO LCA has economic sectors while a Markov chain has a state space. However, in analyzing product behavior over its lifecycle, using the Markov chain model has several potential advantages.

Besides having the ability to estimate the expected total environmental impact of products, a Markov chain model can estimate the number of visits made by the products to a lifecycle stage, the expected quantity of products that visits a lifecycle stage, and products' mean duration of stay in a lifecycle stage. A Markov chain also provides probabilities of absorption. The probabilities can be used to predict the number of products being discarded and incinerated. Furthermore, in this paper, the Markov chain model uses the amount of environmental impact per unit mass in estimating the average environmental impact (different to EIO LCA in which the environmental impact per monetary unit is used). This can minimize inaccuracy in estimating average environmental effects. The use of monetary units may result in inaccuracy in the physical flows within the sectors of the economy [14] because the products of an industrial sector are the aggregate of the products of all industries in that sector [15].

The model presenting in this paper has limitations. First, in the model, it is assumed that the chain has a stationary transition probability. This means that the quantity of products flowing from one lifecycle stage to the others is constant over a period. The assumption may not very fit the real practice. For example, after legislation for recycling is enacted, the number of products being recycled may increase compared to the year before the legislation exists. Nevertheless, the analyzer can overcome this disadvantage by making sure that there are no significant differences between the flows of products used to develop the transition probability matrix **P** and the streams of products when the analysis is conducted. Second, the model is only applicable to products having a monolithic product structure (no components and modules). Finally, since the right policy should consider several aspects [16,17], it is also suggested that the model incorporates cost issues.

6. Conclusions and future works

Markov chain is a well-established concept in probability theory and operations research. It has been applied to many areas such as physics, chemistry, computer science, queuing theory, economics, games, and sports. In this paper, the lifecycle of a product is modeled using the Markov chain. The model is integrated with the information about product lifetime, and the results of an LCA analysis. Based on that, the number of trips and duration of stay of a product in a particular lifecycle stage, the number of products visiting a specific lifecycle stage, the probability of a product being discarded and incinerated, and the expected total environmental impact of the product are predicted. The model assumes that the product has a stationary transition probability.

The presented case study shows that the developed model can perform the above predictions. The results of the case study indicate that on average plastic will visit the production, use, and recycling stages once, 1.56, and 0.11 times, respectively. The overall average duration of stay of plastic (in all types of the market sector) in the use stage is 13.65 years. Out of 407 Mt plastic produced in 2015, the model predicts that the amount of plastic visited use and recycling stages is 635.49 Mt and 42.84 Mt, respectively. For the PET only, the model estimates that the total energy consumption level (for the production, use, discard, and incineration phases) in 2016 was 0.05 MJ/kg.

For future works, it is required to further develop the model so that it can be applied for products having components and modules. Second, the logistics operation behind the transition needs to be modeled so that the accuracy of the model is improved. Third, to aid policymakers in making a comprehensive decision, the economic aspects should be included in the model.

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