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ORIGINAL ARTICLE

Application of Markov chain for LCA: a study on the clothes 'reuse' in Nordic countries

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Abstract The purpose of this paper is to develop a model to count the number of cycles or trips that a clothing product could make in a reuse-based closed loop cycle. The model is primarily based on three scenarios: (i) self-reuse (ii) discard to second-hand market and (iii) disposed to incineration or the recycling stations. The present study extended and complemented the existing literature by presenting the application of the Markov chain to analyse the future of textile products on the basis of probabilities. Subsequently, the proposed model has been used to study the textile waste flow in the Nordic countries, i.e. Denmark, Finland, Iceland, Norway and Sweden. The application of the proposed model on the data from the Nordic Countries indicated that the average number of times the clothes reuse is highest in Denmark, whereas the lowest was found in Finland. Repair and redesign were found a hotspot for the recovery of clothes. Variation in these hotspots can increase the trip number of clothes. A sensitivity analysis is performed and conclusions are made regarding variations of clothes reuse under different scenarios. The proposed model may help in the decision formulation for the companies, government authorities and research agencies which focus on reuse and recycling of textile products. Based on the insights from the present work, the decision maker may take several initiatives to increase the life span of a textile product.

Keywords Fashion value chain · Closed loop · Reuse · Markov chain · Textile waste

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1 Introduction

Recently, the rise in the sustainability concern around the globe has drastically shifted the orientation of firms across different sectors from automotive to textiles [1]. This has resulted in an increase in the number of endeavours to enhance not only firms' sustainability but, the sustainability of the entire value chain (forward and reverse). In the forward value chain, conversion of raw material into finished products takes place, whereas, in the reverse value chain, obsolete products are converted into usable forms [2]. The number of members involved in a value chain and the criticality of the activities tend to determine the complexity of the value chain. There are different ways by which a firm can increase the sustainability of the value chain such as reuse, refurbishing, repair, remanufacturing, recycling or redesign [3]. Reverse value chain complexities are due to the stochastic nature of the return volume, quality and timings. Product configuration, evaluation and reprocessing further enhance the complexity of the value chain [4]. Interestingly, in this case, the reverse value chain may be considered even more complex than forward value chain. Based on the aforementioned conditions, the 'clothing' value chain may be considered as a complex system comprising of a number of critical value chain paths [5]. Several studies revealed various reasons which may be attributed to this consideration, for e.g. (i) description and information about the product is difficult to trace in reverse value chain, (ii) several critical activities like sorting and collection requires immense care while handling,

(iii) scope of remanufacturing or redesigning is limited to restore or improve the functionality of products and (iv) the material flows through multiple channels [6–9].

Farrant, Olsen [10] argued that 'reuse' may be considered as one of the ways to enhance sustainability by diverting usable clothing from the waste stream. Production of new clothes needs to be minimised by increasing replenishment rate of old clothes. This gives an opportunity to the customer to consider second-hand clothes as an alternative way to fulfil their needs. Abraham [11] explored the various aspects of the aftermarket of clothes. The study was an attempt to map the different processes to provide a clear understanding of the whole process starting from the collection to the sale of the product in a second-hand market. Further, the study proposed different activities to increase the life span of a textile product. The study provided a foundation through the various insights for further research focusing on efficiency enhancement of a closed loop value chain.

The existing literature revealed that several attempts have been undertaken to the model formulation through quantitative studies in the reverse value chain of electronic and metal industries [12–14]. However, a limited number of quantitative endeavours have been found capturing the clothing industry [15, 16]. Most of the textile and clothing research are qualitatively depicted, while the research from other industries is quantitatively expressed. The textile and clothing products have various criteria that could be the main problem for the quantitative study. For example, automobile or electronic companies have a limited number of variants of products, while the number of styles of clothes are boundless. The style of clothes differs from each other on the basis of fabric, colour, construction, size etc. However, some of the researchers in the past have taken efforts to solve the problem of clothing industry by application of different mathematical techniques. For example, Ruiz-Torres, Ablanedo-Rosas [15] used linear programming to select a supplier for the textile recycling. Staikos and Rahimifard [16] used the fuzzy technique to make an end-of-life decision for the clothing and footwear.

The objective of this paper is to count or measure the number of times a clothing product can be reused. Markov chain may be considered as a prominent and relevant method to develop a mathematical model to calculate the average life of clothes [17]. Earlier researchers have used the principle of Markov chain to address different problems. For instance, Wu and Shieh [18] used the Markov principle to analyse customer requirements and Chan et al. [19] used the principle of Markov to perform risk and failure analysis. Rodger [20] has used stochastic simulation with Markov blankets to estimate backorders waiting time. The present study is an effort to extend the current literature by contributing broadly in two ways: first, to apply the Markov chain principle for the life cycle assessment of a clothing product and second, to use the proposed model to study the textile waste flow in the Nordic countries, i.e. Denmark, Finland, Iceland, Norway and Sweden. The proposed mathematical model is expected to count the number of cycles or trips that a textile product could make after it gets discarded by consumers. This will enable to identify the hotspots for the reuse-based closed loop value chain. This may also serve as an indicator for assessing the state of clothing used in a certain year, based on the textile material flow in that particular year.

2 The concept

2.1 Reuse-based closed loop clothing value chain

In the recent literature, reuse emerged as one of the dominant practices which may provide sustainability to a close loop value chain. This concept deals with the collection of old clothes that is free from all kinds of defects. These can be used directly after basic washing and finishing [21]. Morley et al. [22] has defined it as the process of restoring basic functionality. The product can be used directly after basic washing and finishing. When a customer lost interest in clothes and no longer want to wear, then these are converted into a usable form by two options: (i) producing second-hand clothes after washing and finishing or (ii) making wipers and rugs to serve inferior functions. These aforementioned tasks depict the practical application of the reuse concept. The product structure could be designed to a modular structure so that a part of the product may be reused if complete product is not good enough to reuse [23]. With the proliferating importance of sustainability in the industrial practices, recently second-hand clothing sector has gained unparalleled attention from scholars and practitioners worldwide. This second-hand market is running in parallel to the new product markets. In the previous decade, the international trade in second-hand clothing has risen dramatically in the Global North by the rapid circulation, consumption and disposal of garments for recycling and reuse in the Global South. Initially, donated clothing products from developed country were sent to the developing world in the form of charity [24]. It is worth emphasising that now, used clothes collected by charities and recyclers for the export to the Global South were overwhelmingly sold for profits [25, 26]. Before reaching the landfill site or energy station for incineration, all kinds of discarded and donated clothes pass through different stages (such as informal exchange to friends and family and second-hand market). The entire movement of clothes throughout the life cycle is stochastic in nature [27]. However, the process of repair and redesign could be used to achieve ecological resilience by minimising the landfill and incineration [28].

2.2 Life cycle assessment

Life cycle assessment (LCA) is a methodological framework for assessing the impact of a product on the environment throughout the life cycle. For the LCA, various system boundaries like a cradle, gate and grave have been defined in the literature. Cradle is the place of raw material extraction, while the grave is the final disposal place after the end-of-life. The gate can be defined as a point from where product passes manufacturing site and enter to market [29]. In the literature, it is evident that the research can capture cradle to grave, cradle to gate or gate to grave depending on the objective. The cradle to grave can be considered as a full LCA study while others may cover only one or two phases. LCA has been used extensively to study recycling (closed loop and open-loop recycling). 'In the closed loop recycling, waste products are recycled into a material that is used for products of the same kind, whereas in the open-loop recycling waste products are recycled into a material that is used for other kinds of products' [30]. 'Hotspot' and 'Trip number' are the prominent terminologies used in LCA studies. The *Hotspot* is the process or stage, which has maximum influence on the life cycle of a product. The *trip number* can be defined as the number of times product can be used before entering to the grave [31]. In addition, the trip number could be applied in the inventory calculation during the life cycle assessment.

2.3 Markov chain principle

Application of Markov principle is quite useful to study uncertainties of any repeated events [18]. Markov model is also very useful in the study of short and long time analysis of any stochastic system. A statistical model is stochastic in nature that evolves over time with a certain probability. The stochastic process has the Markov property if it only remembers the last state. This model assumes that the current state of the system evolves over time from the initial state. The transition from one state to another can be presented by the probability. The Markov chain has a finite stationary state, which can be used to study material movement through a certain number of states. Serfozo [32] has defined Markov chain as follows:

A stochastic process $X{=}X_n : n \geq 0$ with finite set S is Markov chain for any $i, j \in \mathrm{S}$ and $n \geq 0$ if,

$$P\{X_{n+1} = \mathrm{j}|X_0, \ldots, X_n\} = P\{X_{n+1} = \mathrm{j}|X_n\} \\ P\{X_{n+1} = \mathrm{j}|X_n = i\} = p_{ij} \tag{1}$$

The P is probability measure which gives probability p_{ij}, of Markov chain transition from the state i to j. The probability of each individual transition is determined empirically. At any state, sum of all transition probabilities will be one, $\sum_{j\in \mathrm{S}} p_{ij} = 1, \quad i{\in}\mathrm{S}$. Equation (1) is in accordance with Markov property, which state that at any time n, the future state is X_{n+1}can only be determined by the current state X_n and independent of all other previous state $X_0, \ldots, X_{n-1}$ and the value of $X_n \in \mathrm{S}$.

As discussed, state S is finite and countable, which can be written as $\mathrm{S} = \{S_1, S_2, \ldots, S_r\}$ or $\mathrm{S} = \{1, 2, 3 \ldots r\}$. Under this scheme, transition matrix, consisting of all transition probabilities, can be shown as follows:

$$P = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1r} \\ p_{21} & p_{22} & \cdots & p_{2r} \\ \cdots & \cdots & \cdots & .. \\ \cdots & \cdots & \cdots & \cdots \\ p_{r1} & p_{r2} & \cdots & p_{rr} \end{bmatrix} \tag{2}$$

P is stochastic matrix because sum of any row will be 1. A state, $i \in \mathrm{S}$ is called transient if $p_{ii} \leq 1$ and absorbing if $p_{ii} = 1$. It is not possible for any entity to leave the absorbing state once it enters into Markov chain. A Markov chain consists of at least one absorbing state and it is possible to reach this state from all the transient states [33].

Any Markov chain model is determined by state and transition matrix. If the initial moment at $t = 0$, state probability matrix is $\pi^0 \in \mathrm{S}$. Then, future state matrix after n transition at the time $t = n$, π^ncan be calculated with the help of transition matrix P as follows:

$$\pi^1 = \pi^0 P$$

$$\pi^2 = \pi^1 P = \pi^0 P^2$$

This can be generalised as follows for the transition:

$$\pi^n = \pi^0 P^n \tag{3}$$

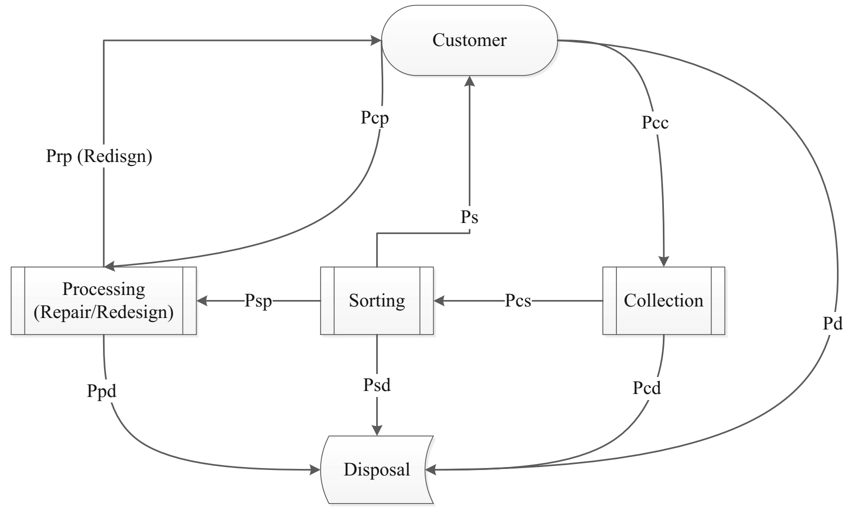
In the finite Markov process, state matrix can be calculated using the above formula [34]. This concept can be applied to the reuse-based closed loop clothing value chain, as clothes could not be returned to the reuse cycle once they reach to the disposal sage. As demonstrated in Fig. 1, disposal is an absorbing state, while consumer and second-hand may be considered as transient states. Clothes will be absorbed the disposal state after passing through different transient states.

Application of Markov principle is a widely used principle for prediction in medical sciences, engineering and management. The patient disease is diagnosed by studying genes of their parents. This kind of trend analysis is used in the field of biotechnology to develop medicines to control new diseases. Prediction of inventory level and machine breakdown can also be done with the Markov principle. The successful model can be built for analysis of customer behaviour and market trends using the Markov principle [18].

3 Model assumptions and formulation

This research methodology has only considered reuse of clothes throughout various stages of the value chain. Reuse of raw material (for fibre or fabrics) has not been considered

Fig. 1 Reuse-based clothing value chain



for the analysis. This paper follows the Markov chain model in which future state can be determined by probability [35]. An independent stage and transition matrix has been considered to determine future stage in Markov chain. Each transition occurs at a fix point of time and dwell time is not considered for any of the stages [36]. Overall, the procedure involves four steps. First, reuse-based Markov chain model will be built by using consumer, second-hand and disposal stages. Second, state matrix will be prepared by considering each of the cases. Third, the transition matrix will be defined based on the probability of material movements. Fourth, the trip number, i.e. an average number of times clothes reuse will be calculated.

3.1 Modelling reuse-based clothing chains

The flow of clothes from the gate to the grave in the Nordic countries has been modelled. This model helps in the calculation of trip number in the reuse-based clothing value chain. Clothes undergo to the following stage via different intermediate stages. Stages can be summarised as follows:

- Consumer
- Collection
- Sorting
- Processing (repair/redesign)
- Disposal (waste/recycling)

Clothes move from one stage to another with a different probabilities. P_d , P_{cd} , P_{sd} and P_{pd} denote probability of clothes disposal from consumer, collection, sorting and processing, respectively. Probability of clothes transition from consumer to collection and processing centre are denoted by P_{cc} and P_{cp}. Movements of clothes to consumer from sorting and processing stage are denoted by the probability P_s and P_{rp}. While P_{cs} and P_{sp} denote probability of clothes movement from collection to sorting and from sorting to processing. This has been demonstrated in Fig. 1.

In the model, the following assumptions have been made to determine stages in the clothing value chain based on the Markov principle:

- All transitions are done at a fixed point of time. The processing time between various stages has not been considered.
- The LCA considers the complete disposal of clothing products, partial or part of a product is not taken into account.
- Collection/sorting/repair is a separate process. But, this has been assumed one unit. Similarly, recycling and disposal have been considered one unit. Even though recycling has own set of the process, but that has not been considered here.
- Intermediate stages and trade have not been considered.
- The quality of clothes for in every trip considered to be same.
- Informal exchange among relative has been considered as consumer use only. Hence, the probability at which consumer will exchange clothes with relatives will be the same as of self-use.
- It has been assumed that clothes exported to developing countries will have a better chance for reuse. At least the old product will be reused for a similar duration as of originating countries.
- Disposal or recycling is considered as absorbing stage.

From the above discussion and assumption, a simplified model can be presented for reuse-based clothing value chain. Following steps can be identified as stages of the Markov chain:

- Consumer
- Second-hand market (collection/sorting/repair)

- Disposal (waste/recycling)

On the basis of the above stages, below Markov Chain can be drawn for simplified reused based clothing value chain:

As demonstrated in Fig. 2, clothes move from consumer to second-hand and disposal stage with different probabilities. Good condition clothes can be used by the consumer or informally exchanged among the friends and relatives. If the owner or relatives do not want to use wearable clothes, that can be donated to second-hand markets. Collected clothes after sorting can be either moved to aftermarket or disposal. Minor reconditioning would be recommended to restore the functionality of clothes. However, value addition activity like redesign, embroidery and reprint can be used to enhance life.

3.2 State matrix preparation

At the initial state, all the clothes assumed to be in the consumer wardrobe. The probability of product at the consumer will be 1, while all other probabilities will be 0. Hence, at the initial moment at =0, state probability matrix is $\pi^0 \in S$ can be written in matrix form as follows:

$$\pi^0 = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

Here, this has been assumed that all clothes, in the beginning, will be with the consumer. The total amount of new clothes purchased in Denmark is 16 kg (kilogramme) in a year. In Finland per year, clothes consumption is 13.6 kg. Consumption is 15 kg per year in Iceland and Sweden while 14.4 kg in Norway [37]. Textile and clothing consumption is highest in Denmark followed by Iceland, Sweden, Norway and Finland. These data have been used to calculate average time of clothes reuse in the cycle.

3.3 Transition probability matrix

The transition probability matrix made based upon the flow of clothes to different stages, i.e. consumer, second-hand market and disposal. The flow of material depends upon the system and facilities of collection, repair and sale of clothes in the aftermarket. Transition probability for each country has been calculated separately. Textile and clothing material flow per capita per year for different cases/countries can be summarised as follows:

Transition probability matrix for different cases calculated on the basis of material flow:

Case 1: Denmark—Total amount of clothing and textile product consumed by a consumer is 16 kg in a year. Out of which 4.4 kg is directly disposed of as waste, 6.3 kg is collected by second-hand market player while remaining 5.3 kg is informally exchanged among the friends and relative. Out of 6.3 kg, clothes moved to second-hand market from consumer wardrobe, 5.2 kg can be reused while 1.1 kg is disposed of as waste. The transition matrix can be defined from the above probability:

$$P = \begin{bmatrix} 0.33 & 0.83 & 0 \\ 0.39 & 0 & 0 \\ 0.28 & 0.17 & 1 \end{bmatrix}$$

Similarly, transition probability matrix for other cases has been calculated and depicted in Tables 1 and 2:

4 Numerical analysis

4.1 Average number of times clothes reuse

The clothes made from raw material were purchased by the consumer in different Nordic countries. The amount of new clothes purchase varies and depends upon consumer behaviour and financial capability. Old clothes are reused through the formal and informal exchange. The methodology has assumed that every time clothes enter in the reuse cycle has same composition and quality as it was in new, irrespective of time clothes circulated in the cycle. Circulations of clothes happen on the basis of its transition probability. Below equation can be used for the calculation of an average number of times, clothes remain in the circulation:

$$\pi^n = \pi^0 P^n$$

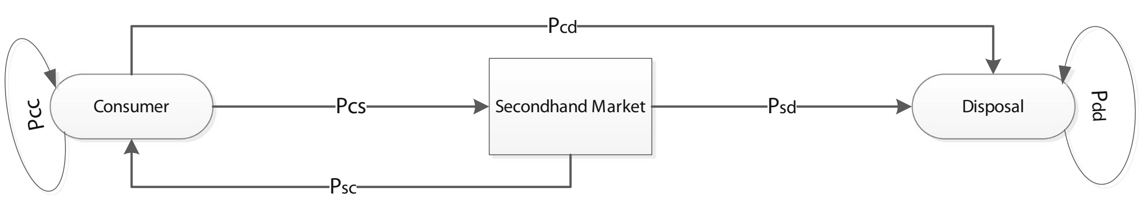


Fig. 2 Simplified reuse-based clothing value chain

Table 1 Flow of textile and clothing in Nordic countries in kg [37, 38]

	Consumer	Second-hand market	Disposal	Total
Case 1: Denmark				
Consumer	5.3	6.3	4.4	16
Second-hand market	5.2	0	1.1	6.3
Disposal	0	0	0	0
Case 2: Finland				
Consumer	1.3	4.7	7.6	13.6
Second-hand market	2.3	0	2.4	4.7
Disposal	0	0	0	0
Case 3: Iceland				
Consumer	0.5	4.5	10	15
Second-hand market	3.6	0	0.9	4.5
Disposal	0	0	0	0
Case 4: Norway				
Consumer	4.4	4.6	5.4	14.4
Second-hand market	4.4	0	0.2	4.6
Disposal	0	0	0	0
Case 5: Sweden				
Consumer	4.5	3	7.5	15
Second-hand market	2.5	0	0.5	3
Disposal	0	0	0	0

Initial state matrix at $t = 0$ is known as

$$\pi^0 = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

The objective is to calculate the value of n so that at $=n$, the state matrix become

$$\pi^n = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

At the end of the cycle, the product will reach completely to disposal. Hence, this can be assumed that at the π^n stage, all clothes will reach to disposal. Value of transition probability, P is known. By using matrix calculation, value of n^{th} stage has been found. Matlab software has used for the simulation to do matrix multiplication. Probability of clothes at different stages after each cycle of reuse can be summarised for different cases as follows:

It is visible that in Finland and Iceland, least number of times clothes can be reused. While in Denmark, reuse can be highest. Details of the finding depicted in Tables 3 and 4.

Initially, all clothes lie with consumers as per assumptions considered during model formulation. Per capita consumption of clothes differs in each of the cases considered for the study. The consumption of clothes is highest in Denmark with 16 kg per capita annual consumption. Per capita consumption of clothes in Iceland and Sweden is 15 kg per year, respectively. An individual in Finland and Norway consume 13.6 and 14.4 kg of clothes, respectively. However, movement of clothes from consumer to second-hand market or landfill depends on different factors. The probability of clothes movement during each cycle illustrated clearly in Table 4. The total amount of clothes that stay in the reuse cycle is calculated on the basis of per capita consumption and the probability of clothes movements. Figure 3, clearly, illustrate the amount of clothes reused in the different Nordic countries. The amount of clothes reuse is highest in Denmark and lowest in Iceland.

4.2 Sensitivity analysis

Sensitivity analysis is conducted on the quantity of clothes reuse, to gain insight into the proposed reuse model. The proposed stochastic model is also validated in this section by varying the disposal rate reflecting the practical situation. A couple of experiments have been performed using previous numerical analysis. The results shown in the sensitivity analysis represents three different scenarios. The disposal of clothes from consumers to landfill or incineration is set to be reduced by 25 and 50%, respectively, for scenario 1 and scenario 2. In scenario 3, the movement of clothes from the second-hand market to disposal is set to be decreased by 50%. The corresponding trend of variation for the clothes reuse is illustrated and discussed for each of the cases.

Case 1 Denmark Sensitivity analysis has been performed for each of the scenarios and actual data of clothes reuse from Denmark. As per the existing condition, nearly 19 times clothes could be used. The reuse of clothes can be increased to 25 or 37 times if the disposal of clothes from the consumer

Table 2 Transition probability matrix

Case 2: Finland	Case 3: Iceland
$P = [0.10, 0.49, 0; 0.35, 0, 0; 0.55, 0.51, 1]$	$P = [0.03, 0.80, 0; 0.30, 0, 0; 0.67, 0.20, 1]$
Case 4: Norway	Case 5: Sweden
$P = [0.30, 0.96, 0; 0.32, 0, 0; 0.38, 0.04, 1]$	$P = [0.30, 0.83, 0; 0.20, 0, 0; 0.50, 0.17, 1]$

Table 3 Number of times clothes reuse

Countries	Total number of trip (n)	Reuse times($n-1$)
Case 1: Denmark	20	19
Case 2: Finland	08	07
Case 3: Iceland	08	07
Case 4: Norway	17	16
Case 5: Sweden	10	09

is reduced by 25% (scenario 1) and 50% (scenario 2). However, with better repair or redesign facilities, clothes reuse can be increased to 22 times for Danish consumer. The variation trend is clearly demonstrated in Fig. 4.

Case 2 Finland Per capita consumption of clothes in Finland is least among all the Nordic countries. The reuse of clothes could be increased to 10 times from 7 if the disposal rate is reduced by 25%. As per scenario 2, if clothes disposal is reduced by 50%, the reuse of clothes can be increased by more than 100%. So, there is a need of a mechanism to bring more clothes to the second-hand markets. The repair or redesign facilities could further increase the reuse by 25%.

Case 3 Iceland Disposal rate is almost 66% in the absence of collection system for textile and clothing product in the Iceland. This is clearly visible during sensitivity analysis. The reuse of clothes can be increased two or threefold if consumer reduced the disposal rate by 25 and 50%, respectively, as per scenario 1 and scenario 2. Scenario 3 analysis also highlights that reduction in the disposal of clothes from the second-hand market can increase clothes reuse.

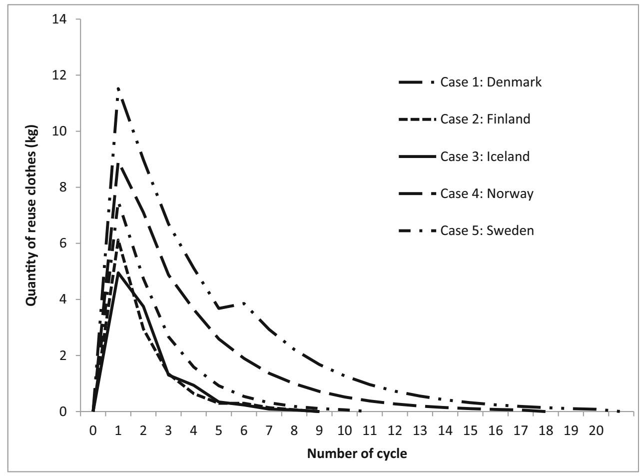


Fig. 3 Quantity of clothes reuse in each cycle

Case 4 Norway The disposal of clothes from Norwegian second-hand markets is very less. This is clearly visible

Table 4 Probability of clothes reuse in each cycle

Number of cycle	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Case 1: Denmark																					
Consumer	1	0.33	0.43	0.25	0.22	0.15	0.15	0.12	0.09	0.07	0.05	0.04	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.00	0.00
Second-hand market	0	0.39	0.13	0.17	0.10	0.08	0.09	0.06	0.05	0.04	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00
Disposal	0	0.28	0.44	0.58	0.68	0.76	0.76	0.82	0.86	0.90	0.92	0.94	0.95	0.97	0.97	0.98	0.99	0.99	0.99	0.99	1.00
Case 2: Finland																					
Consumer	1	0.10	0.18	0.04	0.03	0.01	0.01	0.01	0.00												
Second-hand market	0	0.35	0.04	0.06	0.01	0.01	0.01	0.00	0.00												
Disposal	0	0.55	0.78	0.90	0.95	0.98	0.98	0.99	1.00												
Case 3: Iceland																					
Consumer	1	0.03	0.24	0.01	0.06	0.01	0.01	0.00	0.00												
Second-hand market	0	0.30	0.01	0.07	0.00	0.02	0.00	0.00	0.00												
Disposal	0	0.67	0.75	0.91	0.94	0.98	0.98	0.99	1.00												
Case 4: Norway																					
Consumer	1	0.30	0.40	0.21	0.19	0.12	0.09	0.07	0.05	0.03	0.03	0.02	0.01	0.01	0.01	0.01	0.00	0.00			
Second-hand market	0	0.32	0.10	0.13	0.07	0.06	0.04	0.03	0.02	0.02	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00			
Disposal	0	0.38	0.51	0.66	0.75	0.82	0.87	0.91	0.93	0.95	0.96	0.97	0.98	0.99	0.99	0.99	0.99	1.00			
Case 5: Sweden																					
Consumer	1	0.30	0.26	0.13	0.08	0.05	0.03	0.02	0.01	0.01	0.00										
Second-hand market	0	0.20	0.06	0.05	0.03	0.02	0.01	0.01	0.00	0.00	0.00										
Disposal	0	0.50	0.68	0.82	0.89	0.94	0.96	0.98	0.99	0.99	1.00										

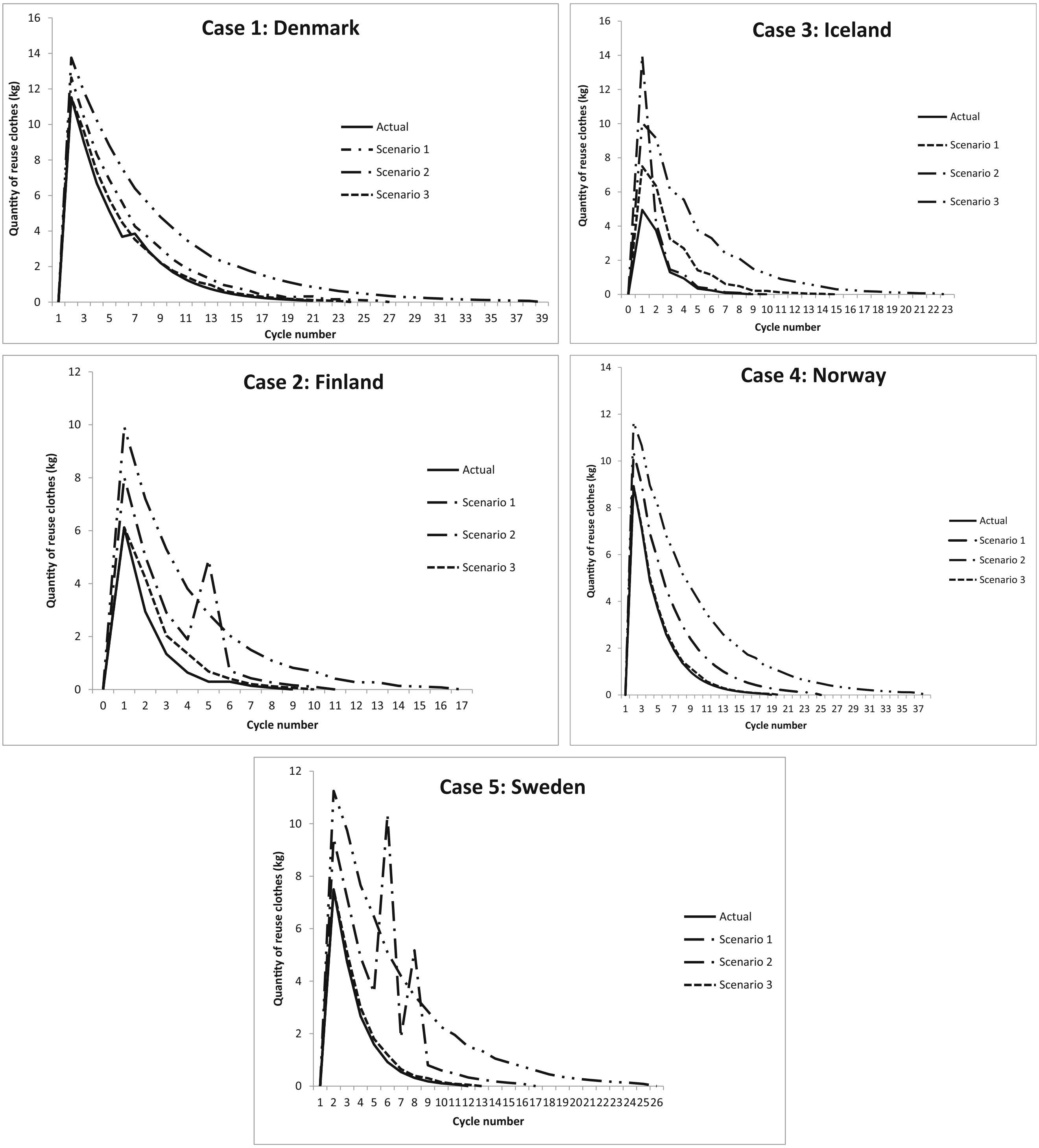


Fig. 4 Sensitivity analysis of clothes reuse

in the scenario 3 analysis as there is not a substantial increase in clothes reuse. However, clothes reuse increases by more than 50 and 100% if consumer reduces disposal by 25 and 50%, respectively. This could be easily understood from scenario 1 and scenario 2 analysis.

Case 5 Sweden A Swedish consumer disposes of 50% of total consumed clothing product. This is quite evident from the scenario 1 and scenario 2 analysis. Reuse of clothes can be increased by two or threefold if disposal of clothes reduced by 25 or 50%. However, there is no significance change if disposal of clothes from second-hand markets is reduced by 50% (scenario 3). This is because Sweden has good second-hand markets.

5 Discussion

There are different ways to a sustainable resource recovery as evident in the literature [39–41]. Reuse of a product focuses on resource recovery at minimum cost and energy consumption. This has attracted a substantial amount of attention from researchers across different areas [3]. The present study showed the application of Markov chain in the clothing industry. Subsequently, the work emphasised that Markov chain principle can be considered as a potential tool to measure how many times clothes can be reused before its end of the life cycle. The clothes can be used $n-1$ times if it makes n trip in the closed loop cycle. Findings also suggested that redesign is the hotspot in the present context (i.e. clothing). A superior repair and redesign processes may aid in increasing the number of trips of the clothing product [31]. A better recovery, sorting, repair and redesign system can also increase the probability of clothes to reuse. This will decrease the disposal rate of clothes from the second-hand market to grave stage. The impact on number of times clothes reused has been measured by changing disposal rate during the sensitivity analysis. The findings from sensitivity analysis demonstrate that 25 to 50% reduction in discard rate could increase clothes by two to threefold.

The application of the proposed mathematical model to study reuse in the Nordic countries revealed several interesting findings. As illustrated in Table 3 and Fig. 3, each Nordic country (i.e. Denmark, Finland, Iceland, Norway and Sweden) exhibited a different life span for clothes under the reuse cycle. The result suggested that Denmark is leading in terms of trip numbers ($n = 20$) of clothes. This implies that clothes discarded by Danish people can be used almost 19 times. The reason for this high reuse is the export of clothes to developing countries. Approximately 6.3 kg of clothes are collected by charity organisations out of the total per capita consumption of 16 kg. Less than 10% of total collections are reused by Danish citizens. Almost 70% of clothes are exported and remaining 20% moved to waste incineration stations [38]. Initially, most of discarded clothes are exported to the European countries, from where these are re-exported throughout the globe. The high reuse rate is calculated based upon the underlying assumption that the imported country will follow the same or higher rate of reuse compare to the Nordic countries. In practice, poor people tend to use clothes till threadbare [42]. Based on the socioeconomic conditions and the findings of the present work, we propose that Denmark can achieve higher sustainability if they focus on self-reuse and recycling.

Considering the case of Finland, we found the seven number of times clothes can be reused. The country has a good system to reuse and recycle. Out of the total collection, almost two thirds are reused. Half of the clothes reused in Finland, while the remaining half are donated or exported abroad. Very small percentages of clothes were burnt at energy stations located in the city and almost 30% recycled. This illustrated that Finland as a country has a better system to handle post-consumer textile waste. The consciousness and awareness of consumers regarding reuse may also consider as an important factor responsible for a better system for reuse. However, companies involved in textile recovery have logistics and economic problem in day to day operation [6]. In the Iceland flow of textile is not very clear. Out of per capita consumption of 15 kg/year, almost 10 kg goes along with other solid waste. The consumer retains 0.5 kg of clothes for self-use while 4.5 kg goes to reuse cycle [37]. Total number trip clothes can make in reuse cycle is calculated 8. This means old clothes originated from Iceland can be reused seven times. The majority of these clothes are used abroad in the absence of a domestic second-hand market.

Table 1 clearly demonstrated that per capita consumption of textile was 14.4 kg/year in Norway. Almost one third is informally used by customer and relatives, while the remaining one third is collected by second-hand actors. In Norway, the textile collection process is dominantly carried out by the charity as well as private companies. The municipality has also collaborated with private agencies to speed up the textile collection. Due to lack of reuse and recycling facility, huge amount of clothes dumped along with the other solid waste. It is estimated that 20–25% of the landfill or incinerated textiles can be reused in the presence of better facility [43]. Further, a domestic reuse of the collected textile is very less. Most of the discarded clothes are exported; this is the reason for the high trip number($n = 17$). As per LCA calculation, a total of 16 times old clothes originated from Norway can be used. Textile waste management need to be improved considerably in Sweden, even though the country is a leader in the solid waste management. Almost 80% of post-consumer wastes are dumped along with other household waste. Only 20% is collected from charity and second-hand shop [38]. Out of the total collection, roughly 73% are donated or sold abroad. While 10–12% is used by Swedish people and remaining 15% burnt at municipal energy station. Due to high amount export of post-consumer, waste trip number in inventory analysis comes around 10. This elaborates that nine times textile can be reused in Sweden by considering all assumptions. One of the key considerations for the recovery of discarded clothes is the available facility for collection and treatment of the textile waste.

6 Implications and conclusion

The present study aims to shed light on the quantitative stochastic nature of post-consumer textile life cycle. The numerical results in a way strengthened the theoretical results of earlier studies that clothes reuse tend to differ among the

Nordic countries. The present study demonstrates that a number of times clothes can be reused is highest in Denmark and Norway among Nordic nations. This was due to the export of discarded clothes to the emerging countries. Clothes trip number for Finland and Iceland was found the same($n = 8$). This shows that in both countries, clothes can be reused for seven times. Finland has better solution for post-consumer textile waste and handling. The domestic reuse of clothes is also highest in Finland as compared to other Nordic countries. Per capita textile consumption of Iceland accounted only 2% of the total Nordic consumption. In Iceland, most of the disposal goes along with the household waste. Out of the total collection 80% are exported. In Sweden, clothes can be reused for only nine times because the country does not have separate channel for the recovery of textile waste. Inventory analysis used to calculate the trip number gives a good quantitative insight. The sensitivity analysis performed by varying the disposal rate further provides insights for organisations and practitioners. They can increase the life of clothes by giving emphasis on the hotspots or the key processes. Future research could be done by reducing the assumption considered during model formulation. For example, the current model has considered reuse of whole clothes; future researchers could extend the current work by formulating a model for part or partial use of clothes. Similarly, the quality of clothes is considered to be constant during each reuse cycle. This also gives scope for future studies. The current research utilised the concept of closed loop for the life cycle assessment. Future researchers are also encouraged to extend this work by capturing the open-loop recycling phenomena, where superior or inferior products can be made out of the discarded clothes.

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