# LCHAPTER III
# METHODOLOGY

## 3.1 System Boundary

In this MFA study, the system boundary was set to cover all processes after the PVC products were produced and distributed to the market. It was agreed that the study focused only on domestic consumption. Figure 3.1 shows the entire life cycle of PVC product, however, the system boundary set in this study covered only use phase, transportation, and end-of-life which includes waste management, landfill, incineration, and recycle (indicated by dashed line).

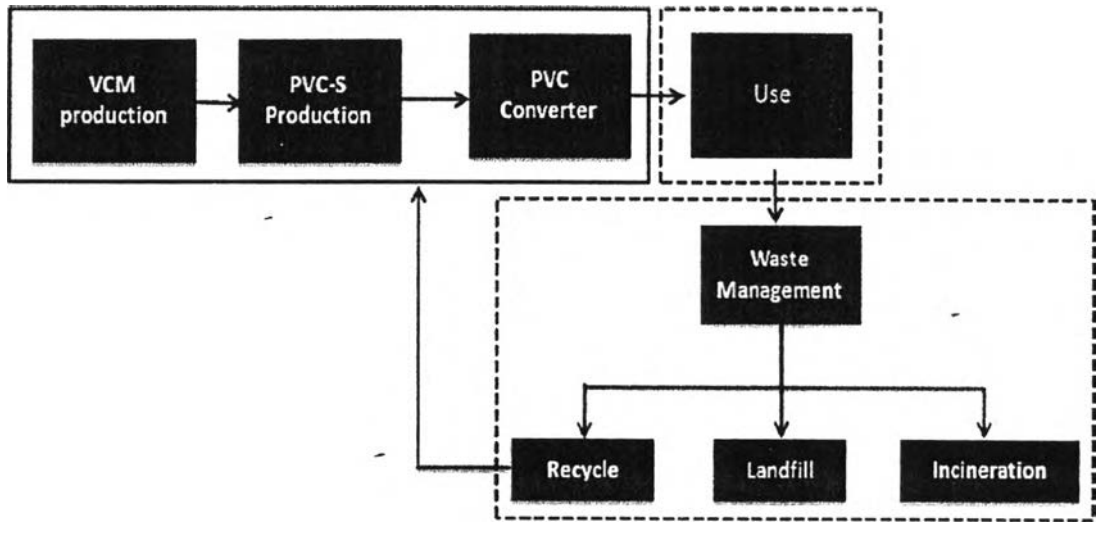



**Figure 3.1** System boundary of this study (dashed line).

## 3.2 Generic Model for MFA of PVC Products and Adjustable Parameters

A generic model of MFA for PVC product is shown in Figure 3.2. The figure shows material flow-in (input) of the product from production into the consumption phase ($Q_{in}$) where the product is used for certain period of time (n years), depending on its service life-time. After its end-of-life, the product turns into waste and flows out of the consumption phase ($Q_{out}$) at certain period of years. We

used average service life-time reported by industrial association and literatures. At this point, the material flow-out in each year ($m^{th}$) can be adjusted by using normal distribution applied to average service life-time (n+j and n-j).

The material flow-out ($Q_{out}$) from consumption phase at $m^{th}$ year is then passed to the waste management phase where the PVC product is sorted out for further treatment. Three disposal technologies were used in the model in this study: landfill, incineration, and recycle. The portion of material flow to each disposal technology can be identified by the user as a percentage (a%, b%, or c%). For recycle, mechanical recycling was assumed to be the main process used which involves cutting, cleaning, grinding, etc. For landfill, PVC waste is buried in the regulated sanitary landfill for a long period of time (i.e., 10-20 years). After that, the landfill might undergo rehabilitation such that non-degradable PVC waste can be recovered and recycled. For incineration, the PVC waste is converted into a form of energy (heat).

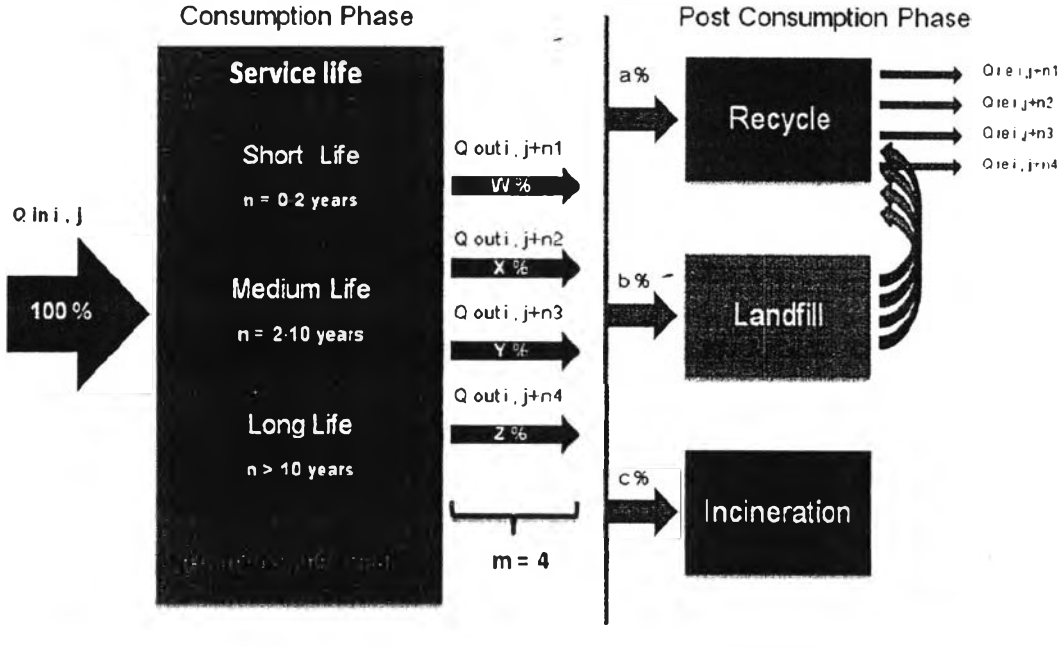



**Figure 3.2** Generic model for MFA of PVC products.

## 3.3 Data Collection

At the beginning of this research project, research team need to consult with ASEAN Vinyl Council association (AVC) and other industrial associations in order to obtain the data which are necessary for running and testing LC-MFA model. Group meetings between research team and AVC were taken place several times during project's period (Figure 3.3) in order to identify and agree with the data being used in LC-MFA model such as the amount of domestic consumption of PVC products, average service lifetime of PVC products, and service lifetime distribution of PVC products. And the sources of data are shown in Table 3.1.

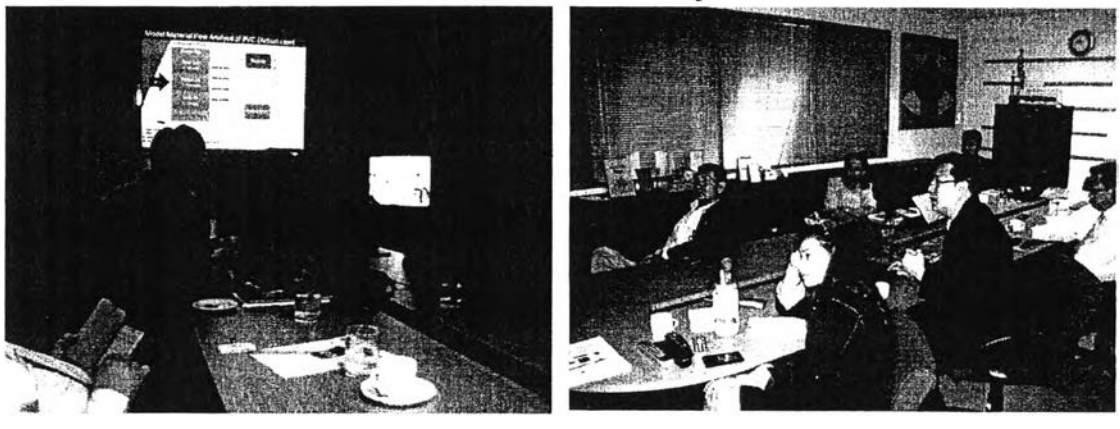


**Figure 3.3** Group meeting with ASEAN Vinyl Council association (April 2013).

3.3.1 Domestic consumption of PVC products

In this study, pipe, fitting, profile, cable, floor tile, floor covering, shoes, and hose were selected as model PVC products in order to represent both hard and soft PVC products used in Thailand. Most of PVC products used in Thailand come from two pathways: domestic production and importation.

*3.3.1..1 Domestic production*

For domestic production, we collected data of domestic PVC resin consumption from ASEAN Vinyl Council (AVC) as shown in Table 3.2. Based on two major PVC producers in Thailand; Thai Plastic and Chemical Public Company Limited (TPC) and Vinylthai Public Company limited (VNT), PVC resin consumption from 1971 to

2013 was allocated into several PVC products in different proportions, and it was assumed that the proportions of PVC resin use in each applications are constant throughout 43 years of PVC resin consumption data. The proportions of PVC resin use in each applications are shown in Table 3.3.

**Table 3.1** Sources of data

| Phase | Process | Source |
|---|---|---|
| PVC product Production (Domestic) | Pipe and fitting | AVC, major manufacturers, industrial associations, PTIT, PITH, FTI, and other sources |
| | Profile | |
| | Cables | |
| | Other products | |
| Consumption or use (Domestic) | Hard PVC products | AVC, major manufacturers, industrial associations, PITH, FTI, construction companies |
| | Soft PVC products | AVC, major manufacturers, industrial associations, PITH, FTI, TIPMSE |
| End-of-life | Recycling | Waste collection centers and PVC recycling shops |
| | Landfill | Waste collection center and Landfill sites |
| | Incineration | Phuket MSW incineration |

**Table 3.2** PVC resin consumption of PVC in Thailand from 1971 to 2013

| year | Domestic Consumtion (ton) | year | Domestic Consumtion (ton) |
|---|---|---|---|
| 1971 | 20,000 | 1993 | 157,000 |
| 1972 | 20,000 | 1994 | 157,000 |
| 1973 | 20,000 | 1995 | 176,000 |
| 1974 | 20,000 | 1996 | 214,000 |
| 1975 | 20,000 | 1997 | 219,000 |
| 1976 | 20,000 | 1998 | 233,000 |
| 1977 | 19,000 | 1999 | 270,000 |
| 1978 | 19,000 | 2000 | 280,000 |
| 1979 | 19,000 | 2001 | 215,000 |
| 1980 | 19,000 | 2002 | 343,000 |
| 1981 | 19,000 | 2003 | 349,000 |
| 1982 | 19,000 | 2004 | 393,000 |
| 1983 | 19,000 | 2005 | 420,000 |
| 1984 | 38,000 | 2006 | 431,000 |
| 1985 | 38,000 | 2007 | 424,000 |
| 1986 | 38,000 | 2008 | 384,000 |
| 1987 | 66,000 | 2009 | 377,000 |
| 1988 | 66,000 | 2010 | 401,000 |
| 1989 | 66,000 | 2011 | 449,000 |
| 1990 | 94,000 | 2012 | 460,000 |
| 1991 | 94,000 | 2013 | 507,000 |
| 1992 | 157,000 | | |

Source: 1971 to 2000 from AVC (2014)

2001 to 2010 from MTEC study (2012)

2013 to 2013 from PTIT (2012)

PVC products are produced from a blend of material which major ingredients is polyvinyl chloride. Other ingredients are including plasticizers, stabilizers, pigments, lubricants, and functional additives which may be compounded with PVC resin. These minor ingredients will vary from compound to compound. The formulations on compounds in this study were obtained from the study of European Commission (2004) and AVC (2014) which are shown in Table 3.4. After compounding process, the PVC compounds will be converted to PVC products. The products produced from manufacturers in Thailand from 1971 to 2013 are shown in Figure 3.4 and Table 3.5.

**Table 3.3** Proportion resin used in each PVC applications

| PVC application | Proportion |
|---|---|
| Pipe & Fitting | 38.68% |
| Profile | 8.56% |
| Cable | 10.57% |
| Floor tile | 0.65% |
| Floor covering | 9.09% |
| Shoes | 2.77% |
| Hose | 1.01% |
| Calendering (Rigid+Flexible) | 18.29% |
| Artificial leather | 3.05% |
| Bottle | 0.21% |
| Film | 3.32% |
| Auto | 1.99% |
| Medical | 1.75% |
| Others | 0.05% |
| **Total** | **100%** |

Source: AVC (2013)

**Table 3.4** Formulations of PVC compound in target PVC products

| PVC applications | Resin | Additives | Product |
|---|---|---|---|
| Pipe & Fitting | 98% | 2% | 100% |
| Profile | 85% | 15% | 100% |
| Cable | 42% | 58% | 100% |
| Floor tile* | 26% | 74% | 100% |
| Floor covering | 42% | 58% | 100% |
| Shoes* | 50% | 50% | 100% |
| Hose* | 61% | 39% | 100% |

Sourec: European Commission (2004) and *AVC (2014)

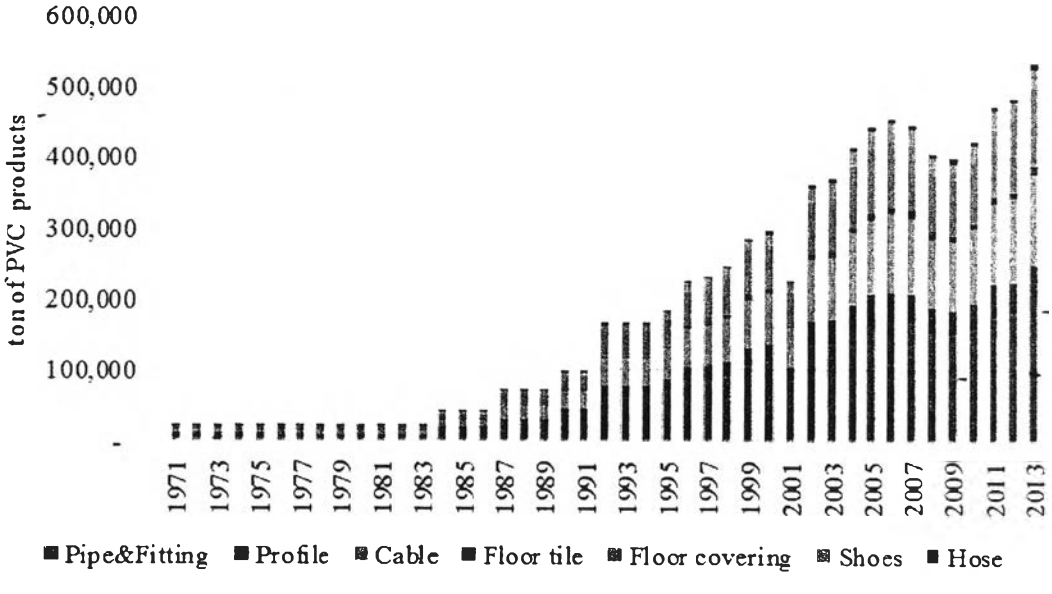



**Figure 3.4** Amount of PVC product production in Thailand from 1971 to 2013 (ton).

**Table 3.5** Amount of PVC product production in Thailand from 1971 to 2013 (ton)

| year | Pipe and Fitting | Profile | Cable | Floor tile | Floor covering | Shoes | Hose | Total |
|---|---|---|---|---|---|---|---|---|
| 1971 | 7,894 | 2,014 | 5,033 | - | 4,327 | 1,110 | 331 | 20,709 |
| 1972 | 7,894 | 2,014 | 5,033 | - | 4,327 | 1,110 | 331 | 20,709 |
| 1973 | 7,894 | 2,014 | 5,033 | - | 4,327 | 1,110 | 331 | 20,709 |
| 1974 | 7,894 | 2,014 | 5,033 | 500 | 4,327 | 1,110 | 331 | 21,209 |
| 1975 | 7,894 | 2,014 | 5,033 | 500 | 4,327 | 1,110 | 331 | 21,209 |
| 1976 | 7,894 | 2,014 | 5,033 | 500 | 4,327 | 1,110 | 331 | 21,209 |
| 1977 | 7,499 | 1,914 | 4,781 | 475 | 4,111 | 1,054 | 314 | 20,149 |
| 1978 | 7,499 | 1,914 | 4,781 | 475 | 4,111 | 1,054 | 314 | 20,149 |
| 1979 | 7,499 | 1,914 | 4,781 | 475 | 4,111 | 1,054 | 314 | 20,149 |
| 1980 | 7,499 | 1,914 | 4,781 | 475 | 4,111 | 1,054 | 314 | 20,149 |
| 1981 | 7,499 | 1,914 | 4,781 | 475 | 4,111 | 1,054 | 314 | 20,149 |
| 1982 | 7,499 | 1,914 | 4,781 | 475 | 4,111 | 1,054 | 314 | 20,149 |
| 1983 | 7,499 | 1,914 | 4,781 | 475 | 4,111 | 1,054 | 314 | 20,149 |
| 1984 | 14,999 | 3,827 | 9,563 | 950 | 8,222 | 2,108 | 629 | 40,297 |
| 1985 | 14,999 | 3,827 | 9,563 | 950 | 8,222 | 2,108 | 629 | 40,297 |
| 1986 | 14,999 | 3,827 | 9,563 | 950 | 8,222 | 2,108 | 629 | 40,297 |
| 1987 | 26,050 | 6,648 | 16,609 | 1,650 | 14,280 | 3,662 | 1,092 | 69,990 |
| 1988 | 26,050 | 6,648 | 16,609 | 1,650 | 14,280 | 3,662 | 1,092 | 69,990 |
| 1989 | 26,050 | 6,648 | 16,609 | 1,650 | 14,280 | 3,662 | 1,092 | 69,990 |
| 1990 | 37,102 | 9,468 | 23,655 | 2,349 | 20,339 | 5,215 | 1,555 | 99,683 |
| 1991 | 37,102 | 9,468 | 23,655 | 2,349 | 20,339 | 5,215 | 1,555 | 99,683 |
| 1992 | 61,968 | 15,813 | 39,509 | 3,924 | 33,970 | 8,711 | 2,597 | 166,492 |
| 1993 | 61,968 | 15,813 | 39,509 | 3,924 | 33,970 | 8,711 | 2,597 | 166,492 |
| 1994 | 61,968 | 15,813 | 39,509 | 3,924 | 33,970 | 8,711 | 2,597 | 166,492 |
| 1995 | 69,467 | 17,727 | 44,291 | 4,399 | 38,081 | 9,765 | 2,911 | 186,641 |
| 1996 | 84,466 | 21,554 | 53,854 | 5,349 | 46,303 | 11,873 | 3,540 | 226,938 |
| 1997 | 86,439 | 22,058 | 55,112 | 5,474 | 47,385 | 12,151 | 3,622 | 232,240 |
| 1998 | 91,965 | 23,468 | 58,635 | 5,823 | 50,414 | 12,927 | 3,854 | 247,087 |
| 1999 | 106,569 | 27,194 | 67,946 | 6,748 | 58,420 | 14,980 | 4,466 | 286,324 |

**Table 3.5** (Cont.) Amount of PVC product production in Thailand from 1971 to 2013 (ton)

| year | Pipe and Fitting | Profile | Cable | Floor tile | Floor covering | Shoes | Hose | Total |
|---|---|---|---|---|---|---|---|---|
| 2000 | 110,516 | 28,202 | 70,463 | 6,998 | 60,584 | 15,535 | 4,631 | 296,928 |
| 2001 | 84,861 | 21,655 | 54,105 | 5,374 | 46,520 | 11,929 | 3,556 | 227,999 |
| 2002 | 135,382 | 34,547 | 86,317 | 8,573 | 74,215 | 19,030 | 5,673 | 363,737 |
| 2003 | 137,751 | 35,151 | 87,827 | 8,723 | 75,513 | 19,363 | 5,772 | 370,100 |
| 2004 | 155,117 | 39,583 | 98,899 | 9,822 | 85,033 | 21,805 | 6,500 | 416,760 |
| 2005 | 165,774 | 42,302 | 105,694 | 10,497 | 90,875 | 23,303 | 6,947 | 445,393 |
| 2006 | 170,116 | 43,410 | 108,462 | 10,772 | 93,255 | 23,913 | 7,129 | 457,058 |
| 2007 | 167,353 | 42,705 | 106,701 | 10,597 | 91,741 | 23,524 | 7,013 | 449,635 |
| 2008 | 151,565 | 38,677 | 96,635 | 9,597 | 83,086 | 21,305 | 6,351 | 407,216 |
| 2009 | 148,802 | 37,972 | 94,873 | 9,423 | 81,571 | 20,917 | 6,236 | 399,793 |
| 2010 | 158,275 | 40,389 | 100,913 | 10,022 | 86,764 | 22,248 | 6,632 | 425,244 |
| 2011 | 177,221 | 45,223 | 112,992 | 11,222 | 97,150 | 24,912 | 7,426 | 476,146 |
| 2012 | 181,562 | 46,331 | 115,760 | 11,497 | 99,530 | 25,522 | 7,608 | 487,811 |
| 2013 | 200,113 | 51,065 | 127,588 | 12,672 | 109,700 | 28,130 | 8,386 | 537,653 |

*3.3.1.2 Imported products*

The data of imported PVC products were obtained from the Custom Department of Thailand (Table 3.6) by tracking from harmonized code. However, the obtained data posed some limitations; for example the Custom Department can provide the data of PVC importation only from 2007 to 2012 and the data do not cover all of our target products. However, it can be seen that the quantity of imported PVC products is relatively small when it was compared with the quantity of domestic products, so we can neglect this quantity when we test the LC-MFA models.

3.3.2 Average service lifetime and service lifetime distribution

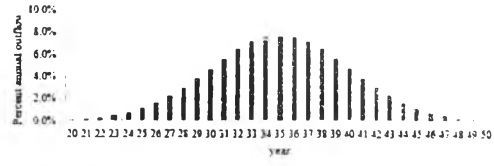
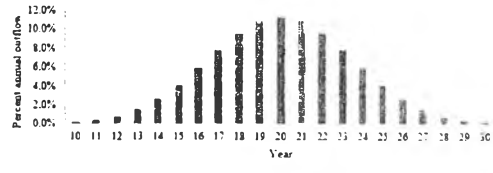
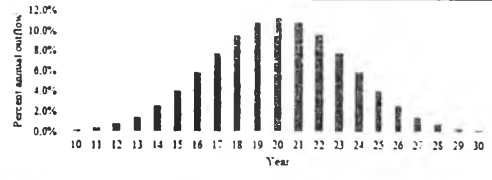
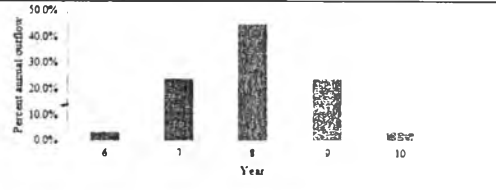
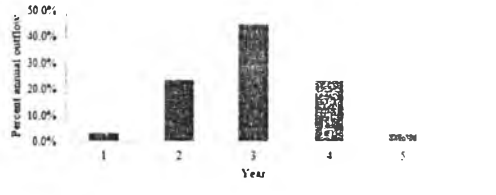
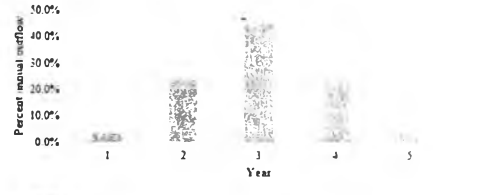
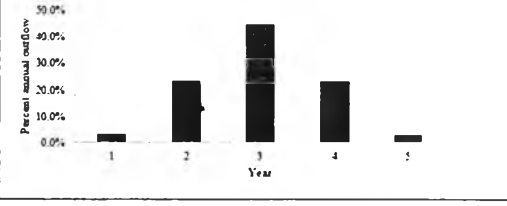
The average service life of PVC products was obtained from industrial associations and literatures as shown in Table 4.6. The material flow-out in

each year ($m^{th}$) can be adjusted by applying the normal distribution to average service life-time (n+j and n-j). From group meeting on April 2014, it was agreed that the number of material flow-out ($m^{th}$) from single year input is equal to number of amount of year during the period of products. Moreover, the material flow-out in each year during products' service lifetime can be adjusted by applying the normal distribution to average service life-time. For example, pipe and fitting have average service life 35 years, and they have service lifetime distribution +/- 15 years that means the range of pipe and fitting service lifetime is started from 20 years to 50 years. And the pattern of service lifetime distribution is like a normal distribution curve.

**Table 3.6** Quantity of imported PVC products (kg)

| **HS-CODE** | 3917.2300 | 3917.4000 | 3916.2020 | 3918.1011 | 3918.1019 |
|---|---|---|---|---|---|
| **Description** | Tubes, pipes, and hoses | Fittings | Rods, sticks and profile shapes | Tiles of polyvinyl chloride | Other of polyvinyl chloride |
| JAN - DEC 2007 | 737,735 | 905,975 | 408,850 | 1,519,565 | 377,286 |
| JAN - DEC 2008 | 648,199 | 1,046,250 | 795,622 | 1,284,025 | 539,252 |
| JAN - DEC 2009 | 673,367 | 1,538,619 | 1,006,512 | 862,860 | 253,604 |
| JAN - DEC 2010 | 1,055,208 | 1,590,838 | 1,482,351 | 934,979 | 229,993 |
| JAN - DEC 2011 | 2,054,378 | 1,979,210 | 1,582,005 | 1,766,417 | 839,776 |
| JAN - DEC 2012 | 2,536,460 | 2,429,259 | 2,514,696 | 1,806,133 | 682,284 |

**Table 3.7** Average service life and service life distribution of target PVC products

| PVC products | Average service lifetime (n) (year) | Lifetime distribution (j) (year) | Profile of lifetime distribution |
|---|---|---|---|
| Pipe and fitting | 35 | +/- 15 |  |
| Profile | 20 | +/--10 |  |
| Cable insulator | 20 | +/- 10 |  |
| Floor tile | 8 | +/- 2 |  |
| Floor covering | 3 | +/- 2 |  |
| Shoes | 3 | +/- 2 |  |
| Hose | 3 | +/- 2 |  |

### 3.4 Model Testing and Scenarios Analysis

In this model, we identified some adjustable parameters including:

1) PVC input (production)
   - Based on single-year input
   - Based on multiple-year inputs
2) Output (post consumption/waste)
   - Average service life
   - Variation in service life
3) PVC waste management
   - Recycle waste ratio
   - Incineration waste ratio
   - Landfill waste ratio

Therefore, we can create several scenarios by varying these adjustable parameter in order to simulate the results under various conditions.

### 3.5 Site Visits

To assess data regarding the amount of wastes or materials flow of PVC products out of the consumption phase after service life-time, it was imperative to have to visit several waste management sites, waste collection centers, disposal sites, landfill sites in many locations around the country. Figure 3.5 shows the amount of municipal solid wastes (MSW) reported by Pollution Control Department (PCD) in 2011 for various areas in Thailand.

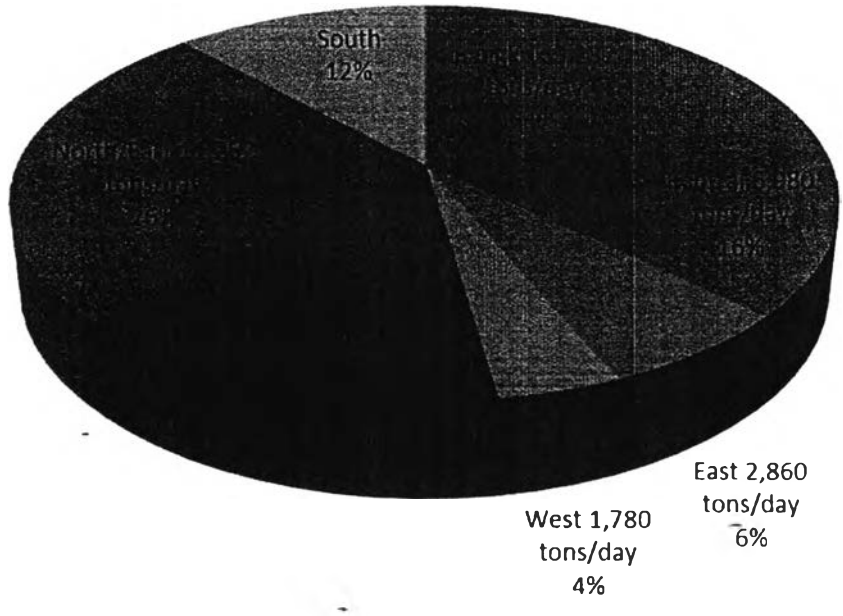



**Figure 3.5** Amount of municipal solid wastes (MSW) in Thailand (PCD, 2011).

Based on information in Figure 3.5, we proposed to visit actual waste management/disposal sites in various sizes (S, M, L, and XL) and different areas (central, north, northeast, east, west, and south) around the country as shown in Table 3.2.

**Table 3.8** Proposed sites to visit in this study

| Regions | Provinces | Waste (Tons/Day) |
|---|---|---|
| Central | • Chachoengsao (XL) - BMA | 3,226 (~40%) |
| | • Nakhon Sawan (L) | 1,210 |
| | • Samut Songkram (S) | 115 |
| East | • Rayong (M) | 507 |
| West | • Kanchanaburi (M) | 434 |

**Table 3.8** (Cont.) Proposed sites to visit in this study

| Regions | Provinces | Waste (Tons/Day) |
|---|---|---|
| North | • Chaing Mai (L) | 1290 |
| | • Chaing Rai (M) | 685 |
| | • Meahongsorn (S) | 128 |
| Northeast | • Chaiyaphum(M) | 582 |
| | • Nakhon Ratchasima (L) | 1,374 |
| South | • Krabi (S) | 189 |
| | • Phuket (Island) (M) | 545 |
| | • Surat Thani (M) | 601 |
| Recycling Shops | • Bangkok (Amorn)<br>• Other provincial recycle shop (Khun Kob) | |

**Note:** S is specified for area which has MSW less than 250 ton/day.

M is specified for area which has MSW around 250-750 ton/day.

L is specified for area which has MSW around 750-1,500 ton/day.

XL is specified for area which has MSW more than 1,500 ton/day.

3.5.1 Sampling Method

The sampling method at landfill sites in this study was adapted from ASTM 5231-92, Standard Test Method for Determination of the Composition of Unprocessed Municipal Solid Waste and PCD (Thailand) sampling method. One cubic meter municipal solid wastes were collected thoroughly from waste collecting vehicle at dumped site. And then, wastes were well mixed again. After that, mix, cone, and quarter the material. Finally, Mix the opposite parts of waste pile together, and we will obtain the final 2 samples from the waste collection vehicle as the following procedures in Table 3.9.

**Table 3.9** Procedures of waste sampling in this study

| Steps | Pictures | Description |
|---|---|---|
| 1 |  | Collect municipal solid waste around 1 cubic meter and mix it together |
| 2 |  | Divine material into four parts |
| 3 |  | Mix the opposite part together |
| 4 |  | Get the final 2 samples |
| 5 |  | Sort and classify types of materials in each-samples |

### 3.6 Material Flow Analysis and Model Tuning

We used data and information obtained from parts 3.1 to 3.5 to do fine tuning of the generic model proposed in Figure 3.2 in order to arrive at a more refined dynamic MFA model as shown in Figures 3.6 and 3.7 for PVC construction products and PVC household products, respectively. Once the model is developed for the target PVC product, it will be tested to check and confirm the correctness of the material flow in and out for specific product in all pathways identified.

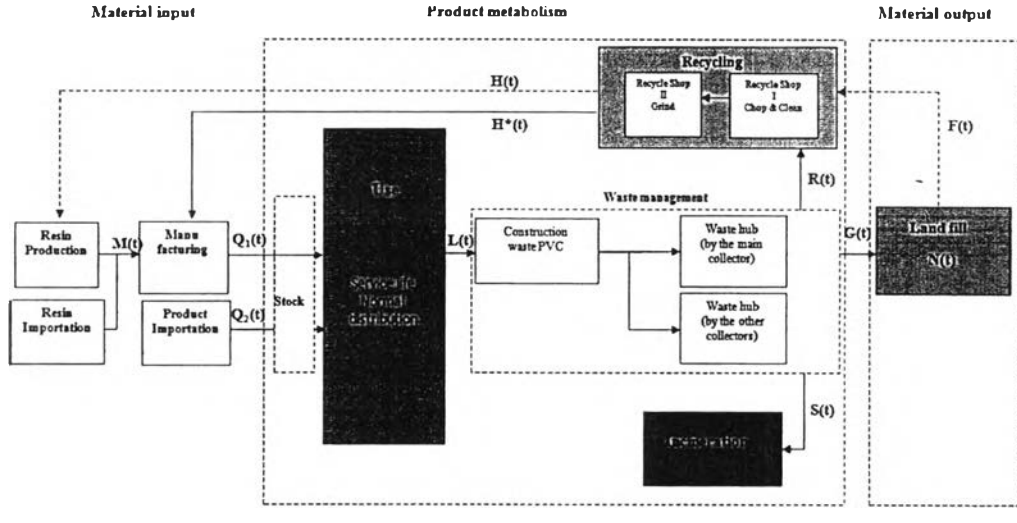



**Figure 3.6** Dynamic MFA model for PVC construction products.

The manufacturing and use of products were indicated as "Manufacturing" and "Use" respectively, and the flow connecting them was symbolized as Q. Disused material, which was represented as Flow L, enters the "Waste Management" process. A part of the waste was reused in the system through two approaches: high-grade mechanical recycling Flow H*, in which the waste returned to the "Manufacturing" process, and low-grade mechanical recycling Flow H, in which the waste returned to the "Production" process. Another part of the wastes, which was shown as Flow S, was changed to another form by "incineration". The rest of the wastes from product metabolism was discharged into the environment through Flow G. Flow N indicated

the waste accumulation year by year. After that the landfill might undergo rehabilitation Flow F such that non-degradable PVC waste can be recovered and recycled.

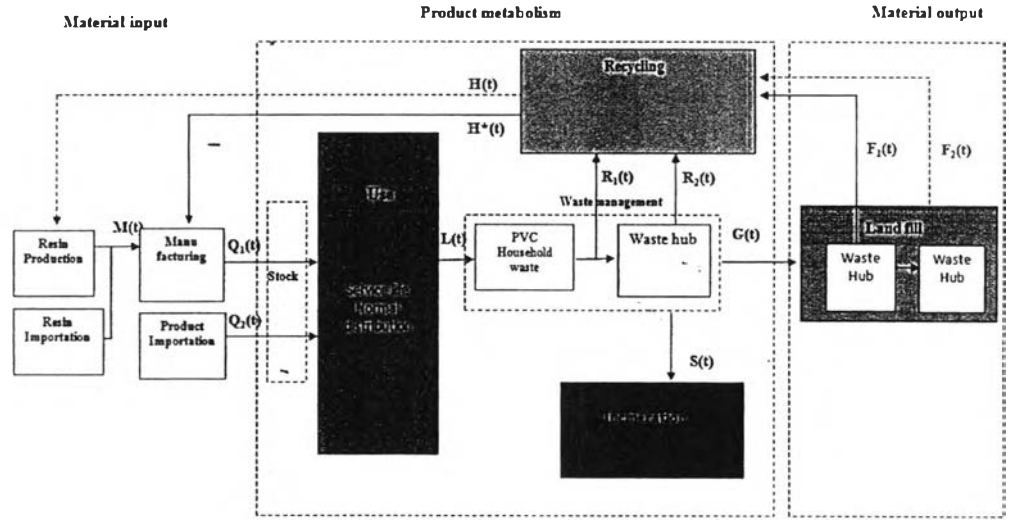



**Figure 3.7** Dynamic MFA model for PVC household products.

### 3.7 Assumptions

1) PVC products consumption in using phase is equal to PVC products production ($Q_1$) in manufacturing phase.

2) Stock of PVC products production is not considered in this study, so that PVC products will enter using phase in the production year.

3) PVC products importation ($Q_2$) is neglected in PVC metabolism because its quantity is relatively small.

4) All products which enter to PVC metabolism are on the specification and standard of each product.

5) The residence time of PVC products in using phase depends on the average lifetime and lifetime distribution.

6) In this study, only 3 waste management technologies are considered for end of life of PVC products which are: Recycle (R), landfill (G), and incineration (S) in the year which PVC wastes are released.

7) It is assumed that every kind of PVC wastes will be treated in waste management phase in the same ratio of recycling, landfill, and incineration.

8) It is assumed that recycled PVC from Mechanical recycling is not used to reproduce the same previous product.