Decision Support for Green Supply Chain Operations by Integrating Dynamic Simulation and LCA Indicators: Diaper Case Study

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SUPPORTING INFORMATION

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S.I Derivation of Environmental Impact Indicators

SI.1 Material balance and diaper composition

The disposable diaper production and environmental impact data used in this paper are mostly derived from a report by the UK Environmental Agency (1). The functional unit used in (1) is the number of diapers consumed in the first 2.5 years of a child's life; based on an average use figure of 4.16 diapers per day, this comes to 3796 diapers. The material balance of diaper manufacture and retail for 3796 diapers is shown in Figure S1, based on Figure 4.2 and Table 4.5 in UK Environmental Agency (1). The plastic landfill of 5.22 kg in Table 4.5 (1) is assumed to be composed of 2.5 kg polypropylene (PP), 2.5 kg polyethylene (PE), and 0.22 kg polyethylene terephthalate (PET), resulting in the diaper component mass balance given in Table S1. Out of 181.98 kg of raw materials input, 168.17 kg are retained within the diapers and 13.81 kg are output from manufacturing (6.3 kg to recycling and 7.51 kg to disposal). The input ratio in Table S1 measures the ratio of input raw material to the amount retained within the diaper.

Case study scenario 1 compares two diaper compositions from year 1987 and 2005. From EDANA (2), diaper weights in 1987 and 2005 are 67 g and 42 g, respectively. Diaper compositions in 1987 and 2005 are taken from Graph 6 in EDANA (3). The raw materials "tape" and "PET" in UK Environmental Agency (1) correspond to "elastics" and "other" in EDANA (3). The raw materials within the diaper are obtained by multiplying the diaper composition from EDANA (3) with the diaper weight from EDANA (2). Assuming the same input ratio from Table S1, the required input raw materials for 1987 diaper and 2005 diaper are calculated by multiplying the input ratio with the raw materials within the diaper (see Table S2).

The stock-keeping unit used in the case study is a carton of diapers, which is a cardboard box consisting of 60 plastic packages of 24 diapers each, i.e. 1440 pieces per carton. Customer orders and diaper production are measured in diaper carton unit. The amount of raw materials required to produce one carton of diapers is given in Table S3.

SI.2 Raw material impact

Eleven environmental impact indicators are considered in this work: abiotic resource depletion (ARD), global warming (GWP), ozone layer depletion (ODP), photochemical oxidation (PO), acidification (ACD), eutrophication (EUT), human toxicity (HT), fresh water aquatic ecotoxicity (FWAE), terrestrial ecotoxicity (TE), water usage (WU), and energy consumption (EC).

For raw material impact, the first nine indicators (ARD to TE) are calculated based on Table 8.12 in UK Environmental Agency (1). These values are based on 3796 diapers and the raw materials input given in Table S1. The impact per kg raw material is calculated by dividing these values by the raw material amount. For example, the ARD for fluff pulp in Table 8.12 (1) is 0.23 kg Sb eq, the fluff pulp amount in Table S1 is 72.17 kg, so the ARD per kg of fluff pulp is calculated as 0.23 / 72.17 = 0.0032 kg Sb eq or 3.2 g Sb eq / kg fluff pulp. The other two indicators, WU and EC, are based on Table 7.3 in UK Environmental Agency (1) and follow similar proportional calculation to obtain the impact per kg raw material. WU is based on "Water" and EC is based on "Coal", "Crude oil", and "Natural gas" in Table 7.3 (1). For the calculation of EC, the amount of coal, crude oil, and natural gas is each multiplied with the corresponding energy content in Table S4 to obtain the energy consumption in MJ. The calculated raw material impacts per kg raw material are given in Table S5.

SI.3 Raw material transportation impact

Raw materials are assumed to be transported by sea freights and 40-tonne trucks in equal proportion. The environmental impact indicators for sea freight and 40-tonne truck are taken from Ortiz (6). Assuming an average trip carries half-load, twice as many trips are required compared to the full-load case. To account for this higher number of trips, the indicator values are multiplied by two. The resulting raw material transportation impacts per t of raw material per km are given in Table S5.

SI.4 Manufacturing impact

For manufacturing impact, the first nine indicators (ARD to TE) are based on Table 8.12 in UK Environmental Agency (1), which reports the impact values for 3796 diapers. The manufacturing impact for one diaper carton (1440 diapers) is taken to be the sum of impacts from “Electricity”, “Heat gas”, “Waste recycling”, and “Waste disposal” in Table 8.12 (1), proportionally calculated by multiplying with 1440 / 3796. EC is based on “Coal”, “Crude oil”, and “Natural gas” in Table 7.3 (1), taking the sum of “Electricity” and “Heat gas” and then multiplying with the corresponding energy content in Table S4 and proportionally converting to one diaper carton basis. WU is based on Table 4.5 (1), proportionally calculated to one diaper carton basis. The calculated manufacturing impacts per diaper carton are given in Table S5.

SI.5 Packaging impact

For packaging impact, the first nine indicators (ARD to TE) are calculated based on Table 8.12 in UK Environmental Agency (1), which reports the impact values for 3796 diapers. The packaging impact for one diaper carton (1440 diapers) can be proportionally calculated by multiplying the impact for “Cardboard and plastic packaging” in Table 8.12 (1) with 1440 / 3796. The other two indicators, WU and EC, are based on Table 7.3 in UK Environmental Agency (1) and follow similar proportional calculation steps to obtain the impact per diaper carton. The calculated packaging impacts per diaper carton are given in Table S5.

SI.6 Product transportation impact

Products are assumed to be transported in 40-tonne trucks. The environmental impact indicators for 40-tonne truck are taken from Ortiz (6). Assuming a common truck dimension of 915 x 250 x 345 cm and carrying area factor of 0.8 x 1 x 0.5, the carrying area is calculated to be 732 x 250 x 172.5 cm. Using a carton dimension of 48 x 24 x 24 inch, a truck can carry around 69 cartons, each of which weighs 60.42 kg. Thus, a full-load trip carries 4.2 t, which is used as a basis to calculate the product transportation impact per km, given in Table S5.

SI.7 Distributor impact

For distributor impact, the first nine indicators (ARD to TE) are based on Table 8.2 in UK Environmental Agency (1). We assume that the distributor has the same impacts as "Retail electricity and packaging" in Table 8.2 (1). These are proportionally converted to one diaper carton (1440 diapers) basis. Based on Fig 4.2 (1), the amount of packaging input to the manufacturer is 13.26 kg (consisting of 5.83 kg cardboard and 7.43 kg PE). The amount of packaging retained in the product is 13.26 kg minus 1.87 kg PE recycled and 2.87 kg cardboard recycled, which is 8.52 kg. WU of the distributor is assumed to be proportional to the manufacturer's WU in terms of packaging amount; hence it is calculated as manufacturer's WU multiplied with 8.52 / 13.26. Based on Fig 4.2 (1), electricity input to the manufacturer is 114.25 kWh and for the retailer it is 23.38 kWh. EC of the distributor is assumed to be proportional to the manufacturer's EC in terms of electricity input; hence it is calculated as manufacturer's EC multiplied with 23.38 / 114.25. The calculated distributor impacts per diaper carton are given in Table S5.

S.II Supply Chain Parameters Used in the Case Study

The case study scenarios involve a horizon of 180 days, where each day is divided into 100 time ticks resulting in a fixed step solver with a step size of 0.01 day. Distance of one unit in the model represents 120 km. The stock-keeping unit is a carton of disposable diapers, which is a cardboard box consisting of 60 plastic packages of 24 diapers each, i.e. 1440 pieces per carton. Customer orders and diaper production are measured in diaper carton unit. The customer orders are set stochastically within the specified limits throughout the simulation runs. As this could result in different performance indicators even for the same SC configuration and policies, we perform 100 simulation runs for each scenario and report the mean value indicators from these runs. Model parameters used in the base-case scenario are summarized in Table S6. In Scenario 1, only the diaper composition is changed. Changes in model parameters for Scenarios 2 and 3 are shown in Tables S7 and S8, respectively.

References

1 UK Environmental Agency. Life Cycle Assessment of Disposable and Reusable Nappies in the UK. http://www.environment-agency.gov.uk; accessed October 28, 2010.

2 EDANA. Sustainability Report: Baby Diapers and Incontinence Products. http://www.edana.org; accessed October 28, 2010.

3 EDANA. Sustainability Report 2007-2008: Absorbent Hygiene Products. EDANA. http://www.edana.org; accessed October 28, 2010.

4 Krajnc, D.; Glavic, P. Indicators of sustainable production. *Clean. Technol. Env. Pol.* **2003**, *5*, 279-288.

5 <http://web.mit.edu/mit_energy>

6 Ortiz, I. M. Life Cycle Assessment as a Tool for Green Chemistry: Application to Kraft Pulp Industrial Wastewater Treatment by Different Advanced Oxidation Processes. Master’s Thesis, Institut de Ciencia I Tecnologia Ambientals, Universitat Autonoma de Barcelona, 2003.

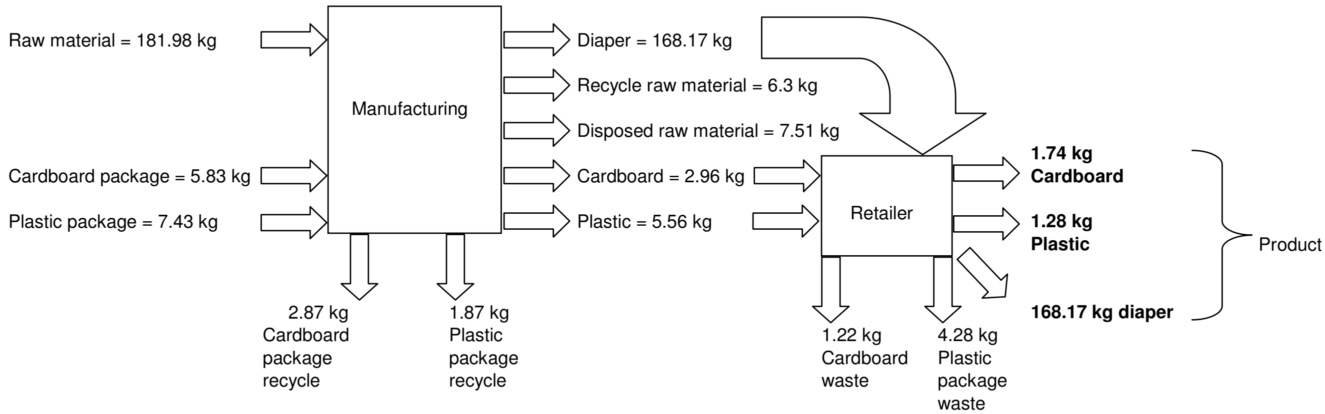

FIGURE S1. Material balance of diaper manufacture and retail

TABLE S1. Diaper component mass balance for 3796 diapers

Component	Input (kg)	Output (kg)	Within Diaper (kg)	Input Ratio
Fluff pulp	72.17	3.05	69.12	1.0441
Superabsorber (SAP)	52.53	0.95	51.58	1.0184
Polypropylene (PP)	24.47	4.41	20.06	1.2198
Polyethylene (PE)	19.74	5.18	14.56	1.3558
Adhesives	5.30	0	5.30	1
Tape/Elastic	1.78	0	1.78	1
PET/Others	5.99	0.22	5.77	1.0381
Total	181.98	13.81	168.17	

TABLE S2. Diaper compositions and the required raw materials input

Component	Input Ratio	1987		2005	
		Within Diaper (g)	Input (g)	Within Diaper (g)	Input (g)
Fluff pulp	1.0441	54.94	57.36	14.57	15.22
Superabsorber (SAP)	1.0184	0.74	0.75	13.65	13.90
Polypropylene (PP)	1.2198	4.36	5.31	7.22	8.81
Polyethylene (PE)	1.3558	4.29	5.81	2.69	3.64
Adhesives	1	1.34	1.34	1.76	1.76
Tape/Elastic	1	0.20	0.20	0.21	0.21
PET/Others	1.0381	1.14	1.18	1.85	1.92
Total		**67.01**		**41.95**	

TABLE S3. Raw materials required to produce one carton of diapers (1440 diapers).

Component	1987 (kg)	2005 (kg)
Fluff pulp	82.60	21.91
Superabsorber (SAP)	1.08	20.02
Polypropylene (PP)	7.65	12.69
Polyethylene (PE)	8.37	5.25
Adhesives	1.93	2.54
Tape/Elastic	0.29	0.30
PET/Others	1.70	2.76

TABLE S4. Energy content of various fuels

Fuel	Energy Content (kJ/kg)	Reference
Coal	29	(4)
Crude oil	43.8	(5)
Natural gas	52.69	(4)

TABLE S5. Environmental impact per unit for each stage in the diaper supply chain.

Stage	Notation	ARD (g Sb eq)	GWP (kg CO_2 eq)	ODP (mg CFC-11 eq)	PO (g C_2H_2)	ACD (g SO_2 eq)	EUT (g PO_4 eq)	HT (g 1,4-DB eq)	FWAE (g 1,4-DB eq)	TE (g 1,4-DB eq)	WU (kg H_2O)	EC (MJ)
Raw materials[a]	$EIRM_{i,r}$											
Fluff pulp		3.2	0.513	0	0.15	5.1	1.1	34.6	2.5	1.2	245	7.0
SAP		29.7	3.122	0	0.67	20.0	1.4	198	2.3	15	143	66.9
Polypropylene		40.9	3.515	0	1.27	37.6	2.3	69.5	1.2	11.9	288	91.5
Polyethylene		36.0	2.634	0	0.71	21.3	1.6	40.5	1.0	9.6	64	81.7
Adhesive		37.7	3.208	0	0.76	22.6	1.9	415	1.9	7.5	145	83.7
Elastic		44.9	3.371	0	1.12	28.1	2.2	169	0	11.2	275	96.8
Others		31.1	4.444	0	0.89	62.2	0	400	8.9	8.9	0	74.1
Raw material transport[b]	$EITRM_i$	0.502	0.077	0.0066	0.013	0.902	0.162	17.9	1.2	0.045	0	1.23
Manufacturer[c]	EIM_i	129.3	22.63	1.796	-0.72	61.1	5.4	5928.1	715.0	68.3	28	443.1
Packaging[c]	$EIPkg_i$	107.8	4.311	0.359	0	50.3	1.1	251.5	10.8	3.6	64	247.4
Diaper transport[d]	$EITP_i$	1.941	0.298	0.254	0.032	3.305	0.674	58.1	4.5	0.088	0	2.86
Distributor[c]	EID_i	64.7	9.70	7.186	2.16	53.9	5.7	3161.6	326.9	32.3	41	246.9

[a]Impact per kg of raw material

[b]Impact per tkm (i.e., t of raw material × km distance traveled)

[c]Impact per carton diaper

[d]Impact per km distance traveled

TABLE S6. Model parameters for the base case

Entity	Parameter Description	Value(s)
Customer	Order frequency (order per day)	0.5
	Minimum order size (carton)	50
	Maximum order size (carton)	300
	Demand random seed	varies
	Number of cycles in 360 days	2
	Amplitude of cycles (carton)	4
	Growth in 360 days (%)	8
	Base daily demand (carton)	60
	Daily uncertainty limit ± (carton)	5
	Due date (days)	15-25
	Location x-coordinate range	Customer Set 1: 0-5 Customer Set 2: 5-10
	Location y-coordinate range	0-10
Manufacturer	Location (x, y) coordinate	(3, 3)
	Initial raw material inventory (kg) for [Fluff pulp, SAP, PP, PE, Adhesive, Elastic, Others]	[21.91, 20.01, 12.69, 5.25, 2.54, 0.30, 2.76] × 3000
	Processing time per carton diaper (days)	0.006666
	Packaging time per carton diaper (days)	0.006666
	Raw material lead time (days)	4.3
	Raw material inventory reorder point (kg)	[21.91, 20.01, 12.69, 5.25, 2.54, 0.30, 2.76] × 2000
	Raw material inventory top-up point (kg)	[21.91, 20.01, 12.69, 5.25, 2.54, 0.30, 2.76] × 3000
	Supplier-plant distance (km)	100
Distributor	Location (x, y) coordinate	(3, 5)
	Transportation time per unit distance (days)	0.5
	Initial distributor inventory (carton)	2000
	Procurement interval (days)	1
	Top-up point (carton)	2000
Economics	Raw material costs ($/kg) for [Fluff pulp, SAP, PP, PE, Adhesive, Elastic, Others]	[3.13, 4.24, 3.73, 3.72, 4.61, 3.26, 3.81]
	Packaging cost ($/carton)	15.38
	Manufacturer processing cost ($/tick)	5
	Manufacturer fixed operating cost ($/tick)	48
	Manufacturer raw material inventory cost ($/kg/tick)	0.0004125
	Manufacturer to distributor transport cost ($/trip)	1930
	Manufacturer product selling price ($/carton)	480
	Distributor product purchase price ($/carton)	480
	Distributor product selling price ($/carton)	750
	Distributor fixed operating cost ($/tick)	40
	Distributor to customer delivery cost ($/carton/unit distance)	24
	Distributor inventory cost ($/carton/tick)	0.039105

TABLE S7. Changes from the base case for Scenario 2

Entity	Parameter Description	Value(s)
Distributor 1	Location (x, y) coordinate	(3, 5)
	Initial distributor inventory (carton)	1000
	Procurement interval (days)	1
	Top-up point (carton)	1000
Distributor 2	Location (x, y) coordinate	(8, 4)
	Initial distributor inventory (carton)	1000
	Procurement interval (days)	1
	Top-up point (carton)	1000

TABLE S8. Changes from the base case for Scenario 3

Entity	Parameter Description	Value(s)
Distributor	Initial distributor inventory (carton)	4000
	Procurement interval (days)	2
	Top-up point (carton)	4000