The dynamic behavior of a zero-to-landfill strategy for consumer products

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Abstract

Environmental strategies such as Zero-to-Landfill are gaining increasing attention throughout the world. Product take back is a significant means of ensuring that products that have reached the end of their useful lives are reclaimed for reuse, remanufacturing, or recycling. Such a strategy is expected to minimize environmental impacts, reduce overall resource consumption, and provide economic value to manufacturers and consumers. The reverse logistics, however, can be quite complicated as product collection, product disassembly, processing, component returns, and component reclamation must be considered. Further, the costs and magnitude of the requisite system must be projected to support appropriate planning and execution. In this paper, we present a model of a reverse logistics system for a consumer product. The impacts of closed-loop policies on material reclamation, product adoption rate, and product costs are investigated. We illustrate how a reverse logistics approach may develop as a function of product adoption, the total value of returned components, product reliability, and product lifetime. A Zero-to-Landfill strategy has a significant potential to improve the triple bottom line – people, planet, and profit – of companies that adopt it.

Keywords: Sustainability, zero-to-landfill, strategy, remanufacturing, extended product responsibility

Introduction

Sustainability is the ability "…to meet the needs of the present without compromising the ability of future generations to meet their own needs." (Brundtland 1987) Rapid growth in population and in standards of living around the world are causing corresponding increases in demand for limited and, in some cases, dwindling resources. The need for sustainable business practices is rapidly growing in importance. Governments and forward-looking businesses are searching for ways to ensure availability of resources to meet growing demand.

There are many ways for businesses to become sustainable, meaning a business "competes in the market place because it delivers goods or services that reduce energy consumption, pollution, and other forms of environmental damage." In this paper, we examine the implementation of a zero-to-landfill (02L) policy in a business producing durable consumer goods. Returning obsolete or replaced products and service components for reuse, remanufacture, or recycling closes the loop on resource usage, thereby increasing the efficiency of material usage. We consider the material stocks and flows associated with the reverse logistics of collecting and disassembling products, segregating and processing the components, and returning processed materials to production. We show that to meet high levels of reclaimed and reclaimable materials, procurement of such components is required because production rates greatly exceed return rates. The simulations demonstrate that processing rates for returned goods have little influence on the amount that is not reclaimable, while cost and processing learning rates have significant impacts on reclaimable material. It is also shown that a true 02L goal is difficult to achieve in the absence of waste-free processing, manufacturer control of the product at end of life, and availability of reclaimable components. Based on our findings, we suggest policies that should facilitate a successful 02L policy and we suggest additions to our model to broaden its applicability and versatility.

Material stocks and flows

Closing the materials loop is becoming increasingly mandated in some parts of the world, particularly Europe and Japan, through extended producer responsibility (EPR) legislation[1]. In the United States, industry opposition to mandatory EPR is causing producers to develop alternatives to eliminating waste and conserving resources. Many visionary companies are adopting the concept of zero-to-landfill products as one means of meeting the objectives of EPR. In a 02L strategy, the materials used in producing goods and services are returned for reclamation in a closed loop. Obsolete products and replaced parts are returned from the field, processed, and then returned to manufacturing for use in another product. The ability to meet this goal and the effects of this strategy on sales and corporate earnings will develop over an extended period, which makes system dynamics an ideal tool to simulate the results of corporate actions. A review of the reverse supply chain and reverse logistics literature found many authors have described the challenges, opportunities, and strategies associated with product recovery (e.g., Hart 1997, Toffel 2004, Prahinski 2005, Biehl 2005). In modeling such systems, extensive use is made of Markov chain (e.g., van der Laan 1996, 1997, 1999) and dynamic programming (Guide 1997, Richter 2001) methods, but no system dynamics modeling was found.

For the purposes of this work, products are defined as "machines," since the specific products we are considering are consumable durable goods, such as automobiles and appliances, rather than consumer products such as toasters and furniture. While material quantities could be described in units of mass or volume or number of parts, we chose to use the unit "machine" throughout. All stocks and flows therefore represent an equivalent number of machines, but, given sufficient details from bills of material or other data, these could just as easily be converted to mass, volume, or numbers of parts to more accurately represent real physical quantities. Fractions are used to indicate the relative amounts of complete machines that enter each of the flows in the

[1] For example, in the EU, *Directive 2000/53/EC of the European Parliament and of the Council on End-of-Life Vehicles*, September 18, 2000, mandates manufacturer responsibilities for automobiles. In Japan, the *Specified Home Appliance Recycling Law*, enacted in 1998 and in effect in 2001, requires product take back of televisions, refrigerators, washing machines, and air conditioners.

model. These simplifications, however, do not impact the conclusions that may be drawn from the results presented here. Additionally, the model is generally applicable to any type of product.

The stock-and-flow structure of a closed loop system is shown in Figure 1. There are four classes of materials and many steps in this system, as described below. Additional detail for the stocks and flows of remanufactured materials is shown in Figure 2. The complete model is provided as an Appendix.

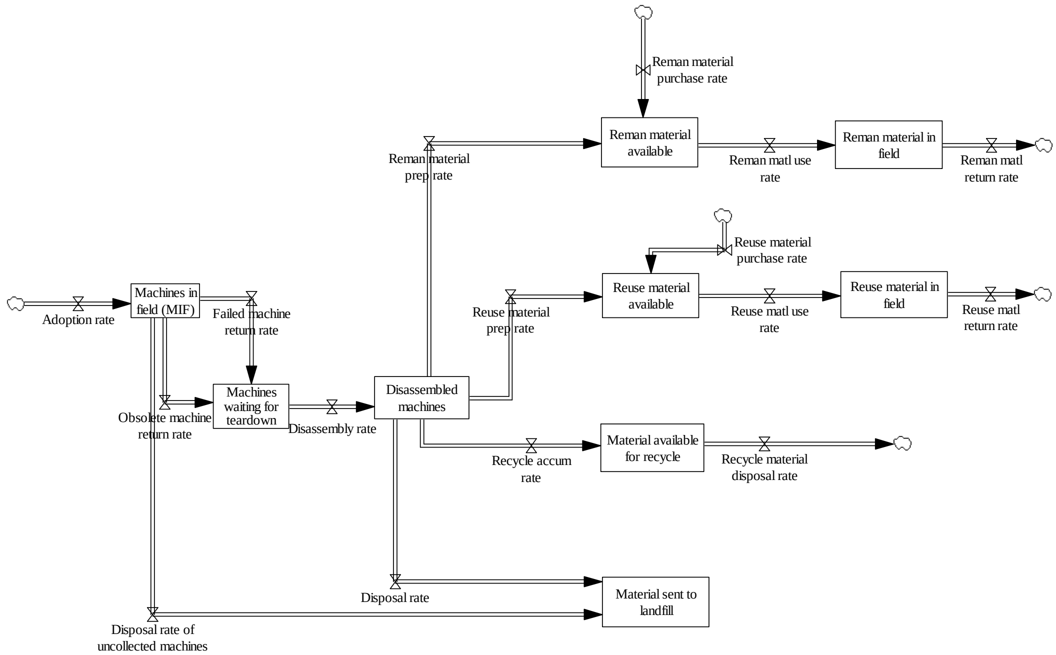


Fig. 1. Material stocks and flows in a simplified closed-loop system.

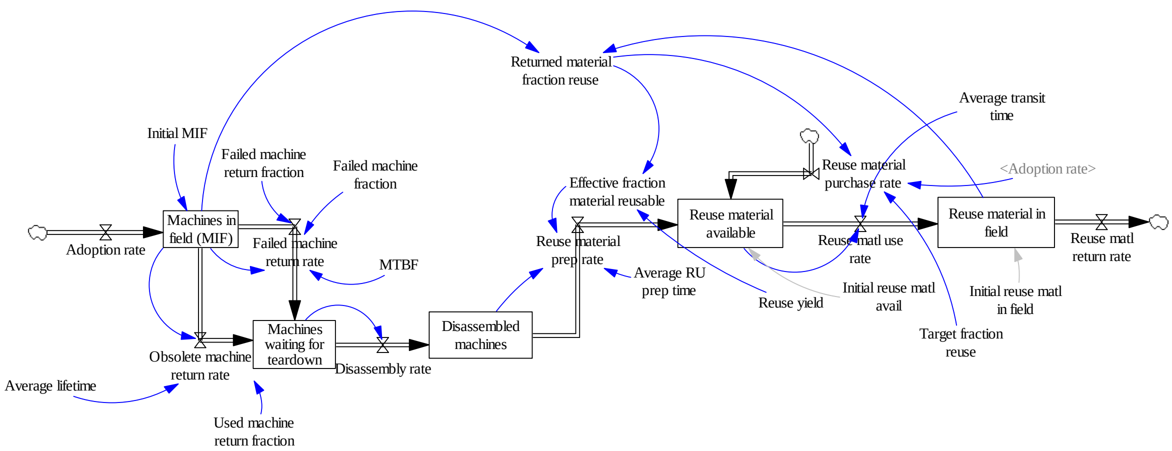


Fig. 2. Portion of complete model illustrating the causal loops associated with material reuse. Some causal links removed for clarity; full model presented in the Appendix.

Installed machines may be removed from service due to obsolescence or due to failure. Components are replaced through preventive or corrective maintenance. Ideally, all of the machines that reach end of life and all replaced components will return to the manufacturer; however, some leakage from the loop is expected. Causes of such “lost” material may include a lack of sufficient incentive or obligation on the part of owners to return obsolete machines, emergence of an aftermarket of buyers and sellers, and greater difficulty and cost for service technicians to return replaced components than to dispose of them.

Once returned to the manufacturer (or perhaps a third-party service provider), machines are disassembled and the materials segregated for reclamation. The model has four parallel material flows, each of which is an aging chain. The four general types of materials are: (1) those that can be reused, (2) those that can be remanufactured, (3) those that can be recycled, and (4) those that are directly discarded. These divisions are based in part on those used by Chen, et al., in defining their cost benefit analysis (Chen 1993) and by Rogers and Tibben-Lembke in their review of reverse logistics trends and practices (Rogers 1998). The following definitions apply:

> *Reuse* – a component is used again for the same purpose, requiring only simple processing such as washing to make it “like new.” Examples might be stainless steel pipes and fittings.
>
> *Remanufacturing* – a component is returned to a “like new” state after some disassembly, cleaning, replacement of worn subcomponents, and reassembly. An example might be pumps returned to production after replacement of bearings.
>
> *Recycling* – a component is reduced to its basic elements (Rogers 1998), which are then used in other products. An example might be rubber hoses and plastic components that are ground up and used as feedstock for new rubber or plastic products.

All other materials are considered to be unusable and destined for disposal in a landfill. In this paper, *reclaimed materials* are the reused and remanufactured components - those that are removed from returned machines, processed, and returned to production.

Several assumptions are made in our model regarding the segregation of returned materials. First, reuse and remanufacturing applies only to those components that may be used again in the manufacturer’s products; if not, they are part of the recycled or disposed quantities. Second, materials sent for recycling are not considered to be automatically returned to the manufacturer in the form of new components. Recycled materials represent a potential revenue stream resulting from the sale of materials that a manufacturer cannot use to processors or other entities.

Since materials that are not returned to the manufacturer are therefore not under the control of manufacturer, it is assumed that material leaking from the system will ultimately end up in a landfill. This may not be the case in actuality, but it is conservative and allows us to simulate the effects of such losses. Material is also assumed to be lost to landfills due to reuse material processing and remanufacturing; again, this provides another opportunity for control of the cycle to minimize waste.

Product returns are assumed to be the result of random events. Newer machines may fail before older machines, for example. Therefore, the fraction of each returned product that falls into each of the material categories described earlier may be estimated as the ratio of the total amount of each type of material currently in the field to the total number of machines currently in the field. For example,

$$\textit{Fraction of returned product reuse} = \frac{\textit{Reuse material in the field}}{\textit{Total machines in the field}} \tag{1}$$

defines the average amount of reusable material in returned machines. In practice, the actual breakdown of returned products may be known based on production records; for this work, an average composition is sufficient to illustrate the behavior of the system.

The model assumes a hierarchy of reclaimed materials, in which reuse and remanufacturing will result in greater value to the manufacturer than will the sale of material for recycling. The cost to reuse and remanufacture components is expected to be less than new components, thereby enabling the final product to be sold for a greater profit or at a lower price with correspondingly greater sales. Disposal is the least preferable not only because it does not meet the intent of a 02L strategy, but also because this end state results in a loss of material from the closed loop while incurring disposal costs. The following relationship is used:

$$\textit{Returned fraction landfill} = 1 - \textit{Returned fraction reuse} - \textit{Returned fraction reman} - \textit{Returned fraction recycle} \tag{2}$$

where *Returned fraction reuse*, *Returned fraction reman*, and *Returned fraction recycle* reflect the composition of the products returned at each time step. Material composition in returned systems is used as an approximation of new production because these fractions are determined from measurable quantities; the fractions could be estimated from consumption rates, but these are after-the-fact and are not as indicative of progress toward zero-to-landfill.

Lastly, the model assumes the existence of reused or remanufactured components outside of the product returns. It also assumes that recycled content represents new materials that may be recycled and may include some recycled content themselves. This is similar to the packaging for many consumer products – the package as purchased contains some recycled material that (most likely) did not come from the package purchaser. Xerox estimates that reclaimed parts can comprise up to 90% of a new machine's weight (Xerox 2001).

Product costs, prices, and adoption

The causal loop diagram for cost, price, sales rate, and material content is shown in Figure 3. To simplify the model, we assume a linear relationship between sales rate and price:

*Adoption rate = (Adoption rate at target price / (Target price - Price no buy)) * (System price - Price no buy)* (3)

The *Target price* reflects an estimate of the market demand curve. *Price no buy* is the price at or above which no sales will be made – the product is too expensive for its value proposition. These define two points on a line that is described by Equation (3). This simplification allows the model to demonstrate trends in lieu of inclusion of a more robust product diffusion model.

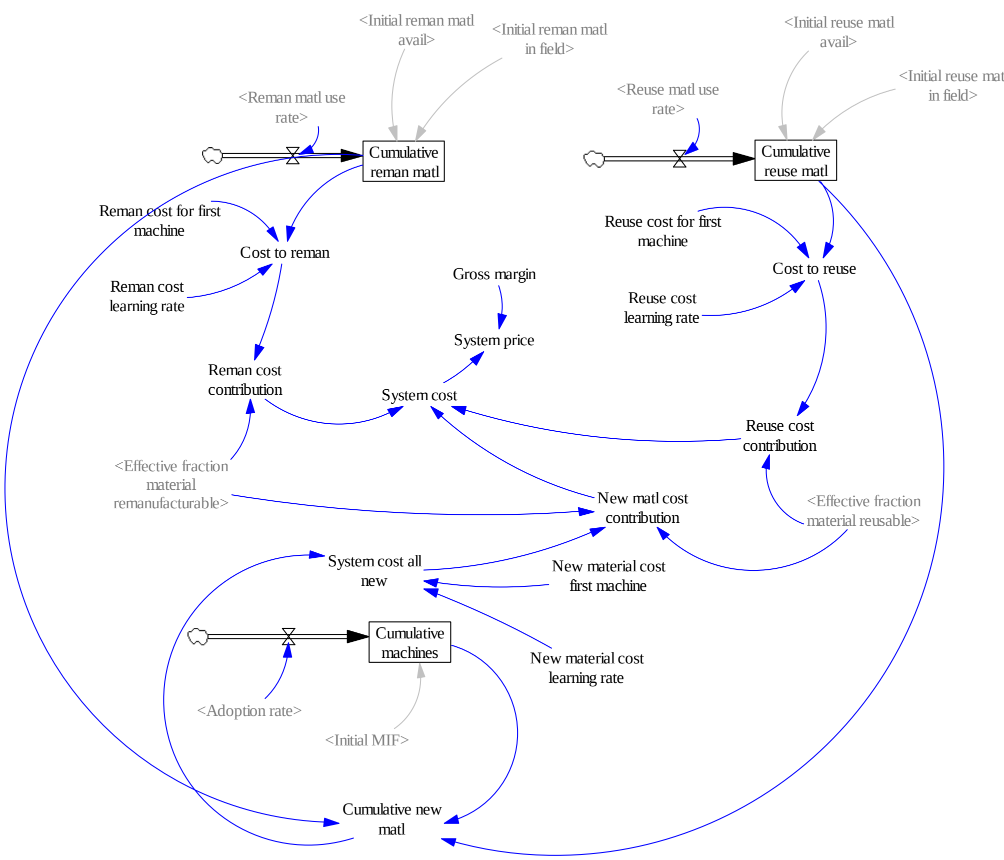


Fig. 3. Cost portion of the model.

Separate cost functions are included for reused, recycled, and new material. It is assumed that these experience curves hold for the entire period of the simulations. For each type of material, the cost for the first machine to be built of that material and a learning rate are specified; these determine the cost as a function of cumulative production according to the following relationship:

$$Cost_2 = Cost_1 * (Volume_1 / Volume_2)^b \qquad (4)$$

where $Cost_i$ occurs at cumulative production $Volume_i$. The learning rate represents the fraction of cost reduction that occurs with each doubling of production due to operator learning, product and process improvements, and economies of scale (Teplitz 1991); therefore, *b*, the slope of Equation 4 on a log-log plot, is

$$b = \ln(1 - \text{Learning rate}) / \ln(2) \tag{5}$$

Costs for reuse and remanufacturing are assumed to represent all costs associated with producing these materials – shipping of returned product, disassembly and segregation, processing, and all associated costs. These represent the direct material costs for reclaimed components and materials. The cost of reused and remanufactured components in new machines is determined using the *Effective fraction material reusable* and the *Effective fraction material remanufacturable*, respectively; these represent the amount of returned product that is returned for production after accounting for processing losses. The relevant equations for remanufactured components are:

$$\text{Effective fraction material remanufacturable} = \text{Returned material fraction remanufacturable} * \text{Reman yield} \tag{6}$$

$$\text{Cost to reman} = \text{Reman cost for first machine} * \text{Cumulative reman matl}\verb|^|(\ln(1 - \text{Reman cost learning rate}) / \ln(2)) \tag{7}$$

$$\text{Reman cost contribution} = \text{Effective fraction material remanufacturable} * \text{Cost to reman} \tag{8}$$

Equations for reused components are similar. Total product cost is the sum of the costs for the reused, remanufactured, and new components. Product price is simply cost plus gross margin, which is assumed to be a constant percentage in this model.

Effects of policies

In our simulations, we examined the behavior of a zero-to-landfill strategy for a manufacturer of durable consumer products. Several simulations were run to examine the effects of different policies and conditions on the company's ability to reach a goal of a zero-to-landfill product over 30 years. The values of the key input parameters for this company are provided in Table 1.

The first case to be examined was the situation where the only source of reusable and remanufacturable materials was the stock of returned products. Because sales rates greatly exceeded return rates, the initial stocks of reclaimed material were rapidly depleted, with returned material being consumed as soon as it was available for production (Figure 4). The fraction of returned machines and the total amount of material thus going to a landfill increase over time (Figure 5). Zero-to-landfill products therefore require an external source of reclaimable components to meet increasing demand.

Table 1. Summary of the values of key input parameters for the simulations. A complete listing of the model is provided in the Appendix.		
Parameter	**Value**	**Units**
Adoption rate at target price	2,000	Machines/year
Average lifetime	10	Years
Average RU prep time	0.25	Years
Average reman time	0.25	Years
Failed machine fraction	0.02	Dimensionless
Failed machine return fraction	0.8	Dimensionless
Gross margin	0.5	Dimensionless
Initial fraction recycle	0.2	Dimensionless
Initial reman matl available	30	Machines
Initial reman matl in field	0	Machines
Initial reuse matl available	30	Machines
Initial reuse matl in field	0	Machines
MTBF	0.5	Years
New material cost first machine	50,000	$/machine
New material cost learning rate	0.15	Dimensionless
Price no buy	100,000	$/machine
Reman cost for first machine	15,000	$/machine
Reman cost learning rate	0.05	Dimensionless
Reman yield	0.9	Dimensionless
Reuse cost for first machine	15,000	$/machine
Reuse cost learning rate	0.05	Dimensionless
Reuse yield	0.9	Dimensionless
Target price	30,000	$/machine
Used machine return fraction	0.8	Dimensionless

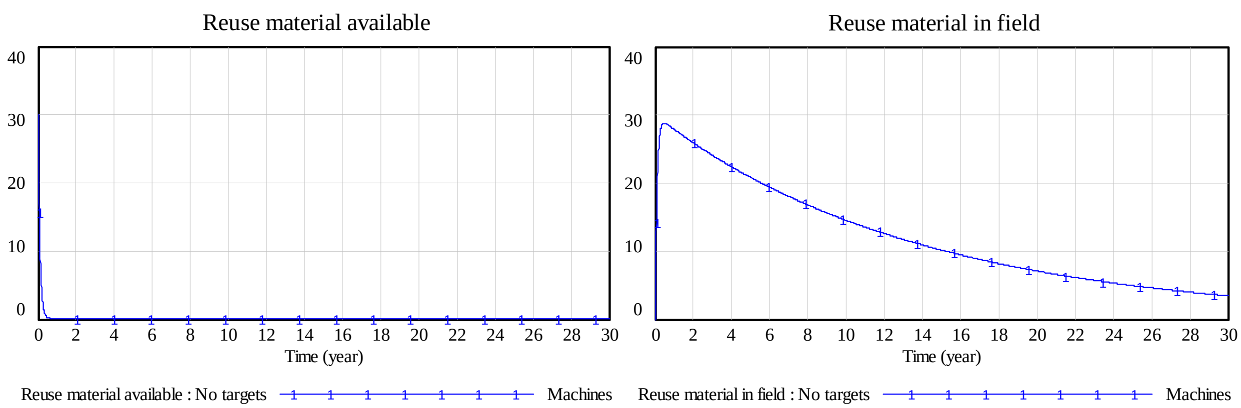


Fig. 4. Behavior of reused material stocks in the first scenario. No product content targets are set, initial stock of available reused parts is 30 machines, and there are no reusable parts in the field at the beginning of the simulation. The behavior of remanufactured material stocks is identical.

The baseline scenario

For the remainder of the scenarios evaluated, the simulations included procurement of reusable and remanufacturable components to meet production requirement in excess of the flow of returned components. Targets were stipulated for both reusable and remanufacturable material content in new products. These simulations therefore clearly assume the availability of a market for reusable and remanufacturable components. Baseline conditions for these simulations are the same as in Table 1 with the addition of specifying *Target fraction reman* = 0.2 and *Target fraction reuse* = 0.8.

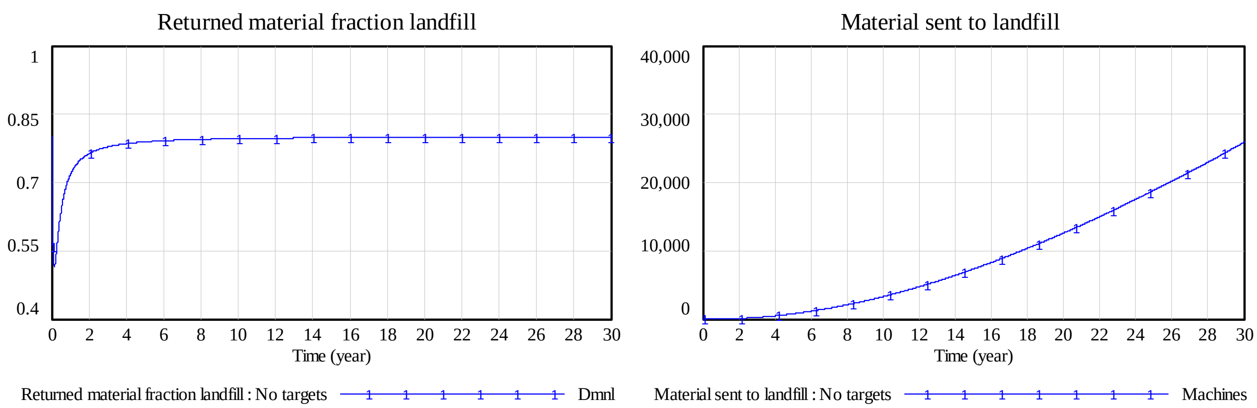


Fig. 5. Landfill fraction and cumulative quantity of disposed material for the first scenario, in which no product content targets are set.

Since recycling is less valuable than the other reclamation options, the amount of recycled material is crowded out by increasing reuse and remanufacturing and the corresponding recycle fraction is estimated as

Returned fraction recycle = max(0, Initial fraction recycle(1 - (Returned material fraction reman + Returned material fraction reuse) / (Target fraction reuse + Target fraction reman))* (9)

As the amount of reused and remanufactured material increases, the amount of recyclable material decreases from an initial fraction, approaching zero as reuse and remanufacturing targets are met. This is shown graphically in Figure 6.

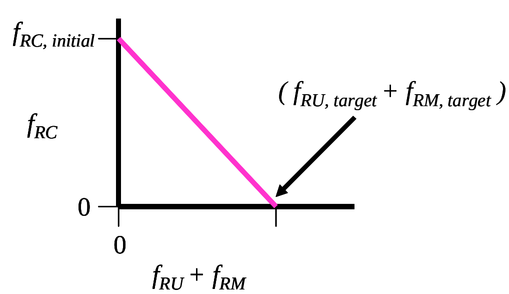
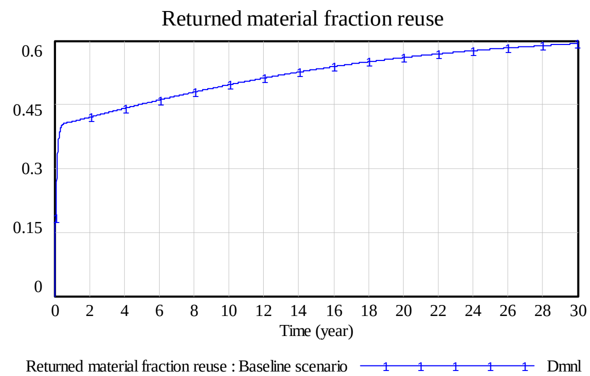


Fig. 6. Assumed relationship between the fractions of reused (f_{RU}), remanufactured (f_{RM}), and recycled (f_{RC}) material in returned products when target fractions are imposed.

There are substantial differences in the baseline behavior of the costs of reused, remanufactured, and new materials. First, the absolute cost of reused and remanufactured materials is less than that for new materials, reflecting lower costs to collect, store, and process used components. Ginsburg (2001) reported that remanufactured products cost 40 – 65% less to produce than new products; an internal study found that the cost of remanufactured and reused component is approximately 70% of that of new ones (de la Puente 2005). An initial ratio of 50% was used in the baseline scenario. Conversely, reclaimed components are assumed to be more of a commodity with a lower learning rate than that of new components. For new materials, we use a learning rate of 15%, which is typical for many products (Dutton 1984); for reclaimed materials, the learning rate is assumed to be 5% (Hess 2001).

The behavior of the baseline scenario is shown in Figure 7. The amount of reused and remanufactured material in new products increases over time, but due to all of the delays in the system, these fractions do not reach their target levels. The amount of waste material is significantly less than in the case with no specified procurement of such materials. These results suggest that, for a single company, achieving a closed loop of materials will be difficult.



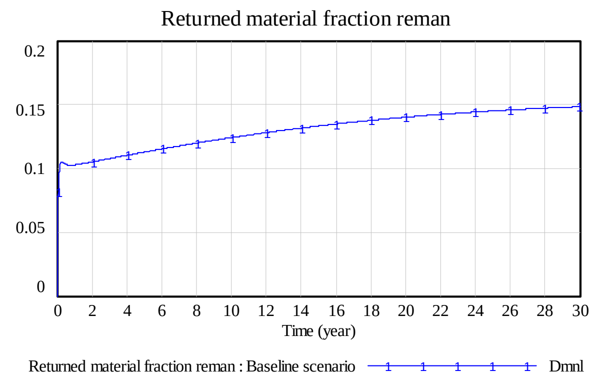
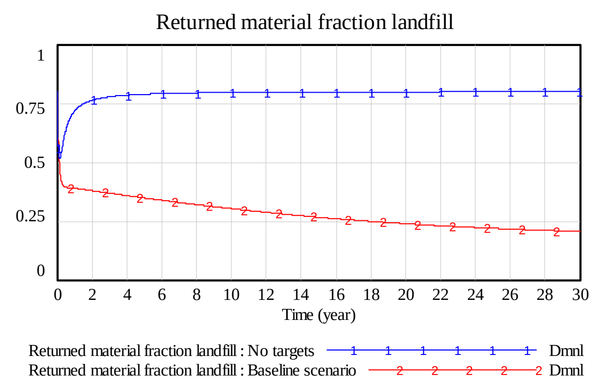


Fig. 7. Behavior of the fraction of remanufactured, reused, and disposable material in new products in the baseline scenario. The implementation of targets and the procurement of reusable and remanufacturable materials result in a significant reduction in the fraction of machines that is sent to landfills.



Product sales for the baseline scenario are compared with those of the initial no-procurement scenario in Figure 8. Sales and adoption rates are less when greater numbers of reused and remanufactured components are included in the product. Increased use of reclaimed materials results in slower price reductions that in turn reduce adoption rates, even with lower initial costs for the reused and remanufactured materials. In this situation, striving for a 02L product reduces sales and revenues. Achieving 02L products requires manufacturers to consider the economic feasibility and implications along with the design and environmental implications.

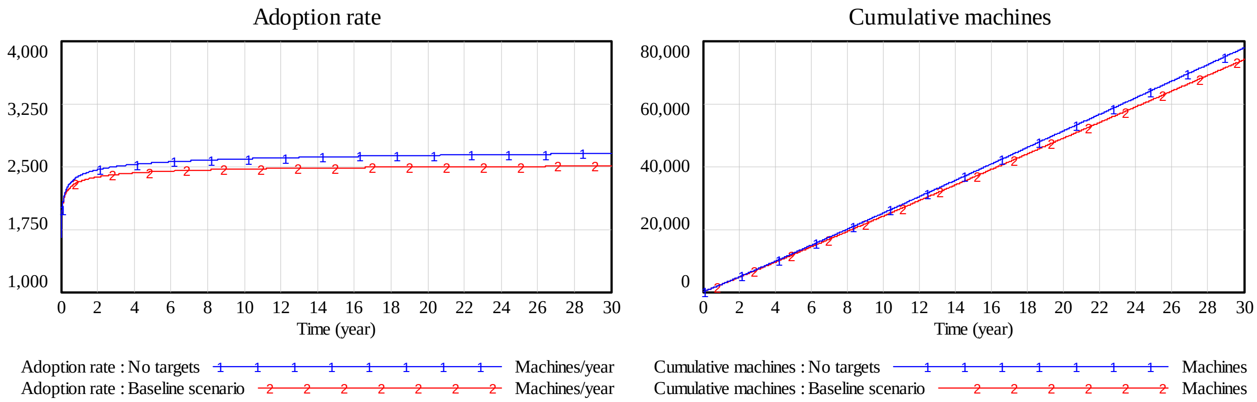


Fig. 8. Effect of implementation of targets and the procurement of reusable and remanufacturable materials on product sales.

In this work, we are considering only those macroscopic factors that impact the ability of a company to manufacture and sell a 02L product. Economic considerations beyond a relationship between price and sales are not made in this work. The stock and flow diagram in Figure 1 suggests several corporate actions that might improve the ability to achieve zero-to-landfill. Specifically, maximizing throughput of returned products is expected to accelerate the fraction of reused components in new products by making more of these materials available for new machines. Reducing the costs and increasing the learning rates of producing reused and remanufactured components will reduce product price and accelerate sales, resulting in more returned products and material for reclamation. Minimizing the leakage of materials from the system will increase the stock of returned materials available for reclamation.

Accelerated throughput rates

Application of more resources or additional equipment will increase the rate of processing materials for reuse or the rate of remanufacturing. By increasing these rates, the inventory of these materials available for production will increase and the need to purchase new materials will decrease. The effects of reducing both the *Average reman time* and the *Average RU prep time* by a factor of two, from 0.25 year to 0.125 year, are shown in Figure 9. This policy of rapid redeployment of returned materials will achieve an even lower landfill fraction without impacting sales relative to the baseline scenario. The increases in remanufactured and reused material content do not increase price enough to significantly impact sales.

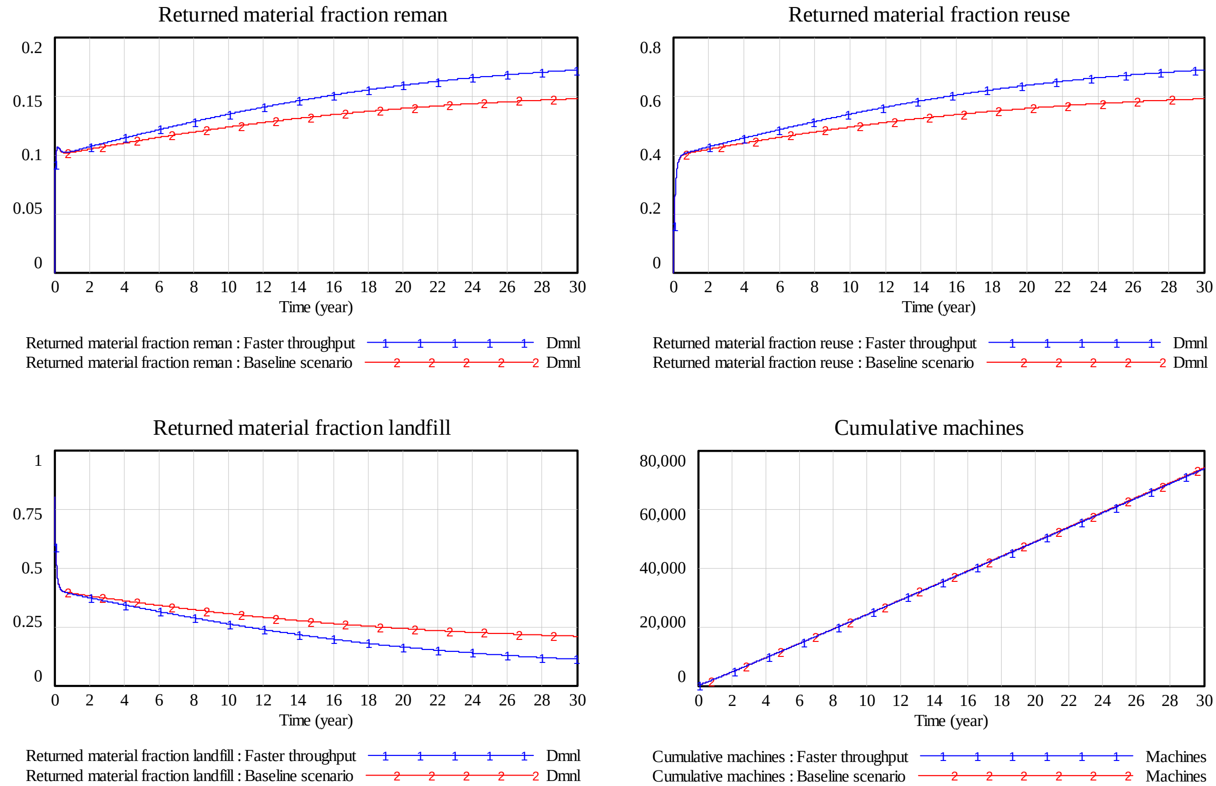
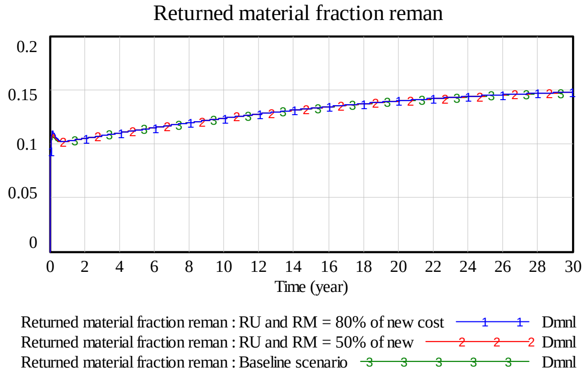


Fig. 9. Halving the time required to process components for reuse or to remanufacture components will significantly reduce the fraction of machines that cannot be reclaimed with minimal impact on sales.

Effect of initial costs of reused and remanufactured materials

In the baseline scenario, reused and remanufactured materials were assumed to be only 30% of the cost of new materials at the start of the simulation. The sensitivity of material fractions and sales to the cost of reclaimed materials was determined by increasing the initial cost of reclaimed materials to 50% and then to 80% of the initial cost of new materials. The results are summarized in Figure 10.



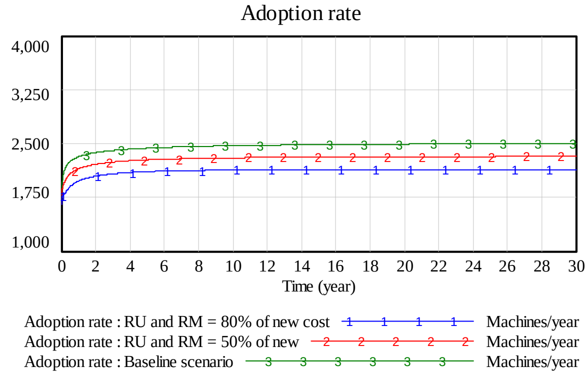


Fig. 10. Effect of initial cost of reused and remanufactured materials on material content and product sales rate.

Reducing the cost of reused and remanufactured materials allows for a lower price to be charged for the same gross margin rate, thereby increasing sales. However, this behavior does not change the ratio of the usage to return rates, so there is no effect on product material content. The total amount of material that ends up in a landfill will increase with increasing sales.

Effect of initial costs of new materials

Cost reductions, whether through design and process improvements or as the results of supply chain activities, will result in lower prices and therefore increases sales. The behavior of the system was as expected – reducing these costs does ultimately increase total sales. As with lower costs for reclaimed materials, the fraction of the product that is destined for disposal is independent of these material costs, while the total number of machines sent to a landfill does increase with decreasing costs. All of the flows are proportional to the number of machines sold and material costs do not impact the processing parameters in the material flows, so no effect on material fractions should be found.

Effect of cost learning rates

In the baseline scenario, the cost of new components decreased more rapidly than the cost of reused or remanufactured components. It is possible that the learning rate for new components may be less than used in the baseline scenario because of slower or fewer design and process improvements over time. Figure 11 illustrates the behavior of the system as the slope, *b*, of the experience curve (Equation 4) of new materials changes.

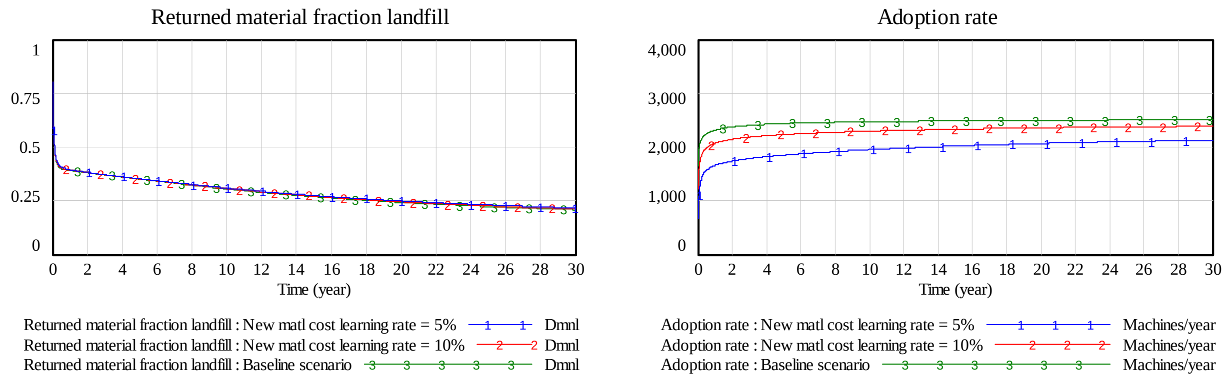


Fig. 11. Effect of learning rate of new material costs on product material content and sales.

The effect of changing the slope of the cost curve for new materials is to change the sales rate. The effect of changing the slope of the experience curves for reclaimed materials are similar to those observed by changing the learning rate of new material costs. Because all material flows are proportional to the number of machines in the field, there is no impact on the content of new products. Acceleration of cost reductions therefore does not by itself contribution to meeting a 02L goal.

Control of ownership at end of life

When a machine reaches the end of its useful life or when components are replaced, the used components may take one of many paths. The machines may be disposed of directly by the last user or, depending on the product, simply abandoned in place. Third parties may purchase the materials to extract any retained value for themselves. Material processing is another source of leaks. The potential leakage from the system reduces the inventory of reclaimed materials and further exacerbates the difficulties associated with achieving a 02L goal.

In the baseline scenario, a return rate of 80% was used. This compares to published product return rates such as 60% of toner cartridges at Xerox (Azar 1996) and 90% of Kodak's single-use cameras (Toffel 2004), but is well in excess of others such as a return rate of 0.18% of power tools in Germany (Klausner 2000). Figure 12 illustrates what happens when the return rate is 100%.

An increase in the product return rate from 80% to 100% results in a slight decrease in the amount of reclaimed material in new products and a corresponding increase in the amount of material for disposal in those products. Because of delays in the system, the ratio of material return rate to material use rate is approximately 2% greater when leases are used than when they are not. This results in a lower net accumulation of reused and remanufactured materials in the field and lower reclaimed material content in new products. This difference is not significant. The important aspect of this policy is that the net accumulation of material in landfills is significantly less when leases are used.

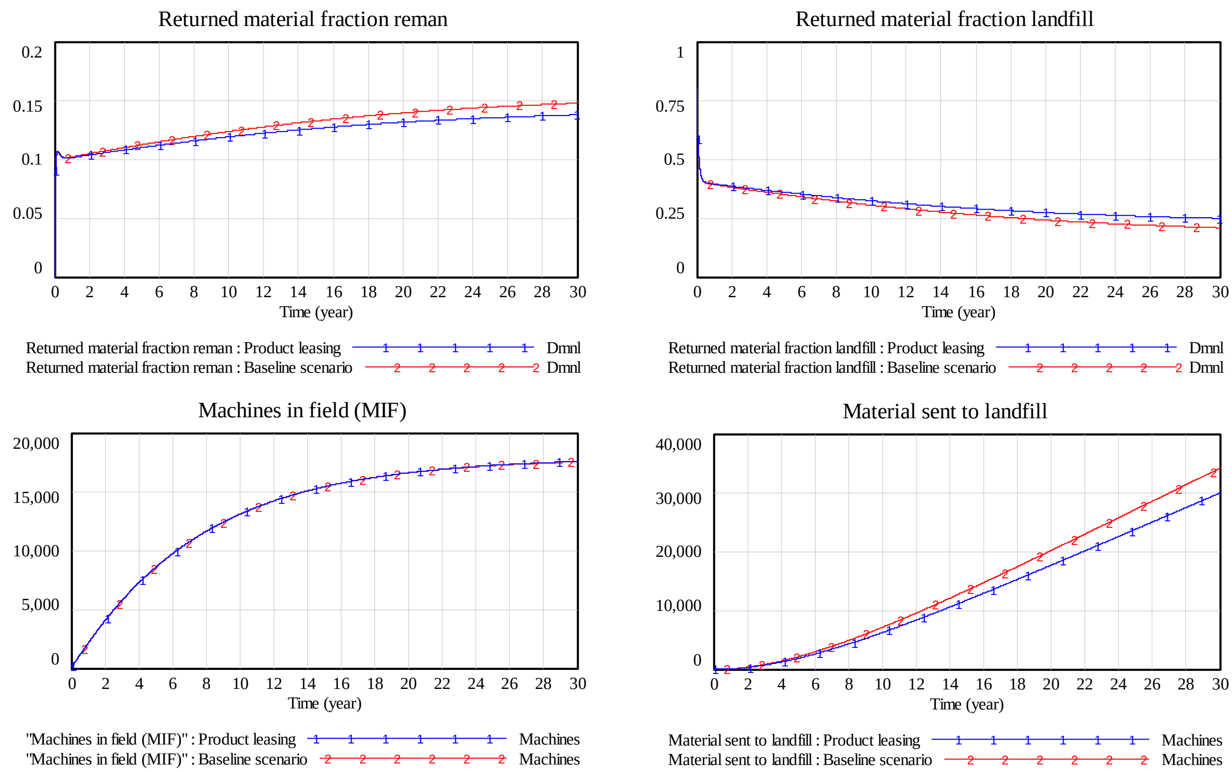


Fig. 12. Effect of leasing on ability to meet a zero-to-landfill goal.

These results suggest that manufacturers need to look to the future and implement policies that will minimize leakage from the system. The imposition of "core charges," similar to those imposed on the sale of lead acid batteries, with new machines sold for a lower price to those who return an old one, may be one means of encouraging returns. Instead of selling the product, the use of operating leases "…increase[s] the likelihood that the manufacturer will retain ownership of the product at end of life and have responsibility for managing it" (Fishbein 2000). Development of reuse and remanufacturing processes with little or no waste will also enhance the ability to meet a zero-to-landfill goal; in addition, such processes may be more environmentally benign in their own right.

Conclusions

Zero-to-landfill products are an important aspect of a sustainable business. The design and economic feasibility of such a goal require understanding of the product, the reverse logistics, and the material stocks and flows in the system. In this work, we have taken a macroscopic view of these aspects of a product take back system to illustrate the effects of corporate strategies on achieving a 02L product.

We have shown that controlling costs will impact product sales and the cumulative amount of materials sent to a landfill, but will not have a significant impact on the final fraction of new products ultimately sent to a landfill. Reducing product costs through the use of low-cost materials and accelerated learning increases sales, as expected. The effect on the financial performance of a manufacturer was not assessed in the simulations, however, and represents one area for enhancement of the model and analysis. A balance between design, environmental, and financial considerations must be struck to ensure that zero-to-landfill goals are economically viable (Chen 1993, Klausner 2000).

Proposed Future Work

The current model is sufficient to provide evaluation of the macroscopic parameters in a zero-to-landfill system. Additional detail is required in the cost models to better ascertain the economic viability of a 02L strategy and to identify more parameters that can be controlled on a local basis. Development of production cost estimates and process time estimates will improve the accuracy and the certainty of the results.

In addition to more accurate cost models, the model will be extended to include corporate financial performance. Infrastructure costs, revenues from the sale of recyclable materials, and variable margins may be added. This work will enable the simulations to project not only the amount of material that is not reclaimed, but also to project the impact on corporate finances.

Incorporation of an appropriate diffusion model will provide more realistic adoption behavior and may provide different insights. Part of this model will include correlations between the amount of reclaimed material in a machine, the customer perception of the quality of that machine, and the resulting price that may be charged for it. Incorporating the Bass diffusion model and extending it to account for customer perception and potential substitution between new and remanufactured products will add richness to the results of these simulations. Some work on a modified Bass model to reflect substitution and endogenous limits on available material has already been reported (Debo 2005).

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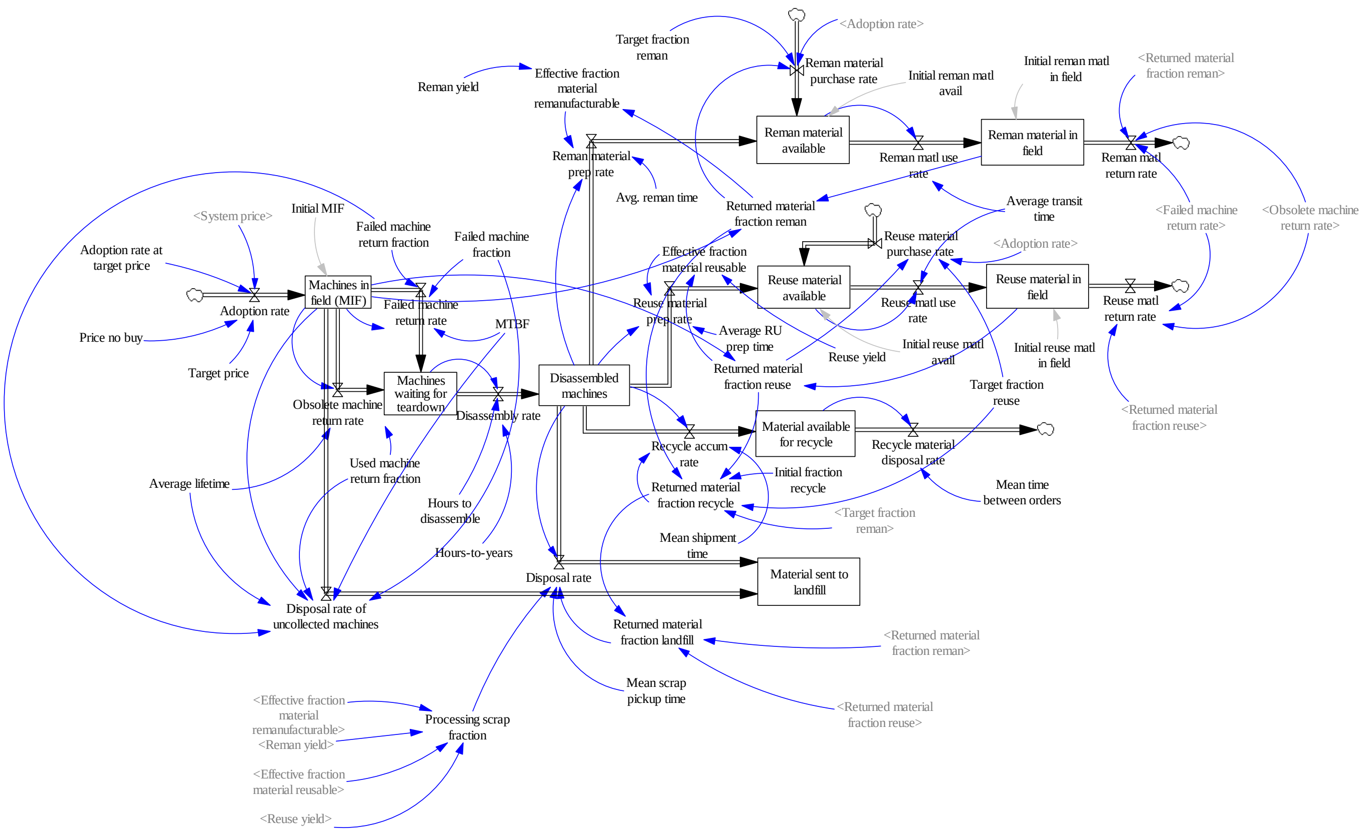
Appendix

The complete model, with the exception of the cost portion shown in Figure 3 of the text, is shown in the following figure.



The Vensim program documentation follows.

(01) Adoption rate=

(Adoption rate at target price/(Target price-Price no buy))*(System price -Price no buy)

Units: Machines/year

Product sales rate.

(02) Adoption rate at target price=

2000

Units: Machines/year

Assumed initial sales rate at the initial price.

(03) Average lifetime=
10
Units: year
Design product life.

(04) Average RU prep time=
0.25
Units: year
Same as for reman.

(05) Average transit time=
0.1
Units: year
Average time to move reman material from storage to production.

(06) "Avg. reman time"=
0.25
Units: year
Average time for remanufacturing.

(07) Cost to reman=
Reman cost for first machine*Cumulative reman matl^(ln(1-Reman cost learning rate)/ln(2))
Units: $/machine

(08) Cost to reuse=
Reuse cost for first machine*Cumulative reuse matl^(ln(1-Reuse cost learning rate)/ln(2))
Units: $/machine
Same as for reman.

(09) Cumulative machines= INTEG (
Adoption rate,
Initial MIF)
Units: Machines
Total number of machines produced over time.

(10) Cumulative new matl=
Cumulative machines-Cumulative reman matl-Cumulative reuse matl
Units: Machines

(11) Cumulative reman matl= INTEG (
Reman matl use rate,
Initial reman matl avail+Initial reman matl in field)
Units: Machines
Total amount of reman material used.

(12) Cumulative reuse matl= INTEG (
Reuse matl use rate,
Initial reuse matl avail+Initial reuse matl in field)
Units: Machines
Same as for reman.

(13) Disassembled machines= INTEG (
Disassembly rate-Disposal rate-Recycle accum rate-Reman material prep rate -Reuse material prep rate,
0)
Units: Machines
The amount of material, expressed as equivalent number of
machines, ready for segregation, disposal, and processing.

(14) Disassembly rate=
Machines waiting for teardown/(Hours to disassemble/"Hours-to-years")
Units: Machines/year
Average time to disassemble a machine.

(15) Disposal rate=
Disassembled machines*(Returned material fraction landfill+Processing scrap fraction)/Mean scrap pickup time
Units: Machines/year
The average rate at which returned material is sent to landfill.
Reflects non-usable and process waste material.

(16) Disposal rate of uncollected machines=
((1-Failed machine return fraction)*Failed machine fraction/MTBF + (1-Used machine return fraction)/Average lifetime)*"Machines in field (MIF)"
Units: Machines/year

(17) Effective fraction material remanufacturable=
Returned material fraction reman*Reman yield
Units: Dmnl
The actual amount of returned material that will be available
for another system.

(18) Effective fraction material reusable=
Reuse yield*Returned material fraction reuse
Units: Dmnl
Same as for reman.

(19) Failed machine fraction=
0.02
Units: Dmnl
The fraction of a machine that will be replaced - through

preventive or corrective maintenance.

(20) Failed machine return fraction=
0.8
Units: Dmnl
Reflects an expectation that some failed or service parts will
not be returned.

(21) Failed machine return rate=
"Machines in field (MIF)"*Failed machine fraction*Failed machine return fraction
/MTBF
Units: Machines/year
The rate at which replaced components or machines are returned
to the reverse logistics chain.

(22) FINAL TIME = 30
Units: year
The final time for the simulation.

(23) Gross margin=
0.5
Units: Dmnl
Converts cost to price.

(24) Hours to disassemble=
90
Units: Hours
Total time, on average, a machine is in the disassembly queue -
includes actual disassembly and waiting time. Smooths the
behavior, which in reality is probably more a step function.

(25) "Hours-to-years"=
8760
Units: Hours/year
Convert hours to years.

(26) Initial fraction recycle=
0.2
Units: Dmnl

(27) Initial MIF=
100
Units: Machines
The existing fleet of products at time = 0. Could be zero or
could represent prototypes.

(28) Initial reman matl avail=
30
Units: Machines
Reflects initial use of reman material.

(29) Initial reman matl in field=
0
Units: Machines
Reflects potential for existing machines to have reman material
in them.

(30) Initial reuse matl avail=
30
Units: Machines
Same as for reman.

(31) Initial reuse matl in field=
0
Units: Machines
Same as for reman.

(32) INITIAL TIME = 0
Units: year
The initial time for the simulation.

(33) "Machines in field (MIF)"= INTEG (
Adoption rate-Failed machine return rate-Obsolete machine return rate-Disposal rate of uncollected machines,
Initial MIF)
Units: Machines
Installed base of product.

(34) Machines waiting for teardown= INTEG (
+Failed machine return rate+Obsolete machine return rate-Disassembly rate,
0)
Units: Machines
Machines entering the reverse logistics path, awaiting
disassembly.

(35) Material available for recycle= INTEG (
Recycle accum rate-Recycle material disposal rate,
0)
Units: Machines
Amount of recyclable material awaiting disposition / sales.

(36) Material sent to landfill= INTEG (

Disposal rate+Disposal rate of uncollected machines,
0)
Units: Machines
Total amount of material sent to landfill.

(37) Mean scrap pickup time=
0.1
Units: year

(38) Mean shipment time=
0.1
Units: year
Avg. time to move material from disassembly to collection point.

(39) Mean time between orders=
0.25
Units: year
Average time between orders for recyclable material.

(40) MTBF=
0.5
Units: year
Mean time between failures - an average for PM and CM.

(41) New material cost first machine=
50000
Units: $/machine
Same as for reman.

(42) New material cost learning rate=
0.15
Units: Dmnl
Same as for reman.

(43) New matl cost contribution=
System cost all new*(1-Effective fraction material remanufacturable-Effective fraction material reusable)
Units: $/machine

(44) Obsolete machine return rate=
"Machines in field (MIF)"*Used machine return fraction/Average lifetime
Units: Machines/year
Rate at which machines reaching end of life are returned.

(45) Price no buy=
100000

Units: $/machine

(46) Processing scrap fraction=
Effective fraction material remanufacturable*(1-Reman yield)+Effective fraction material reusable*(1-Reuse yield)
Units: Dmnl
The amount of returned material that becomes waste via reman and
reuse processing.

(47) Recycle accum rate=
Disassembled machines*Returned material fraction recycle/Mean shipment time
Units: Machines/year
Average rate at which recyclable material is accumulated for
future disposition.

(48) Recycle material disposal rate=
Material available for recycle/Mean time between orders
Units: Machines/year
Average rate at which recyclable material is removed.

(49) Reman cost contribution=
Effective fraction material remanufacturable*Cost to reman
Units: $/machine
The cost for the fraction of a machine made from reman material.

(50) Reman cost for first machine=
15000
Units: $/machine
How much the first machine would cost if made from reman
material.

(51) Reman cost learning rate=
0.05
Units: Dmnl
The rate at which cost is reduced with each doubling of
production.

(52) Reman material available= INTEG (
Reman material prep rate+Reman material purchase rate-Reman matl use rate,
Initial reman matl avail)
Units: Machines
Amount of remanufactured material awaiting use.

(53) Reman material in field= INTEG (
Reman matl use rate-Reman matl return rate,
Initial reman matl in field)

Units: Machines

(54) Reman material prep rate=
Disassembled machines*Effective fraction material remanufacturable/"Avg. reman time"
Units: Machines/year
Average rate of remanufacturing material.

(55) Reman material purchase rate=
max(0,(Target fraction reman-Returned material fraction reman)*Adoption rate)
Units: Machines/year
Average lead and delivery time for purchased material.

(56) Reman matl return rate=
Returned material fraction reman*(Failed machine return rate+Obsolete machine return rate)
Units: Machines/year
Rate of return of remanufacturable material. Reflects average fraction of reman material in the field and the net return rate of material.

(57) Reman matl use rate=
Reman material available/Average transit time
Units: Machines/year
Avg. rate of consumption of reman material.

(58) Reman yield=
0.9
Units: Dmnl
Reflects losses in the reman processes.

(59) Returned material fraction landfill=
1-Returned material fraction recycle-Returned material fraction reman-Returned material fraction reuse
Units: Dmnl
The amount of returned material that goes to landfill. Does not include processing waste.

(60) Returned material fraction recycle=
IF THEN ELSE(Target fraction reman=0, Initial fraction recycle, max(0,Initial fraction recycle-Initial fraction recycle*(Returned material fraction reman+Returned material fraction reuse)/(Target fraction reuse+Target fraction reman)))
Units: Dmnl
Same as for reman. However, assumed that f(RC) = f(RM, RU) and not a constant if there are RM and RU targets.

(61) Returned material fraction reman=
Reman material in field/"Machines in field (MIF)"

Units: Dmnl
The average amount of returned material that is
remanufacturable. Average of total reman in field and MIF.

(62) Returned material fraction reuse=
Reuse material in field/"Machines in field (MIF)"
Units: Dmnl
Same as for reman.

(63) Reuse cost contribution=
Effective fraction material reusable*Cost to reuse
Units: $/machine
Same as for reman.

(64) Reuse cost for first machine=
15000
Units: $/machine
Same as for reman.

(65) Reuse cost learning rate=
0.05
Units: Dmnl
Same as for reman.

(66) Reuse material available= INTEG (
Reuse material prep rate+Reuse material purchase rate-Reuse matl use rate,
Initial reuse matl avail)
Units: Machines
Same as for reman.

(67) Reuse material in field= INTEG (
Reuse matl use rate-Reuse matl return rate,
Initial reuse matl in field)
Units: Machines
Same as for reman.

(68) Reuse material prep rate=
Disassembled machines*Effective fraction material reusable/Average RU prep time
Units: Machines/year
Same as for reman.

(69) Reuse material purchase rate=
max(0,(Target fraction reuse-Returned material fraction reuse)*Adoption rate)
Units: Machines/year
Same as for reman.

(70) Reuse matl return rate=
Returned material fraction reuse*(Failed machine return rate+Obsolete machine return rate)
Units: Machines/year
Same as for reman.

(71) Reuse matl use rate=
Reuse material available/Average transit time
Units: Machines/year
Same as for reman.

(72) Reuse yield=
0.9
Units: Dmnl
Same as for reman.

(73) SAVEPER =
TIME STEP
Units: year [0,?]
The frequency with which output is stored.

(74) System cost=
Reuse cost contribution+Reman cost contribution+New matl cost contribution
Units: $/machine
Reflects all material costs - RM, RU, RC, LF.

(75) System cost all new=
New material cost first machine*(Cumulative new matl)^(ln(1-New material cost learning rate)/ln(2))
Units: $/machine

(76) System price=
System cost/Gross margin
Units: $/machine
Price to end customer.

(77) Target fraction reman=
0.2
Units: Dmnl
A potential corporate goal. Influences purchases.

(78) Target fraction reuse=
0.8
Units: Dmnl
Same as for reman.

(79) Target price=
30000
Units: $/machine
Initial price of system based on initial system cost.

(80) TIME STEP = 0.0078125
Units: year [0,?]
The time step for the simulation.

(81) Used machine return fraction=
0.8
Units: Dmnl
Reflects an expectation that some product will not be returned for a number of reasons.