

THE USE OF ACTIVITY-BASED COSTING, UNCERTAINTY, AND DISASSEMBLY ACTION CHARTS IN DEMANUFACTURE COST ASSESSMENTS

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ABSTRACT

In this paper, the development of an Activity-based Cost (ABC) model is presented for use in design for demanufacture under the presence of uncertainty. Demanufacture is defined as the process opposite to manufacturing involved in recycling materials and product components after a product has been taken back by a company. The crux in developing an ABC model is to identify the activities that will be present in the demanufacturing process of a product, and afterwards assign reliable cost drivers and associated consumption intensities to the activities. Uncertainty distributions are assigned to the numbers used in the calculations, representing the inherent uncertainty in the model. The effect of the uncertainty on the cost and model behavior are found by employing a numerical simulation technique - the Monte Carlo simulation technique. The additional use of disassembly action charts allows the influence of the uncertainty to be traced through the cost model to specific demanufacture process and product design parameters.

OUR FRAME OF REFERENCE

The growing importance of including environmental issues in design has amplified the impetus for companies to more formally consider the entire life-cycle of a product, from cradle to grave or even to reincarnation through recycling and reuse. A crucial issue is the assessment of costs (or profit) related to pursuing environmentally benign products and processes. We believe that in order to provide efficient and effective decision support in life-cycle design, costing methods should: 1) Assess and trace costs and revenues; 2) Handle both overhead and direct costs; 3) Handle uncertainty; 4) Provide decision support for the process of designing.

Attempts to generate formal and systematic design approaches which include environmental considerations, as well as economical, mechanical and other design considerations run aground when confronted with the need to quantify environmental

properties and requirements [1]. Some hurdles to developing environmental impact and cost models are: a) there is a lack of both hard test data and past experience, b) new and different technologies are integrated with unknown effects, and c) designs are incomplete and evolving at the stage where the largest reduction in environmental impact and cost can be made. In addition, the world's environmental processing capabilities are largely uncertain. Hence, the following two questions still remain largely unanswered:

- *What is the cost associated with pursuing environmentally benign products and processes?*
- *Which aspects of both the product and process design have the largest influence on these costs?*

In this paper, we present a method for developing cost models which aid designers in answering these and similar questions in the context of designing for the life-cycle. The core of our method is the combined use of Activity-Based Costing and uncertainty. Several costing approaches have appeared in the literature in the context of designing environmentally benign products and processes. However, when it comes to assessing costs to life-cycle and ecological issues, Activity-Based Costing (ABC) is gaining ground rapidly on conventional costing systems [2-5]. Based on our review of relevant life-cycle costing approaches, we believe that emerging Activity-Based Costing approach has the best potential for efficient and effective cost assessments in the context of designing for the life-cycle [6].

In this paper, we extend the work presented in [6] by including the following issues:

- *The uncertainty associated with the information used in product cost assessments.* In particular, we highlight the modeling and propagation of these uncertainties through cost models using commercially available software.
- *The capability to identify those process and product design aspects that contribute most to the cost using so-called action charts.* This enables a design group to quickly spot the most

cost inefficient parts of the design which allows the group to concentrate the redesign effort and improves design efficiency. The approach will be shown in the context of a subset of life-cycle design, i.e., design for demanufacture¹ of telephones.

ACTIVITY-BASED COSTING

Activity-Based Costing (ABC) has received its name because of the focus on the activities performed in the realization of a product. Costs are traced from activities to products, based on each product's consumption of such activities. Activity-Based Costing differs from conventional costing systems in two distinct ways:

1) In conventional costing systems, the assumption is made that each unit of a given product consumes resources (e.g., energy, material and direct labor), while in ABC the assumption is made that products or services do not directly use up resources, but consume activities. Hence, in ABC, *the cost of a product equals the sum of the costs of all activities that must be performed in the realization of the product* [4].

2) Conventional cost systems are based on unit-level cost drivers (these unit-level cost drivers are often referred to as allocation bases in conventional cost systems) of the product that are directly proportional to the number of units produced. Direct labor hours, machine hours and pounds of material are examples of such "unit-level allocation bases". An ABC system, on the other hand, uses cost drivers that can be at the unit-level, batch-level, and/or product-level. Examples of batch-level cost drivers are setup hours and number of setups. Examples of product-level cost drivers are number of parts, number of times ordered, and number of engineering charge orders [7].

Because of the assumption that a product uses activities and the allowance for batch and product level cost-drivers, it is generally agreed that ABC systems are superior in modeling and tracking costs (see, e.g., [4, 7]). Mostly noted is ABC's capability to separate direct from indirect costs. In [4] it is noted that "traditional cost systems systematically undercost small, low-volume products and overcost large high-volume products". This is due to the inability to trace overhead costs correctly, which in turn results from the use of only unit-level cost drivers and the focus on resource consumption. In depth discussions of ABC can be found in, e.g., [4, 5, 7-9].

We have chosen to use ABC because of the noted superiority in cost-tracing, separation of direct and indirect costs, higher accuracy, and its capability to blend into the Activity-Based Management (ABM) systems that more and more companies are employing (see, for example, [7]). A motivating example for its use in an environmental context can be found in [3] where it is described how Activity-Based Costing and environmental aspects can be combined to give companies the ability to identify more accurately those plants and products which are driving up their environmental expenditures. However, it should be noted that, although many have focused on ABC, the issues of

- a) how to provide efficient and effective decision support in design, and
- b) how to best include the uncertainty involved

¹ Demanufacture: the process opposite to manufacturing involved in recycling materials and product components after a product has been taken back by a company.

are still largely unaddressed. Especially the uncertainty cannot be ignored and should be included when one seeks to assess costs associated with aspects of a multi-year product life-cycle without much historical data.

INCLUDING UNCERTAINTY IN COST MODELS

Although a number of researchers outline methods for assessing and reducing environmental impact (e.g., [10]), hardly any discussion is given to the accuracy of the data used and the sensitivity of the outcome to variations in the inputs. Especially when dealing with ecological issues uncertainty must be included due to a predominant lack of hard data.

Uncertainty can be modeled in a variety of ways depending on what kind of uncertainty is to be modeled. Generally speaking, we have the following possibilities:

- We can model uncertainty based on historical data. This will typically involve statistical analysis along the line of Gaussian Statistics.
- We can model uncertainty based on experience, qualified guessing, etc. One way of doing this is by modeling the uncertainty analogous to fuzzy numbers, but solving the model numerically rather than using fuzzy theory.

In design, and especially in original design, good historical data are often impossible or difficult to get, thus methods based on Gaussian statistics will soon become inappropriate and even impossible to apply. Our method should therefore be designed to deal with 'fuzziness'. This means that we guess, for example based on experience, the type of distribution to use as well as the mean, the left deviation and the right deviation. The uncertainty is simply modeled by assigning distributions to every number in the model for which there exists uncertainty.

Given that the uncertainty is modeled in a cost model, we must determine the effect of these uncertainties on the cost. We have found it useful to use the Monte Carlo simulation technique to find the cost uncertainties resulting from our assumptions.

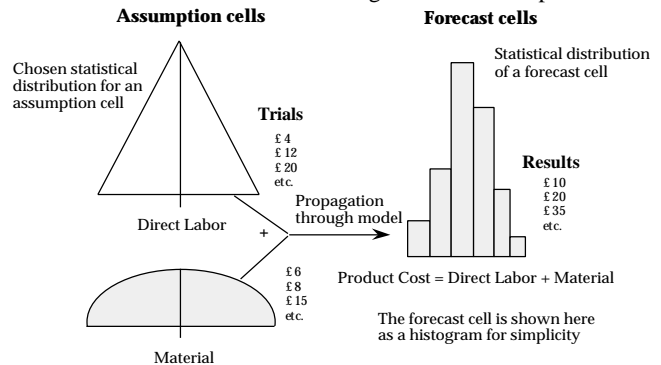


FIGURE 1 – MONTE CARLO SIMULATION EXAMPLE

This technique is a very simple, but powerful numerical approximation method that is simply based on performing a controlled and virtual experiment within a model. Although numerous different simulation methods exist, we have found it advantageous to employ a software called Crystal Ball[®] for this purpose. It allows the definition of 'assumption' and 'forecast' cells in a spreadsheet computer model. The Crystal Ball software adds into Microsoft Excel spreadsheet software, hence we talk about 'cells'. A forecast cell can be looked upon as a response variable, while an assumption cell can be viewed as a

source variable. Consider the example in Figure 1 where product cost is modeled as a simple linear function of material and direct labor cost. Based upon our “assumptions” w.r.t. material and direct labor, we want to “forecast” the associated product cost. In each assumption cell, an uncertainty distribution is defined as is appropriate for the particular value in that cell. In our example (see Figure 1), the ‘Direct Labor’ assumption cell is distributed as a triangular distribution while the ‘Material’ assumption cell is distributed elliptically.

The Monte Carlo simulation provides random samples of numbers in the assumption cells (material and direct labor). The random numbers propagate through relationships/equations in the model and the value of the associated forecast cells (product cost, in our example) is calculated by means of the appropriated relationships/equation. In our example, the value of the forecast Product Cost is a simple summation of the random numbers for Material and Direct Labor. When all the trials have been performed, the calculated values of a forecast cell will form a new statistical distribution (see the Product Cost distribution in Figure 1). Due to the randomness, the numbers that have propagated through the model can be used in ordinary statistical analysis as if we were running a real experiment, e.g., to construct confidence intervals, perform T-tests, etc.

DEVELOPING AN ABC MODEL INCORPORATING UNCERTAINTY FOR DESIGN SUPPORT

Our method for developing ABC cost models that includes uncertainty for decision support in design uses consists of six steps. A flow chart of our method is given in Figure 2. We illustrate our method by developing an ABC model for assessing and tracing the cost of demanufacturing a telephone and show how to guide detailed design changes based on the assessments provided by the model.

Before discussing the details, we point out that our method has the following core components (see Figure 2):

- *Formulation* (steps 1 through 3) – These steps deal with the actual formulation of the model.
- *Solution* (step 4) – The formulated model is solved, i.e., a cost assessment is obtained.
- *Validation* (steps 5 and 6) – The results from the solution process are used to assess and verify the model and reiterate the process if necessary. Step 6 will not be addressed in the paper. More information can be found in [6].

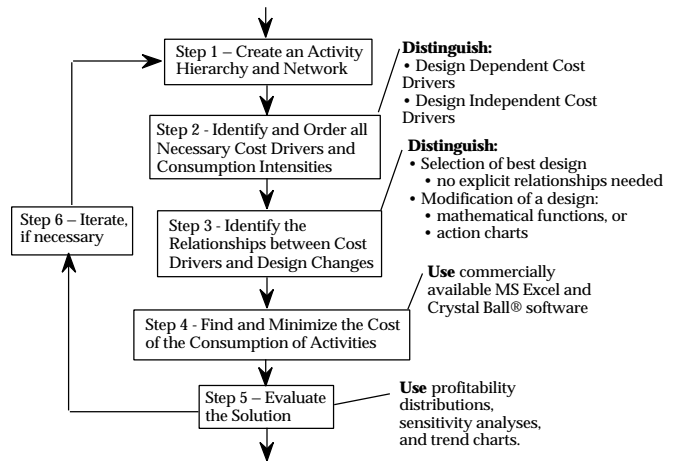


FIGURE 2 – FLOW-CHART FOR DEVELOPING ABC MODELS

Step 1 - Create an Activity Hierarchy and Network.

The purpose of this step is to break down that part of the life cycle which forms the design focus into a hierarchy of activities. A demanufacture process can be broken down into (sub)activities as in Table 1. This is not the only possible hierarchy of demanufacture activities. As depicted in Table 1, three different levels of activities are present. For example, activity A1 (‘Collect’) consists of the level 2 activities ‘Buy-back’, ‘Transport’, and ‘Store’ (A11, A12, and A13, respectively). Of those activities, only ‘Transport’ has lower level activities, namely, ‘Load’ and ‘Move’ (A121 and A122). The purpose of an activity hierarchy is to ensure that all the activities in the part of the life cycle to be studied are considered. If an objective is to identify the effect of changes in design parameters on cost, then it is essential to form activities detailed enough that cost drivers can be assigned and that the lowest level of the activity hierarchy can be assigned directly to the design parameters through the cost drivers.

After identifying all the activities, a network indicating the relationships between the activities is constructed. In Figure 3, the activity network is shown for a demanufacture process corresponding to the activity hierarchy in Table 1. In the demanufacture case study we are interested in two different process scenarios:

- *Dismantling*; this scenario includes only activities related to the process of dismantling a product as much as possible/feasible in order to recover reusable components.
- *Shredding*; this scenario includes only activities associated with shredding a product. There is no dismantling.

Both process scenarios are included the network. Another approach could have been to develop separate models. It is important to note that, in general, an ABC activity network does not have a one-to-one corresponds with a process network. In an activity network, connections and relationships between process activities are given. A single activity may, however, consist of several process actions. Consider activity A311 ‘manual dismantling’. This activity contains all manual dismantling actions, no matter where or in what sequence they occurred in the demanufacturing process. We use the network to identify:

- what effect a change in the design parameters will have on the consumption of activities, and
- what effect a change in consumption of an activity will have on the other activities.

The network also provides the designer a graphical view on how different decisions will affect the activities required.

TABLE 1 – DEMANUFACTURING ACTIVITIES².

Level 1 activity	Level 2 activity	Level 3 activity	Notation
Collect (A1)	Buy back	-	A11
	Transport	Load	A121
		Move	A122
	Store	-	A13
Pre-Clean	-	-	A2
Dismantling (A3)	Non-hazardous dismantling (destructive/non-destructive)	Manual dismantling	A311
		Dismantling using handtools	A312
		Dismantling using light equipment	A313
		Dismantling using special equipment	A314
	Hazardous dismantling (destructive/non-destructive)	Manual dismantling of haz. comp.	A321
		Dismantling of haz. comp. using handtools	A322
		Dismantling of haz. comp. using light equipment	A323
		Dismantling of haz comp using special equipment	A324
Sort (A4)	Non-hazardous sort	Sort non-haz. reusable comp.	A411
		Sort non-haz. recyclable mat.	A412
	Hazardous sort	Sort haz. reusable comp.	A421
		Sort haz. recyclable mat.	A422
Clean reusable comp. (A5)	Clean non-haz. reusable comp.	-	A51
	Clean haz. reusable comp.	-	A52
Inspect reusable comp. (A6)	Inspect non-hazardous reusable comp.	Inspect visually non-haz reusable comp.	A611
		Test non-haz. reusable comp.	A612
	Inspect hazardous reusable comp.	Inspect visually haz. reusable comp.	A621
		Test haz. reusable comp.	A622
Shredding	-	-	A7
Collect reusable comp. (A8)	Collect non-haz. reusable comp.	-	A81
	Collect haz. reusable comp.	-	A82
Collect recyclable mat. (A9)	Collect non-haz. recyclable mat.	-	A91
	Collect haz. recyclable mat.	-	A92
Store reusable comp. (A1a)	Keep records	-	A1a1
	Keep storage	-	A1a2
	Keep max. storage	-	A1a3
Store recyclable mat. (A1b)	Keep records	-	A1b1
	Keep storage	-	A1b2
	Keep max. storage	-	A1b3
Transport reusable comp. (A1c)	Non-haz. transport of reusable comp.	Non-haz. loading	A1c11
		Non-haz. moving	A1c12
	Haz. transport of reusable comp.	Haz. loading	A1c21
		Haz. moving	A1c22
Transport recyclable material (A1d)	Non-haz. transport of recyclable material	Non-haz. loading	A1d11
		Non-haz. moving	A1d12
	Haz. transport of recyclable material	Haz. loading	A1d21
		Haz. moving	A1d22
Manage waste (A1e)	Collect waste from disassembly stations	Collect non-haz. waste	A1e11
		Collect haz. waste	A1e12
	Store waste for landfilling	Keep records	A1e21
		Keep storage	A1e22
		Keep max. storage	A1e23
	Store waste for incineration	Keep records	A1e31
		Keep storage	A1e32
		Keep max. storage	A1e33
	Transport waste to final destination	-	A1e4

² Gray cells represent lowest level activities. The notation refers to the shaded cells. haz. = hazardous, comp. = components, mat. = materials

Landfill	Non-haz. landfill	A1e51
	Haz. landfill	A1e52
Incinerate	Non-haz. incinerate	A1e61
	Haz. incinerate	A1e62

Step 2 - Identify and Order all the Necessary Cost Drivers and Consumption Intensities

The purpose of this step is to identify the cost drivers and corresponding consumption intensities that are necessary to find the cost of the consumption of activities with the desired accuracy. The cost of the consumption of a specific activity is the cost driver(s) multiplied with the consumption intensity. The total costs is found as the sum of the costs of all the activities that the design solution would impose. The properties of ABC depend on the cost drivers chosen. Bad cost drivers may give bad cost estimates. An example of a bad choice would be if a unit level cost driver (e.g., mass per unit) was chosen to keep track of a batch level activity (e.g., inspection).

Having identified the cost drivers, the consumption intensities for each cost driver should be determined next. Furthermore, uncertainties in cost drivers and consumption intensities should be modeled at this stage. It would be beyond the scope of this paper to list all cost drivers and associated consumption intensities with the uncertainty distributions used in the demanufacture cost model. Illustrative examples are listed in Tables 3 and 4. From Table 1 we see that activities A411 and A412 are sorting of non-hazardous reusable components and recyclable material, respectively. As can be seen in Tables 3 and 4, normal and triangular uncertainty distributions are assigned, respectively, to both the cost drivers and consumption intensities in terms of a mean and left and right deviation. The Crystal Ball software allows twelve different distribution types. Among them the triangular and normal distributions as used in Table 3 and 4, but also other types such as the uniform, Weibull, exponential, and user-defined custom distributions.

Step 3 - Identify the Relationships between Cost Drivers and Design Changes.

The next step in our method is to identify the relationships between cost drivers and design changes. The relationships between cost drivers and design parameters are the crux of a design decision support model, because they capture how much a change in one or more design parameters will affect the consumption of the activities, i.e., the cost.

TABLE 3 – COST DRIVER EXAMPLES.

Activity	Cost driver	Consumption intensity			
		Distribution	Mean	Left dev.	Right dev.
A411	Direct labor	Normal [h/batch]	20.0	10.0	30.0
A412	Direct labor	Normal [h/batch]	15.0	10.0	20.0

TABLE 4 – CONSUMPTION INTENSITY EXAMPLES.

Activity	Cost driver	Consumption intensity			
		Distribution	Mean	Left dev.	Right dev.
A411	Direct labor	Triangular [\$/h]	20.0	18.0	23.0
A412	Direct labor	Triangular [\$/h]	20.0	18.0	23.0

A key objective for using an Activity-Based Cost model in design is to identify how changes in different design parameters affect the cost and consumption of the activities. The level of detail and sophistication needed in modeling the relationships between cost drivers and design parameters depends on the purpose and usage of the cost model. In Figure 4, different uses

and ways of modeling the effects of design changes on the cost are illustrated. We identify two distinct uses of an Activity-Based Cost model:

1) *Evaluation of a number of discrete designs* in order to identify the economically best design, that is, the cost of a number of alternative designs is determined and a selection of a design is made based upon the result. Therefore, we do not have to model the relationships between design parameters and cost drivers explicitly. This approach works at the activity level (the top level in Figure 4) and selection of the most cost effective design is the primary purpose.

2) *Identification of "optimal" values for continuous design parameters*, that is, a given design is modified through, e.g., mathematical optimization in order to identify the ideal values of a number of design parameters. Rather than selection of designs, modification of an existing design is the primary purpose. This is shown in the gray area of Fig. 4.

In order to improve design parameter values (usage 2), it is necessary to identify the effect the design parameters have on the cost drivers. The highest amount of detail is obtained if these effects are quantified in detailed mathematical Cost

Driver/Design Parameter relationships which link design changes at the property/dimension level (bottom level in Figure 4) to the cost drivers. This approach allows us to modify designs on a very detailed level and enables cost minimization directly by computing the set of the most cost effective design parameter values using, e.g., optimization algorithms. However, the usage of such mathematical Cost Driver/Design Parameter relationships can become extremely cumbersome in the design of complicated systems where there are many relationships and many changes made over time in the relationships.

In Figure 4, a solution is represented by introducing a level in the middle - where we do not keep track of design properties and dimensions, but rather keep track of how the design properties and dimensions affect specific actions. The aggregated effect on these actions is then transformed into an aggregated effect on the activities and the cost drivers. In the next section, this concept of using "action charts" to identify the aggregated effect of design changes on activities in the ABC model is discussed in detail.

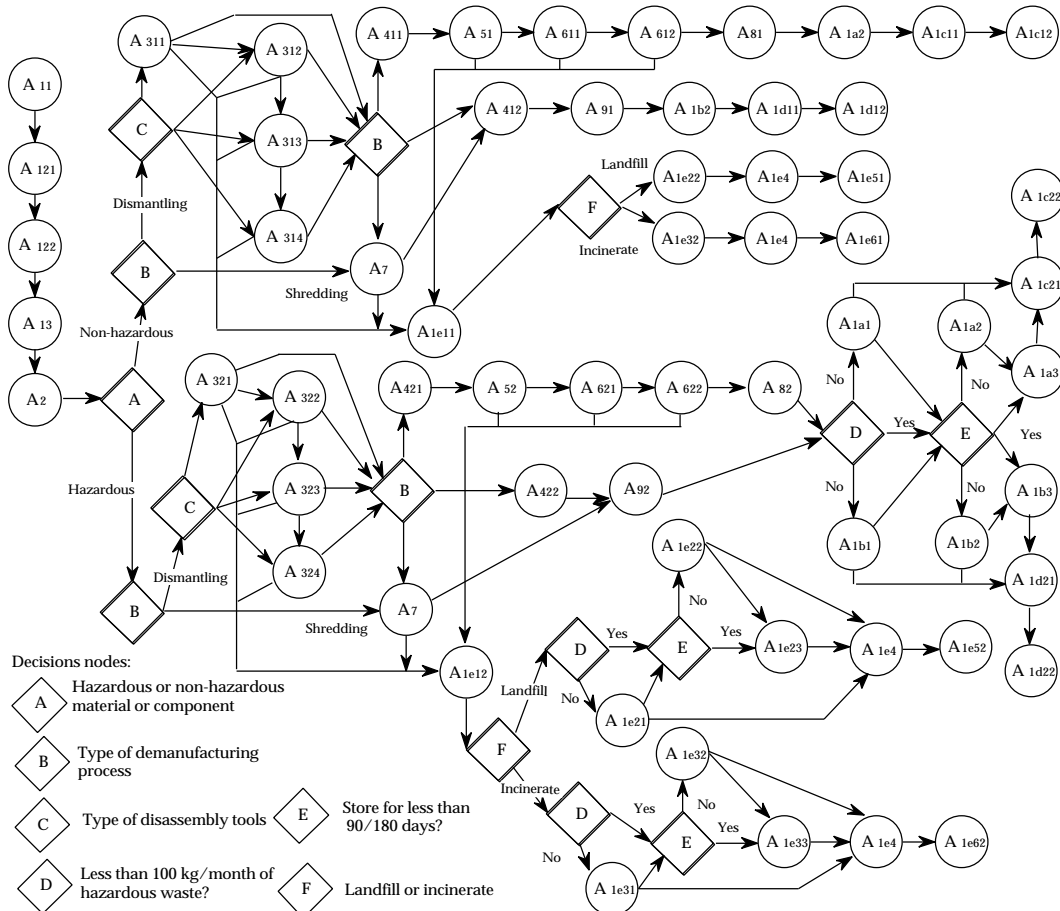


FIGURE 3 – DEMANUFACTURING ACTIVITY NETWORK. THE ICONS ARE THE SAME AS USED IN [11].

TABLE 2 – DEMANUFACTURING ACTIVITIES AND COST DRIVERS.

Activity	Cost drivers	Activity	Cost drivers	Activity	Cost drivers
A11	Buy back	A52	Direct labor; Tooling time; No. of set-ups	A1c22	No. of batches; Fuel; No. of set-ups
A121	No. of batches	A611	Direct labor	A1d11	No. of batches

A122	Number of batches; Fuel	A612	Direct labor; No. of tests	A1d12	No. of batches; Fuel
A13	Volume	A621	Direct labor; No. of set-ups	A1d21	No. of batches; No. of set-ups
A2	Direct labor; Tooling time	A622	Direct labor; No. of set-ups; Number of tests	A1d22	No. of batches; Fuel; No. of set-ups
A311	Direct labor	A71	Tooling time	A1e11	Tooling time
A312	Direct labor; Tooling time	A81	Tooling time	A1e12	Tooling time; No. of set-ups
A313	Direct labor; Tooling time	A82	Tooling time; No. of set-ups	A1e21	Direct labor
A314	Direct labor; Tooling time	A91	Tooling time	A1e22	Volume
A321	Direct labor; No. of set-ups of safety equipment	A92	Tooling time; No. of set-ups	A1e23	Direct labor; Volume
A322	Direct labor; Tooling time; No. of set-ups	A1a1	Direct labor	A1e31	Direct labor
A323	Direct labor; Tooling time; No. of set-ups	A1a2	Volume	A1e32	Volume
A324	Direct labor; Tooling time; No. of set-ups	A1a3	Direct labor; Volume	A1e33	Direct labor; Volume
A411	Direct labor	A1b1	Direct labor	A1e4	No. of batches; Fuel
A412	Direct labor	A1b2	Volume	A1e51	Volume; Mass
A421	Direct labor; No. of set-ups	A1b3	Direct labor; Volume	A1e52	Volume; Mass
A422	Direct labor; No. of set-ups	A1c11	No. of batches	A1e61	Volume; Mass
A51	Direct labor; Tooling time	A1c12	No. of batches; Fuel	A1e62	Volume; Mass
		A1c21	No. of batches; No. of set-ups		

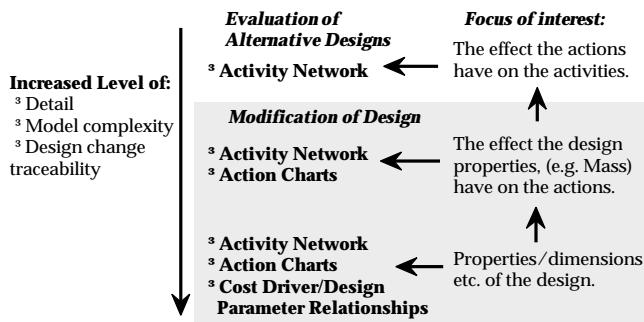


FIGURE 4 – DIFFERENT LEVELS OF MODELING

Tracing Costs to Design Using Action Charts

What are action charts? Activities are formed by grouping actions that have a logic connection together [4, 5]. This is done mainly because it is impossible to achieve credible cost information for every step in a process. It would require an enormous amount of cost drivers and consumption intensities, associated with an even larger amount of possible uncertainty. Thus, actions that occur in a process are grouped into activities. Forming the activities in a way that roughly describes the process is advantageous because this will make the ABC model much easier to understand and use as it coincides with our perception of the process.

The grouping of several process actions into a smaller number of activities opens up the possibility of designing a model with a generic set of low level activities which has design specific inputs - the actions. This is a powerful approach since any process can be described with a set of activities that will always be present, no matter what product we are dealing with. The definition of activities is a function of the desired degree of generality, accuracy and traceability. Increased generality will in general give decreased accuracy and traceability. The usage of aggregated actions is a way of capturing how design changes affect the costs and revenues. It is an approach *in between* a) not modeling any relations at all and merely assessing cost of designs and b) modeling the relationships in detailed mathematical relationships and computing the most cost effective values of design parameters. By aggregating the actions in so-called action charts, we keep track of how the design properties and dimensions affect the actions. The aggregated effect on the actions is then transformed into an aggregated effect on the activities and the cost drivers. In Figure 6, a sample from a dismantling action chart of a telephone is shown, derived from disassembly charts outlined in [12]. Note

the level of details, which is typical for a good action chart. The less detailed an action chart is, the less suitable it is for design modifications.

What purpose does the dismantling action chart serve? The action chart in Figure 6 allows the detailed documentation of a disassembly process. Manual disassembly can be considered as a single activity in an ABC cost model and a reduction of overall disassembly time is clearly advantageous. But on which product component should a designer focus? Time is not the only cost driver in disassembly. A different material or fluctuations in material prices also affect overall revenue. This kind of product design related information is embodied in the dismantling action chart. In essence, an action chart forms an interface between detailed product information and a general demanufacturing ABC model, in our case.

Disassembly activity and object		Disassemblability				Reuseability (Product-Recyclability)				Materials			
No.	Name	Quan- tity	Type A/C	Tool	Force [sec.]	Time [sec.]	Tool for Assembly	Special Pt.	Abra- sion	Fatigue Dir/	Nondest- structive Corr.	Recycl. Material	Mass [kg]
1	Snap off base- handset cable	1	CE	4	4	4	Snap on	Std	4	4	yes	copper, plastic	0.0030
Handset Disassembly													
2	Remove top from bottom	1	SP	3	Crowbar	2	Snap on	Std			No	ABS	0.0060
3	Remove Mass	1	SP	3	Crowbar	3	Glue on	Std	4	4	yes	Lead	0.0140
4	Remove mic. cables and CB	1	SA	3	Crowbar	3	Snap on		4	4	yes		
And so forth													
27	Disassemble circuit board	1	SA	3		4							
28	From 26; circuit board	1	SA					Std	4	4	yes	Mix	0.0580
29	From 26; spring	1	SP					Std	4	4	yes	Steel	0.0001
30	From 26; cover	1	SP					Std	4	4	yes	Thermo- set	0.0001

FIGURE 5 – A PHONE DISMANTLING ACTION CHART.

In order to support the ABC model, each action must be associated with a sufficient set of information. In our opinion, the following set of action information seems to be sufficient input for each activity in a demanufacturing model:

- All actions related to the specific activity, and
- For each action: the number of units, the mass and material composition for each unit, the time to perform an action, the tools used, the process efficiencies, the hazardousness of the units, and the danger in performing the actions.

Uncertainty distributions can be assigned in the action chart, e.g., for specific disassembly times, and the effect of variations in a product design can be traced. In the next section, we discuss the results obtained from using a demanufacturing action chart in our demanufacturing ABC model.

Step 4 – Find and Minimize the Cost of the Consumption of Activities.

Having created the ABC model, defined the relationships between design properties and cost using action charts, and modeled the associated uncertainty, we now proceed to step four of our method, i.e., find (and minimize) the cost associated with

the consumption of the demanufacture activities. To support this step, we have implemented the entire model in Microsoft Excel 4.0 spreadsheet files on a Macintosh platform. A detailed description can be found in [13]. As stated before, we have chosen to use software called Crystal Ball which allows the definition of uncertainty distribution in spreadsheet cells and finds resulting uncertainty distributions numerically using a Monte Carlo simulation. The results obtained in this fashion for telephone demanufacture are discussed next.

Step 5 – Evaluate the Solution

There are many assumptions made in the model (135 assumption cells in 10 model files). An important assumption is that the plant capacity is less than market demand. Another assumption worth noting is that a \$1 buy back price is paid per telephone. Once the model is implemented in spreadsheet structure, several tools are available for evaluating the solution, results, and the effects of the assumptions and design decisions made. We illustrate two tools available, i.e., profitability distributions and sensitivity charts.

Profitability Distributions. The resulting profitability distribution for the ‘Dismantling’ scenario is presented in Figure 7. These distributions provide a good indication of what the effects of the uncertainties in the assumptions are and, in our opinion, provide more valuable information for designers than merely a single number. The mean is estimated to be -\$2.30 if we pay, on average, \$1.00 for the telephones. In other words, it is not economically feasible to dismantle the present telephone design. The results from the ‘Shredding’ scenario are presented in Figure 8. The shredding option is also economically infeasible, but we see that the revenues nearly balance the costs if we would not have paid \$1.00 for old telephones.

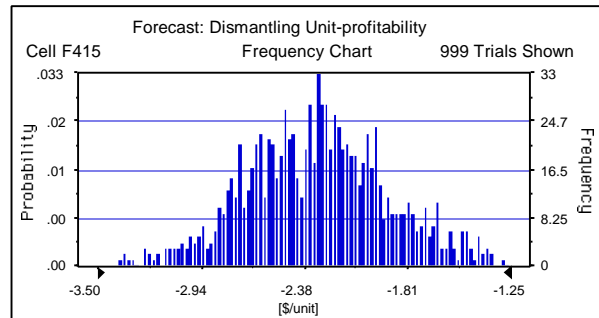


FIGURE 7 – ‘DISMANTLING’ PROFITABILITY DISTRIBUTION

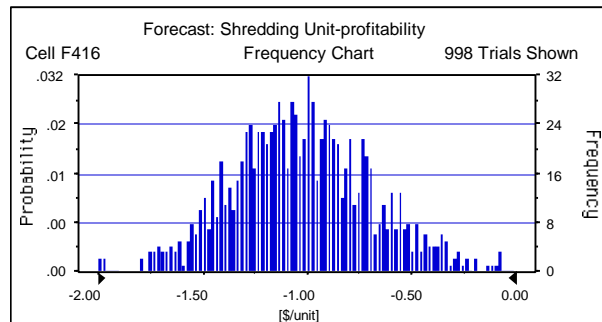


FIGURE 8 – ‘SHREDDING’ PROFITABILITY

DISTRIBUTION

Taking into account that many assumptions have been made and the fact that the upper limit of the distribution is close to a break even situation, we should not rule out the possibility of a break even situation in the real world.

Identifying Largest Cost Contributors Using Sensitivity Charts. Assuming that we want to pursue dismantling of telephones, *what changes should we make in order to boost profitability?* One might argue that a product design should be improved according to Design for Disassembly guidelines, but it may be that process aspects such as labor and interest rates are far more significant than the product design. We employ sensitivity charts to gain insight in these issues.

In Figure 9, a (shortened) sensitivity chart for the dismantling process model is given. Such a sensitivity chart is generated for each simulation by the Crystal Ball software and is based on the so called Spearman Rank Correlation and measures the degree to which assumptions and forecasts *change together*. The larger absolute value of the correlation coefficient, the stronger is the relationship. Positive coefficients indicate that an increase in the assumption cell is associated with an increase in the forecast cell.

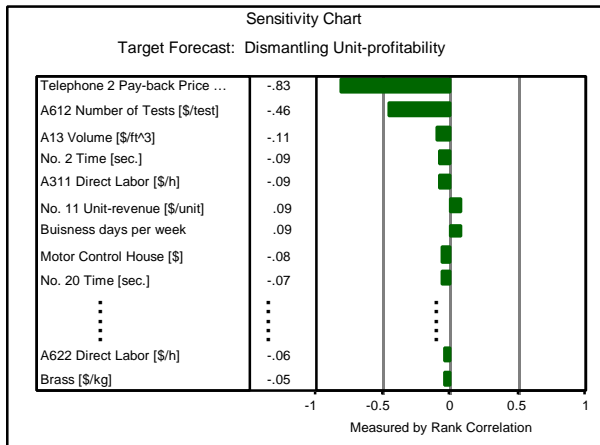


FIGURE 9 – SENSITIVITY CHART FOR ‘DISMANTLING’ PROFITABILITY

As can be seen in Figure 9, the chart allows us to pin point the factors/assumptions for the ‘Dismantling’ scenario that correlates most with the forecast cell. This facilitates studying the importance of the different assumptions in the model. It also indicates what cells should be updated with better, more accurate information. The major cost and revenue triggers are:

- Telephone 2 buyback price,
- A612 Number of tests [\$/test]³, number of tests to check if components are reusable or not,
- A13 Volume [\$/ft³], storage consumption intensity for units in to the demanufacturing plant,
- No. 2 Time [sec.], time to perform action number 2 from the phone action chart - ‘Remove top from bottom’ of the handset disassembly, a product aspect to be redesigned,
- A311 Direct labor [\$/h],

³ From the unit, [\$/test], we understand that this is the consumption intensity of activity A612 and not the cost driver.

- No. 11 Unit-revenue [\$/unit], associated with reusable speakers, and
- Business days per week.

As can be seen, product design as well as process factors affect the cost. Most gain can be made by reducing the buy-back price, but a handset redesign is arguably a pressing product design issue. Sensitivity analyses for other scenarios and using perfect process information are documented in [13]. The more trials performed, the more useful is the sensitivity chart. The reason is that the variability of the correlation coefficient estimates decreases as the number of trials increases because the number of degrees of freedom increases, and that the probability for correlation by chance decreases, see [14].

CLOSURE AND FUTURE WORK

In this paper, we discussed how an Activity-Based Cost model can be developed and used in design under presence of uncertainty. We highlighted the modeling and propagation of these uncertainties through a cost model using commercially available software. The inclusion of uncertainty and usage of Monte Carlo simulation provides the capability to identify those process and product design aspects that contribute most to the cost using so-called action charts. An action chart represents a group of associated actions which together form an activity. We used disassembly actions as an example. The subsequent use of sensitivity charts facilitates identification of the most cost inefficient parts. Profitability distributions and sensitivity charts assist in identifying:

- where we should focus our *data collection efforts*, e.g., because payback prices and direct labor have such significant influence (see Figure 9) we should collect more accurate data in these areas.
- where we should focus our *design efforts*, e.g., with respect to the telephone design, we should focus on the removal of the top from the base because it is the largest cost contributor.

It should be emphasized that especially in the early stages of design, the identification of the largest cost contributors and critical factors is more important than the actual cost.

With respect to validity, we have attempted to make our demanufacturing model as realistic as possible, e.g., the EPA regulations for storing hazardous waste have been incorporated. The model presented in this paper seems to give reasonable results. In fact, the same model has been applied to assess and trace the cost of demanufacturing a car and the results were compatible with real world experiences [13]. We have most likely underestimated the total overhead cost for a demanufacturer, so we would expect that the true costs are higher than estimated. Another aspect to take into account is that most of the plastic revenue information, is based on [15] and reported to be from 1990.

Our focus in future work is on the following key aspects. We are continuing to validate, improve, and expand our method and models. One of our objectives is to utilize the tractability of the costs and uncertainty through an activity network and identify which life-cycle activities are truly critical in a product’s life-cycle.

In the long term, we seek to utilize the ABC method not only for monetary cost assessments, but also for life-cycle assessments of environmental impact in terms of matter and energy consumption. A model which provides an environmental

impact assessment in terms of energy and matter consumption and emission can be used for exploring the global (societal) environmental impact of engineering products and processes. E.g., recycling products is nice, but recycling may cost more energy than a disposal process. The use of an ABC approach may overcome some of the difficulties associated with conventional Life-Cycle Assessment/Analysis tools, e.g., the cumbersome amount of work involved and the lack of common standards. In our opinion, an activity-based Life Cycle Assessment is most easily done for energy where we have a single unit. It will be more difficult for materials where, e.g., we need to distinguish different grades of toxicity.

Although we have focused on demanufacturing as the area of application, It should be noted that our method, as most ABC based methods, is generic in that it can be applied whenever the activities are described in sufficient detail to have cost drivers assigned.

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