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ASSESSING PRODUCT DEVELOPER-SUPPLY CHAIN REPLATIONSHIP FOR THE ECO-CONSCIOUS DESIGN OF ELECTRONIC PRODUCTS

Dr. Ping Ge
Department of Mechanical Engineering,
Oregon State University
Corvallis, OR, 97331-6001, USA
Tel: 541-737-7713, Fax: 541-737-2600
Email: christine.ping-ge@orst.edu

Bo Wang
Department of Mechanical Engineering,
Oregon State University
Corvallis, OR, 97331-6001, USA
Tel: 541-908-0620, Fax: 541-737-2600
Email: wanbo@engr.orst.edu

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1 Introduction

The recycling of electronics products has become a global concern. For electronics product development companies in US, adapting their existing organization, design process, and IT infrastructure, into an Eco-Conscious product design paradigm has become an urgent business need either voluntarily or enforced by RoHS and WEEE directives. Streamlining and strengthening the relationship between product developers and supply chain is one among many challenges. In particular, the effectiveness of their interactions may greatly influence the Environmental impact (E), Quality (Q), and Cost (C) entailed in designing electronics products. The research development in this work includes 1) characterizing product developer-supply chain interaction strategies based on "information overlap", and 2) quantitatively evaluating the interaction strategies' E, Q, C performances using an Activity Based Modeling approach. A case study is provided to demonstrate the use of the assessment method and results.

2 Interaction Strategies Between Product Developers and Supply Chain

A summary report by United Nation based on surveys conducted at a global scale [1] shows that the recycling of electronic and electrical products has become an alarming concern all over the world. With fierce market competition, products like computers have featured themselves with a very short life span and incredible rate of upgrading in software as well as hardware. However, the handling and recycling of retired computers has not been kept up with the same rate and capacity. During the last decade, the deserted computers have been piled up in numerous warehouses and landfills. This has caused a lot of concerns about the possible recycling cost and potential lurching of hazardous chemicals into the soil if not recycled. Restriction of Hazardous

Substances in Electrical and Electronic Equipment (RoHS) directive in the European Union (EU), in conjunction with Waste Electrical and Electronic Equipment (WEEE) [2] are among the first sets of initiatives or regulations in response to this worsening situation. Among other things, the directives mandate that by July 1, 2006, only lead-free electronic and electrical products will be legally salable in member countries.

Under the circumstances, US companies, either voluntarily or forcefully, started at least to talk about adaptation strategies. Well-known electronic product developers like IBM and HP have established Design for Environment (DfE) programs or Product Stewardship group and product-take-back center [3]. However, obstacles still exist when the product developers are trying to implement what the directives require in their product development process. Usually, the electronic product developers work with a group of suppliers for the components through Supply Chain Management (SCM) while they themselves are only responsible for certain core technology and system integration/packaging, as shown in Fig. 1. When product developers wish for their products in compliance with the regulation requirements, they must work with their supply chain partners to actually implement these requirements. As a result, the product developers-supply chain relationship has become a dominating factor in Eco-Conscious design of electronic products.

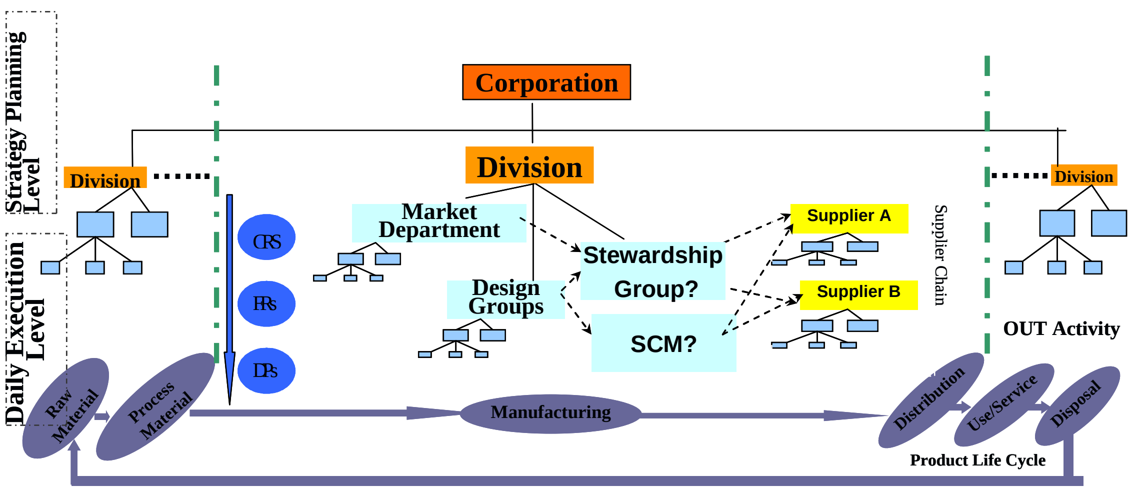


Figure 1. Product Developers -Supply Chain Relationship in Eco-Conscious Design

So far, a substantial amount of political and technical struggles have been observed between the product developers and supply chain as a result of lacking effective interaction strategies for exchanging and sharing information that are crucial to implement the RoHS and WEEE directives. "Shooting in the Dark" is a reality in the current practice. The existing literature has limited discussions on product developer and supply chain interactions in general, and no representation or assessment methods have been found for selecting a suitable interaction strategy that would yield satisfactory E, Q, C performance among many possibilities. In this work, we have developed 1) characterization of the interaction strategies and 2) a quantitative assessment method and process to evaluate the interaction strategies.

Exchanging and sharing information between product developers and supply chain is a crucial part of understanding and effectively executing environmental design requirements in designing electronic products. Here, we propose to use "information overlap" to define and measure information exchanged and shared between product developers and supply chain through a certain interaction strategy. The "information overlap" concept consists of four basic elements: 1) who: stakeholders involved in the interactions, in this case, DfE program, design group, SCM, and suppliers; 2) what: content of the information exchanged and shared; 3) how-much: extent of information exchanged and shared; 4) quantification. Stakeholders, content and extent of information exchanged are used to define an interaction strategy space. In this space, the interaction strategies are classified based on the extent of information overlap among DfE program, design group, SCM, and suppliers, as shown in Fig. 2.

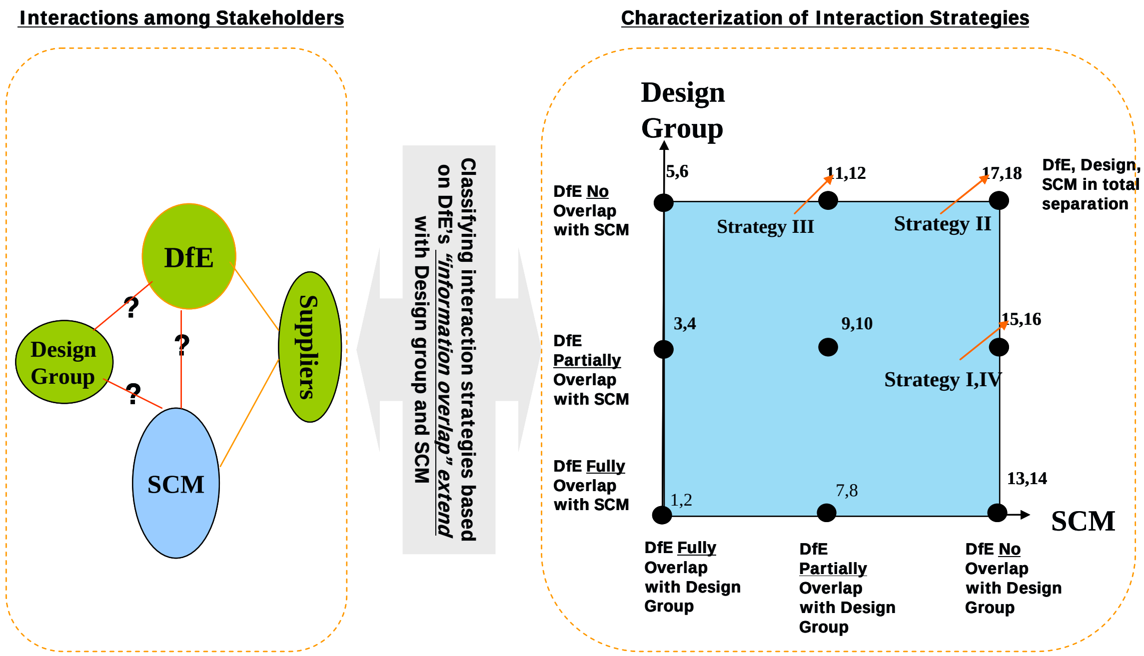


Figure 2. Formation Of An Interaction Strategy Space Based On "Information Overlap"

Along the vertical axis (marked with "Design Group") are interaction strategies by which DfE fully share environmental design requirements with design group. Along the horizontal axis (marked with "SCM"), the farther it is away from the vertical axis, the less information overlap between DfE and design group: partially and no. In the similar manner, along the vertical axis and starting from the horizontal axis, interaction strategies by which DfE share fully, partially, and no information with SCM is shown. For every dot (a certain interaction strategy) in Figure 2, there exist two possible options. For instance, the center points of the square (9, 10) represent the interaction strategies by which DfE has partial information overlap with SCM and partial information overlap with design group; interaction strategy 9 represents the option that DfE has direct interactions with suppliers, and interaction strategy 10 represents the option that DfE has to go through SCM in order to communicate with suppliers since there are no direct interactions between them. Total of 18 interaction strategies are obtained in the interaction strategy space. It has been recognized, though not included in this paper, that a quantifiable measure of the extent of information overlap would be useful to study more varieties of interaction strategies.

Characterization of the interaction strategies based on information overlap among the decision stakeholders enables the use of a standard knowledge database structure (such as object-oriented construct) to represent the interactions among the product developers and supply chain (see Section 4.3.2). The major design activities and information can be identified and defined by different groups, including: Marketing, Design, Manufacturing, Supply Chain Management and Stewardship Group (or DfE program). Information used for each of these groups are then identified and itemized. By combining the itemized information by the stakeholders with an Activity Based Modeling approach introduced in the following section, each interaction strategy can be represented as an activity based model, and then, evaluation methods and process may use this model and quantitatively assess the effectiveness of the interaction strategy, and compare the effectiveness of different interaction strategies.

3 A Three View Activity-Based Modeling Approach

The activity-based modeling originated from business field to monitor and control a firm's accounting practice, i.e., activity-based cost modeling. Motivated by growing concerns on environmental impact of industrial product development, Emblemsvåg *et al.* (2000) integrated the consideration of environmental impact into the original model, and developed an *Activity-Based Cost and Environment Model* [4]. In this new model, Cost, Energy and Waste Drivers are used together for assess the cost and environmental impact generated by a firm's activities.

The success of Eco-Conscious design calls for a modeling approach with simultaneous consideration of environmental impact, product quality, and cost [5]. Since quality is equally important to the environmental impact and the cost, it is necessary to include the quality for performance measure of product development related activities. Though the activity-based C/E model can facilitate both the cost and environmental assessment, it does not explicitly address quality related assessment in performance measure. By adding the consideration of quality into the existing model, we have developed a three view activity-based modeling approach, i.e., activity based E/Q/C modeling [6], as shown in Fig. 3. The expanded model may provide a more realistic economic and environmental assessment of business firms' practice and their products.

As shown in Figure 3, the expanded model has three views: *Life Cycle*, *Quality*, and *Economy*. The expanded model is positioned in a three dimensional space, which reflects three fundamental concerns in product development: life cycle consideration, product quality, and economic restraints. The original activity-based cost model and the activity-based cost/environmental model were developed from a management perspective – monitoring and control based on a consumption chain from Cost Objects to Activities to Resources. In the expanded model, Quality Drivers are integrated into the activity-based cost and environmental model for quality monitoring. The Cost, Energy, Waste, and Quality drivers act on the Activities; the Activities consume Resources and deliver Objects/Products. The effectiveness of various activities can be measured through Performance Measure against environmental, quality and economic objectives. The expanded model is expected to monitoring and controlling Cost, Energy Consume, Waste Generation and Quality Change in a system, such as a business firm. Our current investigation focuses on the quality change in a business firm related to the product development process associated activities.

The Quality Drivers, Cost Drivers, Energy Drivers and Waste Drivers are used as the input of the model. The Quality Drivers act on the daily execution activities that may directly cause the quality change along the product development process. Quality driver is defined as the measure of the change of a certain performance p_i (related to specific customer-preferred quality requirements) caused by an activity, i.e., $\Delta p_i/activity$. With the help of historical documentation and experimental methods, designers can identify the relationships between daily execution activities and a certain performance, estimate how much the performance may be changed caused by the activities, and therefore, set up the quality driver for the customer-preferred quality requirements associated with that performance. Given the performances and quality driver corresponding to customer-preferred product quality requirements, it is possible to trace the quality changes related to the daily execution level activities in product development process, and obtain the performance measure for the quality objectives to guide the process improvement through design.

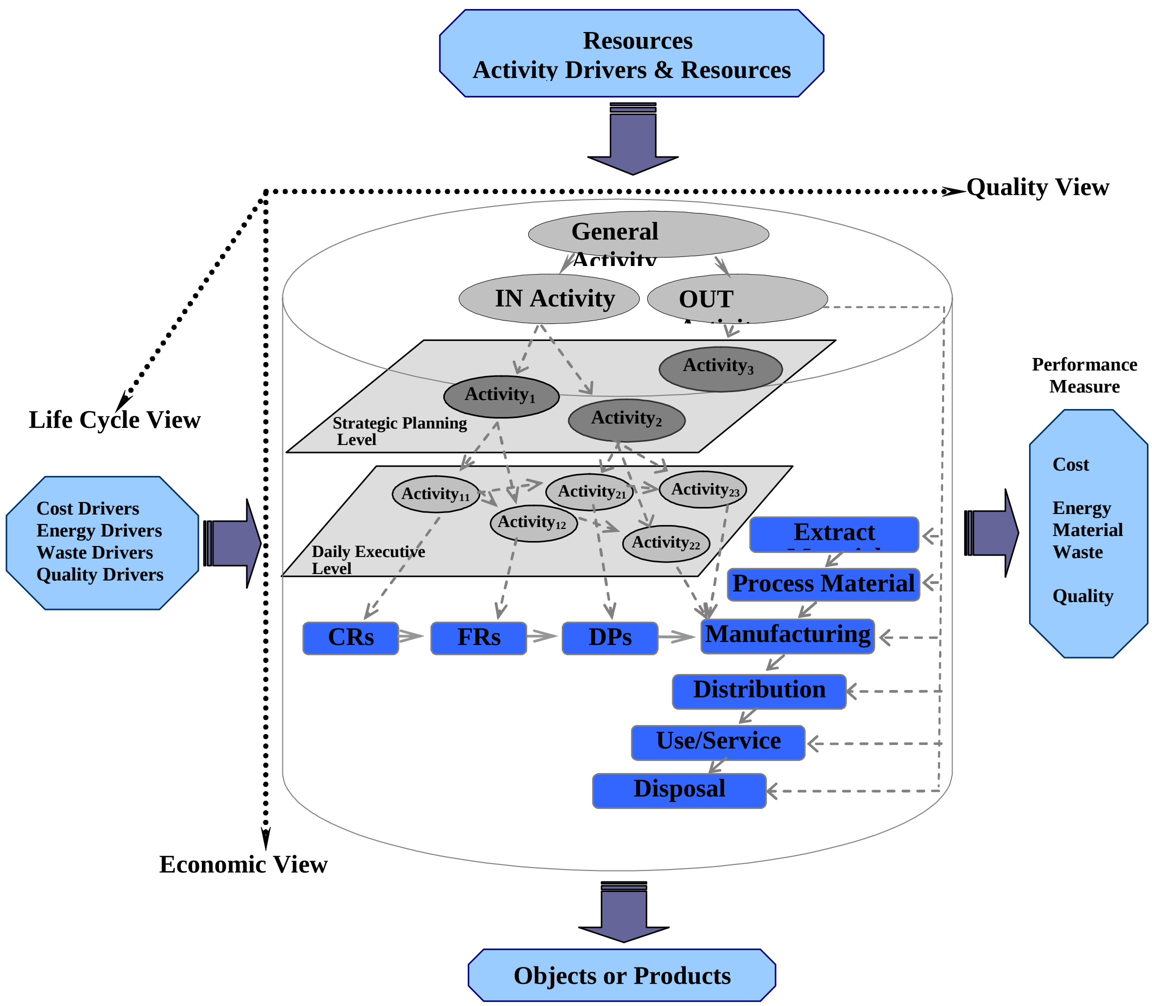


Figure 3. Three-View Activity-Based Modeling For Eco-Conscious Product Design

4 Assessment Method and Process

An evaluation methodology to assess the effectiveness of the interaction strategies between product developers and supply chain has been developed based on the three-view activity based modeling in Section 3. In the following, the methodology is introduced first, and then a case study problem is used to demonstrate the assessment method and process.

4.1 Methodology Overview

For a certain environmental design problem, various strategies could be applied to product developers-supply chain interactions (see Fig. 2). But the question remains: which one is the most effective interaction strategy so that the E, Q, C performances generated through the solution of the environmental design problem by product developers working together with its supply chain would be desirable?

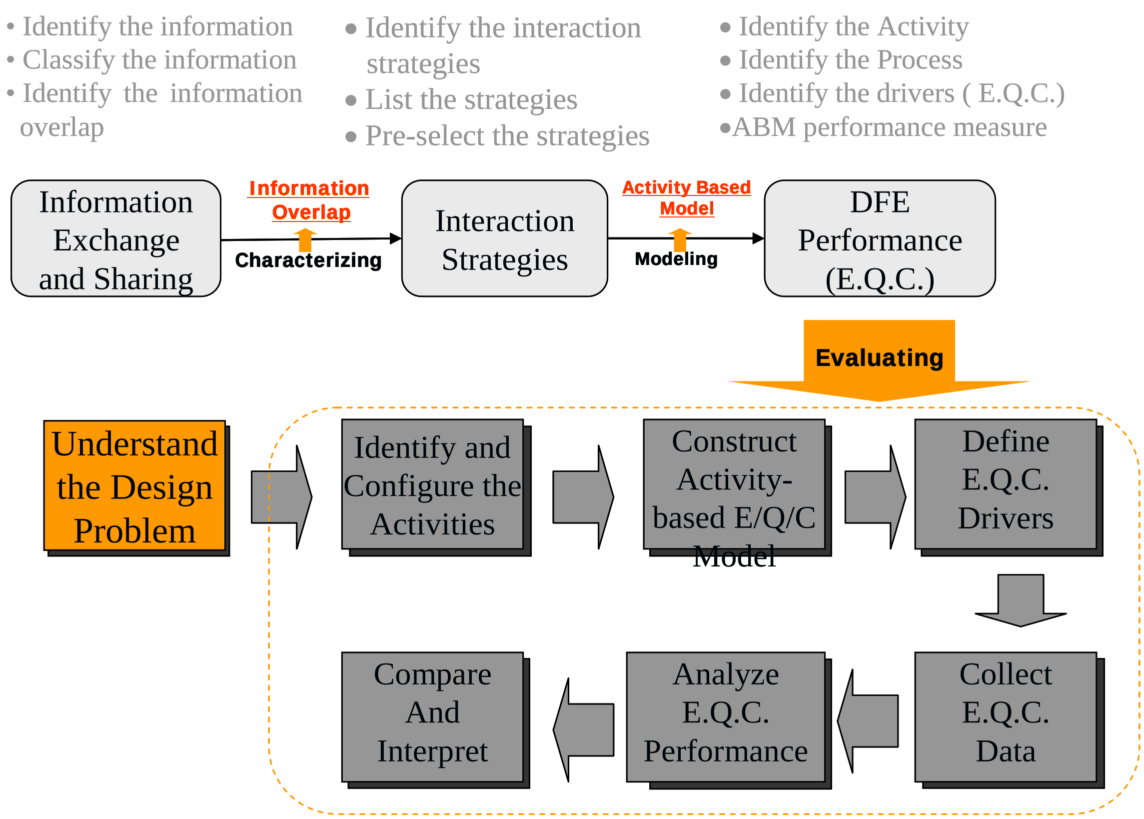


Figure 4. Evaluation Methodology for Product Developers-Supply Chain Interaction Strategies

As shown in Figure 4, the evaluation methodology to assess the effectiveness of interaction strategies between the product developers and their supply chain partners includes six steps. For a certain interaction strategy, the assessment procedure is:

- Step 1 - identify and configure the activities;
- Step 2 - construct an activity-based model;
- Step 3 - define E, Q, C drivers;
- Step 4 - collect E, Q, C data;
- Step 5 - analyze E, Q, C performances;
- Step 6 - compare and interpret the evaluation results.

A case study problem of an electronic product design is selected to demonstrate the process and methods when applying the evaluation methodology.

4.2 Description of a Case Study Problem

A case study problem is the design and manufacturing of Printed Circuit Board (PCB) in developing computer systems [7]. The E, Q, C design requirements are:

- Environmental requirements - less environmental impact during the computer manufacturing and recycle process (as shown in Fig.5); a Product Stewardship Group is responsible for DfE activities.
- Quality requirements - small size, and good multimedia presentation ability, including video and audio.
- Cost requirements - low Price to purchase the product

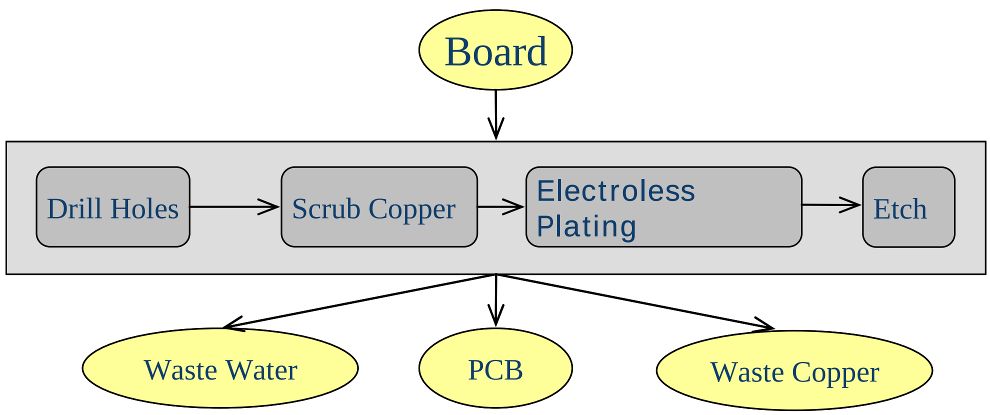


Figure 5. PCB Manufacturing Process

Four typical interaction strategies are selected. They are:

- Interaction Strategy 1 (point 16 in Fig.2)
  - Stewardship Group (DfE) partially overlap with SCM
  - Stewardship Group (DfE) no overlap with Design Group
  - Stewardship Group (DfE) does not communicate with suppliers directly
- Interaction Strategy 2 (point 17 in Fig.2)
  - Stewardship Group (DfE) has no information overlap with either Design Group or SCM
  - Stewardship Group (DfE) communicates with suppliers directly
- Interaction Strategy 3 (point 11 in Fig.2)
  - Stewardship Group (DfE) partially overlap with Design Group
  - Stewardship Group (DfE) no overlap with SCM
  - Stewardship Group (DfE) communicates with suppliers directly
- Interaction Strategy 4 (point 15 in Fig.2)
  - Stewardship Group (DfE) partially overlap with SCM
  - Stewardship Group (DfE) no overlap with Design Group
  - Stewardship Group (DfE) communicate with suppliers directly

4.3 Case Study and Results

Interaction Strategy 1 (as shown in Fig.6) is used to demonstrate the assessment method and process (Steps 1 – 6).

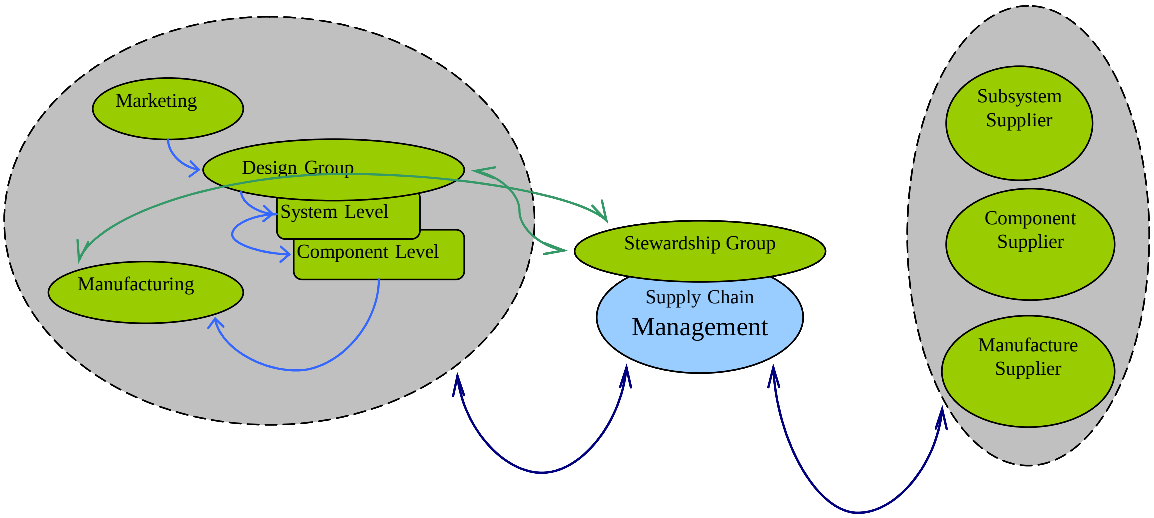


Figure 6. Schematic Illustration of Interaction Strategy 1

4.3.1 Step 1 – Identify and Configure the Activities

All the activities involved in the Design group, Stewardship group, SCM, and Suppliers interactions are identified that would affect environmental impact (E), product quality (Q), and cost (C). An Object-Oriented activity construct is used to represent the activities in a uniform format, i.e. Class. The activity examples of Design group, Stewardship group, and SCM are shown in Fig. 7.

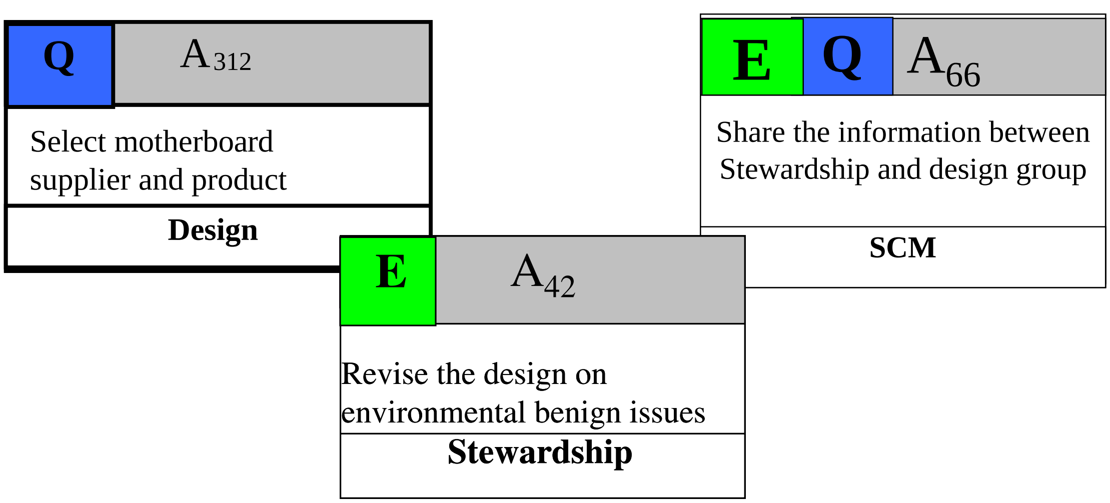


Figure 7. Object-Oriented Activity Classes Examples

4.3.2 Step 2 – Construct An Activity-Based Model

An activity-based model for Interaction Strategy 1 is built by putting all the activities in 1) together based on the information flow through the product development process. The information flow is illustrated in Fig.8.

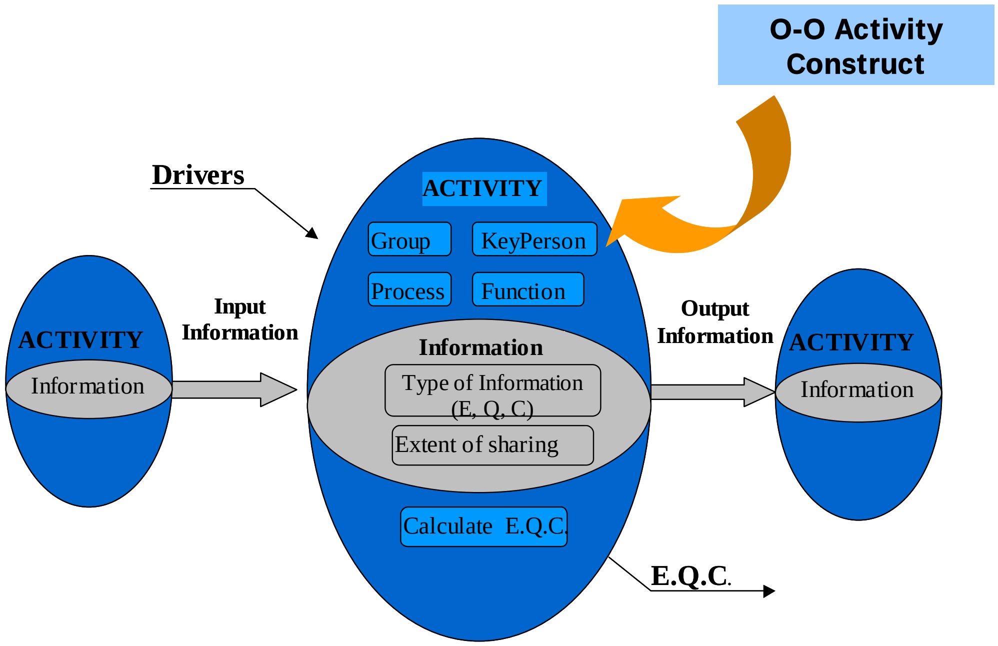


Figure 8. Information Flow through Product Development Process

In product development process, information include the data or facts relevant to the decisions that made by the decision makers. The information relevant to environmental impact, product quality, and cost flow among the decision stakeholders through carriers, i.e. activities along the product development process. The information may be generated by one activity and used by another activity. The Object-Oriented modeling concept is adopted to define an activity construct. The activity construct contains:

- The properties of an activity, includes which group it belongs to (ownership), what function it works to accomplish, which process it is involved, and who is the key person to take charge of the activity.
- Information objects, consisting of the information relevant to the activity. The properties of the information can be retrieved from the information objects, includes the type of information, content of information, extent of information shared.
- The methods to quantitatively measure E.Q.C. (Environmental impact, Quality and Cost) performances through the drivers.

An activity construct has two inputs (E.Q.C. Drivers, and other input information), and two outputs (E.Q.C. performances, and other output information). The information from one activity is passed to another activity through the information flow of inputs and outputs of the activities. The activities are linked through the information flow to constitute an activity-based model of a certain interaction strategy. An activity-based model for Interaction Strategy 1 has been built as shown in Fig.9 (a part of the overall model is shown here due to the limited space).

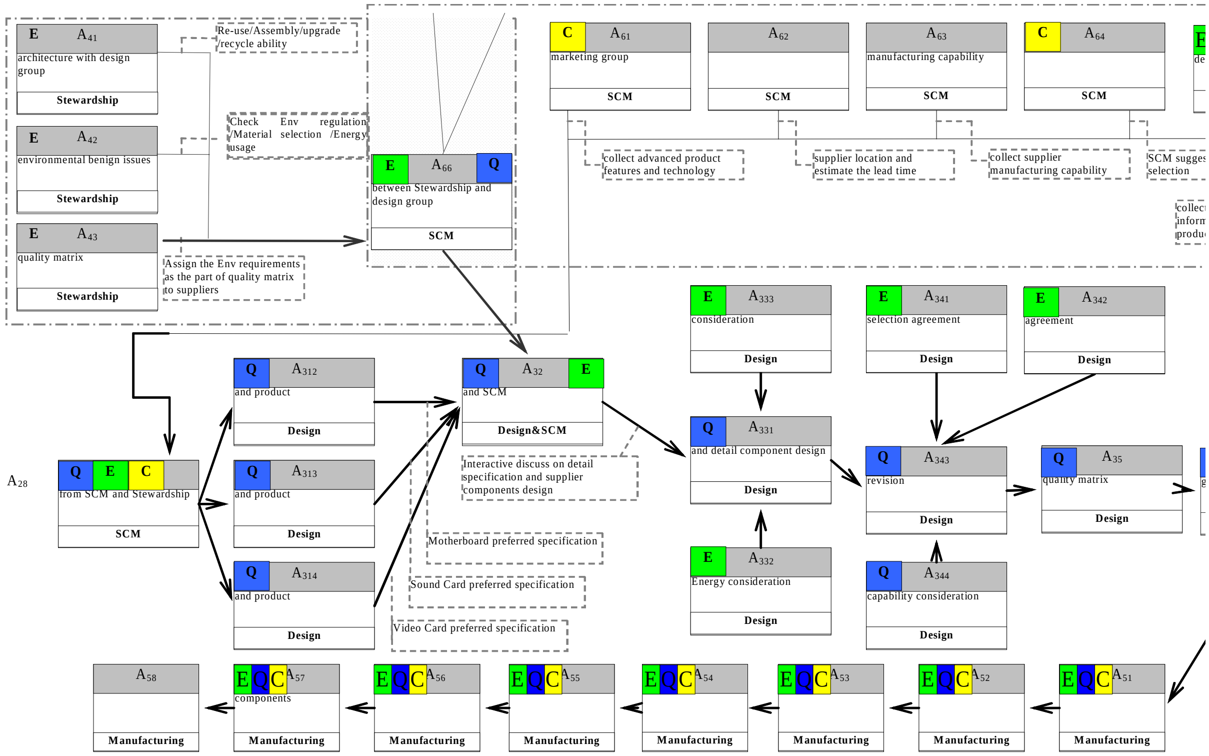


Figure 9. Illustration of an Activity Base Model of Interaction Strategy 1

4.3.3 Step 3 – Define E, Q, C Drivers

The E, Q, C drivers of the activities are identified so that the activities can be quantitatively measured by their E, Q, C performance. The E driver here is *⊿PCB Area (cm^2) /Activity*. It is how much PCB area is changed by an activity. The environmental impact of this activity is calculated by the E driver times the amount of the environmental impact released per PCB area unit. The Q driver here is *⊿Video Memory (M)/Activity*. It is how many megabits the video memory capability is changed by an activity. The quality contribution of this activity is calculated by the quality formula, i.e. Eqn. (2) (see Section 4.3.5). The C driver here is *⊿PCB Area (cm^2)/Activity*. It is how much PCB area is changed by an activity. The cost of this activity is calculated by the C driver times the amount of the cost which is generated per PCB area unit.

4.3.4 Step 4 - Collect E, Q, C Data

The data required to numerically instantiate each activity construct in Fig. 9 are collected, as shown in Tables 2-4 [7]. Table 2 contains the product/component specification information from the suppliers by category. From the left to the right, the names of the suppliers, product model, tech add-in value, PCB area of part, audio quality (optional), and video quality (optional), are listed.

Table 2. Product/Component Specification Information from the Suppliers

Category	Supplier Name	Product Model	Tech Add-In value	Specification: area, stereo output and fill rate
Motherboard	Intel	D925XEBC2	$87	243.84mm*243.84mm stereo output 100 db (assumed)
Motherboard	Intel	D875PBZ	$115	244.61mm* 243.84mm 1.2 *Billion texels/sec* stereo output 100db (assumed)
Motherboard	Intel	D845GVSR	$72	233.69mm*208.28mm
Video Card	BFG	Geforce6800	$95	80.22mm*53.69mm *5.6 Billion texels/sec.*
Video Card	BFG	GeforceFX5600	$66	77.25mm*52.20mm 4 *Billion texels/sec*
Audio Card	Creative	Audigy 4	$35	79.02mm*51.11mm Stereo Output 108db
Audio Card	Creative	Audigy 2 ZS	$28	75.76mm*48.33mm Stereo Output 106db

Table 3 shows the manufacturing cost and the tech add-in cost of each component in Table 2. The Tech add-in value is the pre-investment which is used to develop the components besides the cost of components manufacturing, and it is also considered the profit of the suppliers. Table 4 shows the estimated transportation distance from the parts' manufacturer to the assembly place, which may determine the working process schedule of supply chain management group, and therefore, affect the whole system delivery time to the market.

Table 3. Product Detail Quotation from Suppliers

Product Model	PCB Manufacturing Cost($)	Tech Add-In value($)	Total Component Cost($)
D925XEBC2	5.113	87	92.113
D875PBZ	5.129	115	120.129
D845GVSR	4.185	72	76.185
Geforce6800	0.370	95	95.370
GeforceFX5600	0.346	66	66.345
Audigy 4	0.347	35	35.347
Audigy 2 ZS	0.314	28	28.314

Table 4. Manufacturer Location Data

	Location	Distance (mile)
Assembly Place	Corvallis,OR	0
D925XEBC2	Portland,OR	100
D875PBZ	Seattle,WA	256
D845GVSR	San Francisco,CA	560
Geforce6800	Beaverton,OR	109
GeforceFX5600	San Jose,CA	605
Audigy 4	Boston,MA	3100
Audigy 2 ZS	Boston,MA	3100

4.3.5 Step 5 - Analyze E, Q, C Performances

E, Q, C performances generated by all the activities are calculated by using either physics-based or experiment-based analytical relationships. For E performance (i.e. environment impact), Eqn. (1) is used. The environmental impact generated by each activity is the product of the E driver (see Section 4.3.4) and PCB area change caused by the activity. The total environmental impact is the summation of environmental impact generated by all activities in Fig. 9.

$$Environmental\,\mathrm{Im}\,pact = \sum (AreaPCB * \Delta Env./cm^2) \tag{1}$$

The quality performance is measured by FillRate. For Q performance (i.e. product quality), Eqn. (2) is developed. As shown in Figure 10, the analytical relationship between FillRate and video memory capability is developed by data fitting of the specifications of video cards [7]. Given the video memory change caused by an activity, the FillRate contribution of this activity can be measured. The Q performance of the video card is obtained by the summation of the FillRate contributions of all the activities in Fig. 9.

$$FillRate = \sum (2.5247 * Ln(\Delta memAdd / activity) - 8.5) \quad (2)$$

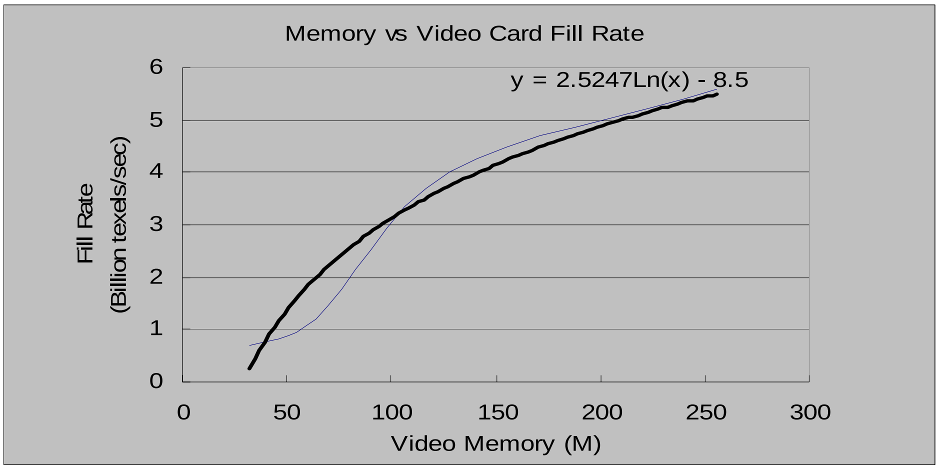


Figure 10. FillRate Vs. Video Memory Characteristics

The cost is measured by dollar. The activity cost generated by each activity is the product of PCB area change per activity (C driver) and cost of PCB area unit. The total cost consists of the summation of the activity cost generated by all activities and the tech add-in value of the components.

$$Cost = \sum (AreaPCB * \Delta \cos t / cm^2) + \sum TechAddinValue \quad (3)$$

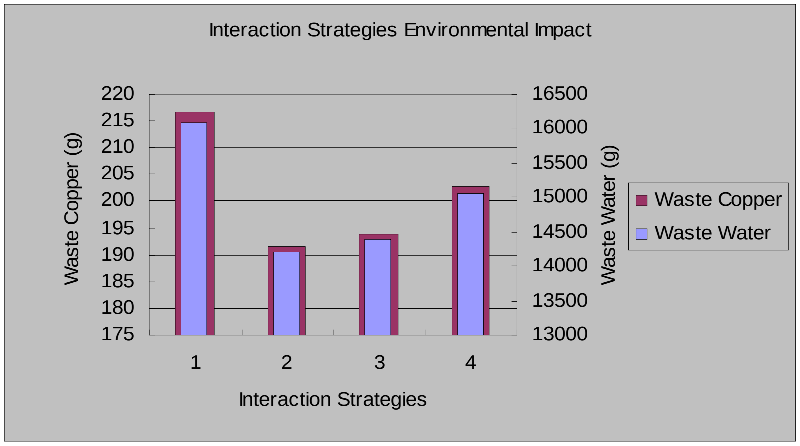
The evaluation results of the Interaction Strategy 1 are shown in Table 5.

Table 5. E, Q, C Performances of Interaction Strategy 1

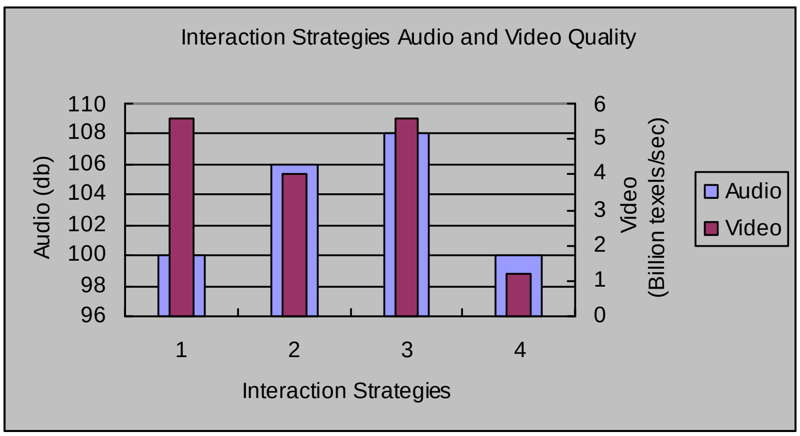
Component	*Model*	*PCB Area (cm^2)*	*Waste Water (g)*	*Waste Copper (g)*	*Cost ($)*	*Quality db/Billion texels/sec*
Motherboard	D925XEBC2	594.58	14998.86	202.16	92.11	
Video Card	Geforce6800	43.07	1086.49	14.64	95.37	
Subtotal		637.65	16085.35	216.80	187.48	100/5.6

4.3.6 Step 6 - Compare And Interpret The Evaluation Results

(a) Environmental Impact Result Data Chart



(b) Quality Result Data Chart



(c) Cost Result Data Chart

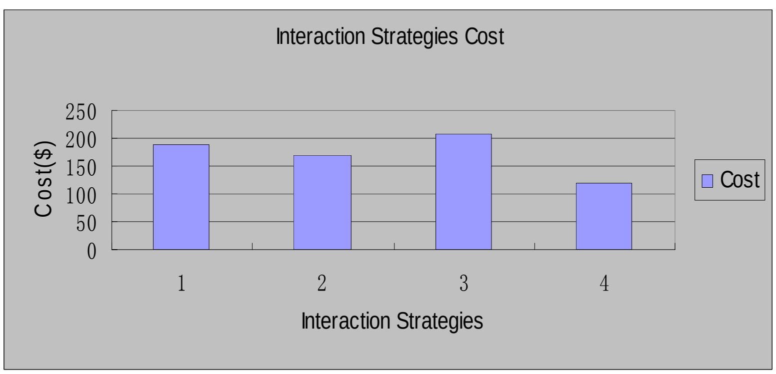


Figure 11. Comparison of the Evaluation Results of Interaction Strategies 1-4
(a) Environment Impact; (b) Quality; (c) Cost

The Steps 1-5 demonstrated by using the Interaction Strategy 1 (Section 4.3.1 – 4.3.5) can be repetitively applied to evaluate Interaction Strategies 2-4. The evaluation results of all the four interaction strategies can then be obtained and compared. As shown in Figure 11.a, the horizontal axis shows the four interaction strategies (1-4), and the vertical axis is the amount of waste copper (solid) and water in gram. The results show that Interaction strategy 1 generates the maximum waste copper and water among the four interaction strategies. As shown in Figure 11.b, the video quality is indicated by billion texels/sec with red bar, and the audio is indicated by decibel with blue bar. The results show that Interaction Strategy 3 lead to the best product quality in terms of video and audio card performance. As shown in Figure 11.c, the different cost of interaction strategies are plotted, and the unit is dollar. The results show that Interaction Strategy 4 is the least costly.

Table 6. Ranking Table of Interaction Strategies

	Environmental Impact	**Quality**	**Cost**
Interaction Strategy 1	IV	III	III
Interaction Strategy 2	I	II	II
Interaction Strategy 3	II	I	IV
Interaction Strategy 4	III	IV	I

Based on the E, Q, C performances shown in Figure 11.a-c, a ranking table (Table 6) is created to summarize the performance ranking of the four interaction strategies assessed from "I" (the best) to "IV" (the worst). The ranking table and the plots in Figure 11 may then be used to select a suitable interaction strategy to achieve desired environmental impact, product quality, and cost of designing and manufacturing PCB.

5 Conclusion

The growing concerns of the environmental impact of developing electronic products have motivated the development of an activity-based modeling approach to quantitatively assess the product developer and supply chain relationship. Based on the content and extend of "information overlap" among decision stakeholders, an interaction strategy space is constructed, and interaction strategies are classified. An object-oriented activity construct is then combined with the three view activity based modeling to construct an activity based representation of the interaction strategies, which is the basis for quantitative assessment of their effectiveness in terms of their E, Q, C performances. An example problem of electronic product design is selected to demonstrate the use of the assessment method and process. The effectiveness of four typical interaction strategies are evaluated and compared. The evaluation results can provide useful knowledge and guidance for the selection of a suitable interaction strategy in order to achieve desired Eco-Conscious design of electronic products. Future work includes automation of the evaluating process by software development and integration with a design methodology.

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Corresponding author name: Ping Ge
Institution/University: Oregon State University
Department: Mechanical Engineering
Address: ROG 204, ME/OSU, Corvallis, Oregon 97331-6001
Country: USA
Phone: 541-737-7713
Fax: 541-737-2600
E-mail: christine.ping-ge@orst.edu