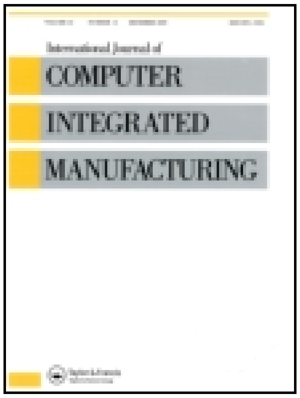

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System dynamics modelling of product carbon footprint life cycles for collaborative green supply chains

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Governments, environmental groups and industry associations are reducing greenhouse gas emissions to insure environmental sustainability. Manufacturing plays an important role in economic development but is a main cause of global warming since production requires energy consumption. The supply chain leadership coalition has requested all members to publish their carbon emission data and to reduce emissions. In addition, the International Standard Organization (ISO) has legislated and published ISO14064 as an industrial guideline to control global greenhouse gas emissions. The British Standards Institution developed PAS2050 as the world's first government regulation to control a product's carbon footprint. Providing carbon labelling on products increases product appeals and sales revenues, but also increases manufacturing costs. This research aims to minimise a product's carbon footprint, while controlling its manufacturing cost during collaborative green product design and production planning. An economic input–output life cycle assessment approach is used to evaluate the carbon emissions of new products. The life cycle assessment identifies problematic carbon emissions within the supply chain. Based on the input and output data, the research applies system dynamics modelling to simulate and identify green product redesigns with cost-effective carbon footprints during manufacturing. The purpose of this research is to derive optimal means to reduce the carbon footprint for green product development and production. Finally, the paper uses the case of an electronic image projector to demonstrate the application of the methodology.

Keywords: product carbon footprint; economic input–output life cycle assessment; system dynamics; mass customisation

1. Introduction

Industrialisation has caused global pollution, increased the amount of CO_2 emissions and ultimately has started global warming. According to the Intergovernmental Panel on Climate Change report (IPCC 2009), if we do not take action on global warming over the next 50 years, the earth's average temperature will increase and the sea levels will rise with large land areas disappearing under the sea. Most likely, global warming will significantly harm and alter the earth's environment and permanently alter land masses and biodiversity. In 1988, the World Meteorological Organization and United Nations Environment Program established an IPCC to research climate change. In 1994, 150 countries adopted the United Nations Framework Convention on Climate Change. Three years later, the Kyoto Protocol was enacted to stabilise greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system (UNFCCC 2009).

The Carbon Disclosure Project (CDP) consists of 385 globally dispersed institutional investors. The objective of CDP is to require corporations to publish their carbon emissions and to propose a strategy for managing emissions to minimise climate change (CDP 2009). The Supply Chain Leadership Coalition, which consists of 500 corporations worldwide, has also joined the CDP. A carbon footprint measures the emission of carbon dioxide and its environmental impact. In 2008, the British Standards Institution (BSI) published a product carbon footprint specification PAS2050 (BSI 2009a), which serves as a general assessment guideline (BSI 2009b). The International Standard Organization (ISO) will publish an international product carbon footprint standard ISO14067 in 2011. Many countries are establishing regulations for product carbon labelling. These efforts will first reduce the environmental impact of products (including disposal) and then focus on all aspects of green production including design, transportation, and reuse. Carbon disclosure is

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essential to reduce carbon emissions. Likewise, creating low carbon products is the new trend for mass market customisation.

This research integrates economic input–output life cycle assessment (EIO-LCA) and system dynamics (SD) modelling to develop a cost analysis methodology. The methodology reduces carbon emissions and reduces the carbon footprint for the mass customisation environment. Finally, a case demonstrates the effectiveness of the methodology for reducing carbon emissions while mass producing electronic projectors. The paper is organised in the following sections. In Section 2, the related background and research literature are reviewed, including carbon footprints, life cycle analysis and SD. Section 3 presents the methodology for integrating life cycle analysis and SD modelling. A detailed case study is presented in Section 4. Section 4 presents the mass customised product's bill-of-material (BOM), supply chain hierarchy and the model for reducing the overall carbon footprint and cost structure. Finally, conclusions are drawn in Section 5.

2. Literature review

This section reviews the related background and research literature including carbon footprints, life cycle analysis and SD. A carbon footprint is a measure of carbon emissions produced by direct and indirect activities throughout the product life cycle (Wiedmann and Minx 2007). Carbon footprints include individual, organisational and product carbon footprints, where the total greenhouse gases emitted during production are measured in tons (or kilograms) of carbon dioxide equivalent (Carbon Footprint 2009). The primary footprint is a measure of the direct emissions of CO_2 from the burning of fossil fuels during daily activities such as domestic energy consumption (electricity, natural gas) and driving a car. Individual consumers have direct control of these emissions. The secondary footprint is a measure of the indirect CO_2 emissions from the life cycle of products used. The secondary footprint of CO_2 emissions is associated with the products' production and eventual breakdown and disposal.

An organisation's carbon footprint measures the carbon emissions attributable to the activities of the organisation. According to the ISO standard ISO 14064, there are three categories for an organisation's carbon footprint (ISO 2005a, 2005b, 2005c). The first category accounts for the direct emissions from equipment including boilers, internal transportation, refrigeration and septic tanks. The second category includes indirect emissions produced by activities such as electricity generation. An organisation uses electricity, but these gas emissions are attributed to the power plant that generates the electrical power. The third category covers emissions caused by business trips, outsourcing transportation, and product storage and disposal contracted to third parties. According to previous research (Huang *et al.* 2009), the first and second categories contribute less than 25% of the total direct and upstream carbon footprints for the majority of businesses. Carbon emissions for the third category have a significant impact on the overall carbon footprints for organisations. Thus, the ISO14064 standard for greenhouse gas management includes the following stipulations:

(1) Specification with guidance at the organisation level for quantification and reporting of greenhouse gas emissions and removal (ISO 2005a).
(2) Specification with guidance at the project level for quantification, monitoring and reporting of greenhouse gas emission reductions or removal enhancements (ISO 2005b).
(3) Specification with guidance for the validation and verification of greenhouse gas assertions (ISO 2005c).

Measuring the carbon footprint from manufacturing a product or providing a service includes several accounting categories that relate to the product and its supply chain. The BSI published the world's first product carbon footprint standard PAS2050 in October 2008 (BSI 2009a). PAS2050 is the reference used by ISO14067 to develop the product carbon footprint standard guideline. PAS2050 was developed as a consistent method for assessing greenhouse gas emissions throughout the product or service life cycle. Full product life cycle greenhouse gas emissions include emissions caused by extracting or producing raw materials, transportation, packaging, manufacturing processes, storage, product use and final product disposal (BSI 2009a). On the other hand, the primary product life cycle gas emissions include emissions from manufacturing processes and transportation, particularly for manufacturers (Carbon Footprint 2009). There are two approaches used for the measurement and assessment of product carbon footprints. The business-to-business (B2B) assessment calculates the primary gas emissions from the manufacturing and transportation perspectives. The business-to-consumer (B2C) assessment measures the entire emissions from raw material extraction, production, to the usage and final disposal of a given product. Figure 1 depicts the steps used to calculate product carbon footprints (BSI 2009b).

Carbon labels provide reliable references for consumers to choose environmentally friendly products (Brenton *et al.* 2009). The United Kingdom, the

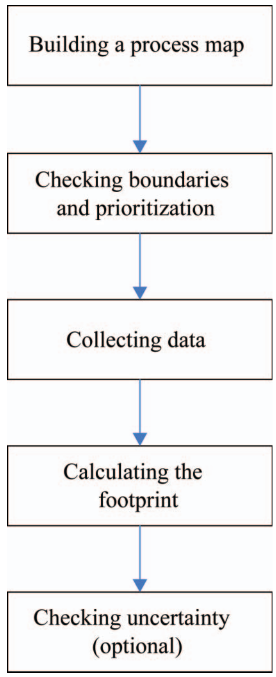

Figure 1. The five steps for calculating the product carbon footprint.

United States, Canada, France, Japan, Korea and Thailand have implemented consumer carbon labelling policies. The British market research institutes (GfK NOP 2010, LEK Consulting 2010) report that carbon labels effectively increase sales. About 67% of the customers surveyed preferred to buy products with lower carbon footprints. The manufacturers of electronic products play an important role in promoting initiatives and designs that lower carbon footprints in order to sustain an environmentally aware consumer market.

2.1. Life cycle assessment

Life Cycle Assessment (LCA) is the investigation and valuation of the environmental impact of a given product caused by its introduction, use and disposal in the marketplace. LCA is used to evaluate the inputs, outputs and the potential environmental impacts of a product from use of raw materials to the final disposal or recycling of components (ISO 2006). The main function of the assessment is to identify the various stages of pollution and energy consumption. Several scholars have proposed methodologies for environmentally conscious product design that considers the entire product life cycle. Jianjun *et al*. (2008) developed a life cycle engineering design methodology and a comprehensive life cycle assessment tool for mechanical and electrical products. Houe and Grabot (2007) developed an assessment software tool that uses life cycle analysis and ecological design methods to consider and improve a product's environmental performance during the design stage rather than trying to correct environmental design flaws after a product is manufactured and introduced into the marketplace. ISO has proposed an LCA but several and more simplified assessments have been proposed (Jensen *et al*. 1998, Todd and Curran 1999). The simplified LCA approaches include screening (Bretz and Frankhauser 1996), streamlined assessment (Todd and Curran 1999, Staikos and Rahimifard 2007), matrix approaches (Hur *et al*. 2005) and the EIO-LCA (Hendrickson *et al*. 2006). Among these approaches, this research selects and uses the EIO-LCA due to the reported increased reliability of the results (Hendrickson *et al*. 2006).

ISO proposes LCA using a bottom-up concept, which complicates measuring the carbon footprints for large scale and detailed processes. On the other hand, EIO-LCA implements a top-down approach, which solves the problem of large scaled analysis requiring too detailed initial definition and assessment. The EIO-LCA was well studied by Carnegie Mellon University to assess the cause of carbon emissions from extracting raw materials and other manufacturing supply chain activities while consuming energy resources. EIO-LCA uses two simplifying assumptions (Hendrickson *et al*. 2006):

(1) If 10% more output from a particular factory is needed, each of the inputs will have to increase by 10% proportionally.
(2) All production facilities that make products and provide services can be aggregated into their economic sectors.

The additional assumptions of this life cycle analysis approach were further defined by Chiang and Wainwright (2005):

(1) Each industry (sector) produces a unique product.
(2) Each industry output uses a fixed input ratio, i.e. the linear relationship between input and output quantities.
(3) The production and revenues in each industry define a linear correlation.

Economic input–output modelling applies macroeconomic theory and assumes that each industry (or sector) produces a single product. Thus, life cycle analysis uses sector-level data for aggregation, which allows for the identification of differences between different products and to understand product specific emission contributions. The advantages of EIO-LCA summarised by Lave *et al*. (1998) include low implementation costs and easy access to economic input–output data from government statistics.

2.2. System dynamics

Gordon (1978) noted that a system is an aggregation, based on certain pre-defined rules, of all things and elements that interact and inter-rely on each other. SD is a modelling approach used to describe and model the behaviour of complex systems over time. SD is different from other system modelling approaches since it uses feedback loops, stocks and flows to display the dynamic nonlinearity of systems. Forrester defined SD as a modelling approach to study the feedback behaviour of management information systems. SD uses models to design the system structure and assist decision-making when systems are complex and dynamic (Forrester 1968).

SD was first applied to business management. The book 'Limits to Growth' (Meadows *et al*. 1972) built a model to simulate the future scenarios of a world with limited resources and uncontrolled economic growth. Sterman (1989) designed the famous Beer Game to simulate the behaviour of supply chains including the bullwhip effect and safety stocks. For management and social systems, researchers and policy makers have used SD models to conduct policy experiments (Mohapatra *et al*. 1994). SD is also often used to analyse and assess the environmental impact (Vizayakumar and Mohapatra 1993) of global warming and greenhouse gas emissions (Nail *et al*. 1992, Vrat *et al*. 1993, Anand *et al*. 2005). The advantages and applications of SD are defined by Sterman (2000):

(1) SD deals with the problems of modelling high-level, non-linear systems with complex feedback.
(2) SD shows the relationship between internal and external factors in the model world.
(3) SD sets the various control factors of the system and observes how the system behaves and reacts to trends.
(4) SD models can be built at an abstract level with limited data.

The causal feedback loop diagram is the basis of SD modelling and allows users to analyse the system variables, positive and negative feedback structure, causality and time lag effects for complex problems. The causal feedback loop diagram allows users to define the following concepts:

(1) The system boundary, i.e. the main variables of the system,
(2) The causal relationship and direction in system variables, and
(3) The basic structure of the system or the major feedback loop.

Figure 2 is an example of a positive causal link that links two related variables. The combination of several links creates a causal loop. When a causal loop is closed, the loop is called a causal feedback or closed loop. The characteristic of a positive feedback loop is that the system continuously shows growth over time, which represents the divergence of the mathematical model. The negative feedback loop in the system shows asymptotic growth or decline patterns over time that represents the convergence of the model (Sterman 2000).

Figure 3 is an example of the causal feedback loop diagram that analyses population change. The birth rate increases and thus the total population increases. The left of the diagram shows a positive feedback loop. On the other hand, population growth will cause the increase of mortality in the formation of a negative loop, so the system tends to reach a balance on the right hand side of the diagram.

After defining a causal feedback loop diagram, the system is modelled using simulation software. Common software applications for SD include STELLA, Vensim, Powersim and iThink. These applications provide four basic objects which are the stock, flow, connector and auxiliary. The stock represents the state of the system variables at a given time. The value of a stock depends on the inflow and outflow of a substance such as water flowing from a water tank. A flow represents the change of stock per unit of time. Stock values may be determined by interactions with other stock variables and auxiliary variables. A connector (arrow) is used to link stocks, flows and auxiliary

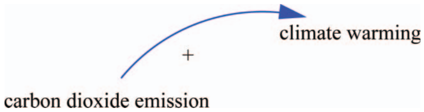

Figure 2. A positive causal link with direction.

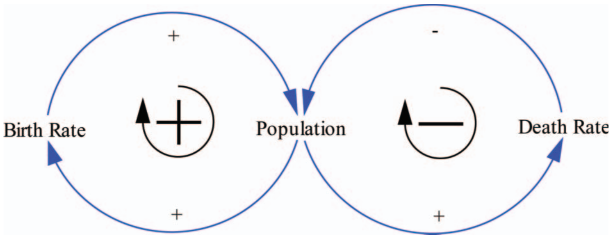

Figure 3. A population causal feedback loop.

variables. Auxiliary variables are values of input parameters. Figure 4 depicts a simple population model.

Figure 4 shows that birth and death are flows in the model that control population. The rates of birth and death are the auxiliary variables and these variables are usually constants. This simple model can be used to simulate birth, deaths and their impacts on population change. Sterman (2000) pointed out that models should be simple, with clear goals, and all unimportant variables should be removed. The behaviours and interactions in system models can be simulated using the software functions. For example, the delay function models dynamic effects and time delay gaps whereas the table function models non-linear relationships while considering the characteristics of variables and the decision-making processes. Therefore, SD is a suitable method for decision-making dynamic analysis (Hsiao 2004).

3. Methodology

This research uses life cycle analysis and SD to analyse and control the cost of carbon footprints during product redesign for mass customisation. Figure 5 shows the three-layer procedure for carbon footprint analysis.

3.1. *Life cycle analysis layer*

Figure 6 depicts the standard process of conducting an EIO-LCA (Hendrickson *et al.* 2006). A target product (or process) for assessment is selected and the output vector of the product's final demand is estimated. The input–output table is defined, the final output vector is computed and the environmental impact factors of the product are estimated.

After the target product is selected and the associated supply chain is defined, the input–output data are collected from published government statistics to construct Table 1.

In Table 1, X_{ij} represents the output of Sector i to Sector j. The total input of Sector i is I_i, which is the sum of the intermediate inputs from all sectors. Further, Sector i's added value is V_i. The total sector output O_i is the sum of all intermediate outputs. The final demand F_i represents the output demand from Sector I's customers. The EIO-LCA mathematical formulas are briefly listed as follows.

$$\sum_{i=1}^{n} X_{ij} = I_j \qquad \sum_{j=1}^{n} X_{ij} = O_i \qquad I_k + V_k = O_k + F_k = X_k \tag{1}$$

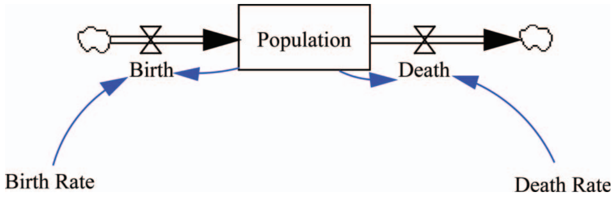

Figure 4. A simple population system model.

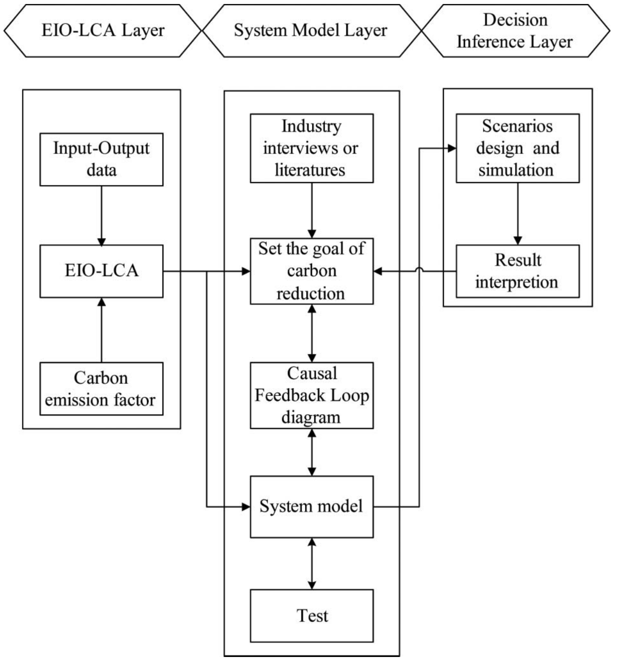

Figure 5. The three-layer procedure for carbon footprint cost analysis.

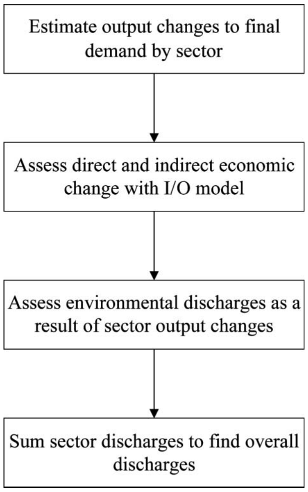

Figure 6. The standard process of EIO-LCA (Hendrickson *et al.* 2006).

Table 1. The input–output table (Green Design Institute CMU 2008).

	Input to sectors				Intermediate output O	Final demand F	Total output X
Output from sectors	1	2	3	n			
1	X_{11}	X_{12}	X_{13}	X_{1n}	O_1	F_1	X_1
2	X_{21}	X_{22}	X_{23}	X_{2n}	O_2	F_2	X_2
3	X_{31}	X_{32}	X_{33}	X_{3n}	O_3	F_3	X_3
n	X_{n1}	X_{n2}	X_{n3}	X_{nn}	O_n	F_n	X_n
Intermediate input I	I_1	I_2	I_3	I_n			
Value added V	V_1	V_2	V_3	V_n		Gross domestic product (GDP)	
Total input X	X_1	X_2	X_3	X_n			

After constructing the input–output table, the requirements matrix A is derived from Table 1 using the following formula:

$$A = \begin{bmatrix} \frac{X_{11}}{X_1} & \frac{X_{12}}{X_2} & \cdots & \frac{X_{1n}}{X_n} \\ \frac{X_{21}}{X_1} & \frac{X_{22}}{X_2} & \cdots & \frac{X_{2n}}{X_n} \\ \vdots & \vdots & \vdots \cdots & \vdots \\ \frac{X_{n1}}{X_1} & \frac{X_{n2}}{X_2} & \cdots & \frac{X_{nn}}{X_n} \end{bmatrix} \quad (2)$$

Matrix A is used for the assessment of the environmental impacts from all sectors in the supply chain.

$$x_{\text{direct}} = (I + A)y \quad (3)$$

where x_{direct} is the direct vector of required inputs, y is the vector of the desired output and I is the identity matrix. In Equation (3), x_{direct} represents the combination of production of the manufacturer's own output ($I \times \boldsymbol{y}$) and the first level suppliers' contributing output ($A \times \boldsymbol{y}$). The output of the second level suppliers is calculated using ($A \times A \times \boldsymbol{y}$) and

$$b = Rx \quad (4)$$

where $\boldsymbol{b}$ is the vector of the environmental burden and R is a matrix with diagonal elements representing the emissions per output dollar (i.e. the coefficients of carbon emissions) from each sector. Therefore, using the life cycle analysis principle, the environmental emissions of a given product can be estimated using the sum of all supply chain sector outputs multiplied by their corresponding environmental impacts. Considering that most supply chains have multiple tiers, the Leontief inverse matrix [Equation (5)], is used to account for the environmental impact of multi-tier supply chains:

$$x = (I - A)^{-1}y \quad (5)$$

In our case study, the carbon emission coefficients for all industrial sectors (R) are obtained from the Taiwan's Bureau of Energy and other relevant statistics (Bureau of Energy 2010). Using Equation (4), the supply chain assessment data are summed to obtain the carbon emissions of the product. Finally, after completing the life cycle analysis procedure, sectors that contribute most to the carbon footprint can be identified and targeted for future reduction in emissions.

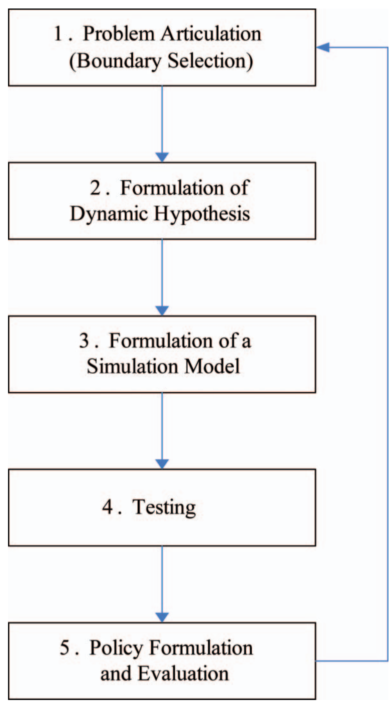

Figure 7. The standard procedure of SD modelling and application.

3.2. *System dynamics*

In order to reduce carbon emissions for frequent product redesigns during mass customisation, this research creates an SD model. The model simulates different scenarios for decreasing the costs of carbon emissions and selects the most cost effective and environmentally friendly product design. Using the

Table 2. The SD model carbon footprint inputs.

Inputs		Explanation
Material stage	The carbon footprint of processes	The carbon footprint of energy and resource consumption during the raw material extraction stage.
	The carbon footprint of transportation	The carbon footprint due to transportation from suppliers to manufacturer.
	Total carbon footprint of materials	Total carbon footprint during materials stage.
Manufacturing stage	The carbon footprint of assembling	The carbon footprint of energy and resource consumption during the manufacturing stage.
	Controlling the carbon footprint	Controlling the carbon footprint by applying new materials, new production techniques and new energy sources.
	The cost of implementing control	The cost of implementing carbon footprint controls.
	The financial data of the corporation	The financial data of the corporation including business income, gross profit, and research and development spending.
Logistics stage	The carbon footprint of transportation	The carbon footprint of transportation from manufacturer to consumers.
Use stage	The carbon footprint of product usage	The carbon footprint related to product usage.
Waste stage	The waste stage carbon footprint	The carbon footprint associated with final disposal or the waste stage.

Table 3. The outputs of the product carbon footprint SD model.

Outputs	Explanation
Product carbon footprint	The product carbon footprint after implementing controls.
Cost for controlling the carbon footprint	The cost of implementing controls.

life cycle analysis results, problematic carbon emission processes for newly designed products are selected as improvement goals. Figure 7 displays the standard procedure of SD modelling and applications (Sterman 2000) and is divided into qualitative and quantitative analysis (Towill 1996). The dynamic hypothesis is derived during the stage of qualitative analysis, whereas the simulation model is created to execute the quantitative evaluation.

The input items of the system model include the impact factors and related parameters, such as the carbon footprints of raw materials, production and transportation during supply chain operations. The parameter values are transferred from the life cycle analysis results. The SD outputs are the resulting costs of the carbon footprint. The starting point for the SD model is the required quantity (output) of a product. The product demand is the starting point for the model simulation. Using the flow parameter values during the life cycle processes (e.g. extracting raw materials, product manufacturing and sales), the changing costs for carbon dioxide reduction can be dynamically observed. Factors and parameters affecting the SD simulation results are listed in Tables 2 and 3.

Using the SD causal feedback loop diagram, the causal relationships impacting carbon footprint reduction can be identified for different stages of the supply chain. After defining the causal feedback loop diagram, the Vensim Ventana (2009) software package is used to model and graphically represent the input variables (stocks and flows) and their relationships. The reliability and validity of the model are evaluated by checking the model consistency, evaluating the validity and reliability of results for extreme cases, and studying the reproducibility of the behavioural results for real world operations. Based on the PAS2050 standard, the analytical method of product carbon footprints are divided into two perspectives.

(1) The reduction of carbon footprints from the B2B viewpoint
   - At the raw materials stage, by reducing the number of suppliers, reducing the transportation distances of the raw materials and using low carbon emission components.
   - At the manufacturing stage, by improving the energy efficiency in the factory and using alternative sources of energy.
   - At the distribution stage, by improving the fuel consumption of vehicles or shortening the transportation distance.

(2) The reduction of carbon footprints from the B2C viewpoint
   - At the usage stage, reducing the carbon footprint by improving the energy efficiency of alternative components.
   - At the recycling stage, by reducing the carbon footprint of recycled products.

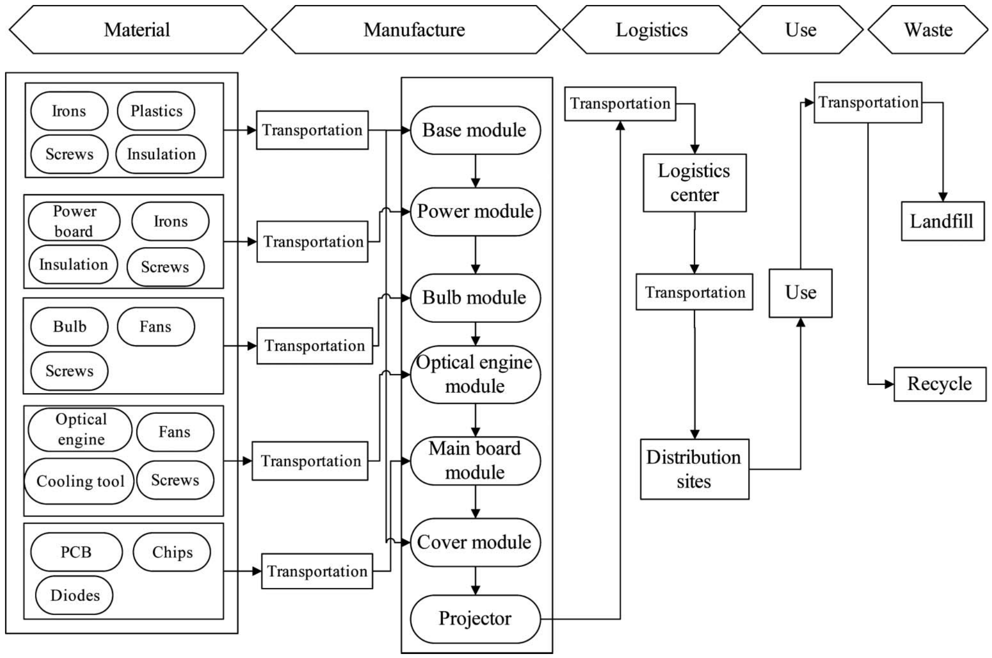

Figure 8. The complete value chain for a front projector product.

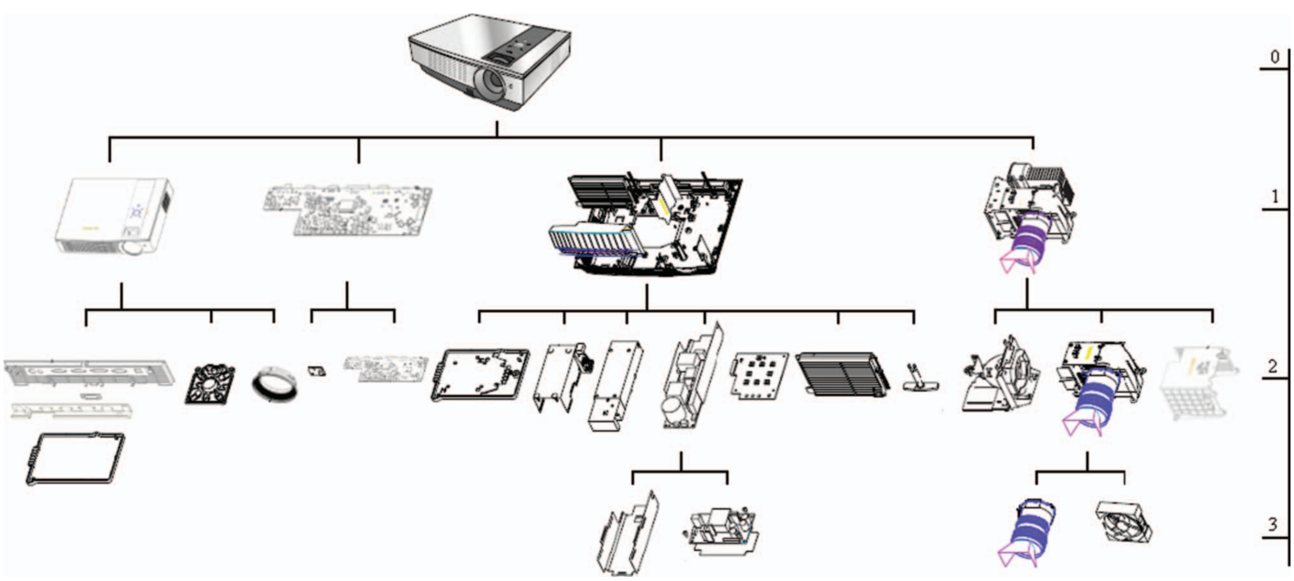

Figure 9. The bill-of-materials for a front projector (LG 2010).

4. Case implementation

The case study uses a photonic front projector, a product that is frequently subjected to redesign and is mass customised for a wide range of target customers. According the Pacific Media Associates marketing survey, the front projectors' global market is forecasted to grow 40% annually from its level of 6.33 million units in 2009 to 8.65 million units in 2010 (Photonics.com 2010). Figure 8 shows the entire value chain, from supply chain to demand chain, of the front projector. The oval nodes represent physical components of a projector during the production process. The rectangle nodes represent the transactional procedures. The system factors include key parts such as LCD panels and special optical engine system components. The prime manufacturer (i.e. the end product producer) assembles the parts and components to produce the final products, which often has several configurations required for mass

Table 4. The total requirement matrix $(I - A)^{-1}$ for the projector product.

Inputs	Metal	Iron	Aluminium	Optoelec material	Electronic component	Optical instrument	Bulb	Electricity	Water	Land transport	Sea transport
Metal	7.6864	3.7022	0	0	0	0.0005	0	0	0	0	0
Iron	0	1.0604	0	0	0	0.0001	0	0	0	0	0
Aluminium	0	0.0283	1.4914	0.0294	0.0111	0.0243	0.2092	0	0	0	0
Optoelec material	0	0	0	2.3634	0.0059	0.2531	0	0	0	0	0
Electronic component	0	0	0	0.1333	1.4595	0.0673	0	0	0	0	0
Optical instrument	0	0		0.0053	0	1.2376	0	0	0	0	0
Bulb	0	0	01	0.0006	0.0007	0.0058	1.1613	0	0	0	0
Electricity	0.1262	0.0883	0.0947	0.0749	0.0710	0.0502	0.0552	1.2303	0.0704	0.0053	0.0044
Water	0.0338	0.0297	0.0048	0.0030	0.0049	0.0018	0.0015	0.0017	1.4097	0.0003	0.0018
Land transport	0.1143	0.0665	0.0268	0.0164	0.0124	0.0170	0.0150	0.0097	0.0024	1.0025	0.0114
Sea transport	0	0	0	0	0	0	0	0	0	0	1.8335

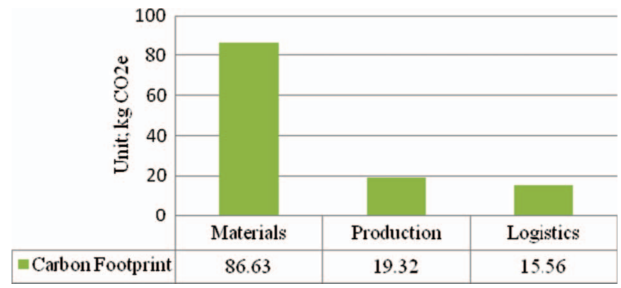

Figure 10. The EIO-LCA-derived carbon footprint assessment for a computer projector.

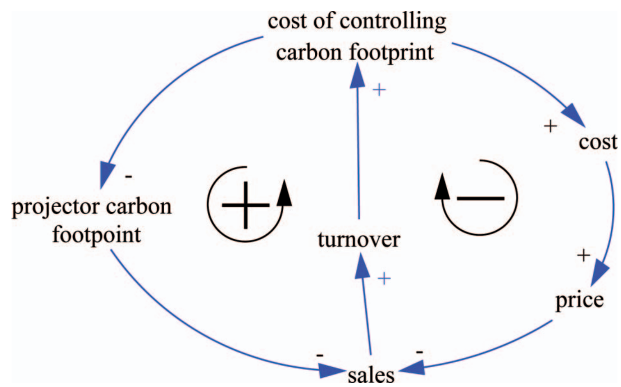

Figure 11. A causal feedback loop for carbon footprint reduction.

customisation. The projector's bill-of-materials (BOMs) is used to calculate the various product configuration carbon footprints. Figure 9 displays the BOM of a modularised (and mass customised) projector. A common projector structure contains four modules including the superstructure, the motherboard, the chassis and the power supply.

4.1. Life cycle analysis for the case

Using the industrial statistics published by Taiwan Directorate General of Budget, Accounting and Statistics (2010), the scope and explanations of the product sector classifications are recorded. Eleven industrial sectors related to the projector production are selected to calculate the economic input and output coefficients. A front projector is categorised under the optical instruments sector. Table 4 shows the total requirement matrix $(I - A)^{-1}$ related to the product type, projector and its production.

First, the output vector ($\boldsymbol{F}$) for the projector is used as the output vector of other optical equipment sectors. Then, the input vector ($\mathbf{x}$) for various departments is computed. The carbon dioxide emission coefficients for

Table 5. Strategies for reducing the carbon footprint of a projector.

Control strategy	Performance of controlling carbon	References
Improve production efficiency		
Improve machines	More products assembled or produced at the same time	Foundation of Taiwan Industry Service
Improve energy efficiency	Saving a kilowatt-hour can reduce 0.636 kg of emissions	Foundation of Taiwan Industry Service
The use of lower carbon materials		
Replace with LED	Reduces the carbon footprint by almost 30%	D Corporation
Replace with small boxes	Reducing the transportation times by half reduces the carbon footprint by half	Hitachi Website
Improve Waste Electrical and Electronic Equipment (WEEE) recycle rate	Recycling can reduce product life cycle carbon emissions. Referring to the case study of AUO's LCD TVs, the carbon footprint can be reduced 8–10% by implementing a WEEE-complying recycling plan	D Corporation and AUO Corporation

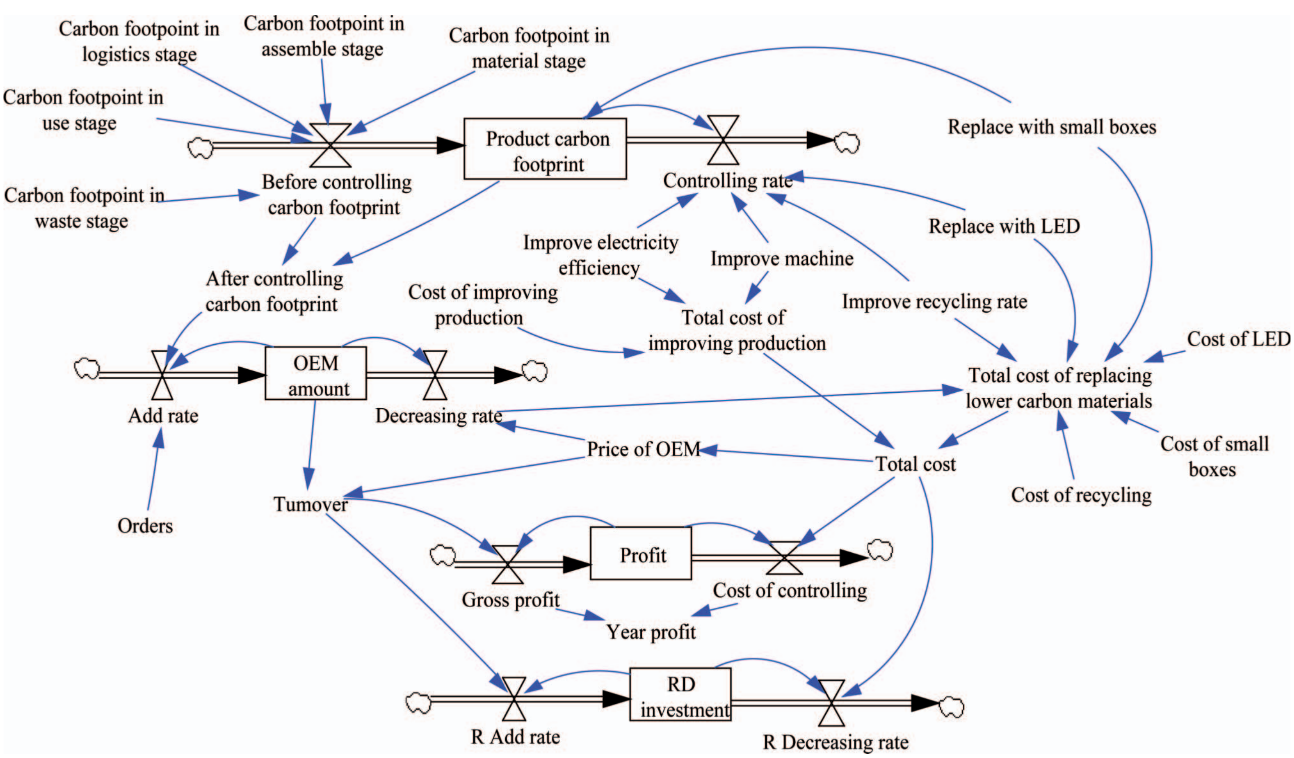

Figure 12. The system dynamics model for front projector carbon footprint reduction.

each industry are obtained from the report 'Update and Maintenance of the Resource Utilization Model and Policy Analysis' (Lin and Huang 2006) to construct the environment matrix for the front projector. The carbon footprints of the projector are shown in Figure 10. From the above analytical results, it is determined that the stage of raw material extraction produces the greatest carbon footprint. Thus, the material stage is considered as a critical point for reducing the carbon footprint. Although

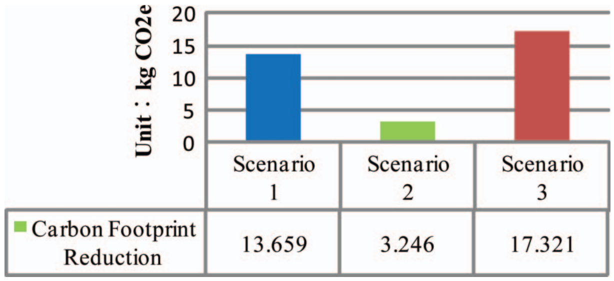

Figure 13. The simulation results for three scenarios.

there are a large number of electronic components for each projector, the assessment of the carbon footprint can be simplified by systematically collecting and organising the data for analysis.

4.2. *System dynamics model construction*

A projector manufacturer faces the challenge of reducing carbon emissions and controlling the carbon footprint. Assuming that the OEM manufacturer is responsible for designing and manufacturing the products, they are also responsible to reduce the carbon footprint. When manufacturers are dedicated to the reduction of carbon footprints, the sale of green products enhances their competitiveness and brand reputation. The SD model simulates the trade-off between the cost and the carbon reduction. Figure 11 shows a simple causal feedback loop used to analyse the effectiveness of carbon footprint reduction.

According to interviews with industrial engineers, the methods used for reducing the carbon footprints of the projector include enhancing production efficiency and lowering the carbon footprints of components. After reviewing the research results and reviewing relevant literature and technical reports, a strategy of reducing the carbon footprints for computer projectors is presented in Table 5.

Using the above strategies, this study divides the reduction of carbon footprints into three scenarios. The first scenario replaces traditional materials with new materials that have low carbon footprints, but the cost is higher. The second scenario enhances the efficiency of the manufacturing processes, which in turn lowers the manufacturing related carbon emissions. In this case, the cost is lower than the first scenario and there is a trade-off between cost and carbon emission. The third scenario combines these two strategies. Figure 12 shows the detailed SD model describing the causal feedback effects. Consequently, Figure 13 illustrates the simulation results for the three scenarios, respectively.

5. Conclusion

The European Union, Australia, California, Japan, Korea, Thailand and Taiwan have established regulations for carbon label standards. If manufacturers make significant progress on reducing product carbon footprints, the efforts will improve the reputation, brand and sales of green products. This paper used a low-cost assessment method to estimate carbon emissions and identifies the process sources that significantly increase carbon footprints. Based on the findings, an SD modelling approach was adopted to clarify the feedback loop structures among the various interacting factors. The derived model was tested and simulated under several scenarios. The simulation results were discussed to justify the cost-effective method to reduce the carbon footprints and provide data for strategic recommendations.

This paper provides a preliminary study to help corporations accurately assess and reduce the carbon footprints of mass customisation products. According to the results, it is argued that the SD approach is appropriate for the carbon emission issues and the proposed model serves as an adequate base for analysing carbon emissions of similar products in a larger context.

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