Integrating System Dynamics with Life Cycle Assessment: A Framework for Improved Policy Formulation and Analysis

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Abstract: System dynamics has been shown to be a beneficial tool for policy formulation and analysis. Numerous "yardsticks", for example monetary cost / benefit, and unemployment figures, are used to measure the expected economic and social impact that may arise during the implementation of a policy. However, when it comes to environmental impacts the "yardsticks" used are too specific in nature, reflecting a particular aim of the policy framework. This may lead to the formulation of environmental policies that has an overall adverse impact on the environment, whist addressing a particular environmental issue of concern. This paper aims to provide a framework to overcome this through integrating life cycle assessment (LCA) methodology with system dynamics. LCA is a material accounting tool that analyse the environmental burden of a product / process from "cradle to grave". It is used to compare the environmental impact of different processes. Fundamentally, LCA provides quantitative environmental indicators while system dynamics brings to LCA the dynamic characteristics missing in its original framework. In addition, the holistic nature of LCA broadens the scope of system dynamics modelling to examine all "cradle to grave" processes. Consequently, the integration of LCA with system dynamics provides an analytical tool, that considers the economic, social and environmental impact, that could be used to improve policy and decision making processes.

Keywords: System dynamics; Life cycle assessment; Decision support tool.

1 INTRODUCTION

1.1 Policy Process, Formulation and Analysis

Policy is formulated and analysed through the integration of models, where expert knowledge is seen as the basis for formulating strategies to solve identified problems. The policy process could be seen to consist of a number of processes including analysis of policy instruments, consultation, coordination, implementation and evaluation [Bridgeman and Davis, 2000, p 27]. The process is often influenced by the flow of actions that leads to a number of opportunities for choice where the choice is impacted by previous actions and commitments [Colebatch, 1998, p10]. Consequently, decision making in reference to policy formulation and analysis is influenced by the structure of the system, where policy choice alters the system structure and the system structure itself influences the opportunity for choice.

Greater awareness of the environment has seen the policy process evolve to adopt the sustainability[1] concept. This is reflected by gradual increases in capacity to address environmental issues by government, through the proliferation of environmental institutions [Davis and Keating, 2000, p 159]. Despite the adoption of sustainability in policy formulation and analysis, the integration of environmental objectives has failed to live up to expectation. This is because the incorporation of sustainability in the policy process requires the resolution of conflict between the values of environmental protection, economic development and social welfare.

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[1] Sustainability comprises of the following core principles: Intergenerational equity; Intrageneration equity; Biodiversity; Precautionary principles; Recognising global dimension; and Integration of economic and environmental goals.

This paper contains part of the authors Phd's research in the area and aims to highlight how the integration of system dynamics and life cycle assessment could contribute to improve policy formulation and analysis under the sustainability paradigm.

1.2 System Dynamics

System dynamics is a feedback model using simulation techniques to examine the behaviour of the system when subjected to varying conditions. System dynamics focuses on the structure and behaviour of systems [Goodman, 1988, p 5] composed of interacting feedback loops. System dynamics models concentrate on closed loop approach to decision making where policy decision affects the environment which itself provide input into decision-making which aims to influence the environment [Vennix, 1999, p 43]. System dynamics models are different from other optimisation and equilibrium models as it focuses on the disequilibrium dynamics and feedback complexities, through decision rules, stocks, and flows. The application of system dynamics has been broad, ranging from electro-mechanical control systems, to effects of economic development, to applications in ecology, psychology and physiology, and energy policy studies [Sastry and Sterman, 1992].

The strength of system dynamics is its ability to examine how the system structure influence decisions and how systems react to these decisions over time. This makes system dynamics ideal for the examination of a policy initiative.

1.3 Materials Accounting Tools

Materials accounting tools focus on an index or set of indices, associated with the use of material in relations to its sustainability and environmental impact. Some of the emerging material accounting tools are: Material Input Per Unit Service (MIPS), Material Flux Analysis (MFA), Substance Flux Analysis (SFA), Life Cycle Assessment (LCA) and Sustainable Process Index (SPI). These tools allow a deeper understanding of the problem at the interface between the economy and the environment. Further, this understanding could lead to improved material use within the economy so to avoid future potential environmental problems [Moore and Brunner, 1998].

In this study LCA was chosen as the tool of choice, as it allows the examination of impact resulting from specific processes. Life cycle assessment was developed from the evaluation of whole of life costs of major equipment and facilities, it was subsequently adapted to industrial systems, starting with the extraction of raw materials from the earth and tracing all operations until its final disposal as wastes back into the earth (cradle to grave). It later evolved into a methodology that concentrated on energy and raw materials; air emissions, water emissions, and solid waste were later incorporated in the calculations. In conducting an LCA, at each step of a product life an inventory of materials, energy use and environmental emissions are recorded. The environmental impact profiles are then calculated from the inventory, and later characterised into a number of impact categories. The impact categories may include; global warming potential; acidification; eutrophication; summer and winter smog; human toxicity; eco-toxicity, etc.

2 INTEGRATING SYSTEM DYNAMICS WITH LIFE CYCLE ASSESSMENT

System dynamics starts with the specification of the problem being modelled, which in turn determines the system boundary and elements of the system, which are most relevant. This invariably involves the simplification of the "real world", hence there is a significant degree of human judgement which has led to criticisms of system dynamics as being "unscientific" [Forrester, 1980, p16]. The model structure is firstly derived from an interviewing process, where the decisions, resources, rules, interactions and relationships are extracted from stakeholders [Ansoff and Slevin, 1968]. System dynamics takes a causal view of reality. The completed model is used to both understand better the operation of the system and to derive the system recommendations for policy and structural change [Lane and Oliva, 1998]. Consequently, system dynamics is fundamentally a goal-orientated approach to modelling.

The system boundary is significantly affected by the problem specification and aggregation level. This in turn influences the variables and essential components of the system that create the structure of interest [Legasto and Marciariello, 1980, p 25]. Accordingly, as the modelling process proceeds, the system boundary must be systematically challenged to determine whether they are too broad or too narrow.

As noted, LCA makes a holistic "cradle to grave" analysis. However, the traditional LCA gives only static indication of environmental impacts of processes or activities, totally ignoring system changes to subsequently feedback input.

The integration of system dynamics with LCA give rise to an innovative framework for policy formulation and analysis. Fundamentally, LCA provides quantitative environmental indicators while system dynamics brings to LCA the temporal and feedback characteristics missing in its original framework. Consequently, the integration of system dynamics with LCA provides a tool, which will be referred to as System Dynamics Life Cycle Model (SDLCM), that considers the economic, social and environmental impact, that can be used to improve policy and decision making processes.

3 CASE STUDY

The proposed framework will be demonstrated through a case study that examines container glass recycling in Sydney. The case study will illustrate how material flows in the economy are affected by policies and how the system may limit the long term viability of the policy.

3.1 Container Glass Recycling

ACI Glass Packaging dominates the container glass market in Sydney and is the only Australian producer and recycler of container glass. The market for cullet (recovered glass material) is a competitive monopsony, with only one significant buyer (ACI), but is influenced by the threat of international buyers if the price falls below a certain threshold [EcoRecycle Victoria, 1998]. Secondary markets for used / recycled container glass are being developed for its use as construction aggregate and abrasive materials.

In the primary market ACI sets the cullet buy back price to be equivalent to the raw material price. This has been nationally standardised at $72/t [Nolan and SKM Economics, 2001, p. 17].

3.2 System Dynamics Life Cycle Model (SDLCM)

The NSW EPA's Industry Waste Reduction Plan (IWRP) - Beer and Soft Drink - has set a recycling target of 55%, from the domestic glass recycling stream by 2003 [IWRP, 1999]. The current container glass system was modelled using the SDLCM to determine the economic and environmental cost; and long term viability of current and proposed recycling targets.

The model's boundary extends to include the extraction of virgin materials, manufacture, consumption, disposal and the recover of glass containers. The model is divided into four sub-modules; Raw Material Extraction; Recycling and Beneficiation; Material in the Economy; and Manufacturing of Materials. Other sub-modules are included to examine the economic and environmental cost and benefit of the system. The SDLCM is shown in Figure 1.

The monopsony nature of the container glass industry, dominated by ACI, limits the availability of first hand data as it is considered to be commercial and in confidence. The Australian Bureau of Statistics does not keep an account of the amount of glass container produced in Australia. Therefore data were obtained from second hand sources in the form of overall Australian production, reported recycling rates in Sydney and industry reports. Accordingly, the reference mode and the subsequent model contain calibration errors. This however this does affect the validity of the structure nor detract from the objective of demonstrating the application of SDLCM.

Time series data from 1990 to 1998, shown in Figure 2, for overall Australian recovery rates was used for the steady state calibration of the model; the parameters and assumptions used to calibrate the model are;

- Flow is tonnes / week
- There are abundant raw virgin materials hence its usage is not constrained.
- Recycled material can be substituted for virgin material without loss of quality.
- One unit of raw material makes one unit of product
- Production capacity capped at 5000 t/wk, equivalent to 260,000 t/yr. Assume shipping orders drives production, maintaining inventory in the economy at 26 times weekly production rates. Assume production maintains factory inventory at 8 weeks production capacity. Shipping of material is revised and processed on a weekly cycle, whereas the production is revised and updated on a monthly basis.

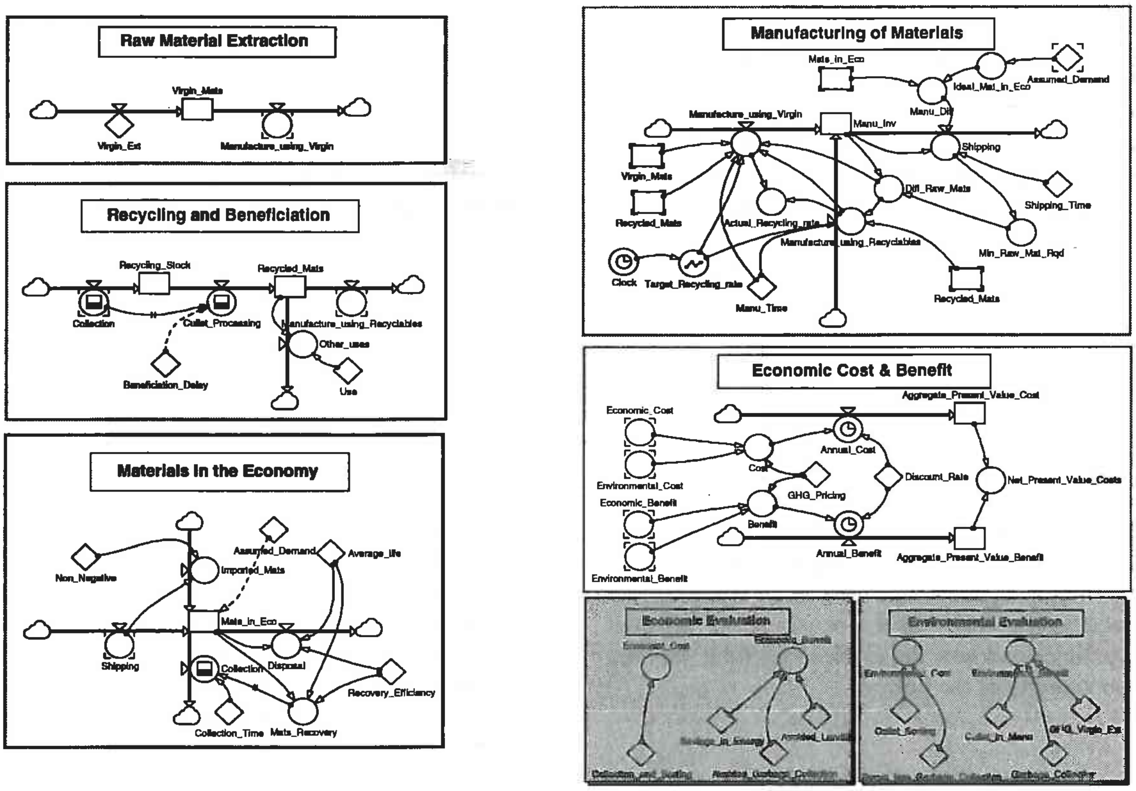

Figure 1: SDLCM - Glass Recycling System.

- Assume demand in the economy for glass average at 4,500 t/wk. Glass in the economy is estimated to be 26 weeks times the weekly glass demand. Usage of glass in the economy is estimated to have an average life time of 26 weeks.
- Assume collection and sorting of recyclable takes 2 weeks and the beneficiation process takes 4 weeks to complete.

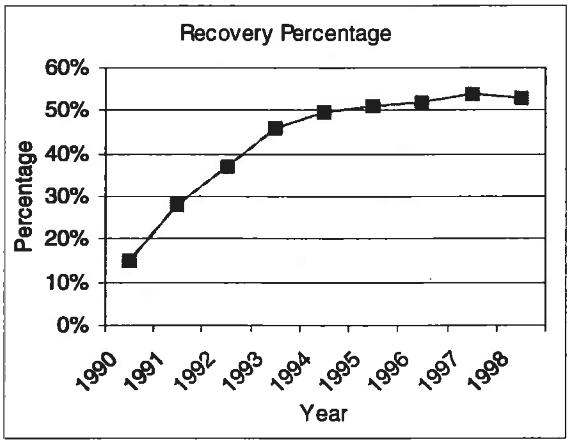

Figure 2: Recovery percentage 1990-1998.

- Post consumption recovery is approximately 43% of the containers in use [NEPC, 1998; cited in Grant et al, 1999]
- Manufacturer source virgin material when recycled material is not available.

3.2.1 Marginal Economic Cost / Benefit Sub-module

Marginal economic cost / benefit of providing glass recycling services were evaluated by considering the difference between the extra costs in providing recycling services (including recycling collection and sorting costs; reduction in manufacturing cost; savings from avoided garbage collection and landfill costs) against sending the materials to landfill.

The marginal economic costing shown in Table 1, indicated that there is a net economic cost in providing recycling services, where the cost benefit structure depends on landfill costs, this is to a large extent controlled by the government, through the provision of landfills and landfill levies.

Table 1: Marginal Cost Benefit of Container Glass Recycling.

DESCRIPTION	$/t
Recycling Collection and Sorting	$ 192.69
Avoided Garbage Collection	-$ 87.63
Avoided Landfill Costs	-$ 69.37
Calculated Energy Savings	-$ 6.23
Marginal Increase (Cost)	$ 29.46

3.2.2 Marginal Environmental Cost / Benefit Sub-module

The marginal environmental cost / benefit of providing recycling services were derived from Gabi3 LCA modelling software from IKPUniversität Stuttgart. The LCA models representing the raw material extraction, manufacturing, collection, sorting and transportation were constructed in Gabi3. The models were reduced to examine only the avoided products and process alterations associated with the use of cullet in place of virgin materials. There are numerous impact categories that could be used to examine the overall environmental impact, but, for the purpose of demonstrating this methodology, only one impact category, global warming potential was selected in this paper. Table 2, shows the environmental impact in terms of global warming potential associated with glass recycling.

Difficulties arise when monetary cost and benefit are assigned to environmental impacts; the fundamental contention is how to correctly assign a price to the environment. This case study will adopt a global warming potential value at $20/t of CO_2. This would be used to give a monetary indication of the cost and benefit of increases in recycling.

3.3 Simulation of the Glass Container Recycling SDLCM

Simulation of the glass container recycling SDLCM for the Sydney region revealed that the target-recycling rate of 55% is not sustainable in the long term. This is shown in the Figure 3, which indicated that that the target 55% recycling rate can only be sustained for a short period of time, then the system would settle to a recycling rate of around 46%. The limiting factor that inhibits the sustained higher level of recycling is the efficiency of the recovery process.

The economic valuation module revealed that glass recycling system costs around $30/t more when compared to the cost of sending the material to landfill.

The environmental valuation module revealed that the environmental benefits outweigh the environmental cost, by 61.34 kg of CO_2 per tonne of cullet recycled (at 45% recycling content). Since we have adopted a monetary value of $20/kg of CO_2, therefore the monetary benefit of recycling is $1226.80/t of cullet used in glass production.

Table 2: Summary of Global Warming Impact Potential.

COST	GWP (kg CO_2/t)	BENEFIT	GWP (kg CO_2/t)
Recyclables to MRF	13.64	Garbage to Transfer Station	11.94
Sorting	5.13	Avoided Collection to Landfill	12.12
		Landfill Processing	0
		Avoided Virgin Mat. Extraction	5.65
Sub Total	18.77	Sub Total	29.71
		Avoided Energy in Production Process[2]	1.12 x % cullet
Total	18.77	(assuming 45%)	80.11
		Difference	61.34

4. CONCLUSION

The SDLCM offers an alternative analytical tool that could be used for policy improvement and decision support. This approach can identify potential resource issues that prevent the realisation recycling targets. It provides managers and policy makers with additional insights, which can assist with the implementation of new policies. In addition, the economic and environmental modules provide an indication of

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[2] Energy savings resulting from the usage of cullet is 2.5% per 10% of cullet used in the glass batch. The energy required to melt glass is 8.38 MJ per kg of glass [Grant et al, 1999]. Therefore the energy saving per tonne of glass produced is 20.95 MJ/t/%cullet. Where the GWP per MJ of energy from natural gas is 0.05692 kg CO2 per MJ of energy.

the projected economic and environmental impacts.

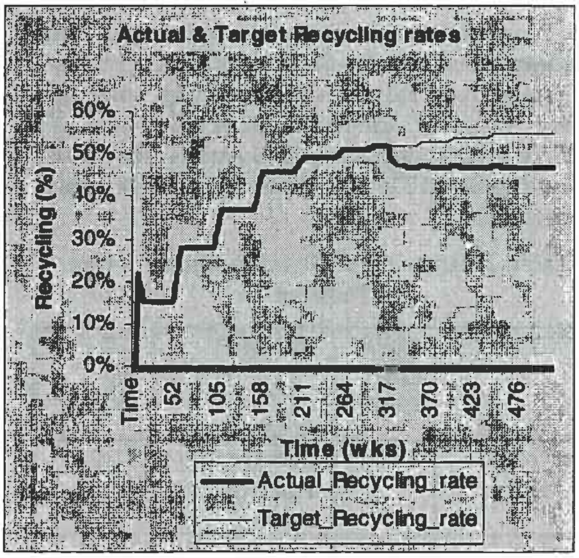

Figure 3: Actual and Target Recycling vs Time.

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APPENDIX A - LCA Model Assumptions

Garbage and Recycling trucks environmental emission are represented by Australian inventory for 15 t Articulated Trucks, travelling on average 35 km and 40 km per pick up trip respectively.

Manual sorting of cullet at MRF requires 4.5 kWh of electricity and 0.02 hr of Front end loader per tonne of cullet sorted.

Glass is a considered to be inert in landfill, hence it does not contribute to leachate and bio-gas production.

55 MJ of energy from fuel oil and 2560 L are required for the extraction of 1 tonne of sand, a significant virgin material input in glass batch.