INTEGRATED LIFE CYCLE ANALYSIS APPROACHES TO STRATEGIC DECISION MAKING IN WASTE TO ENERGY

PhD Thesis

Answers to Review of Prof. Janos Abonyi

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Q1: Please overview the existing strategy maps handling environmental aspects (e.g. balanced scorecards). Please explain, what makes a radar chart to strategy map that can be used for strategy development and monitoring.

Answer to Question 1:

Kaplan and Norton (1992) proposed the Balanced Scorecard as a framework that is used to help in the design and implementation of strategic performance management tools within organizations. The basic idea is to provide a simple structure to link the main strategic direction of a company with the performance of required actions. Balanced scorecards are therefore thought to help managers to execute the company strategy.

The way the Balanced scorecard, as designed by Kaplan and Norton, works is to link four generic “perspectives” (Financial, customer, internal business processes and Learning and Growth) with some performance indicators that can be mapped in a cockpit chart, useful to track actions.

Following some concerns on how to really link the generic perspectives and therefore the Balanced scorecard devised to the long term strategy of a company, brought further refinements of the concept (Kaplan and Norton 2004), with the definition of the Strategy Maps. The strategy map is a device used to communicate context and illustrate the basis managers have used for choosing a subset of the available measures to report on an organisation's progress in implementing a strategy.

The applicability of the concept of a business Balanced Scorecard to environmental issues and in general sustainability has been investigated recently. Mendesa et al (2012) propose the use of a balanced scorecard in the analysis of Municipal Solid Waste in order to ensure sustainable development principles and best management practices. Their definition is based substantially on the main perspectives proposed by Kaplan and Norton (clients, internal processes, learning and growth and finances). Overall, in the Portuguese PA service, the BSC is able to: i) contribute to the precepts of modern public waste management; ii) focus on the strategic management of the client–customer relationship; iii) guarantee the best combination of improvement in service, through monitoring and a follow-up process; and iv) achieve management objectives (Mendesa et al, 2012).

Recent research (Lundberg et al 2009) also confirm the importance of Scorecards in linking strategy, objectives and actions within the framework of environmental performance. Reinforcing the main direction to have sustainability as a main business driver in the Scandinavian countries, the model proposes a framework constructed using the causal-chain framework pressure-state-response (PSR) and the management system management-by-objectives (MBO), respectively measuring and managing performance towards both strategic and operational objectives. The Environmental Management System serves as a toolbox, encompassing and coordinating the environmental objectives and the tools for performance measurement.

Further evidence of the importance of performance measuring in integrating sustainability issues into company decision support systems has been presented by Hallstedt et al (2010). The assessment approach indicates that successful companies should: (i) integrate sustainability into business goals and plans, backed up by suitable (ii) internal incentives and disincentives and (iii) decision support tools.

These ones, and similar approaches in applying Balanced Scorecards in the sustainability discussions, focus on creating a snapshot of a given situation. Based on this snapshot, and relying on the quality of the choice of the main indicators for this cockpit chart, the practitioner can understand the need of further actions in one or the other dimension. Scorecards do not prove as effective tools for strategic decision making as the interpretation of one or the other dimension might differ from company to company or even from practitioner to practitioner.

The work presented in this Thesis aims at delivering a tool that is mainly used for strategic decision making and not for monitoring and performance measuring. The radar or web chart presented, defined as Environmental Performance Strategy Map, is just a powerful way to visualize the Strategic Performance Indicator (SEPI) graphically. The map has therefore very little similarities to the concept of Strategic Map as originally devised by Kaplan and Norton, and surely cannot be assimilated to the concept of Balanced Scorecard as it is mainly intended to be used as a supporting tool comparing different options in the strategic decision making process, more than providing a snapshot of results of a performance measurement.

Q2: Bottom-up footprint calculations are based on detailed information about raw materials and energy demands of the technology steps. Please, explain what is the added value of the proposed env-BOM methodology compared to the "classical" bottom-up calculation.

Q3: Please, present the features of advanced BOM management tools and show how these systems handle health and environmental aspects. Based on this analysis please conclude what are the similarities to the proposed env-BOM representation, and what are places of improvement of these tools and env-BOM.

Answer to Question 2 and 3:

The ecological footprint is a measure of our resource use, and indicates the extent to which we are overshooting the available biocapacity of the earth. Bottom-up calculations of ecological footprints are devised to calculate sustainability for limited systems where clear boundaries need to be drawn. Traditionally companies are happy to account for the operations and the final product, and increasingly the supply chain, external activities and the product use are accounted for as well. A further challenge is for an organisation to look at their influence, both on their own sector, their supply chain, and on the external infrastructure their business requires or leads to. Bottom up approaches offer tis advantages. It is necessary to start by conducting a life cycle analysis (LCA) of each product consumed, taking into account every resource used from cradle to grave, and then sum up the total resources used to support that social unit's consumption levels.

However, the bottom-up, process-based approach, does not distinguish between intermediate and final users. Therefore, it cannot comprehensively describe supply chains that are crucial for allocating responsibility to the final consumer and identify driving forces. In addition, the bottom-up approach mainly concentrates on agricultural and food products, but lacks detail describing industry and products and services (Kuishuang et al 2011).

While the Technology Routing proposed can be assimilated to a process based or bottom-up calculation approach, the thesis brings clarity on how to couple its use with the ENV-BOM to overcome these challenges. Moreover it must be noted that ENV-BOM proposed a higher level of aggregation of information as compared to bottom-up approaches, limiting the difficulty of the system boundaries definition while still allowing a higher lever of granularity as compared to the SEPI.

Finally both tools must be used as “building blocks” of the Environmental Strategy Map and within this framework of strategic decision making. This new approach allows wide flexibility: the impact of changing a component, material or a production process will be reflected immediately on the Map.

An attempt to correlate bottom-up approaches with the decision making process has been proposed by Tahil and Darton (2010) with the Process Analysis Method in which the indicator set is designed from a detailed consideration of the production operation. The indicators characterize the impacts of the operation on the capital residing in the three domains: the environment, the economy and the domain of human/social capital. The Process Analysis Method provides a set of sustainability indicators and metrics tailored to the particular operation, in the context of its business environment. This set will be similar for similar production processes, facilitating comparison and benchmarking. Also, the value of a particular indicator can be traced back through the analysis to a particular activity, which is especially helpful in guiding remedial action, since cause is linked to effect by the method (Tahil and Darton, 2010).

All manufacturing and process companies have recognized the importance of managing the Bill of Material in a thorough way. Usually this urgency comes from the need to manage product variants in the most economical way as well as from supply management topics or environmental regulatory requirements. There are nevertheless cases where advanced BOM tools, included and or interconnected to PDM systems, are also used to link different steps of product development to the sustainability topics. Luh et al. (2010) present a methodology based on generic modularized product architecture that facilitates data management of green product development. The four-level architecture allows one unified representation for multiple product models. An option control mechanism enables a quick generation of their BOMs (bills of material). A procedure consisting of seven steps is proposed to accomplish this. PDM functions are implemented to demonstrate the effectiveness of the methodology using a real LCD TV family as an example.

Starting with the use of Excel companies have recognized the need of a supporting tool to sustain their Bill of Material data management activities. All major players within the PLM (Product Lifecycle Management) arena offer also module or standalone tools that provide BOM capabilities (Dassault Systemes with MatrixOne, PTC with Windchill, Siemens with TeamCenter and so on). The definition of an Engineering Bill of Material and a Manufacturing Bill of Material is standard task for all kinds of product development and more and more this task requires to be linked to the rest of the company ERP functions. The most advanced tools for BOM management are defined within the Product Data Management (PDM) framework. Product data management (PDM) serves as a central knowledge repository for process and product history, and promotes integration and data exchange among all business users who interact with products — including project managers, engineers, sales people, buyers, and quality assurance teams. The central database will also manage metadata such as owner of a file and release status of the components. The package will: control check-in and check-out of the product data to multi-user; carry out engineering change management and release control on all versions/issues of components in a product; build and manipulate the product structure bill of materials (BOM) for assemblies; and assist in configurations management of product variants. All these elements are again linked to a way to control the different elements of the BOM for economic or regulatory reasons. Apart from inclusion of Material Safety Data Sheets or collection of different elements required by environmental regulations (as the Green Dot), there is very limited use of these tools towards sustainability issues. Moreover, these tools seem to be mainly geared towards mitigation of Supply management risks.

The approach proposed in the Thesis allows to draw on the learnings of BOM management, but proposes to apply these learning in the support of a possible selection of the most sustainable component or manufacturing process.

Nevertheless, developing a database of Environmental Performance Points for standard items/materials/process in each main industry would be beneficial. This would improve the definition process for the ENV-BOM and allow the diffusion of this method to a wider audience. Plant Managers or industrial operators could directly reference the standard databases and calculate the Sustainable Environmental Performance Indicator speedily. Additionally the sensitivity analysis for a given option could also be improved by the definition of software to re-calculate the performance points based on the databases available.

Q4: Please, show how the fuzzy model was designed and applied. Please give information about what were the uncertainties and how the parameters of the fuzzy model were tuned to represent these.

Answer to Question 4:

Fuzzy logic was introduced in the sixties (Zadeh, 1965). It simplifies the process of taking decisions by simulating the way of reasoning of a human expert in environments characterized by uncertainty and imprecision. The idea behind of fuzzy logic is that an element can belong partially to several subsets, unlike Boolean logic where belonging or not to a set are mutually exclusive. The degree of belonging to a set is a value between 0 and 1, usually determined by to what extent an element belong to a fuzzy subset or a category of a variable.

Fuzzy logic is applied in the building of fuzzy systems, which establish the relationship between an input space and an output one. The breakthrough regarding traditional mathematical models lies in the fact that the relationship is not determined by complex mathematical equations, but by means of a set of logical rules that reflect the way of reasoning of an expert. These rules consist of an antecedent (in which several input variables are related by means of logical operators) and a consequent (where the same process occurs amongst the output ones). Once defined the membership functions and the rules, the fuzzy inference process occurs in several steps, as follows:

1) Fuzzification: The first step is to identify for each value of the input variables,

the degree of membership registered in each established label or category.

2) Aggregation of antecedents: Once known the values registered in the labels present in the antecedents, different methods of aggregation can be used in order to obtain a unique global degree of truth for the antecedent. Although different methods of assessment can be defined for the logical operators, the most accepted criteria are taking the lower degree of truth in the variables on the antecedent for AND operator, the higher one for OR and the gap to 1 in the case of NOT.

3) Inferencing: From the global degree of truth of the antecedent, a membership function can be derived based on the membership function of the label of the output variable present in the consequent. For achieving this, several methods can be applied, the most accepted being PROD (which weights the membership function in the consequent by the value of the degree of truth of the antecedent) and MIN (which truncates the function of the activated label in the consequent according to the value of the degree of truth of the antecedent).

4) Composition: As several rules may affect the same output variable, it is necessary to look for a way of aggregating the membership functions obtained in the inference of all the rules. The most common methods are SUM (which offers as the final membership function the sum of the ones obtained after inferencing all the rules), MAX (which offers a function that takes in each point of the output domain, the maximum value of the ones obtained in each particular membership function) and PROBOR (which is very similar to SUM, but offers the sum of the values obtained in each output variable minus the end result of their multiplication).

5) Defuzzyfication: Finally, a method has to be applied for converting the membership function obtained in the previous step into a crisp value. Some common methods consist in taking the output value corresponding to the minimum, medium and maximum of the maximums of the membership function. The bisectrix method, however, looks for the value that divides the surface between the output function and the x-axis into two sections with the same area. However, the most adopted method is the centroid, which offers as the output value the x coordinate of the center of gravity of the surface between
the function and the x axis. Gonzalez et al (2002).

This Thesis presents a proposal for applying fuzzy logic during the assessment stage of the definition of the EPSM. The aim is to spread the methodology to situations of uncertainty in the input data.

In order to explain the concept and how it links to the EPSM calculations an example from the process industry is introduced in the Thesis and the target to define the Carbon footprint values is taken into consideration.
The operation of a fertilizer production plant is divided in 4 main technology steps which cause impact:

- neutralization reaction,
- 3-stage concentration,
- prilling and
- packaging and shipping.

The variables relative to the Carbon Footprint are therefore defined with reference to these four steps:

Neutralization	*Concentration*	*Prilling*	*Shipping*
$x_{c,n}$	$x_{c,c}$	$x_{c,p}$	$x_{c,s}$

The output variable is defined as the value for the Carbon Footprint (CF).

The first step is therefore the definition of the membership function. The linguistic set proposed is “very low, “low”, “high” and “very high”. For the purpose of this study a triangular function was assumed. That means that the association between the input variable and the definition of the linguistic set is a triangle with the vertex on the main value associated.

The membership functions showed in Fig. 4 in the Thesis describe the different membership functions for each input variable. The association of the membership function represents a first uncertainty element. If not directly available these values can be obtained by expert panel interviews. In this case they were evaluated with reference to the previous case studies used to define the EPSM in Chapter 2.

The second step is therefore the aggregation of the antecedents. As in this case we are considering successive steps of a production process, the natural operator to consider for aggregation is AND:

Xc,n AND Xc,c AND Xc,p AND Xc,s => Carbon Footprint

The subsequent step to define the inference rule is to define the consequent (in this case how the Carbon Footprint is defined out of values assigned to the antecendent).
The consequent is reshaped using a function associated with the antecedent (a single number). The input for the implication process is a single number given by the antecedent, and the output is a fuzzy set. Implication is implemented for each rule. In this particular case the AND method is used: min (minimum), which truncates the output fuzzy set. The consequent – in this case the value for the carbon emission dioxide – is considered in this study to belong to the following classes: unacceptable, neutral and acceptable.

It is finally possible to link the input and the output variables defining the allowed combinations of values of the fuzzy sets. Here we encounter then another source of uncertainty. Defining what is “acceptable” and “not acceptable” might depend on the definition of the system boundaries as well as from subjective observations of the practitioner. In this case the adoption of a triangle distribution was chosen to limit this bias. Moreover, the definitions were mainly derived from observations of the case study of Chapter 2. Table 4.1 presents all possible combinations of the fuzzy rules.

	IF				THEN
	Xcn	Xcc	Xcp	Xcs	Xc
1	very-low	low	high	very-high	unacceptable
2	very-low	low	very-high	high	unacceptable
3	very-low	high	low	very-high	unacceptable
4	very-low	high	very-high	low	neutral
5	very-low	very-high	high	low	neutral
6	very-low	very-high	low	high	unacceptable
7	low	very-low	high	very-high	unacceptable
8	low	very-low	very-high	high	unacceptable
9	low	high	very-low	very-high	unacceptable
10	low	high	very-high	very-low	acceptable
11	low	very-high	high	very-low	acceptable
12	low	very-high	very-low	high	unacceptable
13	high	low	very-low	very-high	unacceptable
14	high	low	very-high	very-low	acceptable
15	high	very-low	low	very-high	unacceptable
16	high	very-low	very-high	low	neutral
17	high	very-high	very-low	low	acceptable
18	high	very-high	low	very-low	acceptable
19	very-high	low	high	very-low	neutral
20	very-high	low	very-low	high	unacceptable
21	very-high	high	low	very-low	acceptable
22	very-high	high	very-low	low	acceptable
23	very-high	very-low	high	low	neutral
24	very-high	very-low	low	high	unacceptable

Table 0.1 Fuzzy rules for carbon footprinting calculation

The input for the defuzzification process is the fuzzy set obtained after inputting in the inference rules, a set of values for the antecendent. The aggregate of a fuzzy set encompasses a range of output values, and so must be defuzzified in order to resolve a single output value from the set. The defuzzification method used in the case study is the centroid calculation, which returns the center of area under the curve.

Even though not a new idea, the application of fuzzy logic to ecological footprint method has been applied here to verify its validity within the strategic decision making process. IN terms of improvements to account for uncertainty in a more detailed way, we could also define different weights for each rule, in case a more refined characterization of the impacts might be needed.

Q5: Please, discuss how the proposed techniques applicable to W2E technologies.

Answer to Question 5

Chapter 5 of the Thesis presents the main contribution where all elements introduced previously, related to the introduction of environmental indicators, are compiled into an end to end methodology. Apart from Chapter 1, Chapter 5 is also dedicated to the application of the proposed methodology to the Waste to Energy (W2E) and more general Waste-to-Value field.

When looking at W2E issues, it becomes clear that a methodology that is able to evaluate the overall environmental impact, as well as the impact of each step in the process, and is also able to deal with uncertainty estimation, is highly valuable. As mentioned in the thesis (Olsson, Kärmann, Gustafsson 2006, Liamsanguan, Gheewala 2007, Schmidt, Hold, Merrild, Christensen 2007, Fruergaard, Astrup 2011, Slagstad , Brattebø 2012, Slagstad , Brattebø 2013, Othman, Noor, Abba, et al. 2013) have identified in W2E the potential of LCA in the decision making process. These and other studies have nevertheless fallen short of providing an overall methodology to define a complete picture that takes into account not only the environmental burden, but also the cost perspective. Chapter 5 validates the use of the SEPI methodology with a case study geared towards re-use of the coconut husk, a typical by-product of the coconut consumption in the Philippines.

Even if the different elements of the E3 methodology have been developed in the frame of the W2E energy filed, they can be applied easily to any kind of process or manufacturing industry. The case studies of Chapter 2 and 3 have proven this.

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