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Group Model-Building to identify potential sources of environmental impacts outside the scope of LCA studies: causal links and feedback loops in washing machine and road vehicle product systems

Rafael Laurenti^{1*}, David Lazarevic¹, Sofia Poulikidou², Valeria Montrucchio³, Luigi Bistagnino³, Björn Frostell¹

¹ KTH Royal Institute of Technology, Division of Industrial Ecology. Teknikringen 34, SE-100 44 Stockholm, Sweden.

² KTH Royal Institute of Technology, Division of Environmental Strategies Research. Drottning Kristinas väg 30, PL-100 44 Stockholm, Sweden.

³ Polytechnic of Turin, Architectural and Industrial Design Department. Viale Mattioli 39, 10125 Turin, Italy.

*Corresponding author: rafa@kth.se. Mobile: +46 764 099 608. Fax: +46 8-790 50 34

Abstract

Life Cycle Assessment (LCA) is a tool to assess the potential environmental impact of a product throughout its entire life cycle, and identify 'hot-spots' of environmental impact for amelioration. However, there are other important variables outside the product life cycle such as market demand, infrastructure, taxes, etc. that also can influence its environmental impact through cause-effect links. This study utilises the Group Model-Building (GMB) method to identify, and Causal Loop Diagram (CLD) technique to make explicit, variables which may not be typically considered in LCA studies, but may have significant influence upon environmental impacts of a product or service through cause-effect links and feedback loops. Household washing machine and conventional passenger vehicle are chosen as cases of product system to illustrate the utility of the GMB method and CLD technique. A literature review on LCAs concerning the two product systems is performed to investigate what are the commonly used functional unit, life cycle stages and system boundaries. The LCA studies contained variables mainly pertaining to physical structure, whilst GMBs identified cause-effect relations and feedback loops between variables pertaining to physical and behavioural structure. It is necessary to move beyond slogans about interconnectedness, need for multidisciplinary research, etc. Consequently, specific methodologies that consider a more comprehensive/diverse set of parameters must be explored by the LCA community. GMB and CLD can serve as a basis for (i) delimitating appropriated system boundaries for LCA and (ii) identifying variables/areas to be included in sensitivity and scenario analysis. Sensitivity and scenario analysis examine the influence that those variables/areas have on the environmental impacts of the product and describe both different contexts and profiles of users. GMB and CLD have the potential to bridge the divide between quantitative and qualitative variables, for more robust understanding of the causes and mechanisms of environmental impacts and improving conclusions and recommendations in LCA.

Keywords: Group Model-Building, Causal Loop Diagram, Life Cycle Assessment, Product systems

1. Introduction

Life Cycle Assessment (LCA) is a 'cradle-to-grave' approach for assessing the potential environmental impacts of a product¹ service over its full life cycle; including resource extraction, production, use, transport and end-of-life stages (ISO, 2006a). It allows for the identification of 'hot-spots'² of potential environmental impacts according to design specifications as well as the comparison of different design alternatives and improvement options (Ekvall and Weidema, 2004; Finnveden et al., 2009; Tillman, 2000; Zamagni et al., 2012). The interpretation of LCA results are framed by the goal and scope definition, system boundaries and selection of the functional unit of the product to which the environmental impacts (negative or positive) are associated (Clift et al., 2000).

Consequently, suggestions for optimization are traditionally made on the basis of a single unit, not taking into account, for instance, the product fleet³ (Field et al., 2000; Levine et al., 2007; Stasinopoulos et al., 2012), infrastructure systems (Chester and Horvath, 2009), the interrelations between the products and the infrastructure system (e.g. how consumers use the products considering the available infrastructure), the consumption response to income change, product improvements, etc. and "policy resistance"⁴. This approach may hinder the possibilities of achieving higher levels of efficiency and reducing the negative environmental impacts in a predefined product system.

Products are not part of an isolated life cycle (i.e. cradle to grave). On the contrary, there are different levels of connections among the natural and technical environments, consumers, and other products or services. For instance, a product can be more efficient in different user concepts, or consumption patterns may affect resource availability in a regional or global perspective. Therefore, these important variables and links should be taken into consideration when developing a LCA.

The process of finding and electing pertinent variables, causal links and feedback loops can be carried out by the Group Model-Building (GMB) method (Hovmand et al., 2012; Richardson, 2013; Rouwette et al., 2002). GMB is used to engage people in a team in the process of conceptualising a system model (Vennix, 1996). A important premise for systems is that the behaviour of a system is primarily determined by the characteristics of the whole and not by the characteristics of its individual parts (Meadows, 2008; Skyttner, 2005). Therefore, the modes of behaviour under study are created by the interaction of the system variables within a closed boundary (Forrester, 1969, 1961; Groesser and Schaffernicht, 2012; Martinez-Moyano and Richardson, 2013). This implies that decisions within a system are embedded in feedback loops (Vennix, 1996). The outcome of the GMB is a system model describing variables and interrelationships of the system of interest (Andersen et al., 2007).

The aim of this study is to use GMB for identifying variables which may not be typically considered in LCA studies, but may have a significant influence upon the environmental impacts of product system through causal links and feedback loops. Household washing machine and conventional passenger car (using gasoline or diesel) were chosen as product systems and Causal Loop Diagram (CLD) as system model technique for the purpose of investigating whether the GMB process could be a useful complement to LCA.

¹ The term 'product' is being referred in this paper as a good or service.

² The stages, processes or activities that contribute most to the potential environmental impacts.

³ All the products in use, rather than a single product.

⁴ "Policy resistance" refers to the tendency for our attempts to solve problems to be delayed, diluted or defeated by unintended reactions of the system to these interventions (Meadows, 2008, 1982; Sterman, 2012, 1994). 'The reasons lie in the counterintuitive nature of complex systems and in their insensitivity to parameter changes' (Forrester, 1969, pp. 110–111).

2. Methodology

There is a distinction between the modelling process and the system model as an outcome of the process in GMB (Andersen et al., 2007). The process of assembling a system model in GMB is a way of eliciting mental constructs, ideas about how things work in order to clarify and structure debate about a situation which is seen as problematic (Vennix, 1996). The system models built as a “product” (Andersen et al., 2007) of the GMB process are a system description (Richardson, 2013; Wolstenholme and Coyle, 1983) of a situation seen as problematic (Vennix, 1996).

These system models can be either a quantitative (Coyle, 2000; Rouwette and Vennix, 2006; Vennix, 1996; Wolstenholme, 1999) or qualitative (Coyle, 2000; Vennix, 1996; Wolstenholme and Coyle, 1983; Wolstenholme, 1999, 1985). The quantitative models are system dynamics models (Andersen et al., 2007; Richardson and Andersen, 1995) while the qualitative models are CLDs (Lane, 2008; Nguyen and Bosch, 2013; Rouwette and Vennix, 2006; Rouwette et al., 2002; Schaffernicht, 2010; Videira et al., 2012). System dynamics models are focused on dynamic behaviour over time, have stocks and flows, represent feedback loop structures, and require specific parameters, equations and computer simulations to run (Coyle, 1977; Forrester, 1961; Richardson, 2011; Sterman, 2000). CLD represent causal links between variables, polarities of the links and feedback loops (Lane, 2008; Richardson, 1997; Schaffernicht, 2010).

As described above, one of the main goals in a GMB process is to elicit variables and relations (structure) that describe the behaviour of a system of interest and represent them in a system model. Yet, vast literature also points at intangible outcomes attained from the GMB process (Andersen et al., 2007; Hovmand et al., 2012; Richardson and Andersen, 1995; Rouwette, 2012; Rouwette and Vennix, 2006; Rouwette et al., 2011, 2002, 2009; Videira et al., 2012). Rouwette et al. (2009) present intervention goals of GMB in four levels:

- i) Positive reaction, mental model refinement, commitment and behavioural change are intervention goals identified at an Individual level
- ii) Increased quality of communication, creation of shared language, consensus and alignment are intervention goals identified at an Group level
- iii) System changes, system improvement or results are intervention goals identified at an Organisation level
- iv) Further use and efficiency are intervention goals identified at an Method level

Additionally, Rouwette et al. (2002) report, after reviewing 107 published applications of GMB, that GMB is used in a wide forms of variations, ranging from a single short session wherein CLDs are constructed, to building a simulation model over a time span of years. Rouwette and colleagues distinguish GMB cases in four different types: (i) demonstration or training applications that do not focus on implementation, (ii) qualitative models, (iii) small quantitative models of 50 equations or less, and (iv) large quantitative models.

The intended outcomes in facilitated interventions must be explicit (Andersen et al., 1997). The GMB of the present study focuses on eliciting variables and relations that may cause environmental impacts though cause-effect chains. The CLD (qualitative model) is adequate for achieving this purpose thus chosen as the system model representation. Furthermore, our main purpose with the CLD is to represent the GMB participant’s view (Group level) of the washing machine and passenger vehicle product systems (section 3.2); yet, reflections on the GMB sessions to build these models (Method level) are also presented (section 4.2). These methodological choices are aligned with the aim of the study indicated in

the introduction, which is *“to use GMB for identifying variables which may not be typically considered in LCA studies, but may have a significant influence upon the environmental impacts of product system through causal links and feedback loops”*.

In order to accomplish the aim of the study, firstly, a literature review was conducted on LCA studies on washing machine and passenger car product systems to investigate the variables, system boundaries and functional units that are commonly adopted. Furthermore, two parallel GMB sessions were organised to elicit relevant variables and relations in the washing machine and passenger vehicle product systems and build in a first version of CLDs. Following the GMB sessions, individual interviews with the participants were undertaken to refine and validate the system models. Subsequently, final versions of the system models were built. This whole process was adapted from the GMB process described in Vennix (1996, pp. 174–182).

The next subsections describe the steps taken to carry out the literature review (2.1), GMB (2.2) and individual interviews (2.3), the justification on why the washing machine and passenger vehicle product systems were chosen as cases (2.4) and, lastly, the CLD technique (2.5).

2.1. Literature review

A literature review was performed in order to identify studies that investigate and evaluate the life cycle environmental impact of the two cases (i.e. road vehicles and washing machines). Searches of the scientific literature were performed using the scientific databases Science Direct and Google Scholar. The key words that were used are detailed in Table 1.

Table 1 – Key words used in the literature review

Road vehicle product system	Washing machine product system
LCA, life cycle assessment	LCA, life cycle assessment
environmental impact	environmental impact
transport	washing machine
cars	household appliances
passenger cars	soap
road vehicles	detergent
	clothes

LCA studies (cited in section 3.1) which include the vehicle/washing machine system (washing machine, detergent and clothes washing options/vehicle, fuel and automobile technologies) were identified. Seven studies were selected for each case based on the relevance of the LCA study to the research project. During the analysis of the selected studies the following aspects were observed:

- functional unit adopted
- life cycle stages considered
- variables included and analysed related to the boundary selection.

The results of the analysis are presented in Section 3.1.

2.2. Group Model-Building sessions

Two parallel GMB sessions were organized to build a preliminary version of the CLDs. The GMB sessions on washing machine and conventional passenger car product systems were organized at the Polytechnic of Turin (Italy), and at KTH, the Royal Institute of Technology, Stockholm (Sweden), respectively. Experts were invited to attend the workshops from a range of disciplines. However, due to

constraints concerning the availability of the participants, five participants from the Department of Architecture and Design with backgrounds in industrial design and systemic design attended the workshop in Turin and five participants with backgrounds in environmental economics, transport and LCA attended the workshop in Stockholm. The intention of having a homogeneous group (Turin group) and a multi-disciplinary group (Stockholm group) was to increase the robustness of the findings when cross analysing the results to draw conclusions.

The purpose of the GMB sessions was to gain a first view of:

- the system in which the studied products are embedded
- the variables that influence the environmental performance of the product through cause-effect links within that system
- the nature (positive or negative) of the relationships between these variables, in order to get a better understanding of how the chosen variables may affect the environmental impact of the studied product through the cause-effect links

The aforementioned purpose was sent to the experts together with an explanation about the project in an invitation letter. No previously background literature was sent. The sessions lasted for approximately 2 hours.

The first step of the GMB session was to introduce the CLD technique to the participants. Examples of CLDs were shown and the procedure of building CLDs was explained. The starting variable of the CLD was defined as the environmental impacts⁵ of cars/washing machines. In the second step, the experts were asked to brainstorm the five most relevant variables they could think of, connected to the starting variable.

After this step, group members were invited in a round-robin fashion to name one variable (from their list) which was perceived as a potential cause of the starting variable (environmental impacts). The variables were transferred to a white board, then the participants identified the causal links and their polarities between the variables. This procedure was repeated until all the perceived causes were placed in the CLD.

In the next step, the participants were asked to consider the potential consequences (effects) of changing the main variable by looking at their list of variables. They were then added to the CLD.

Finally, the participants were invited to look for connections between consequences and causes, i.e. consequences which in turn can be considered as causes of the ‘original’ causes, thus identifying feedback loops.

Not all of the variables were included directly in the diagram and new variables were allowed to be included the diagramming process, which were not mentioned in the brainstorming phase (i.e. not just the initial ‘five most relevant variables participants could think of’). The initial draft CLDs produced in each GMB session are provided as supplementary figures (see Appendix 1 and 2).

2.3. Individual interviews

Due to time constraints during the GMB sessions, only preliminary versions of the CLDs were developed. There were still missing links and loops between variables in the CLDs. The CLDs were further developed by the participants together with the authors in individual interviews to complete the

⁵ E.g. use of resources and environmental consequences of releases related to the functional unity of the respective product system (ISO, 2006b)

CLDs. Three interviews were conducted for each case study (the other four missing participants were not accessible for interviewing).

In each interview the first version of the CLD was presented to the expert. Then, variables, links and their polarity were discussed. Special attention was also given to naming the variables. The expert and authors verified the consistency of the causal links and the relevance/importance of each variable to the system represented in the CLD.

Furthermore, it should be noted that the CLDs are mental models, thus they represent the participants' beliefs about the networks of causes and effects as well as which variables are judged important to be included or excluded.

2.4. Product Systems

The product systems of washing machine and conventional passenger cars were specifically selected as:

- a) Both product systems have dependent products embedded within them; e.g. the washing machine, detergent and clothes, and the vehicle and fuel.
- b) For the aforementioned embedded products, the use-phase is the greatest contributor to the lifecycle environmental impact
- c) In LCA studies where the use phase is responsible for the greatest environmental impact for primary product system in question and the embedded products (see Cullen and Allwood (2009) for the case of washing machines), there is a risk that during the interpretation phase, the hot-spots of environmental impact outside the use phase are overlooked (Cullen and Allwood, 2009).

It is considered that a product system encompasses not only the infrastructure and associated services necessary to design, transport, manufacture, use and dispose of a product, but also the activities and other products related to these life cycle phases, as can be deduced from the justification above. In other words, physically, a product system can entail the extraction of necessary raw materials, production and assembly of parts, utilisation, material recycling, incineration and land filling, including the electricity production required in all phases of the life cycle of the product. On an intangible level, consumer behaviour, design paradigms, purposes, function and objectives, business processes, performance measures, stakeholder perspectives, cultural values, and economic development are parts of a product system. These assumptions are aligned with the concept of socio-technical systems (Clegg, 2000; Davis et al., n.d.; Geels, 2012, 2005, 2002) and soft systems methodology (Checkland and Holwell, 2004; Checkland, 2000, 1999)

2.5. Causal Loop Diagrams

In a CLD the variables are connected by arrows denoting the causal influences among the variables (Sterman, 2000). Each arrow is assigned a polarity, either positive (+) or negative (−) to indicate how the cause (at the arrow's tail) changes when the effect (at the arrow's point) changes (Schaffernicht, 2010; Vennix, 1996). Figure 1 shows examples of variables connected by a causal link with a polarity.

Figure 1 - Examples of variables connected by a causal link with a polarity. Adapted from Sterman (2000, p. 138).

A causal link with a positive link polarity means that the coupled variables may change in the same direction (Vennix, 1996). In the definition of Sterman (2000, p. 139), a positive link means that “if the cause **increases**, the effect **increases** above what it would otherwise have been, and if the cause **decreases**, the effect **decreases** below what it would otherwise have been”. In Figure 1, the positive link polarity represents that if *Birth rate* increases, *Population* increases above what it would otherwise have been, and if the *Birth rate* decreases, the *Population* decreases below what it would otherwise have been.

Yet, a negative link signifies that the connected variables may change in the opposite direction (Vennix, 1996). That is to say, “if the cause **increases**, the effect **decreases** below what it would otherwise have been, and if the cause **decreases**, the effect **increases** above what it would otherwise have been” (Sterman, 2000, p. 139). In the example of Figure 1, the negative link polarity symbolises that if *Birth rate* increases, *Population* decreases below what it would otherwise have been, and if the *Birth rate* decreases, the *Population* increases above what it would otherwise have been.

Feedback loops form the basis for qualitative analysis in CLDs (Wolstenholme and Coyle, 1983). Feedback loops occur when the effect of a change propagates around the variables in a system (through cause and effect chains) and respond (“feed back”) to the original change (Meadows, 2008). This response can either reinforce or oppose to the original perturbation. If it reinforces the original change, it is a reinforcing loop; if it opposes the original change, it is a balancing loop (Sterman, 2000).

The important loops are highlighted by a loop identifier which shows whether the loop is a reinforcing (“R”) or balancing (“B”) feedback. See Figure 2 for an example of reinforcing and balancing feedback loop. Note that the loop identifier circulates in the same direction as the loop to which it corresponds. In the example, the reinforcing feedback relating *Birth rate* and *Population* is clockwise and the negative *Death rate* loop is counter clockwise (Sterman, 2000).

Figure 2 – Examples of reinforcing and balancing feedback loops. Adapted from Sterman (2000, p. 138).

It is important to note that link and loop polarities do not describe the behaviour of the variables. They describe the structure of the system. Link and loop polarities describe what would have occurred if there were to be a change in the system. In the example given in Figure 2, in order to know whether *Population* is increasing or decreasing, one must know its net rate (births less deaths) of change (Sterman, 2000).

3. Results and analysis

3.1. Literature review

The results of the literature review are illustrated in Tables 2 and 3 representing the washing machine and road vehicles case studies, respectively. The information presented in the tables provide a general overview of the LCA studies. In each case, similarities were observed with regard to the functional unit, life cycle stages considered and the boundary selection.

Washing Machine Life Cycle Assessments

Of the seven studies selected, five were LCAs conducted on washing machines (Bourrier et al., 2011; Faberi et al., 2007; Koerner et al., 2011; Rüdénauer et al., 2005; WRAP, 2010), one concerned comertial detergent (Dewaele et al., 2006) and one concerned comertial cloths (Collins and Aumonier, 2002). Table 2 details the functional units, life cycle stange and variables of the selected studies.

Table 2 – Summary of the literature review on washing machine product system for washing machine, soap and cloth.

Functional unit	Washing machine product system		
	Life cycle stages	Variables (boundary selection)	
Number of washing cycles per year, load, temperature mix and lifespan (Bourrier et al., 2011; Faberi et al., 2007; Rüdénauer et al., 2005; WRAP, 2010)	Materials (7/7)	Packaging (3/7)	Cloths (2/7)
	Transportation material (7/7)	Washing machine type (3/7)	Wash quality (2/7)
	Production (7/7)	Wash load (kg) (4/7)	Energy for washing (hot water and operation) (7/7)
Washing and drying one kg of clothing (Koerner et al., 2011)	Distribution (product to retailer) (6/7)	Frequency of wash (5/7)	Water use-phase (7/7)
	Use (7/7)	Detergent/softener (4/7)	Energy for drying (5/7)
	Recycling washing machine(4/5)	Maintenance of washing machine (1/7)	Waste water treatment (3/7)
1 average home laundry in France (Dewaele et al., 2006)	Refurbishment washing machine (1/5)	Program washing machine (3/7)	Waste treatment of packaging (3/7)
Number of washings of 1 pair of polyester trousers; 3 pairs of men's briefs (Collins and Aumonier, 2002)			Washing machine lifespan (5/5)

The numbers in parentheses indicate the number of studies out of a total (five for washing machine and six or five for detergent and/or cloths) that considered each life cycle stage and variable. For the functional unit, the correspondent LCA study is referenced.

The functional units considered by Bourrier et al. (2011), Faberi et al. (2007), Rüdénauer et al. (2005) and WRAP (2010) referred to the amount of laundry washed within a defined lifespan. The amount of laundry and the lifespan varied according each study. This resulted in a specified weight of clothing washed per year, thus excluding user behaviour. In contrast, Koerner et al. (2011) took user practices into account, defining the functional unit as the washing and drying one kg of clothing. Hence, this case, it is the assumptions pertaining to user behaviour that influence the results.

All life cycle stages for the three products (washing machine, detergent and clothing) were included in the LCAs, with the exeption of Bourrier et al. (2011) that did not include the end-of-life phase. The five LCAs on washing machines include recycling as an end-of-life option and one study (WRAP, 2010) included recycling and refurbishment.

The variables wash load, frequency of wash, detergent/softener, energy for washing, energy for drying, and washing machine lifespan were recurrent variables in the studies. The variables packaging, washing machine type, maintenance of washing machine, cloths, wash quality, waste water treatment and waste treatment of packaging appeared with lower frequency (see Table 2).

Four out of seven studies (Bourrier et al., 2011; Collins and Aumonier, 2002; Faberi et al., 2007; Koerner et al., 2011) included the detergent/softener in their scope. Of these four studies, (Dewaele et al., 2006) solely focused on the detergent. In the studies which did include the detergent/softener it is important to be aware, when recommended actions are proposed, that the use-phase impacts are being overemphasised.

Passenger Vehicle Life Cycle Assessments

Of the seven LCA studies selected, six were on passenger vehicles (Castro et al., 2003; Finkbeiner and Hoffmann, 2006; Nemry et al., 2008; Schweimer and Levin, 2012; Spielmann and Althaus, 2007; Sullivan et al., 1998) and one on vehicle fuels (Lane, 2006) (see Table 3). Of the LCA studies on vehicles, five considered the functional unit as “a passenger vehicle over the vehicle lifespan”, and one adopted “100 km distance driven” as a functional unit (the references are specified in Table 3). The study on fuels set the functional unit as MJ/km (quantity of energy per kilometre).

Most of the studies included all the life cycle stages on their scope, as seen in Table 3. The fuel cycle was not always considered, apart from the process of fuel consumption which was integrated in the use phase of the vehicle. In the studies which did include the fuel cycle it is important to be aware, when recommended actions are proposed, that the use-phase impacts are being overemphasised.

Four LCAs were on an average passenger vehicle (average weights and compositions, use, etc...) (Castro et al., 2003; Nemry et al., 2008; Spielmann and Althaus, 2007; Sullivan et al., 1998) and two on a specific car model (Finkbeiner and Hoffmann, 2006; Schweimer and Levin, 2012). All the studies encompassed weight and material composition of the vehicle, fuel consumption, lifespan of the vehicle, distance driven, life cycle energy needs, and recycling rates. The majority of the studies included vehicle technology, type of fuel used, cylinder capacity, maintenance activities, and waste generation. Driving cycle (urban, road, rural, motorway driving related to speed, engine load, torque, acceleration over time) was considered in three studies (Finkbeiner and Hoffmann, 2006; Nemry et al., 2008; Schweimer and Levin, 2012) and waste water treatment in one (Schweimer and Levin, 2012).

Table 3 – Summary of the literature review on road vehicle product system for vehicle and fuels.

Road vehicle product system			
Functional unit	Life cycle stages	Variables (boundary selection)	
A passenger vehicle over the vehicle lifespan (Castro et al., 2003; Finkbeiner and Hoffmann, 2006; Schweimer and Levin, 2012; Spielmann and Althaus, 2007; Sullivan et al., 1998)	Materials (7/7)	Average passenger vehicle (4/6)	Lifespan of the vehicle (6/6)
	Assembly of parts and components (5/6)	Weight and material composition of the vehicle – type and amount of materials (6/6)	Distance driven (7/7)
	Production of vehicle (6/6)	Vehicle technology, fuel used – gasoline, diesel etc. (4/7)	Life cycle energy needs – electricity and fuels (7/7)
	Transportations (4/7)	Fuel consumption (7/7)	Maintenance activities, washing (6/7)
	Use of the vehicle (6/6)	Driving cycle (3/7)	Recycling rates (6/6)
	Fuel cycle – Production of fuel / distribution / use (5/7)	Cylinder capacity (4/6)	Waste generation (6/7)
	End-of-life management – dismantling, shredding, separation, recycling, reuse, waste disposal (6/6)		Waste water treatment (1/7)
100 km distance driven (Nemry et al., 2008)			
MJ/km (Lane, 2006)			

The numbers in parentheses indicate the number of studies out of a total (six for road vehicle and seven for road vehicle plus one for vehicle fuels) that considered each life cycle stage and variable. For the functional unit, the correspondent LCA study is referenced.

3.2. Causal loop diagrams

Figures 3 and 4 illustrate the CLDs of washing machine and road vehicle product systems, respectively. The CLDs show the causal links between the variables, the polarity of these causal links (positive or

negative), and the feedback loops (Reinforcing or Balancing). For each of the feedback loops, a designator (R1, R2, B1,...) and a name were assigned (e.g. *design for disassembly*, *consumption rebound effect*,...).

Figure 3 – CLD of washing machine product system (Note: There should be time delays on many of these links). The variables marked in underlined text represents variables found in the LCA studies (see Table 2). A detailed description of all loops can be found in Appendix 3.

Figure 4 – CLD of passenger vehicle product system (Note: There should be time delays on many of these links). The variables marked in underlined text represents variables found in the LCA studies (see Table 3). A detailed description of all loops can be found in Appendix 4.

Variables pertaining to physical structure and behavioural structure, which became evident during the GMB process, have been elicited to describe the washing machine/vehicle product systems. Variables of the physical structure relate to the products (washing machine/vehicle) and background infrastructure (*technology developments, design improvements, level of air/toxicity/noise pollution, energy use, etc.*); whereas the behavioural structure concerns the decision rules used by the people in the product system (*government policies and taxes, pro-environmental attitudes, market demand, economic growth, etc.*). Moreover, in the washing machine CLD an extra variable, *characteristics of the territory* which expresses other relationships than causal, was included. This was a wish from the participants of the workshop, who defined *characteristic of territory* as: available resources (materials, available energy sources, etc.), climate peculiarities and territorial history (culture, traditions, religions, etc.).

The loops *consumption rebound effect*, (R10 in Figure 3 and R8 in Figure 4), refer to offsets of environmental gains from design improvements due to increased consumption. When a new product with *design improvements* is launched into the market, the current product is seen as *obsolete*. This stimulates the *market demand* and *sales* of that product. Increased consumption fosters the *economic growth*. The more *economic growth*, the more financial capital is available to invest back in more *design improvements*.

Figures 3 and 4 illustrate that the physical structure and the behavioural structure interact with each other to form the feedback loops. In this interpretation, the impacts on *quality of the environment* in Figure 3 and on *level of air/toxicity/noise pollution* in Figure 4 are influenced not only by cause and effect links from the physical structure (*technology development* and *design improvements*) and but also by cause and effect links from the behavioural structure (*pro-environmental attitudes*). It is also interesting to note that these cause and effects links are reinforced in the loops by *government policies and taxes related to environmental impacts*.

Examples of cause and effect links from the physical structure influencing *quality of the environment* and *level of air/toxicity/noise pollution* can be visualised in Figure 5 (selected variables from the washing machine

CLD) and Figure 6 (selected variables from the passenger vehicle CLD), respectively. A low *quality of the environment* or a high *level of air/ toxicity/ noise pollution* creates pressure for *government policies and taxes related to environmental impacts* to be implemented. These policies lead to an increase in *technology development* and greater *design improvements* to be developed by companies towards reduction of *natural resources use*. A low *natural resource use* leads to a higher *appreciation of a clean environment*, building up pressure upon *government* to extend the original *policies and taxes related to environmental impacts*. The new *policies and taxes* stimulate more development in *technology* and *design improvements*. In these loops, reductions in *natural resource use* are attained by *reuse* (*design for disassembly* reinforcing loops), *recovered material* (*design for recycling* loops) and *energy use* (*energy efficiency* loops).

Figure 5 – Selected variables from the washing machine CLD showing cause and effect links from the physical structure affecting *quality of the environment* and forming feedback loops with *government policies and taxes*.

Figure 6 – Selected variables from the passenger vehicle CLD showing cause and effect links from the physical structure affecting level of air/toxicity/noise pollution and forming feedback loops with government policies and taxes.

Improvements in the design of cars to increase *reuse* and *material recovery* alone are not likely to be effective unless matched by *government policies and taxes* to stimulate the usage of recovered parts and materials (Figure 4). Increasing the number of these *policies*, the *market demand and infrastructure of recovered parts and recovered materials* expands. In turn, the *reuse of parts* and the *material recovery* increases, which reinforces the loops *design for disassembly* (R2), *design for recycling* (R3), *dismantling* (R6) and *shredding* (R7).

Cause and effects links in the behavioural structure also affect *natural resource use* and are reinforced by *government policies and taxes*. Figure 7 highlights cause and effect links of the behavioural structure and their respective reinforcing feedback loops (R1, R6 and R8) of the washing machine CLD. These cause and effect links show that, the more *pro-environmental attitudes* people have the lower *washing temperature*, higher *washing load* and less *detergent* they use. These attitudes save *water, energy* and *detergent* thus decreasing the use of *natural resources*. Lower *natural resource use* leads to greater *quality of the environment*, increasing the *appreciation of a clean environment*, which in turn, built up public pressure on the *government* for more *policies and taxes related to environmental impacts*. These *policies and taxes* reinforce back *pro-environmental attitudes*.

Figure 7 – Selected variables from the washing machine CLD showing cause and effect links from the behaviour structure affecting *quality of the environment* and forming feedback loops with *government policies and taxes*.

The cause and effects links in the behavioural structure of the passenger vehicle CLD differ a little from those in the washing machine CLD. An increase in *pro-environmental attitudes* (carpooling, commuting by bicycle or on foot, etc.) related to individual transportation decreases *market demand for cars*. *Market demand for cars* also declines by improving/expanding *public transportation development (infrastructure and services)* when there are *government policies and taxes* concerning this matter. Less *demand for cars* makes the *level of car ownership* (car per person of driving age) falls. Fewer people owning a car reduce the *frequency of driving* and *car travel*, thus lessening the *traffic volume* and the *level of air/toxicity/noise pollution*. A lower *level of pollution* in the cities makes people to *appreciate a clean environment* more, reinforcing *pro-environmental attitudes* (R4 going carless) and *government policies and taxes related to environmental impact* (R5 take the bus). These cause and effect links and loops are highlighted in Figure 8.

Figure 8 – Selected variables from the passenger vehicle CLD showing cause and effect links from the physical structure affecting level of air/toxicity/noise pollution and forming feedback loops (R5 and R4) with government policies and taxes. The feedback loops newcomers (R9) and capacity expansion (R10) are also shown.

Finally, other interesting feedback loops highlighted in Figure 8 are *newcomers* (R9), *capacity expansion* (R10). *Newcomers* (R9) signifies that new potential consumers are getting into the market due to rising in the *standard of living*. This increases *car ownership*, stimulating *economic growth*, which in turn rises the *standard of living* of other people bringing them to the status of potential consumers. *Capacity expansion* (R10) occurs when the response to an increase in the *traffic volume* is building more roads. More roads available stimulate the *frequency of driving*, which leads to more *car travel* and *traffic volume* (reinforcing the initial perturbation).

4. Discussion

The results have shown that cause and effect links of both technical structure (related to design improvements, technology development, etc.) and behavioural structure (referred to user's habits, market demand, government policies, etc.) in a product system affect environmental impacts. LCA studies reviewed in this paper typically capture the causal and effect links of the physical structure but neglect the behavioural ones (see Tables 1 and 2, section 3.1). CLDs have demonstrated an interwoven relationship between physical and behaviour structure. Moreover, the CLDs have provided a view of where the variables considered in the LCAs stood in relation to the variables identified in the GMB process.

Nevertheless, these pieces of knowledge are not new. It is necessary to move beyond slogans about interconnectedness, need for multidisciplinary research, etc. Specific methodologies that consider a more comprehensive/diverse set of parameters must be developed to provide more robust recommendations for actions to lessen environmental impacts.

For an analysis of the environmental impact of products, a combination of the physical and behavioural structures (context/behaviour) of a product system is the appropriate unit of analysis. Assumptions

regarding influenced by variables related to the behavioural structures on the environmental impact of a product should explicit be declared in LCA. In this section we will discuss how CLDs and LCA could be combined to consider and make explicit not only the technical structure but also the behaviour structure. Reflections about our experience in using the GMB process to identify potential sources of environmental impacts outside the scope of LCA studies are also presented.

4.1. Integration of CLD and LCA with GMB

A LCA study is performed in four iterative phases: Goal and Scope Definition, Inventory Analysis, Impact Assessment and Interpretation (ISO, 2006a, 2006b). The CLD technique can add to LCA in the following activities:

- Outline the goal and scope definition
- Develop sensitivity analysis and scenarios (Interpretation phase)

CLD and Goal and Scope Definition in LCA

It is impractical to include all the cause and effect links of a product system in a LCA model. The choice of the variables to be included is dependent on the definition of the goal and scope of the study.

Hence, the goal and scope of the LCA and the CLD can still follow the iterative process of LCA. An initial goal and scope can serve as a cut-off criterion on what to include and exclude in a preliminary GMB session. As new variables are deemed to be important during the GMB process, the initial LCA goal and scope is adjusted. At the end, the GMB process delivers information on appropriate systems boundary, key parameters, assumptions, etc. in the form of a CLD.

GMB would be particular helpful to reach agreements on and communicate casual assumptions between different stakeholders (industries, policy makers, consumers, academia, etc.) involved/affected by the project. Werner (Werner, 2005, Chapter 23) provides general guidelines on how to use the GMB process in LCA.

CLD and Sensitivity analysis with scenarios in LCA

ISO (2006b, p. 42) states that “sensitivity analysis ... tries to determine the influence of variations in assumptions, methods and data on the results. Mainly, the sensitivity of *the most significant issues identified* is checked” (emphasis added). In other words, sensitivity analysis is a way of expressing and analysing the influence sources of variation/uncertainty in LCA.

“The most significant issues” (2006b, p. 42) can be identified in the GMB process and then treated as sources of variation in the sensitivity analysis. Significant variables in a CLD are variables that affect many other variables and controlling meaningful feedback loops. In the CLDs discussed in section 3.2, *design improvements*, *pro-environmental attitudes* and *government policies and taxes* are examples of important variables identified.

The variation on the output actually shows the strength of the cause-effect links between input and output variables. For instance, the strength of the causal links from the physical and behavioural structures can vary thus also varying the intensity of environmental impacts. *Design improvements* or *pro-environmental attitudes* influence *natural resource use* by causing a change on *water use*, *energy use* and *detergent use*. Running the sensitivity analysis is possible to find out which of the two structures have greater influence environmental impacts and the intensity of the influence.

Sensitivity analysis can be applied with an arbitrary selected range of variation (Björklund, 2002). For a single selected variable this can be done through running a sensitivity of various values of this variable. In cases where several variables are identified as significant, especially for behavioural aspects, different types of user profiles may be able to reflect such complexity. Different types of user's profiles exist which can cause more or less environmental impacts (depending on the *pro-environmental attitudes*). A "green" user may use a high *washing load*, low *washing temperature* or drive the car not so often (*frequency of driving*).

The definition of different types of user's profiles can be achieved through the use of scenarios. A scenario in LCA is defined by the SETAC-Europe LCA Working Group 'Scenario Development in LCA' as "a description of a possible future situation relevant for specific LCA applications, based on specific assumptions about the future, and (when relevant) also including the presentation of the development from the present to the future" (Pesonen et al., 2000, p. 23). This means that scenario analysis in LCA involves calculating different scenarios, to analyse the effect of identifying the influence of the selected variables (input parameters) on the environmental impacts (output parameter values) of the product system (Björklund, 2002). Therefore, scenarios should be used to take into consideration a range between a best case scenario and a worst case scenario. Cluzel et al. (2013) suggest the following types of different scenarios: best case, worst case, baseline (expected future), and a highly different alternative.

The SETAC-Europe LCA Working Group 'Scenario Development in LCA' distinguishes between two basic approaches for scenario development in LCA studies: What-if scenarios and Cornerstone scenarios. What-if scenarios are used to gain operational information with a short time horizon whilst the Cornerstone scenario offers strategic information for long term planning (Pesonen et al., 2000).

The What-if scenarios can be applied in the causal links that have a short time horizon between the cause and its effects such as high *pro-environmental attitudes* causing high *washing load*, low *washing temperature* and low *detergent use*, and these, in turn, decreasing *water*, *energy* and *detergent use*. What-if scenarios are also applicable to efficiency gains due to *design improvements*.

Cornerstone scenarios can be used in causal links with long time horizon, i.e. when there is a relative long time delay between the cause and its effects. Thus, Cornerstone scenarios can be applied to analyse the influence of variables such as *government policies and taxes*, *market demand* and *technology development*.

4.2. Reflections on the GMB process and intangible outcomes for LCA studies

Several studies have shown that the GMB process facilitates learning by the participants (Andersen et al., 2007; Hovmand et al., 2012; Richardson and Andersen, 1995; Rouwette, 2012; Rouwette et al., 2011, 2002, 2009; Videira et al., 2012). Several levels of learning may be distinguished in the literature: single loop, double loop, and triple loop learning. Single loop learning (Argyris and Schon, 1974) is the most common form of learning, which leads to the improvement of practices (i.e., design improvements for reuse and recycling). Double loop learning (Argyris and Schon, 1974; Argyris, 1982; Sterman, 2000) involves learning which changes the underlying assumptions for action and hence a redefinition of goals and objectives and thus strategies (i.e., the salient areas of increase of natural resource use, often result from the interaction of the physical structure and the behavioural structure). Triple loop learning (King et al., 2002) includes changing the institutions that govern single and double loop learning (i.e., the realisation that reusing and recycling strategies alone will not lead to an increase in reusing and recycling; there must be a market demand and infrastructure for that). LCA practitioners involved in GMBs may have the opportunity to see the system consequences, cause-effect chains that influence the functional unit of an LCA study. Additionally, it can potentially increase use of scenarios/sensitivity analysis for LCA for and products that are significantly influence by qualitative variables.

Indeed, loop learning was observed in the GMB carried out. Participants highlighted the necessity of including qualitative aspects in the analysis of potential causes of environmental impacts in product design (single loop learning). They stressed the relevance of context (*characteristics of the territory*) as an influencing factor for several variables, including, *pro-environmental attitudes* and *government policies and taxes*, *design improvements* and *technology development* (double loop learning).

According to the systemic approach (Bistagnino, 2011), in fact, the territory with its specificities influences the behaviour of the inhabitants. Thus, a “factor of locality” or “context” should be taken into consideration during the design of a product, or a service, and also in the calculation of its environmental impact. This may, for example, includes such behavioural factors as choice of wash temperature, the importance of having a full washing machine before it is used, etc.; and physical ones like integrating energy flows between the washing machine and the tumble dryer for a cold country or not including the dryer phase-cycle in the design of washing machine for a warm country. These factors may also be related to socio-economic factors and cultural aspects.

Finally, during the GMB session of the washing machine product system, some difficulties related to building the CLDs were experienced. Firstly, the participants were not familiar with +/- labelling of link polarities of the CLD technique, remarking that the +/- labelling was “too constraining”. This suggests that there was either (i) a need to express other relationships than causal so the need for employing other systems modelling techniques, or (ii) an inadequate understanding of the requirement to identify patterns of reinforcing and balancing feedback loops. Future work could explore these issues by indicating of how strong the influence of one variable on another is and/ or an indication of how many of the experts agreed each variable was important/ influential.

5. Conclusion

In this study, a literature review on household washing machine and conventional passenger vehicle product systems was performed to investigate what are the commonly used functional unit, life cycle stages and system boundaries. Then, the Group Model-Building (GMB) method was utilised to underline variables that are normally not included in LCA studies but may influence the overall environmental impact of those products by means of cause-effect links and feedback loops. A Causal Loop Diagram (CLD) was built for each product system with the elicited variables and feedback loops.

The variables not included in the LCAs were mainly soft variables, dependent for instance with user behaviour, market demand and government policies and taxes. In order to move beyond slogans about interconnectedness, need for multidisciplinary research, etc., specific methodologies that consider a more comprehensive/diverse set of parameters must be explored in the LCA community. Those variables could be considered in LCAs through sensitivity and scenarios analysis to examine the influence that they have on the environmental impacts of the product and describe both different contexts and profiles of users.

Therefore, GMB and CLD (as a systematic approach) would still be a valuable aid for the purpose of identifying which are those relevant variables and to describe in a qualitative way how they potentially interact. This could serve as a basis for delimitating system boundaries during the definition of Goal and Scope in LCA and identifying variables/areas that could be included in sensitivity and scenario analysis. Furthermore, the GMB and CLD can help to bridge linkages between quantitative and qualitative variables and to include macro rather than only micro effects in LCAs. This could strengthen the robustness of the recommended actions from quantitative detailed analyses.

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688 **Appendix 3 – Feedback loops in the washing machine CLD - Loop number, length, name and**
689 **variables**

R1 of length 4 – User behaviour on detergent

Natural resource use
Quality of the environment
Government policies and taxes
Pro-environmental attitudes
Detergent use

R2 of length 5 – Detergent requirement

Natural resource use
Quality of the environment
Government policies and taxes
Washing machine technology development
Washing machine design improvements
Detergent use

R3 of length 5 – Design for recycling

Natural resource use
Quality of the environment
Government policies and taxes
Washing machine technology development
Washing machine design improvements

R4 of length 5 – Design for disassembly

Natural resource use
Quality of the environment
Government policies and taxes
Washing machine technology development
Washing machine design improvements
Reuse

R5 of length 5 – Energy requirement

Natural resource use
Quality of the environment
Government policies and taxes
Washing machine technology development
Washing machine design improvements
Energy use

R6 of length 5 – User behaviour on energy

Natural resource use
Quality of the environment
Government policies and taxes
Pro-environmental attitudes
Washing temperature
Energy use

R7 of length 5 – Water requirement

Natural resource use
Quality of the environment
Government policies and taxes
Washing machine technology development
Washing machine design improvements
Water use

R8 of length 5 – User behaviour on water

Natural resource use
Quality of the environment
Government policies and taxes
Pro-environmental attitudes
Washing load
Water use

R9 of length 5 – Detergent efficiency

Natural resource use
Quality of the environment
Government policies and taxes
Detergent technology development
Detergent quality
Detergent use

R10 of length 4 – Consumption rebound effect

Washing machine design improvements
Washing machine obsolescence
Washing machine market demand
Volume of washing machine sales
Economic growth

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692 **Appendix 4 – Feedback loops in the passenger vehicle CLD - Loop number, length, name and**
693 **variables**

R1 of length 6 – Energy efficiency

Level of air/ toxicity/ noise pollution
Appreciation of a clean environment
Government policies and taxes
Vehicle technology development
Vehicle design improvements
Direct vehicle energy use
Natural resource use

R2 of length 6 – Design for disassembly

Level of air/ toxicity/ noise pollution
Appreciation of a clean environment
Government policies and taxes
Vehicle technology development
Vehicle design improvements
Reuse
Natural resource use

R3 of length 6 – Design for recycling

Level of air/ toxicity/ noise pollution
Appreciation of a clean environment
Government policies and taxes
Vehicle technology development
Vehicle design improvements
Material recovery
Natural resource use

R4 of length 7 – Going carless

Level of air/ toxicity/ noise pollution
Appreciation of a clean environment
Pro-environmental attitudes
Road vehicle market demand
Car ownership
Frequency of driving
Car travel (km travelled)
Traffic volume

R5 of length 8 – Take the bus

Level of air/ toxicity/ noise pollution
Appreciation of a clean environment
Government policies and taxes
Public transport development
Road vehicle market demand
Car ownership
Frequency of driving
Car travel (km travelled)
Traffic volume

R6 of length 5 – Dismantling

Level of air/ toxicity/ noise pollution
Appreciation of a clean environment
Government policies and taxes
Recovered parts and recovered materials market demand and infrastructure
Reuse
Natural resource use

R7 of length 5 – Shredding

Level of air/ toxicity/ noise pollution
Appreciation of a clean environment
Government policies and taxes
Recovered parts and recovered materials market demand and infrastructure
Material recovery
Natural resource use

R8 of length 4 – Consumption rebound effect

Vehicle design improvements
Vehicle obsolescence
Road vehicle market demand
Car ownership
Economic growth

R9 of length 3 – Newcomers

Standard of living
Road vehicle market demand
Car ownership
Economic growth

R10 of length 3 – Capacity expansion

Traffic volume
Road construction
Frequency of driving
Car travel (km travelled)

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