Sustainable car lifecycle design
taking inspiration from natural systems and thermodynamics

Martinez, V.G., English, S., Conti, M.

In the last decade the world economy has been struggling with severe endemic problems (Krugman, 2008; Stiglitz, 2010; Brooks 2011), and design is integral to these problems (Manzini 2009). Designing, producing and consuming under the cradle-to-grave philosophy will lead to a severe scarcity of resources among many other significant problems (Heinberg, 2007; Jackson, 2009; Manzini, 2007; McDonough & Braungart, 2002; Meadows et al. 2004). In the design profession is important to search beyond our field to find broader possibilities in order to increase the designer's potential for sustainable product development and expanding design activities and influence.

This paper exposes the search for a tool and method, which from a systems approach, adopt the rules and logic that govern our physical context (biosphere) in order to provide guidelines that the car industry could use to achieve an ideal state for ecological, economical and social sustainability. Therefore, understanding the boundaries of our resources, the economic structure that organises it all and what equitable human wellbeing levels should be pursued is mandatory. A new car industry should respond in novel ways to variables like the ecosystem carrying capacity, energy flows and matter transfer, population number, its distribution and growing rate, allocation of benefits, business and service models and ultimately aspire to an absolute decoupling (Jackson, 2009) of physical objects production from the pursuing of human wellbeing.

I. Introduction

According to the International Road Federation there are nowadays more than 600 million cars running in the world's streets (IRF, 2002 statistics points to 590 million). All together they are responsible for 6.3% of global CO^2 emissions [Stern, 2007]. In the US alone, paradigm of western civilisation, it is estimated that 60% of all national carbon dioxide emissions are emitted by motor vehicles (Black, 2006). Beyond the amount of vehicles, we must also consider the powerful fact that cars have become a psychological need, a cultural reference and even part of the structure of human society. "It is very unlikely that everyone in the future will be travelling on foot and by bike, and specially not by public bus… and the individual flexibility, comfort and convenience the car provides is going to disappear" [Kingsley and Urry, 2009].

Since its first appearance in the beginning of 20th century cars have been associated with freedom and very soon were displayed as an emblem of social status. The amazing energy embedded in fossil fuels and its rapidly falling cost, together with Ford's production lines provided cars to millions of people in just a few years; the car industry became the pinnacle of the industrial revolution and modern society. Timothy O'Brien, Deputy Chief of Staff Ford Motor Company, declares that 50,000 pounds of raw materials are necessary to create a vehicle of 3,000 pounds, showing an efficiency of just 6% (*Waste = food*, 2006).

Together with the industrial revolution the primary base on which our economy and society performs was developed: the consumption of goods; but once the basic needs are covered, in order to maintain the structure of the economy, other tools are necessary to keep on consuming products that sustain economic growth and thus welfare. It was then, when planned and perceived obsolescence came into play, that Schumpeter called it "creative destruction". Nowadays the social trend of consuming products as fast as possible is to maintain the primary structure of western civilisation and its main objective: economic growth and ideally through it welfare (Jackson, 2009).

II. Implications

The creation of mass produced goods is evidently related to the use of materials derived from natural resources that, currently, can only be found on our planet; and in the energy required to transform that matter, mainly obtained from fossil fuels. This is a supply our planet possesses in conjunction with the main source of energy our planet receives: the sun. The very structure in which our economy functions is taking Earth's resources to its limits (Heinberg, 2007), due to the neoclassical economist important miscalculation of considering the planet's biosphere and its resources, as part of the economic system, which must grow continuously in order to provide welfare, thus perceiving them as limitless (Daly and Farley, 2004). The linkage between economic growth and the exploitation of physical resources, together with the increasing rate of consumption is stressing the planet to its limits. Many implications can be subtracted from this situation; the more evident ones are the depletion of ecosystems and non-renewable resources, whereas other ones being less evident as missing the ultimate goal of economic growth: bringing well-being to the entire population. The strongest evidence in this sense is that basic elements of human well-being like life expectancy and accessibility to education have no correlation with increasing per capita GDP beyond a certain point (HDR, 2011; UNDP, 2011; and Rosling, 2006).

The basic index that nations all around the world use for measuring growth is Gross Domestic Product (GDP); which basically is "the sum of all value added to raw materials by labour and capital at each stage of production, during a given year" (Daly and Farley, 2004). With this definition we can infer that the more efficient the labour is, the less capital is needed and more added value can be obtained. This basic fact is what makes technological improvements happen, the continuous search of efficiency; which in turn creates another complex linkage with the urgent need for continuous growth: the balance of unemployment (Jackson, 2009). In order to keep people employed and avoid social collapse more products must be created. This trend is well defined by Jevons' paradox, where technological efficiency instead of easing pressure on the planet and people it creates more demand, consumption and dependency (Jevons, 1865). The way we design, build and use products, and even keep social cohesion is based on a constant structural need for avoiding collapse, fed by positive feedback loops that only increase its negative impacts.

With this basic concept in mind it is clear that searching for a possible solution to our physical limits, and ensuring a future without resource scarcity implies changes in economic, social and environmental systems. Under the same logic the evident response to the dilemma of growth is the concept of decoupling, by "reducing the rate of use of resources per unit of economic activity" (OCDE, 2002; and UNEP, 2011). This is a controversial idea as globalisation contributes to it: even when some countries like Germany or the UK today claim that their rates of consumption are reducing as their GDP is growing. This could be evidence of decoupling, although what is really happening is the externalisation of costs, as many of the impacts are being exported to developing countries like China. Looking at global statistics of CO_2 emissions, loss of ecosystems and social inequality it appears that they are still growing (Jackson, 2009), giving an even greater global systemic attribute to the challenge.

Within this context and the inevitable need for urban mobility the next questions arise:

- How should the car industry and its products react to address these systemic issues?

- What manufacturing and distribution processes, materials and business models can change the current pattern and play under biosphere and resources rules?

- What behaviour must we encourage in users (e.g. culture), manufacturers (e.g. production systems) and governments (e.g. policies)?

- What products will look like? How, where and who is going to produce them and under which business models will they reach users in a decoupled economy?

- Is there any work done in other areas of knowledge that could be useful base ground for an industrial design systemic approach to a sustainable personal vehicle design?

These questions are formulated from an industrial design point of view; if we are to manufacture products in order to satisfy user needs it is imperative to change today's perspective and tackle the challenge in a 'systems approach'. To do so it is necessary to adopt a multidisciplinary understanding of each professional area in order to discover what knowledge has been created and what tools can Industrial Design find useful. Therefore, literature review was performed on the topics relevant to this research and the next findings are proposed as starting ground knowledge for the development of such tool (fig 1).

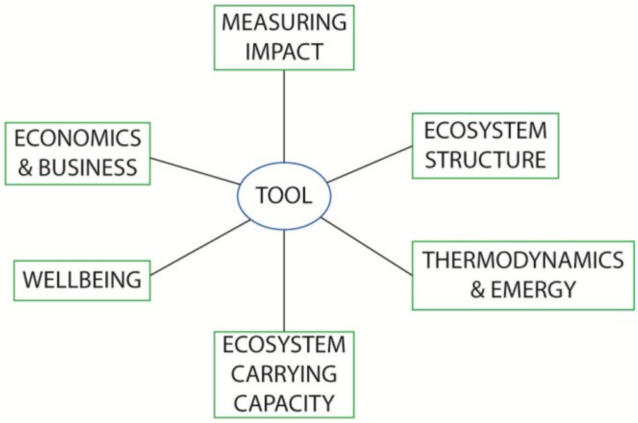

Fig. 1 Tool proposed relevant areas

III. Measuring impact

Nowadays there are several tools used to measure each stage of products manufacturing, its energy and material usage as well as ecological impact. The most commonly used is Life Cycle Assessment (LCA). It is a highly complex, long and expensive process, which ultimately will not result in a “sustainable grade” as it will only identify areas where work is needed. Its accuracy and the criteria used to create final reports can be used to “mask” bad products (Environmental Protection Agency, 2006).

Other similar tools where identified: Product Lifecycle Management (PLM TG, 2011) and Eco-costs (TU Delft, 2011) among the most popular ones. Both tools, with different approaches, deal with the same parameters, measuring impacts on human manufacturing and distribution according to materials and production processes; all these tools have been designed to measure impacts on “business as usual” bases, attempting to consider the “less worst” possible scenario.

The Wuppertal Institute for Climate, Environment and Energy has developed the Material Input Per Service unit (MIPS), which is an indicator of material usage in the manufacture of a product or service; and intends to stimulate business decisions towards efficient resources use and management. It calculates the resource extraction from the source and the related impacts in terms of abiotic (non renewable resources), biotic (renewable resources), air, water and soil removal (Ritthoff 2002).

IV. Ecosystem structure

Life is organised in the most efficient way as consequence of 3.7 billion years of evolution. It is clear that all matter and energy flows within the Earth’s system under very specific physics and chemistry laws. When it comes to life, organisms are classified according to their role in the food chain, in it Trophic Levels is where energy flows and matter transfer occurs (Mader, 2010).

In the first level Autotrophs can be found, these are organisms that create their own food by metabolising basic chemicals extracted from the soil and using the energy coming from the sun; more simply they are called Photosinthesizers. The next level features Heterotrophs, organisms that take food from an exterior source; within these there are Herbivores, Carnivores and Omnivores. Finally, there are Detritivores, which are important organisms in charge of decomposing organic matter again into basic chemical compounds, which in turn will be used again by Autotrophs. Each level aims to obtain enough energy to perform work[1] in the form of: growth (which stabilises when adults) and reproduction (autopoiesis). All the interactions among trophic levels and the environment that sustains them are called ecosystem; this means all abiotic and biotic matter (Mader, 2010).

Müller (2005) discussed the potentials of self-organisation, based on the ecological principle called orientors, a system-based theory on ecosystem development founded in non-equilibrium thermodynamics and network development. The selection of orientors is strictly related to the understanding of the "Eco-targets" within the analysed ecosystem, these differ among ecosystems in relation to contextual conditions (Fig. 2).

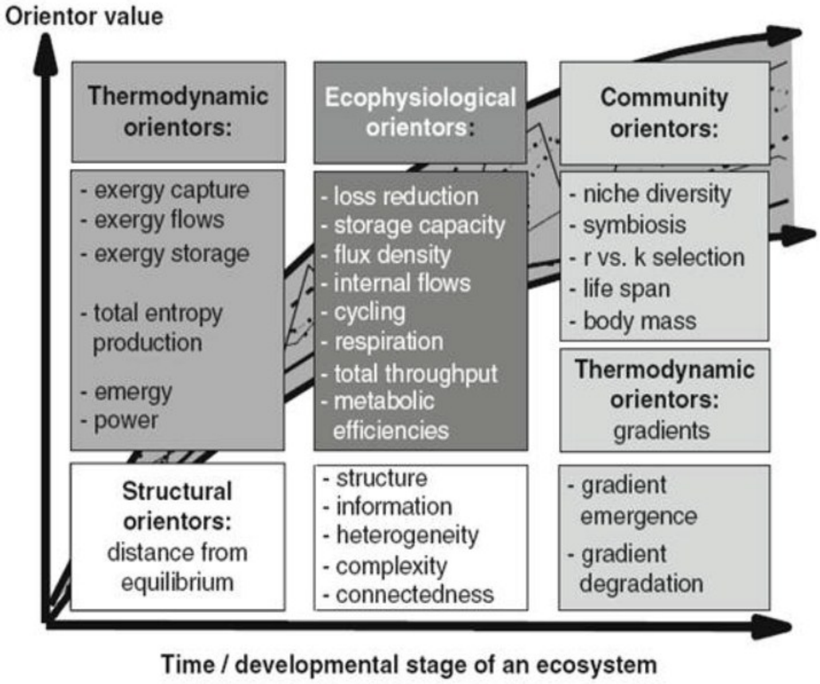

Fig. 2 Müeller's orientors set according to its value and the time of ecosystem development

"So far as ecological systems are characterised by a very high capability for self-organisation and have been evolving for billions of years it makes sense to use and apply the orientors' signals in practical management of a more near-nature manner, that can prove to be a profound and promising strategy which contributes to the ecological goals of sustainable development" (Scott and Witte, 2009). Bossel (2001) proposes 7 basic orientors that can be applied to any ecosystem: Existence, Effectiveness, Freedom of action, Security, Adaptability, Coexistence and Psychological needs.

V. Thermodynamics & emergy

The first physical laws to consider when examining Trophic Structures derive from thermodynamics. In each level only a small amount of energy is truly passed to the next level (exergy), this is due to the loss of energy (entropy) and by cellular respiration and energy transferred to detritivores (Mader, 2010). This fundamental fact explains why each consequent level is smaller than the previous one. In other words, it explains why there are more herbivores than carnivores (in biomass terms and not only population number). This also explains the distribution patterns of populations and reproduction rates according to the available resources. Distribution patterns can be identified in: clumped, random and uniform, whereas reproduction is regulated by density-dependent factors (biotic) and density-independent factors (abiotic) (Mader, 2010).

1 Work in thermodynamics is intended as the quantity of energy transferred from one system to another accounted by changes in the external generalised mechanical constrains, and this can be: chemical, electromagnetic, on pressure/volume, among others.

According to Odum (1996) emergy (written with an m) is the amount of energy that is used up in transformations directly and indirectly to make a product or service. The name is derived from "embedded energy". Almeida et al. (2010) propose it as an "environmental accounting method… as a tool to assist in product design. This tool may be inserted into the conventional design methodology to facilitate the selection of materials and processes as well as the actual design of the products". Odum (1998) clarifies the terms: energy hierarchy and scale, emergy terms of transformity, emergy storage, empower, mass emergy, empower density, work and emdollars, and with them he illustrates the profound meaning of the emergy concept in production, objects and their impact on our ecosystem.

VI. Ecosystem carrying capacity

Each ecosystem, according to the nutrients it contains, has a carrying capacity; this defines the maximum number of individuals the environment can support (Mader, 2010). In order to translate all this knowledge and logics into a sustainable industry it is imperative to measure, not only the carrying capacity, but also energy flows, efficiency, population number, growing rate and distribution patterns.

In 1990 researchers Mathis Wackernagel and William Rees at the University of British Columbia created the concept of Ecological Footprint which measures how much land and water area a human population requires to produce the resources it consumes and to absorb its carbon dioxide emissions, using prevailing technology (Ewing et al., 2010a & b). They developed an efficient way of measuring ecosystem carrying capacities: land and water area are scaled according to its biological productivity. This scaling makes it possible to compare ecosystems with different bio-productivity in different areas of the world in the same unit. Bio-capacity and Ecological foot print indicators focus on the biomass-based flow of ecosystem's provisioning services and the waste uptake of its regulating services (Ewing et al., 2010).

Bio-Capacity = Area x Yield factor x Equivalence factor

The yield factor is the ratio of national-to world-average throughput. The equivalence factor translates the area supplied or demanded of a specific land use type into units of world average biologically productivity, which varies by land use type and year (Ewing et al., 2010). There are 6 different land types: Cropland, Grazing land, Forestland, Carbon footprint, Fishing grounds and Built-up land.

Together with the Ecological footprint there is the Millennium Ecosystem Assessment promoted by the UN and first launched in 2004. MEA "assess the consequences of ecosystem change for human Wellbeing and the scientific basis for action needed to enhance the conservation and sustainable use of those systems and their contribution to human Wellbeing" (MEA, 2011).

VII. Wellbeing

The ultimate purpose of economy, production and progress should be to provide well-being to humans. GDP creator Simon Kuznets stated in the US congress in 1934 "the welfare of a nation can scarcely be inferred from a measure of national income" (Kuznets 1934). It is still today a matter of high controversy to define what wellbeing is, but it is clear that economy should ensure it; and a way of keeping track must be put into practice, as well as part of companies' social responsibility is to take it into consideration in their business plans.

Merriam-Webster dictionary defines well-being as "the state of being happy, healthy, or prosperous". The Wellbeing Institute of Cambridge University refers to it as "positive and sustainable characteristics which enable individuals and organisations to thrive and flourish". Manzini proposes a change of society's search for fulfilment from a "product based" to a "context based", being the context the physical space and social set-up (Manzini, 2007). Jackson talks about shifting our "novelty driven" society into a "flourishing" one (Jackson, 2009).

-The *Human Development Index*, created by the United Nations Development Program is a summary of human development in 3 dimensions: Long and healthy life, Access to knowledge and Decent standard of living. For each dimension an adjustment is made to measure inequality across the population, other adjustments concern gender inequality (in order to reflect women's disadvantage in reproductive health, empowerment and labour market). A final layer is represented by multiple poverty deprivations (United Nations Development Program, 2011).

VIII. Economics & business

It has been mentioned above the unavoidable relation between ecological, social and economical sustainability. The same applies to the severe omissions of neoclassical economics. However, there is relevant research on finding new structures in economy, which are more coherent with today's global context and the physical and chemical laws that govern it. For this research Ecological Economics and its derivate Thermoeconomics are the most relevant ones. These are founded in the works of Georgescu-Roegen, Boulding, Daly and Constanza who proposed a "qualitative improvement in the ability to satisfy wants (human needs and desires) without quantitative increase in throughput beyond environmental carrying capacity" (Daly and Farley, 2004). This is achieved "through thermodynamics and entropy throughput and flows" (Daly and Farley, 2004).

"The common denominator of all usefulness, consist of low-entropy matter-energy. Technological knowledge help us use low entropy more efficiently; it does not enable us to eliminate or reverse the direction of metabolic flow" (Daly and Farley, 2004).

In a conference held at the University of Vermont in 2003 (GundInstitute, 2011), Daly described the focus of ecological economics through: Allocation of resources, Distribution of income and Scale of the economy relative to the ecosystem upon which is reliant.

Daly's view on scale is particularly important due to the exponential growth of population and uneven distribution and the difference of ecological services among ecosystems. He states that limiting scale will increase efficiency; and he proposes an ecosystem valuation with two different types of values (GundInstitute, 2011): Direct use value attributed to direct utilisation and Indirect use value attributed to indirect utilisation, through the positive externalities that ecosystems provide to others

Georgescu-Roegen proposes the differentiation from flow and service as follows: Amount of flow is equal to the units of substance; the rate of flow is equal to the substance consumed in a period of time and service is equal to the substance multiplied by the time keeps on delivering its function. This is fundamentally due to the fact that "only flows can be embodied in a product… services on the other hand belong to mixed dimensionality in which time enters as a factor". Hence there is a clear "connection between low entropy and economic value" (Georgescu-Roegen, 1999).

In general, ecological economists believe that infinite growth (also referred as "business as usual") can turn out to be uneconomic, as true costs of growth are higher than the benefits. As a result the optimum scale of economies is often questioned.

The way economic structures operate on a daily basis and deliver value to people is through businesses that directly operate, transform and deliver matter in the form of goods. All businesses run under a model on which the main characteristics and performance of a company are regulated. Osterwalder & Pigneur produced the most relevant work found on business model innovation. They define business model as: "…the rationale of how an organization creates, delivers and captures value", and propose a canvas on which 9 consecutive phases must be followed in order to innovate in business model generation (Osterwalder and Pigneur, 2010). These phases are: Customer segments, Value proposition, Distribution channels, Customer relationship, Revenue streams, Key resources, Key activities, Key partnerships and Cost structure.

X. Reflecting upon literature findings

What has been previously discussed is the absolute lack of consideration for the limits of our biosphere in neoclassical economics structure, terms that in turn defines the way we manufacture, distribute, use and dispose products. This can be clearly seen in the way a business model is created, focusing on demand whilst neglecting the main source of material goods and the health of the system that contains them. With this in mind it is clear that it is imperative to work within the boundaries and under the same rules that dominate the natural world. Therefore, it was decided to take a top-down approach. This means on the one hand setting first the desirable performing outputs of a new car industry with the lowest possible impact, and on the other the generic variables of ecosystem boundaries and cycles. Then the aim is to go backwards to define the new structure characteristics (product, service, business model) and its ideal structure for each particular case (ecosystem or geographical site).

A first clear conclusion is that there is useful ground knowledge in areas like biology, ecology, economics, business and social sciences in order to answer, from an industrial design point of view, the key questions formulated above. This knowledge can be applied through the use of the Ecological footprint and the Millennium Ecosystems Index which can be helpful to measure ecosystems carrying capacities and the output impact. The UN's Human Development Index provides an objective universal well being measurement; and concepts like Daly's scale of economy and ecosystem valuation together with Georgescu-Roegen's differentiation of flow and service can contribute to establish a metric on which new structures may be founded.

At this stage of the research process the most relevant finding is the concept of trophic level organisation, which in itself contains energy, biomass exchange and its flow, as well as derived important issues of population size and distribution, all ruled by thermodynamic laws. An analogy of these levels in natural systems needs to be drawn alongside the initial idea of economic and matter flow in a production/distribution human system (Fig 3).

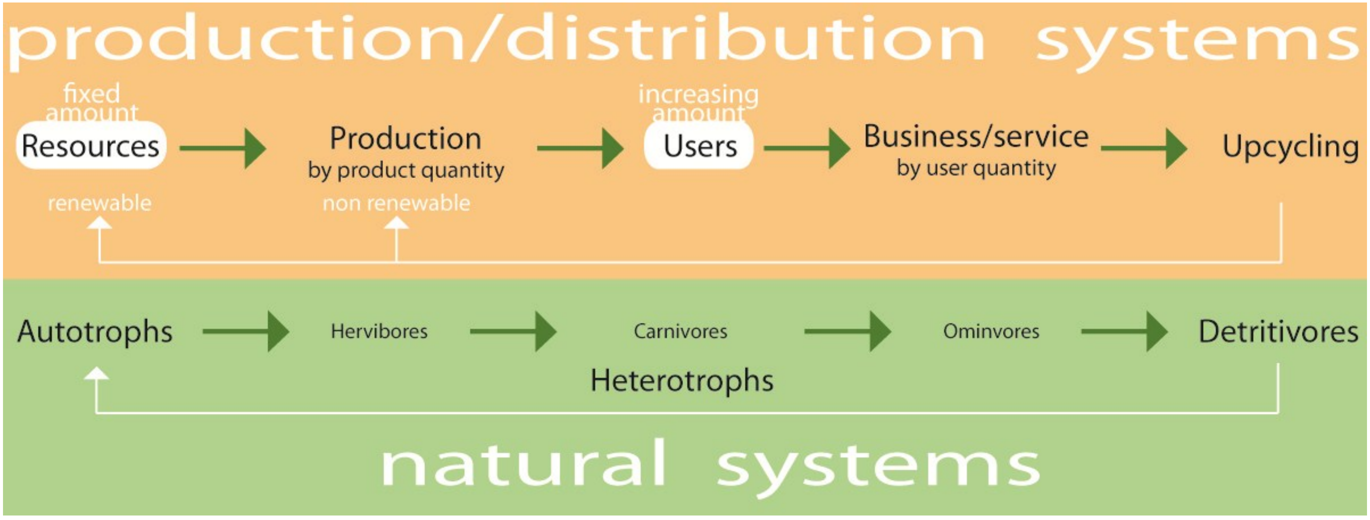

Fig. 3 Trophic structure – Production/distribution structure analogy

It is relevant to note that "resources" or some of the previously called "generic variables" are fixed in amount and the "users" are increasing in number. This gives the opportunity to work with production and business structures, its distributions and allocations. As a result all this could derive in "production capacity" and in turn to a distributed business/production/service model for each case (ecosystem or geographic region) (Fig 4).

It is the main task of this research project to build upon that knowledge, and through the understanding and use of ecosystems carrying capacities, thermodynamics and emergy accounting create a tool that leads to an advanced and sustainable way of designing, producing, distributing and using vehicles.

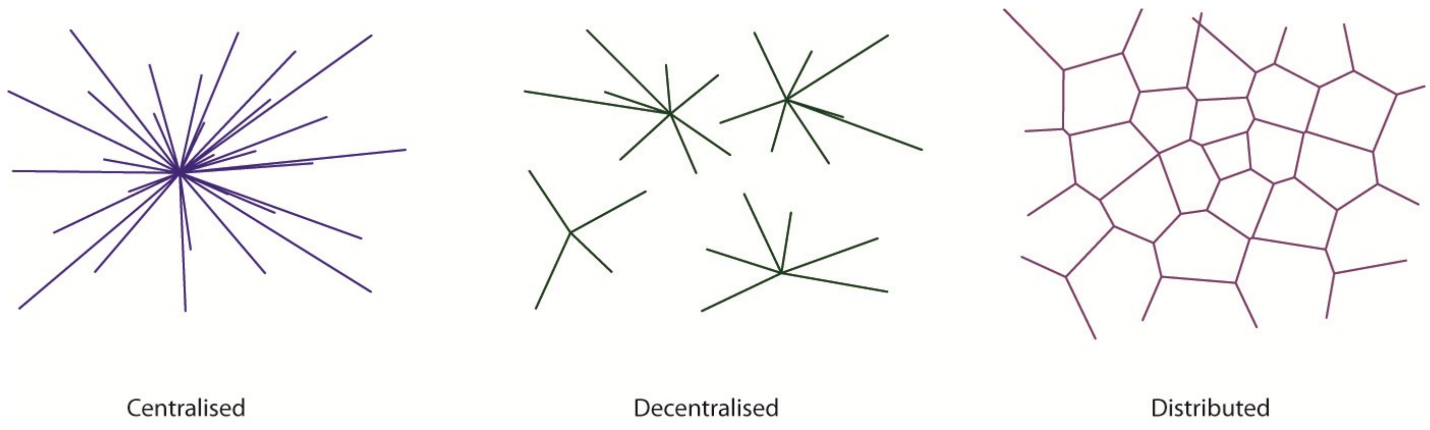

Fig. 4 Types of organisations.

The way this tool is intended to work is first by defining the product to be developed, population segment addressed and the geographical areas from which the resources will be taken from as well as the amount required and industrial processes that will transform them into the final product. According to these variables the boundaries and characteristics available for the new structure will be specified, then using Osterwalder & Pigneu's nine steps for business model innovation together with the selected Eco-Targets and Orientors, the shape of this structure will be formed in order to obtain as an output the new product, manufacturing and related business solutions characteristics (Fig 5).

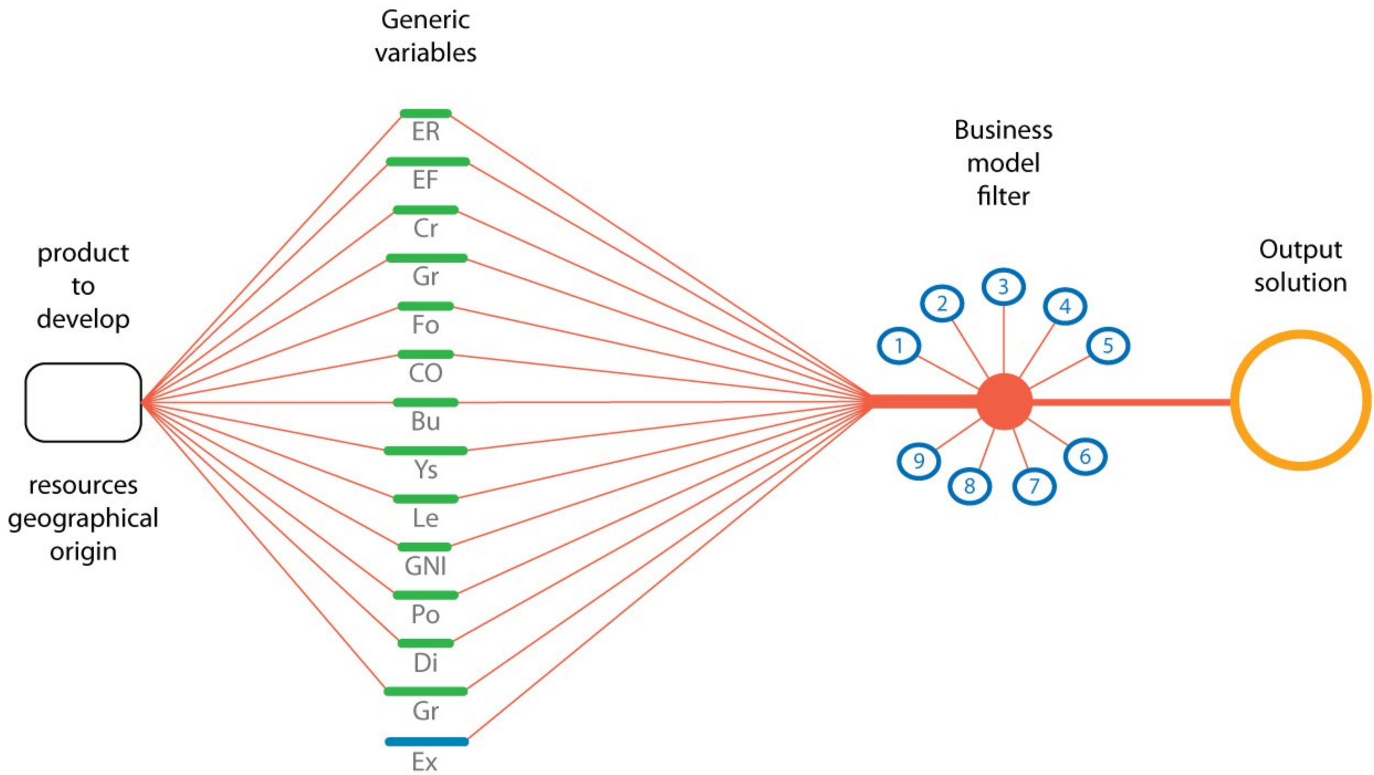

Fig. 5 Trophic economics method's structure.

ER: Energy renewable, EF: Energy fossil, Cr: Cropland, Gr: Grazing land, Fo: Forest, CO: CO_2 capturing, Bu: Building up land, Ys: Years of school, Le: Life expectancy, GNI: Gross national income per capita, Po: Population size, Di: Population distribution, Gr: Population growth rate, Ex: External needs not present in ecosystem. 1 to 9 refers to Osterwalder & Pigneu's business model canvas.

XI. Aims and objectives

Considering the fixed amount of resources as “generic variables”, the increasing amount of population and its urbanisation distribution patterns trends a first hypothesis is proposed:

By analysing sustainable performance from a natural systems point of view through the trophic structure of energy flow and biomass transfer (thermodynamics), the boundaries and mechanics of a sustainable car industry can be identified for later structuring it by using a business model innovation tool. This may generate as output new business models and manufacturing/product characteristics for each geographical region, these while remaining feasible with the decoupling of progress and prosperity from resources depletion.

In order to achieve this, a method to develop a new structure from the “generic variables” will be created. Starting from the ground knowledge the different variables such as: ecosystems location and area, human population distribution, human population growth rate, renewable resources characteristics, sustainable rate of consumption, ecosystem waste absorption rate, etc. will be input and a coherent distributed business/production/service model will be deployed for each case.

XII. Expected contribution

From a theoretical point of view the use of trophic structures and the combination of knowledge from biology, economics, thermodynamics and business that reside in the proposed method will increase the designer’s potential for sustainable product development deriving in a novelty approach for design activities and influence.

The direct research contribution is intended to be a tool that will guideline the way for sustainable innovation in the automotive industry where vehicles can be designed, produced, distributed and put into use with the lowest possible ecological impact and socially responsible, as well as an integral evaluation method incorporating ecological, economical and social measurements (Fig 6).

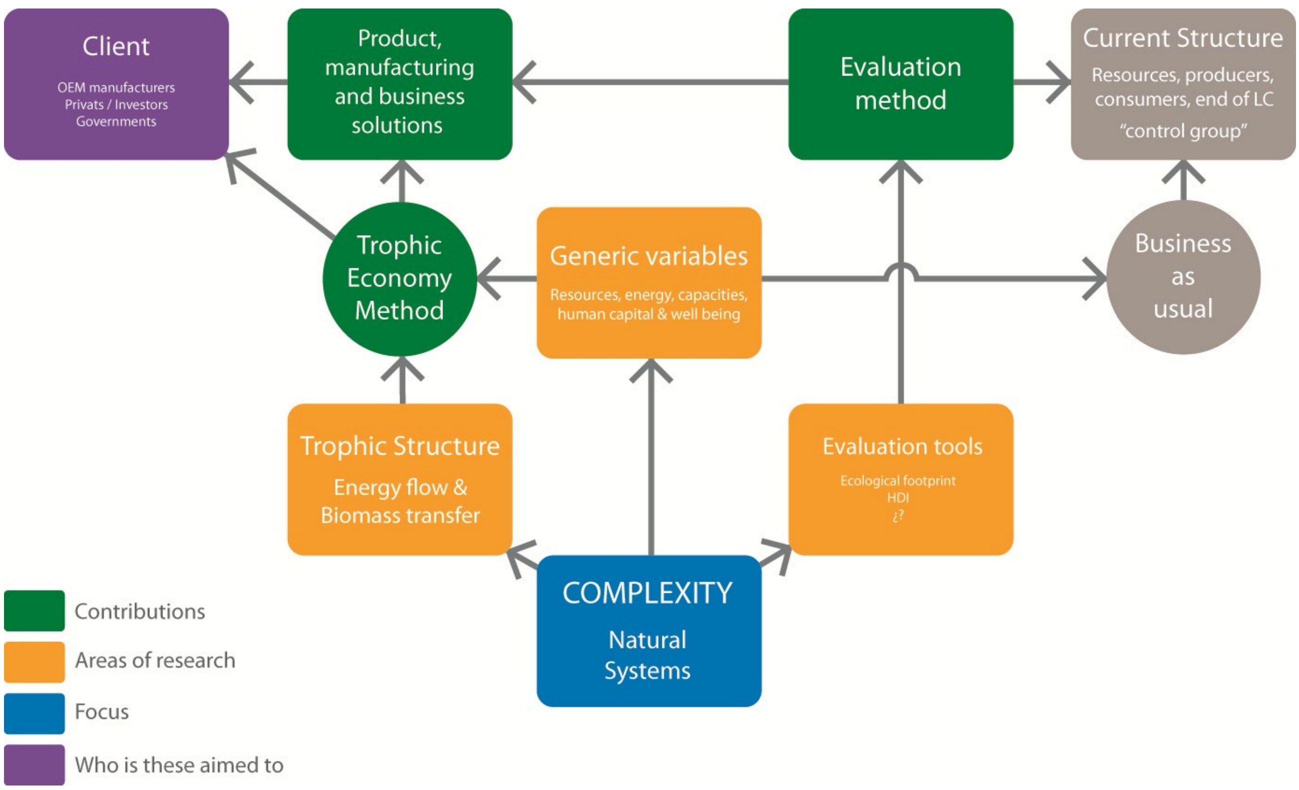

Fig. 6 Research map: research focus, work areas and expected contributions.

XIII. Methodology

The methodology adopted to achieve this research expected contributions is divided in two main phases; the first one relates to the build-up of the structure and contents of the proposed method, which requires deep knowledge of the multiple perspectives involved in generating the criterion in order to select the generic variables to use and understand their interconnections, all of these will be translated in a set of relevant and manageable data. English (2011) proposes a multiple perspective problem framing method on which through the use of integrated mind mapping, design space framing and the development of different mental models the network and its interrelations can be analysed and the designer's perception developed.

Once the variables are identified, the necessary data collection will be mainly performed through accessing global statistics from institutions like United Nations Development Program, United Nations Environment Program, World Bank, International Monetary Found, etc. For each data category it will be indispensable to set the boundaries of sustainable performance (that often depends on other variables due to complex network interconnections), which would be stated by the Ecological footprint method and the Millennium Ecosystem Index. It is foreseen that for this step mapping the system will be necessary in order to understand the interconnections among variables and be able to build the economy, matter and energy relations that are impossible to predict. Research has been conducted and several free open-source complex network mapping software have been found, the most relevant ones are: Pajek, Graph-tool, Tulip, NteworkX and particularly important for its design capacities: Processing.

The last part of phase one will be to analyse the business model innovation steps in order to reorganise them more coherently with the trophic structures (resource-driven) for later function as filters and give shape to the new proposals into practical applications. These business model steps have been mentioned above, some of them are: value proposition, production processes, production quantities, facilities distribution, key infrastructure, etc.

The second phase will be about testing the tool by designing an experiment within which different design groups can use the proposed tool in order to create products solutions for geographical areas determined in cases designed specifically for this experiment. It is planned to have three different cases and rotate them among three design groups, this last in order to have proposals for the same problem coming from different participants. The outcomes then will be measured and compared in relation to their ecological and social impact using the Ecological footprint tool, the Millennium Ecosystem Index and the Human Development Index. Comparing the results will enable the process of drawing conclusions about the effectiveness of the tool (Fig. 7).

		CASES		
		1	2	3
GROUPS	A	A1	A2	A3
	B	B1	B2	B3
	C	C1	C2	C3

Fig. 7 Experiment structure

Due to the complexity of data management and interaction, the tool is planned to be a computer application on which variables can be introduced for latter the user modify parameters and in real time see graphically the results of its choices in order to determine the best option. A collaboration agreement has been achieved between the School of Design and the Computer, Engineering and Information Sciences faculty, both from Northumbria University, to develop the software by master students under the requirements of this research.

XIV. Conclusions

Even though the relation of climate change and its human origin is still a matter of debate in some forums, and the reluctance of neoclassic economics in facing the limiting characteristics of our natural context, there is no argument against the search of resource efficiency and a possible economic benefit from it. This paper discussed a possible way of organising new knowledge (new for the industrial design profession) in order to find more efficient ways of manufacturing, using and disposing of our products.

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