Environmental Assessment approach for the first stages of product design

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Titre : Approche d'évaluation environnementale pour les premières étapes de la conception de produits

Résumé en français :

Les responsables de la conception des produits que nous utilisons tous les jours ont un grand pouvoir car ils sont responsables de la conception d'une très partie du monde qui nous entoure. Tous les produits et services d'aujourd'hui n'étaient autrefois qu'une partie de la nature et l'impact des activités humaines sur cette nature devient de plus en plus préoccupant. Des efforts sont faits à tous les niveaux, des utilisateurs aux multinationales, pour réduire l'impact des hommes mais ce n'est pas une tache simple.

Dans une première partie, cette thèse présente le processus de la conception de produits et différents moyens qui peuvent être utilisés pour conduire ce processus vers des solutions plus respectueuses de l'environnement. La conception de produits est une activité complexe qui peut être modélisée comme un processus composé de trois phases – *conceptual*, *embodiement* et *detailed*. Les décisions prises au cours des premières étapes de ce processus conduisent à la majorité des coûts finaux, monétaire, environnementaux, etc., d'un projet. Après ces étapes, toutes modifications apportées au projet augmentent les coûts mais peuvent aussi ne pas être réalisables. Les responsables de la conception de produits ont accès à certains outils afin de produire des objets plus respectueux de l'environnement, dont les directives Design for Environment, qui ne fournissent pas de données quantifiables, et des méthodes basées sur l'ACV, extrêmement gourmandes en ressources et ne donnent pas de résultats fiables avant la modélisation finale.

Afin de pallier aux différents points faibles de ces méthodes, cette thèse propose l'approche DA-Ex basée sur l'exergie et l'analyse dimensionnelle. Le but de cette approche est d'utiliser des données faciles d'accès qui peuvent être stockées dans une base de données de faible taille, être applicable lors des premières phases du processus de conception lorsque l'artefact étudié n'est pas encore défini en sa totalité, fournir des résultats de qualité comparable à ceux obtenus avec des méthodes et outils existants, et offrir la possibilité d'élargir les domaines étudiés en dehors de l'évaluation environnementale. L'approche DA-Ex considère trois aspects - l'efficacité de la transformation de l'exergie, l'efficacité d'utilisation des ressources, et les émissions environnementales. La possibilité d'extension de l'approche est illustrée avec l'analyse des coûts. Plusieurs études de cas ont été réalisées pour tester l'approche DA-Ex. Les résultats obtenus avec cette approche ont été comparés à ceux fournis par des méthodes et indicateurs existants.

Mots-clés : conception de produits, génie mécanique, évaluation environnementale, éxergie, analyse dimensionnelle

Résumé en Anglais :

Engineering designers wield a tremendous power as they are responsible for the design of a large part of the world that surrounds us. All artificial products and services were once a pristine bit of nature and the impact that mankind has on this planet is a growing concern at all levels, from single customers to world-wide companies and governments. The task of producing something that does not contribute to this impact is daunting.

The first part of this thesis elaborates on engineering design and the ways of influencing product design towards more environmentally conscious solutions. Engineering design is a complex activity that can be modelled as a process made up of three basic phases - conceptual, embodiment, and detailed design. The decisions made during the early stages of this process are responsible for the majority of the final costs, monetary, environmental or otherwise, of a project. Any changes made to the design after these stages not only unnecessarily bring up the costs, but there are also fewer opportunities to make them. The question remains of how designers can be supported during the design process to produce more environmentally conscious artefacts. Design for Environment guidelines are a good start but they do not provide quantifiable data, full LCA methods are extremely resource consuming and do not provide robust results before the design is finalised, etc.

In order to alleviate the shortfalls of these methods, the thesis proposes the DA-Ex approach based on exergy and dimensional analysis. The aim of the approach is to use readily available data that can be stored in a lightweight database, be applicable during the early phases of the design process when the studied artefact is not yet fully defined, provide results of comparable quality to those obtained with existing methods and tools, and offer ways of expanding the studies to fields related to sustainability beyond environmental assessment. The DA-Ex approach first considers exergy transformation efficiency, resource use efficiency, and environmental emission metrics. An expansion is also proposed to cost analysis. Several case studies were performed to test the DA-Ex approach. The results obtained with the approach were compared to those provided by existing methods and indicators, although they could not be compared number to number due to the fact that all methods and indicators function with different characterisations and base hypotheses. The next step for the DA-Ex approach is to include a systemic view, as to not only cover the designed artefact in a study but also its environment and what impact it has on it.

Key words: product development, engineering design, environmental assessment, exergy, dimensional analysis

Visa du Directeur de thèse :

eric coatanea

Czy wiesz, która gra jest lepsza:
Ta, którą myślisz, że możesz przejść lecz nie możesz...
Czy ta, która wydaje się niemożliwa do przejścia, lecz taka nie jest.
- Bishop (Avalon, 2001, directed by Mamoru Oshii)

Roughly translated from Polish, the above quote gives, "Which game is better, one that you think you can beat but in the end can't or one that seems impossible but in reality isn't?" and Bishop goes on to say that game developers must find the perfect balance of the two types of games in order to keep players interested. Although that quote is from a science-fiction film and Bishop talks about the development of a virtual reality game, I believe it captures the essence of what doctoral work should cover. Looking back, in the last few years, I'd like to believe that my PhD somehow managed to strike that balance with moments of immense joy and utter despair. One moment I could easily see the end and the next I felt like I had to start everything over from scratch. This balance kept me going and has taught me quite a bit about myself and the world in general but, of course, none of this could have happened without the help and support of a small army of people.

First and foremost, my mum and dad deserve a nod as they have always been pillars in my life and have quietly, but efficiently, guided me throughout my adventures and have accepted my choices and obsessions, even if at times those might have been eccentric. I take the biggest comfort in knowing that there is always a place for me to crash when I need a break and it comes with amazing boeuf bourguignon, tomato soup, skiing trips, runs and walks in the calanques, and so many other things that make life just that much better. My sister deserves more recognition than she, or anyone, probably realises. I doubt I would have gone through prépa, into mechanical engineering, etc. if it hadn't been for her. Kso and JB, both, have been amazing in showing interest in my work and sometimes it's these small things that really matter. Road trips to catch stages of the Tour de France and spending afternoons in mazes aimed at children are also definitely a good way of getting extra good marks in my books!

During the last four years or so, the Product Development research group at TKK, and now Aalto University, has become a bit of a home away from home. I cannot possibly express the full extent of my gratitude towards Eric Coatanéa who has supervised my work from the first day and has allowed me to concentrate on topics that truly interest me and has given opportunities to dip my toes in other fields such as teaching. I

could not have hoped to have a better supervisor and friend to drive this work to completion. Over the years many have come and gone in the research group but all have contributed through formal group discussions and random sessions remodelling the world over lunch or a cup of coffee or tea. A huge thanks to everyone in room K235 and on the 2nd floor, in general, for making my working experience rather great!

On the French side, the research team at SupMéca definitely made my year in France fantastic. A huge thank you to Dominique Millet, my thesis co-supervisor, for implanting the idea that a PhD is an option back in my engineering school days. It was with great pleasure that I came back to Toulon and the great group of people on the 5th and 6th floors!

Alas many will remain unnamed even though their contribution to keeping me sane has been immense. Notably, my friends in the Helsinki area have been amazing in welcoming me into a city I knew nothing about. My interwebs friends have been a patient group, listening, and possibly ignoring, my many ranting, whining, and squeeing sessions, without judgement, thank you to all.

Thank you, thank you all, you are all brilliant!

Contents

List of Publications

This thesis consists of an overview and of the following publications which are referred to in the text by their Roman numerals.

I Medyna, G., Nordlund, H., and Coatanéa, E. Study of an exergy method for environmental evaluation assessment in the early design phase using comparative LCA and exergy approach. *International Journal of Design Engineering*, Volume 2 (3), pp. 320 - 345, 2009.

II Medyna, G., Coatanéa, E., and Millet, D. Comparative study of environmental evaluation assessment using exergetic LCA implemented in existing software and a novel exergetic approach during the early design phase. In *Proceedings of the ICED 2009 conference*, Stanford, USA, August 2009.

III Medyna, G., and Coatanéa, E. Decision making and value considerations during the early stages of engineering design. *Global Product Development (Extended Proceedings of the 2010 CIRP Design Conference)*, Bernard, Alain (Ed.), pp. 397 - 402, 2011.

IV Medyna, G., Coatanéa, E., and Millet, D. Environmental and Economic Evaluation of Solar Thermal Panels using Exergy and Dimensional Analysis. *Glocalized Solutions for Sustainability in Manufacturing (Proceedings of the 2011 CIRP International Conference on Life Cycle Engineering LCE)*, Jürgen Hesselbach and Christoph Herrmann (Eds.), pp. 647 - 651, May 2011.

V Medyna, G., Coatanéa, E., and Millet, D. Evaluation of parts of a boat cabin based on exergy - focusing on environmental and economic assessments. In *Proceedings of the ASME International Mechanical Engineering Congress 2011*, Denver, CO, USA, November 2011.

VI Medyna, G., Nonsiri, S., Coatanéa, E., Bernard, A.. Modelling, Evaluation and Simulation During the Early Design Stages: Toward the Development of an Approach Limiting the Need for Specific Knowledge. Accepted for publication in *Journal of Integrated Design and Process Science*, accepted September 2012.

VII Coatanéa, E., Medyna, G., Mbeo Ogeya, C., and Ritola, T. Early design stage support using a systemic perspective: sustainable design of pyrolytic stove eco-system. *Journal of Cleaner Production*, submitted June 6th 2012.

Publications and Author's Contribution

Publication I: "Study of an exergy method for environmental evaluation assessment in the early design phase using comparative LCA and exergy approach"

The article develops the theoretical background of exergy as an approach for environmental assessment during the early stages of design. Metrics are obtained allying exergy and dimensional analysis. The approach is applied to the case study of a foundry part obtained through two production methods. As a widely accepted method of Life Cycle Assessment, Eco-Indicator 99(H) was used as a comparative base for the results obtained with the exergetical method.

The author performed the calculations linked to the environmental impact of the studied products, contributed the content on environmental assessment and impact indicators. The discussion was elaborated in collaboration with the co-authors. The author was also responsible for the final editing.

Publication II: "Comparative study of environmental evaluation assessment using exergetic LCA implemented in existing software and a novel exergetic approach during the early design phase"

The approach based on exergy and dimensional analysis to obtain environmental impact metrics is further tested on two alternative solutions for a sand casting mould. The validation of the results is done through a comparison with results obtained of LCA studies performed using Eco-Indicator 99(H) and Cumulative Exergy Demand (CExD) methods, which are widely used in industry for environmental impact studies.

The author was responsible for the entire work. The article was published in the proceedings of the 2009 International Conference on Engineering Design (ICED) following a peer review process. The work was presented by the author at aforementioned the conference.

Publication III: "Decision making and value considerations during the early stages of engineering design"

The work elaborates, for the first time, on the possibility of expanding the approach with metrics based on exergy and dimensional analysis to fields outside of environmental impacts. The proposed expansion is towards value considerations in engineering design.

The author was responsible for the entire work. The work was first submitted and accepted following a peer review process as part of the 20th CIRP Design Conference in April 2010 where it was presented by the author. It was published, after modification, in the expanded proceedings, *Global Product Development*.

Publication IV: "Environmental and Economic Evaluation of Solar Thermal Panels using Exergy and Dimensional Analysis"

The article focuses on the study of a commonly-used alternative energy source, solar thermal panels. The environmental impact assessment is performed using metrics based on exergy and dimensional analysis, dubbed for the first time the *DA-Ex approach*, and the results are validated through a comparison with results obtained with LCA studies based on Eco-Indicator 99(H) and Cumulative Exergy Demand (CExD) methods. The work goes on to study the cost repartition of the different parts of the solar thermal panels during the extraction and assembly phases. This expansion towards cost analysis metrics is an evolution of the value considerations presented in the previous work.

The author was responsible for the entire work. The article was published in the proceedings of the 2011 CIRP International Conference on Life Cycle Engineering (LCE) following a peer review process. The work was presented by the author at the aforementioned conference.

Publication V: "Evaluation of parts of a boat cabin based on exergy - focusing on environmental and economic assessments"

The article studies alternatives for the cabin of a boat based on their environmental impact as well as the associated costs. These studies are performed using metrics based on exergy and dimensional analysis. The boat studied is part of a project developed for a hybrid propulsion passenger ferry for a port in the south of France.

The author was responsible for the entire work. The article was published in the proceedings of the 2011 ASME International Mechanical Engineering Congress following a peer review process. The work was presented by the author at the aforementioned conference.

Publication VI: "Modelling, Evaluation and Simulation During the Early Design Stages: Toward the Development of an Approach Limiting the Need for Specific Knowledge"

The design team has limited monetary, time, etc. resources during the early stages of the development process for modelling and evaluating concepts and ideas, even though the early stages of the design process are critical. The article proposes to an approach to model of a concept design for an artefact without having to look up specific information, such as specific laws, thus limiting the resources needed. The approximated model is obtained through dimensional analysis and consideration of the generic laws associated with organs. This model is then simulated using the principles of system dynamics in order to further support decision making in the early stages of the design process.

The author was responsible for the development of the modelling approach based on previous work. The application of a system dynamics approach to the model was done conjointly with the other authors. The author was also responsible for the final editing.

Publication VII: "Early design stage support using a systemic perspective: sustainable design of pyrolytic stove eco-system"

The introduction of an artefact can cause changes in the surrounding environment that cannot be predicted through traditional LCA studies and methods such as the proposed with metrics based on exergy and dimensional analysis, which are essentially static. A more systemic approach studying the global interactions linked to an artefact allows a deeper understanding of the issues at hand and the possibility to predict emerging positive or negative behaviours that can arise. Such an approach, coupled with more traditional environmental impact studies, makes the field of environmentally oriented engineering design all the more efficient.

The author was responsible for developing the dynamic model and analysis of the emerging behaviours of the studied stove. The discussion and future evolution of the work related to system dynamics were conjointly done with the first author. The author also contributed to the elaboration of the state of the art and performed the editing of the work.

Nomenclature

Artefact - umbrella term used in this work to represent a product system that can be a product or a service. In order to simplify expression, artefacts are sometimes referred to as simply "products", they encompass though both products and services.

CExD - Cumulative Exergy Demand, available as an impact category indicator in the Life Cycle Assessment SimaPro software. As it is based on exergy, it takes into consideration the quality of energy and the integration of non-energetic resource, making it more comprehensive than the CED indicator [3]. CExD is one of the indicators used as part of the validation of the results obtained with the proposed DA-Ex approach.

Design for X (DfX) - umbrella term for design practices aiming to improve a certain area of design. In this work, Design for Environment (DfE) is often cited. It is a set of environmentally conscious design practices that aim to reduce the overall impact an artefact.

DA-Ex - approach developed based on exergy (Ex) and dimensional analysis (DA) for environmental assessment, as proposed in this work.

Dimension - in mathematics and physics, quantities have two characteristics, a numerical measure and a concept - the dimension. Most commonly used dimensions include , *e.g.*, force, mass, and length. It is a key notion in dimensional analysis, especially in fields where dimensions are not as clearly known as in physics.

EI-99 - Eco-Indicator 99, one of the multiple available calculation methods and impact category indicators for Life Cycle Assessment. As it shows the final results as a single score, it is widely used by designers in order to evaluate and compare the environmental impact of artefacts. Three damage models were developed for this indicator, damage to human health, to ecosystem quality, and resources [47]. EI-99(H) is one of the indicators used as part of the validation of the results obtained with the proposed DA-Ex approach.

Energy - the capacity to produce change. As described in the Second Law of Thermodynamics, energy can only be transformed from one form to another, it cannot be created or destroyed. Measured in joules (J).

Exergy - the maximum amount of theoretical useful work that can obtained when a thermodynamic system or flow is brought into equilibrium with a reference environment by means of processes in which the system only interacts with the chosen environment. Noted as Ex with Ex_{Pt} as potential exergy, Ex_{Kn} as kinetic exergy, Ex_{Ph} as physical exergy and Ex_{Ch} chemical exergy. Measured in joules (J).

LCA - Life Cycle Assessment, a widely used assessment tool that assesses the environmental impacts and resources used by a product system throughout its life-cycle. Several software exist for performing LCA studies, they include multiple databases as well the possibility to view results based on impact categories, characterisation methods, etc. that are of interest to the user.

Product - umbrella term referring in this work to "product system", thus covering both products and services rather than just physical products. It is often used interchangeably with "artefact".

Sustainable development - most commonly defined as development meeting the needs of the present without compromising the ability of future generations to meet their own needs [77]. It is commonly referred to as revolving around three main pillars, environmental protection, economic growth, and social equality. Unless otherwise specified, "sustainable" and "sustainability" related to "sustainable development".

1. Introduction

In the grand scheme of things, the history of mankind is nothing more than a blip on the radar of the evolution of the Earth, the Solar System, our Universe. Yet in the short span of its presence, the *Homo sapiens* species has managed to wrestle pristine nature into serving its purpose and has changed the surface of the planet in remarkable ways. The last centuries, in particular, are an extraordinary example of how quickly a single population can influence and shape its surroundings. While we have enjoyed, and still relish, living in a society shaped by the Industrial Revolutions, the coming of the fast transportation methods of the Space Age, the development of worldwide communication networks of the Information Age, etc., the impact of our collective lifestyles on the environment cannot be ignored.

Humans are surrounded by transformed bits of nature, especially in developed and developing countries. These bits of nature have been transformed to fit our needs in the shape of things we can consume. New products and services are introduced to markets every day, often making their six month old predecessors obsolete and further promoting the trend of a throw-away society and the cult of instant gratification and materialism. On the long term, current practices are not sustainable as more and more resources are getting scarce, landfills are filling up, pollution levels are constantly on the rise, and conflicts related to these issues arise. Many people, companies, and governments now consider mitigating the stress caused on the environment, or not causing any in the first place, to be a fundamental preoccupation. On a more global scale, the issue of pursuing life as a sustainable society is also becoming more and more relevant.

Points of view on the urgency of adopting a more environmentally conscious, and overall sustainable, lifestyle for all diverge, but the fact that we will be facing major problems if nothing is done cannot be disputed.

The spectrum goes from James Lovelock's claim that even a sharp rise in sustainable development practices cannot help avoid drastic changes happening to our habitat in a not-too-distant future [29] to Bjørn Lomborg's positive, but widely considered quite controversial, outlook on the current, and future, state of our civilisation as we stand before climate change and other crises [25, 26]. In between these two extremes, one can find motivation for contributing towards a more sustainable society in Lester R. Brown's description of what is ahead of us - a massive challenge that will require a response of "wartime speed" in order to sustain current life levels, but it is not a challenge that we cannot surmount [4, p. xi]. We are not doomed, we just need to work a bit, or rather a lot, for it to stay that way.

1.1 Background

Modern artefacts are the result of design, production, manufacturing, distribution, etc. teams. Design teams shoulder a large responsibility as many studies indicate that as much as 80 to 90 % of a project's life-cycle economic and ecological costs are committed during the early phases of development [63, p. 1]. In order to facilitate and make engineering design activities more efficient, design has become in recent decades the subject of scientific research and this has yielded the point of view that these activities are part of an *engineering design process* (e.g. [45], [34]). Even though multiple models of the process exist, it is generally considered to consist of three phases - conceptual, embodiment, and detailed design.

The conceptual and embodiment phases largely shape the final outcome of the design process and the decisions made during these phases are the ones that lock-in most of the final costs. Changes to the architecture and design of an artefact that are made later on, especially when the production launches, are not easy to make, they also cannot make up for a bad initial design, and they highly increase a project's costs. Nevertheless, in practice many design projects still rely on these late changes [49].

Many tools, methods, and approaches exist to support the work of the design team during the early stages of the design process with such activities as idea generation (e.g. brainstorming, TRIZ), design formalisation (e.g. 2D or 3D modelling), and design choices (e.g. Analytical Hierarchy Process). The evolution of the design process and its increased complexity make it so that these tools are, in many cases, difficult to get acquainted with or apply. Moreover, the design process is becoming more multi-disciplinary than ever with new constraints imposed due to emerging legislation and companies focusing on points such as issues linked to safety and environmental impact while still requiring high levels of innovation.

The current state of tools and methods for making more environmentally conscious design decisions is limited and should be developed. The early design phases are mainly supported by Design for Environment (DfE) guidelines and prior experience inside the design team; these do not provide quantitative metrics that can be used to positively modify designs, especially when considering radically innovative solutions. Tools such as Life Cycle Assessment (LCA) cannot be easily applied to designs that are not finalised, while Simplified LCA studies often require large databases or extensive knowledge on the subject of environmental issues that are necessarily accessible to all engineering designers. The current work focuses on these issues linked to making decisions geared towards environmentally conscious choices during the early stages of the design process.

Although the issue of sustainability and sustainable development is not a key focus of this thesis, the subject has played a part in the motivation for the research work. It is a relatively new field of research that has yet to finds its final place in the scientific world [22], the related research and literature are quickly developing and expanding and this makes it an exciting prospect for future work and the expansion of the current thesis. There are strong ties between environmental issues, and mitigation of environmental impacts, and the engineering design community; as such, approaches favouring more environmentally conscious designs provide a stepping stone for further positive developments from engineering designers encompassing all the different principles of sustainable development.

1.2 Research problem

Engineering design teams do not easily have access to quantitative data on the environmental impact of their project during the early stages of the design process. There is a need for quantitative metrics that can be calculated based on the available data on the artefact being developed and relying on a limited and open database.

1.3 Aim of the work

The present work aims to create a useful and lightweight approach that can be used by engineering designers during the early stages of the design process, the conceptual design and early embodiment design phases, to generate quantitative metrics describing the environmental impact of an artefact in development.

1.4 Methodology

The present work was developed from a study of existing problems that engineering designers face when having to produce environmentally oriented artefacts. This was performed based on a state of the art study of existing widely used tools, methods, and approaches promoting reduced environmental impact or its mitigation and how they can be applied during the early stages of the design process.

The method proposed of environmental impact assessment metrics based on exergy and dimensional analysis results from the fact that these two bases can alleviate the shortfalls of existing methods (e.g. lack of quantitative data, heavy-weight or closed-source databases, extreme aggregation that does not allow the user to understand the results). The explicit reasons of the choice of the two bases can be found in Chapter 3.

The validation of the proposed approach is done through a comparison of the results obtained with those from similar studies performed with existing LCA software and two widely used indicators. The comparison is done on the overall results and not number to number as the indicators do not provide the same metrics as those from the proposed method. A further description of the indicators used to perform the comparative tests can be found in Section 3.4.1.

1.5 Scope of the research

This thesis touches on multiple subjects from environmental sciences to decisions making to the engineering design process and thus cannot cover in depth all these fields. The current work limits itself mainly environmental impact assessment and the early stages of the design process - the conceptual and embodiment phases. This scope is expanded when the proposed approach is applied to fields outside environmental impact assessment but still remains in the realm of sustainable development.

1.6 Contribution of the author

The contribution of the author on each article presented in this compilation can be found on p. 9 - 12. Overall, this thesis expands and tests an approach first proposed by Coatanéa [10] for environmental impact assessment metrics for the early stages of development metrics based on exergy.

1.7 Structure of the thesis

The structure of this thesis follows the development considered in the introduction - first the motivation and positioning of the research problem is presented, then the theoretical background of the proposed approach is exposed and finally case studies performed to validate the approach are presented before a concluding discussion and an enunciation of possible expansion of the work.

Chapter 2 covers in a first part (Section 2.1) the engineering design process, its evolution towards the structure it is often assigned today, its increasing complexity and the ties it holds with environmental considerations. Section 2.2 focuses on the state of the art of environmental impact mitigation and assessment methods, tools and approaches with special attention paid to those that can be applied during the early design phases. Through this study of the state of the art surrounding the engineering design process and environmental tools, the research problem is positioned.

The proposed method, dubbed DA-Ex, and its theoretical bases are the focus of Chapter 3. Section 3.1 highlights the aim of DA-Ex as well as the appropriateness of the chosen tools of exergy and dimensional analysis. These two bases are elaborated on in Sections 3.2 and 3.3, respectively. Section 3.4 presents the full DA-Ex approach as well as the validation method for the results obtained. This section covers the approach described in Publication I, for the metrics proposed concerning environmental impact assessment, and in Publication II, for the expansion of the approach to cost considerations.

Chapter 4 summarises the case studies performed to validate the developed DA-Ex approach in Publications I - V. Section 4.1 details the different parts that were studied using the DA-Ex approach and the hypotheses surrounding these studies. The results of the studies and their comparison with results obtained from studies performed using widely accepted LCA indicators can be found in Section 4.1. A discussion of the results follows in Section 4.2.

Chapter 5 concludes the thesis with final remarks on the DA-Ex approach and the results obtained. Shortcomings of existing environmental impact mitigation and environmental impact assessment methods and tools are further highlighted with the inclusion of Publications VI and VII. Indeed, an evolution towards dynamic environmental assessment methods is essential in order to provide more performant designs. The final part of this chapter presents the possibility of expanding the work on environmentally conscious design through a system approach, thus making it a dynamic tool.

2. Evolution of artefact design and the design process

For the most part, our surroundings are artificial. Besides small patches of grass and trees and glimpses of the sky, nature has been wrangled to fit our needs, from the computer used to type this sentence to the tea that is cooling to my right. Before these objects came to our vicinity, someone had worked on making them happen, their transformation from a piece of nature to their final state was artificially designed and completed. As such, it is obvious that being responsible for the design of anything yields an immense power, and engineering designers can have a tremendous influence on the world we live in.

Prior to the development of fast and reliable transportation of goods, the design of a product largely depended on what was available to the manufacturer and his or her set of skills. Users had to make do with the provided design or enhance and personalise it to fit their needs. Over time it became possible to acquire goods from far away manufacturers, thus increasing competition, creating large markets of supply and demand, and the needs of users started being more and more taken into account. With this evolution, the way that things are designed has gone through multiple changes [35]. Furthermore, technological advances have opened new possibilities, from the introduction of mass-produced goods after the Second Industrial Revolution, necessitating one-fits-all designs, to the rise of designs embracing plastics and the needs of a throw-away society. Multiple works have been produced on current trends, their origins, and the problems that they generate; among others McDonough and Braungart provide a good coverage [33, Chapter 1]. Although technology and manufacturers' abilities still have a large influence on the tasks of an engineering design team, new constraints are being introduced into the design process [35].

In this work, the *design of a product* is considered to be its engineering design rather than solely artistic design; it is also considered to be a process completed by a designer or design team as further expanded upon below. Engineering design activities are extremely complex and broad, the aim of this chapter is not to cover the entirety of the issue but rather to situate the two main areas of interest of the doctoral work, the early design stages and environmental considerations and their impacts on the design of artefacts.

2.1 The design process

The notion of engineering design being a process, and thus that it can be modelled, was born in large part due to the need for more efficiency in design activities. A good understanding of the design process and a suitable model of its different phases help simplify the task of finding the optimal solution to a problem, and this is crucial in a world where products, markets, and engineering design became more and more complex. Multiple models of this process have been developed and described in literature; most have evolved over time in a way that one may argue that they hold the same base structure with only "cosmetic variations" [39].

Models of the engineering design process divide its activities into three major phases, described in iconic works in the field (e.g. [45], [20]) as *conceptual* design, *embodiment* design, and *detailed* design. Depending on the definition of *design*, R&D, planning, etc. phases can be included. Visual representations are often used to illustrate the successive and iterative steps in the process, from V-shaped to more linear approaches [45] (see Fig. 2.1). The latter is the main basis for the representations used in this work.

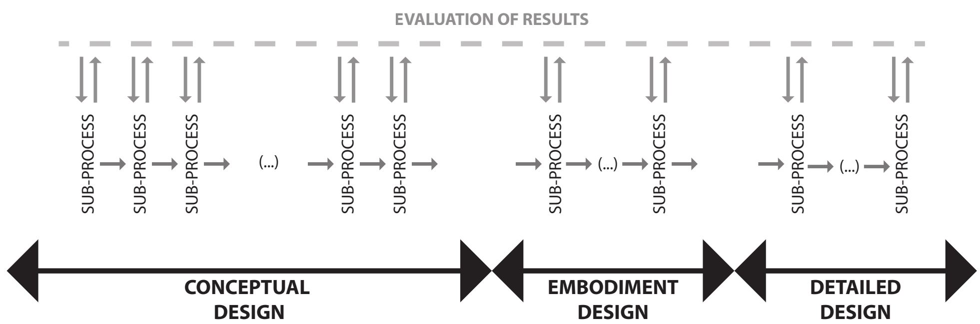

Figure 2.1. Three main phases creating the backbone of the design process.

The *conceptual design* stage begins with the specification of the design problem and the establishment of design requirements. Architectures for concepts of solutions are generated; the ideas and concepts at this stage are both of a technical and non-technical nature. Engineering designers will often focus on choosing relevant technological solutions that can be used. Several tools and approaches have been developed to help the design team during this stage, for example for generating ideas (brainstorming, mind mapping, etc.), formalising solutions (mock-ups, sketches, etc.). This is followed by the *embodiment design* stage where the design of the concept is further developed into being a real product with dimensioning, selection of materials, etc. This is done with the help of Design for X guidelines, 2D sketches, CAD models, schematics, mock-ups, and so forth. Prototypes are especially useful during this stage to test configurations, technical principles, and ergonomics. The third phase, *detailed design*, includes the establishment of the final optimisation and drawings of the solution, as well as the checking that the solution fits all relevant standards. Once all elements are finalised, the manufacturing of the product can begin, but at least part of the design team needs to remain on stand-by as liaison with the production team.

The engineering design process plays an essential part in the development of the artefacts that we use every single day. This process, although having been the highlight of recent research, is still difficult to fully grasp due to its complexity and the ties it has with surrounding fields such as innovation. Innovative artefacts are sought out, creative ideas and concepts are talked about, but their link and influence on the design process is not easy to understand, especially during the early stages.

Design and innovation

A company's competitiveness is linked to its ability to innovate and propose artefacts that fit customers' evolving needs. Although *innovation* is often referred to, the notion itself is not easily definable. Commonly innovation is described as a novelty that is widely embraced; for example in the case of products, they should be produced on a relatively considerable scale. Beyond producing new or significantly improved artefacts, companies can also introduce innovations in marketing methods or on an organisational level [71]. *Creativity* is also often linked to novelty and there is a certain confusion and ambiguity in the definitions of of the two notions in related works, examples can be found in [34]. Long seen as merely depending on divine inspiration [64], research on creativity began to grow in the 1950s. Since the 1920s, the idea of a creative process has been largely developed and multiple models, with more or less loosely organised stages or sub-processes, of this process exist (e.g. Wallas and Smith's four stage model, Guilford's convergent and divergent thinking model).

Both the innovation process and creativity present interconnections with the design process and these are of interest to the current work. As developed above, the design process is a complex multi-disciplinary and multi-stage process. One of its essential properties is its creative nature that has been widely pointed out in related works [34], although it had been forgotten for some time in Western design tradition. More specifically, the notion of *ingenium* describes a creative rationality that is key in the design process. Moreover, the design process plays a central role in the innovation process as developed by [23]; for example, companies that rely on a design process are not only more likely to produce new products but also radically innovative ones [70].

Figure 2.2 (a) depicts creativity as a fundamental component of the design process, which is itself an essential part of the innovation process. This point of view was developed in [34] as opposed to the model proposed in [65] (Fig. 2.2 (b)) marking design as a way of expanding available ideas and increasing the chances of successfully commercialising them.

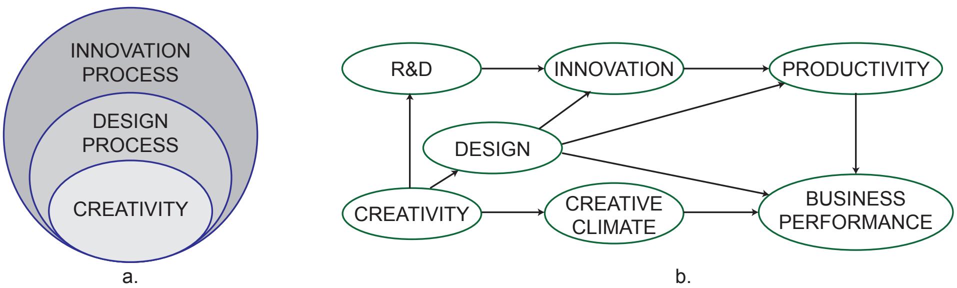

Figure 2.2. Two types of models of the links between creativity, the design process, and the innovation process. a. presents the model proposed in [34]. b. presents the model proposed by [65].

Considering Figure 2.2 (a), the creative and innovative aspects of the design process cannot be ignored. The results of this process present a great probability of utilising new approaches and solutions, thus the methods and tools promoting must be adapted. As further developed in Section 2.2, the current methods and tools cannot be easily applied to radically innovative artefacts. Their accuracy highly relies on previous knowledge gathered from previous generations of an artefact, which do not exist for a radically innovative one.

Decision making in the design process

The decisions made during the very early phases of design are highly responsible for the final cost of a product [63]. The task of making the best decision possible, during those early phases, is all the more daunting that the information available is scarce and contains a certain degree of uncertainty (PVI). This is especially true when the artefact being developed presents novelties that were not found in previous generations or there were no previous generations at all. Moreover, design often involves multiple disciplines and multi-disciplinary teams that need to communicate while taking into account a number of constraints - a product or service should be structurally sound, monetarily viable, follow sustainability guidelines, respond to a real need, etc. The importance of these first decisions and the need for support for designers, faced with the complexity of the design process, in these decisions is often talked about but concrete solutions rarely surface.

As exposed above, the design process aims at facilitating the task of finding the optimal solution to a design problem. When the design process progresses, a product's design is more and more set, tying down many costs, monetary and otherwise, that will follow in later stages such as manufacturing and distribution. Moreover, while in theory the design of a product should be finalised and polished in the detailed design phase at the latest, in reality many changes are still made later on [49] (see blue dashed line on Fig. 2.3). These changes could be avoided with judicious decisions in the early design phases where the cost of a design change is limited.

Although Figure 2.3 focuses on monetary costs, the timing of a decision also involves others costs, for example on the environmental front, among others. Figure 2.4 concentrates on the opportunities of environmental impact minimisation and the linked costs during the different stages of the development and manufacturing of a product. The best decisions minimising environmental impact can be found during the phases of Research & Development and conceptual design, and to some extent during what Yang [78] considers the "engineering design" phase, representing the later

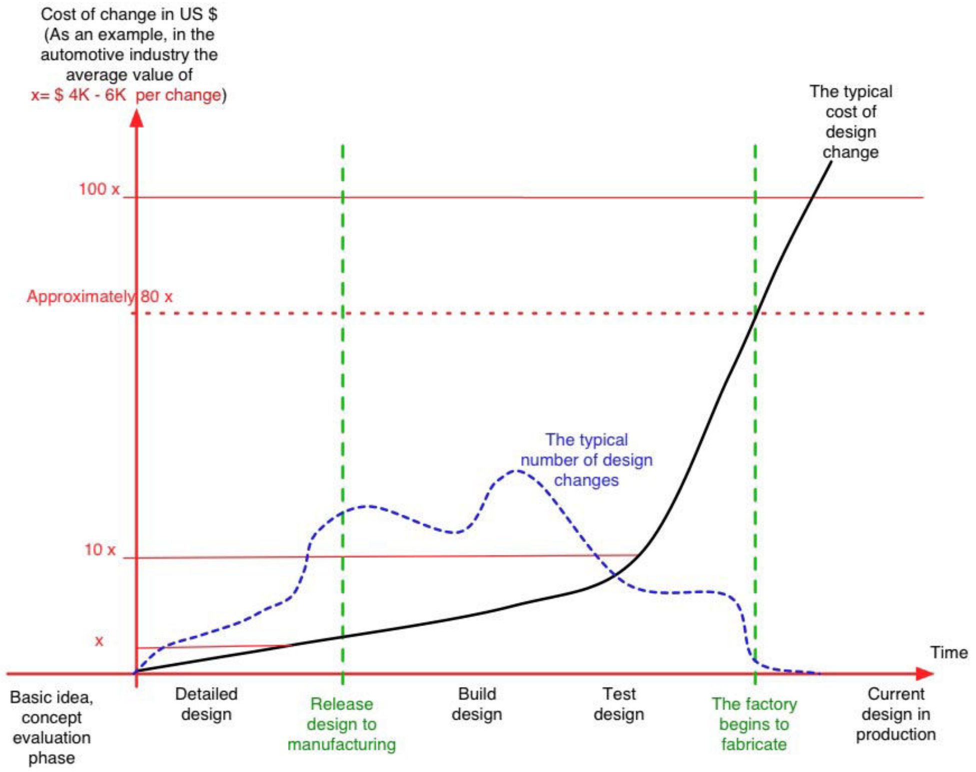

Figure 2.3. Cost of changes depending on the time they're made and typical timeline of changes made during the development of a product [49].

part of the embodiment design and detailed design phases in the model used in this thesis. Indeed, during these phases, the monetary cost of any decision shifting the design towards a more environmentally conscious product is low while the number of opportunities is high. When production starts, with plant construction, modification of existing plants, etc., very little can be done to change the environmental impact and every single decision to make a change will have a large monetary cost.

While the importance of making well informed and suitable decisions early in the design process is undeniable, it is not an easy task. In fact, for every problem on which a decision must be made, there is a multitude of alternative solutions and many things can influence the final outcome. A design team's knowledge, experience, company policies, governmental policies, raw material availability and price, etc. play a significant role in what the final decision will be. While an experienced designer might propose a suitable design having considered very few alternatives, the task gets more complicated as the number of variables increases. Without appropriate support tools, innovative ideas might get overlooked because of a lack of resources to model and study certain alternatives and thus make informed decisions. Ng [41] presents a thorough literature review

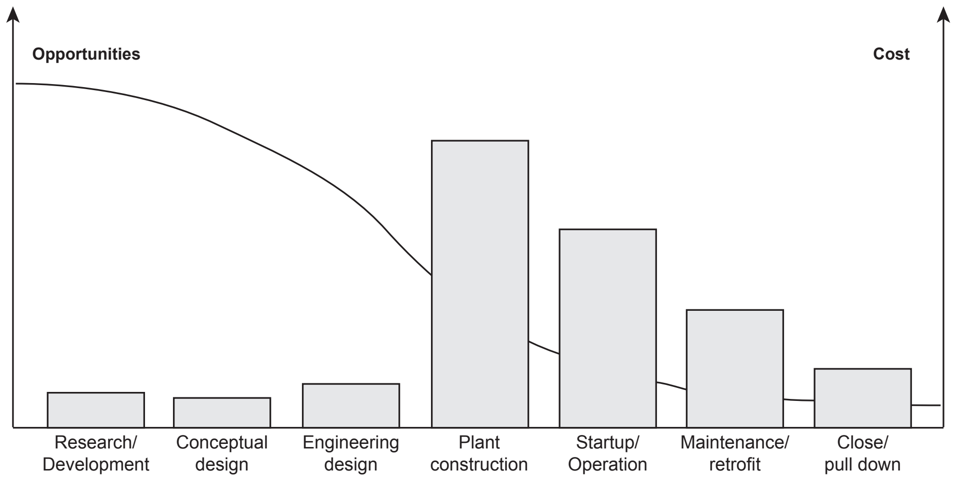

Figure 2.4. Opportunities of environmental impact minimisation along product design and manufacturing cycle (based on [78])

of design methodologies and decision making with the different decision making aid tools available as well a proposal for the key points that a performant decision making aid tool should have.

Rather than integrating aspects leading to making better environmental decisions into a specific existing decision making aid tool, this thesis considers decision making in general and how an approach can influence decision making to promote more environmentally conscious designs. In order to understand the mechanics and rationale, or lack thereof, behind the decisions we make, decision making can be depicted as a mental process [9]. Figure 2.5 is a model of the process involved clarifying and simplifying decision making (PIII). Such an approach can help the design team assess decisions with objectivity. As with all tools and approaches necessitating human input, there is a level of subjectivity which can only be minimised. Human input is necessary for the determination of the appropriate metrics and modelling of the alternatives, for example.

Viewing decision making as a process also helps situate design aid tools and how they can help make better informed decisions. When evaluating design concepts, support tools step in during the third stage, decomposing and modelling of the generated solutions. For example, Publication VI proposes an approach to support designers when modelling solution alternatives; as the approach described in Chapter 3, it is an evolution of the approach partially developed by Coatanéa [10]. The modelling is based on generic organs and the generic laws applicable to them, as well as the Vaschy-Buckingham theorem and dimensional analysis, both pre-

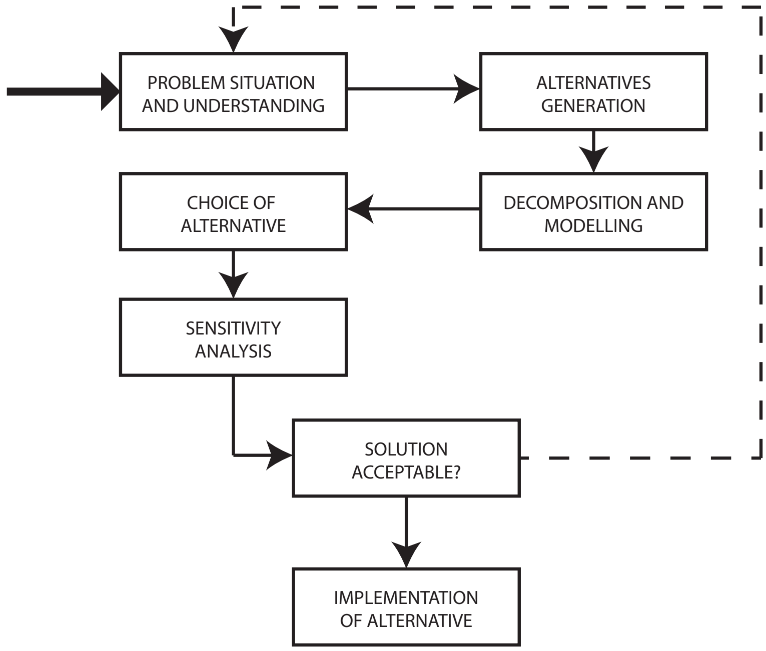

Figure 2.5. Decision analysis approach (adapted from [9]).

sented in Part 3.3. Such an approach allows the design team to consider and model solution alternatives for which specific behavioural laws are unknown.

Nevertheless, the work presented in PVI does not consider environmental impacts and mitigation, which are an increasingly important area of focus of requirements in artefacts. As with other design support approaches, environmental impact assessment metrics should be deployed during the third stage of the decision making decomposition shown in Figure 2.5. In the context of more and more complex and regulated products, being able to provide pertinent decisions rapidly is a great advantage for a design, but which resources one can use today in order to promote making the *right* decisions when it comes to environmental issues?

2.2 Environmental mitigation and assessment during the design process

The increased awareness of the fragility of our habitat and of the massive impact that humans have and can have on it have pushed towards more environmentally conscious products, both through legislations and market demand. Environmentally conscious design practices, often falling under the umbrella of Design for Environment (DfE) practices, are being developed to respond to an urgent need to shift closer to a more sustainable society and not concentrate solely on traditional requirements based on costs and customer needs. Environmental sustainability is one of the three commonly named pillars of sustainable development, along with economic and social developments [77]. It is a popular and often cited priority from single customers to companies and governments; this can be easily seen with the rise in products that claim to be "green" or "eco" available on the markets.

Overall, environmentally conscious practices are still a new development in engineering design and there are few specific worldwide guidelines and regulations, much as for global practices related to sustainability [22]. Policies are emerging at all levels but they are limited to imposing quotas for not using up resources or poisoning the environment too quickly [33, p. 18]. It is, indeed, difficult to promote positive development on a large scale and, as with all new developments, they are not always welcome as they can put strain on existing strong bastions. Legislations often face lobbying from different industries [72] that prefer, for the time being, to concentrate more on profit generation rather than environmental aspects, although at time both aspects are not necessarily contradictory [62]. Nevertheless, attempts must be made to push more environmentally oriented designs to the forefront and make them a priority in all design teams.

Clear efforts have been made to provide guidance, if not actual legislations, on a more holistic level through standards and certifications, for example. The ISO 14000 family of measures is one of the most known environmentally geared certifications for businesses and is awarded to organisations that minimise the harmful effects on the environment of their activities and achieve continual improvement of their environmental performances [44]. By the end of 2009, over 220,000 organisations were certified ISO 14001:2004 in 159 countries [43]. Unlike previous attempts at environmental regulations, the ISO 14000 standard does not provide set targets for environmental performances levels beyond the compliance with local environmental regulations, this makes the standard applicable to a wide array of organisations in many industries. Continued improvement of environmental performances is key in the certification and can be seen as one of the most important aspects; this puts into place practices in the organisations that tend to promote an environmentally conscious production. Customers can also contribute by seeking out products that have been deemed as respecting the environment more than most of their counterparts, "green" labels and certifications are making the task easier although one must be wary of "green-washing", i.e. deceptive and with little claims at being environmentally conscious, practices [73].

Environmental impact assessment and environmentally oriented design literatures provide many tools, methods, and approaches that should promote more environmentally conscious designs, yet a very limited number of those are used in real life applications [8]. Two major approaches stand out - tools based on Life Cycle Assessment and Design for Environment practices. Life Cycle Assessment (LCA) studies are widely accepted as good sources of information on a product's environmental impact over its lifetime. The Design for Environment (DfE) approach is a set of tools, methods, principles, and guidelines that are also widely spread in engineering design. DfE is aimed at the early stages of design and therefore quite different from classic LCA methods. LCA studies are best performed during the final stages of design or on existing products as detailed artefact descriptions and information are required and these may not be available during the crucial early stages. Simplified (or Streamlined) LCA studies can be performed in order to screen what the main environmental impacts might be based on simplifying hypotheses the design team is willing to make. Both SLCAs and DfE guidelines embody lessons learnt from previous LCA studies; previous design projects also provide the best support possible to the design team to make informed simplifying hypotheses. Figure 2.6 depicts the stages of the design process that are covered by the approaches.

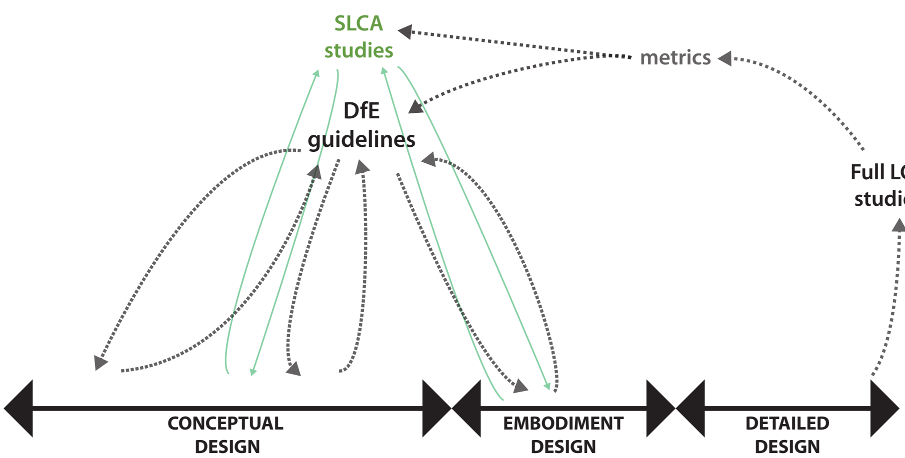

Figure 2.6. DfE guidelines and LCA studies linked to design process phases.

Design for Environment practices

A large quantity of literature has been written covering DfE practices for specific life cycle stages and product families. They often form stacks of guidelines that should be followed if they can be applied to the design being developed, making the compilation and understanding of all the principles difficult for any designer. Moreover, the principles are often contradictory and do not necessarily lead to the most environmentally sound system [48, 68]. The exploration of previous designs and their environmental impacts, through such approaches as LCA, provide the bases for more accurate DfE design guidelines for specific industries and product families. Thus if a previous generation of an artefact exists and the new generation does not present large innovations, DfE guidelines can provide a good foundation for environmentally oriented decisions. If a new artefact is radically innovative, e.g. is based on a completely new design, for example with previously unused materials or techniques, the guidelines can fall short of their goals and they need to be backed-up by approaches based on specific studies of the impacts of the introduced components.

Some methods falling under the DfE umbrella include Design for Recycling, Design for Remanufacturing, etc. As their title indicates they provide guidelines for specific stages of an artefact's life cycle. Many companies have long been putting together lists of company-wide practices to promote more environmentally conscious designs internally [36], these can also be considered DfE guidelines (e.g. HP's *Design for Environment* company-wide guidelines include "Reducing the number and types of materials used, and standardizing on the types of plastic resins used" [19]).

An example of generic lists of guidelines that might be used during the early phases of design can be found in [69]. They include such propositions as "Ensure sustainability of resources by: Specifying renewable and abundant resources; Specifying recyclable, or recycled materials, especially those within the company or for which a market exists or needs to be stimulated; (...)", among others. Applying such guidelines during the idea generation process and when producing the very beginnings of a product's architecture provides essential steps towards more environmentally conscious designs.

Life Cycle Assessment based tools and methods

As the development of an artefact advances, it is important to be able to reliably detail and quantify the progress and the choices being made. Design guidelines do not provide explicit ways of obtaining such types of information, showing the limits of DfE guidelines in the field environmentally oriented design. Although environmental metrics and indicators do exist, there is, yet, no consensus on what the common metrics and indicators for engineering design should be, making comparisons of results among design and research teams difficult [56]. Nevertheless, methods based on LCA are widely used in industry and a large number of case studies in scientific literature, despite some shortfalls. Besides LCA-based methods, multiple other approaches exist. They include Environmental Management System (EMS), Factor X, Ecological Footprint, Environmental Risk Assessment (ERA), etc., but as they are less common, they are not described here but related literature can be easily found (e.g. [40]).

The LCA framework has been widely adopted, since the mid-1990s, as an environmental assessment tool. Although there are multiple established issues with the approach [51], it remains a useful tool for analysing the environmental impacts of an artefact during the different stages of its life cycle. Commercial software helping with LCA studies include SimaPro, GaBi, etc. and there are multiple tools and approaches that have been developed by research groups that focus on specific areas of application, e.g. Impact Estimator from the Athena Sustainable Materials Institute [21]. Case studies are published on a regular basis in such publications as the *International Journal of Life Cycle Assessment*.

LCA studies are defined by the ISO 14040 series to consider the potential environmental impacts and resource uses throughout the life of an artefact, from raw material acquisition to waste management [42]. These studies are characterised by four phases:

1. *Goal and scope definition* - boundaries of the system, functional units, choice of methods used in later phases,
2. *Life cycle inventory analysis* - as defined by ISO 14041 and 14044, the material and energy flows into, through and from the system,
3. *Life cycle impact assessment* - raw inventory data is converted into environmental impact estimates, based on ISO 14042 and 14044,
4. *Life cycle interpretation* - the LCA practitioner draws conclusions from

the LCA study and may formulate recommendations based on the results.

A full LCA study is a retrospective tool as it requires a fully specified design, thus it cannot be used effectively during the design process itself, thus making it largely irrelevant during the development of innovative products. Each study is highly dependent on the establishment of the inventory data and on the database that provides information for life cycle impact assessment on each material and process involved. Databases have been developed as part of national or regional projects (e.g. Swiss ecoinvent database) or are released by important industries (e.g. plastics database released by APME). Most LCA software provide several databases for users but they are data heavy, very limited geography-wise, often proprietary, and cannot be easily used outside the context of the software. The final results are obtained after characterisation and normalisation, and possibly weighting. Overall, a full LCA study necessitates a large amount of resources (time, money, humans, etc.) to obtain correct results.

During the early phases of the design process, Streamlined LCA (SLCA) approaches are preferred. As the establishment of the inventory data is the most time consuming part, it is generally targeted with simplifying hypotheses. There are no specific recommended methods for simplifying studies, most SLCA applications rely on previous LCA studies in the field and new research findings in those that are not covered by extensive LCA studies [52]. Nevertheless, these assessments still rely on the same databases as full LCA studies and thus present the same problems.

Generally speaking the main shortfalls of current LCA-based methods are found in their databases, which do not always provide appropriate and consistent data and cannot be used outside the context of specific software; the use of heavily normalised and weighted indicators, instead of easily comprehensible metrics; and the limited specific categories of impacts that cannot be expanded to cover the multi-disciplinary aspect of sustainability.

The wide acceptance of LCA-based methods and software in industry and scientific publications cannot be ignored; for this reason this work uses the LCA software SimaPro and two popular indicators to assess the quality of the results obtained from the approach developed, described in the next chapter. SimaPro has users all over the world and provides multiple databases and indicators [59]. The two indicators considered for comparison are Eco-Indicator 99(H) (EI 99(H)) and Cumulative Exergy Demand (CExD).

EI-99(H) is damage-oriented, with its results expressing damage to human health, ecosystem quality, and resources. It has been developed to limit the number of impact categories in order to simplify the understanding of the results. The Hierchist (H) perspective was chosen as it presents, what the author believes to be, a neutral approach to the future; it considers the effects of major substances on the long-term and the possibility of damage being avoided by good management [46]. More information on the ecoinvent database, which is used for the data, can be found in [13].

CExD calculates the total exergy removed from nature to provide a product [3]. A further explanation of exergy follows in Section 3.2 as it is also used in the approach proposed in this work. CExD provides the exergetic value of the elements present in the ecoinvent database. The final result is presented as removed exergy through fossil fuel, nuclear power, hydropower, biomass, other renewables, water, minerals, and metals. The method does not include normalisation and all impact categories hold a weight of 1 [46].

3. DA-Ex approach for environmental impact assessment and expansion

The development of an approach to provide metrics facilitating environmentally oriented decisions during the early phases of the design process was mainly motivated by the existing shortfalls of tools and methods for environmental impact assessment and mitigation. As presented in Section 2.1, the design process is growing more complex due to increased constraints and the sheer complexity of products to develop. The decisions that lock-in most of the costs of a product are made before the design is finalised and therefore methods such full LCA studies cannot provide reliable results and are too costly. Other widely spread methods also yield unsatisfactory results, especially in the case of radically innovative products (see Section 2.2).

Although the works I - V present the proposed approach based on exergy and dimensional analysis, none go in depth into the two tools but rather concentrate on the approach itself and obtained results. Thus the following sections dwell on the reasons behind the choice of the two tools and their backgrounds. The approach is detailed in Section 3.4 followed by results of the application of the approach in Chapter 4.

Publications VI and VII are extensions of the proposed approach. Each work tackles issues that were not considered in the core aim of this doctoral work; they are, nevertheless, vital to the research developed and are presented in more detail in Chapter 5.

3.1 Aim of the approach and choice of base tools

The main aim of the developed approach was to attempt to alleviate the shortfalls of existing methods. Namely the approach should:

- provide results of comparable, or better, quality as compared to those obtained with existing methods and tools,

- use readily available data,
- rely on a relatively small database,
- be applicable during the early stages of the design process when not all attributes of a product are known,
- offer ways of expanding the approach to aspects related to sustainability beyond environmental assessment.

In his PhD work, Coatanéa [10] proposed that dimensional analysis can be used as a way of assessing design solutions without introducing weighing factors that can contribute to subjectiveness. A short mention was made of the possibility of using dimensional analysis for environmental impact assessment with the addition of entropy [10, p. 171]. The current work is partially a continuation of that research.

The two tools used for the approach can be found in the way it was dubbed - *DA-Ex* - Dimensional Analysis and Exergy. The choice of exergy as one of the pillars follows the fact that it is an efficient thermodynamic metric and already has multiple applications in environmental impact assessment in certain fields. Exergetic data is readily available for most materials and processes, the majority being in scientific publications or in industry studies. As only exergetic data is needed, the linked database is lightweight. Dimensional analysis is a powerful tool that allows two concepts to be efficiently compared as it gives access to easy scaling of the results and allows the use of orders of magnitude rather than precise data, thus making it applicable during the early stages of the design process.

3.2 Exergy

Access to energy and raw materials are key elements in modern society as they are major players in the development of nations and industries. The study of energy alone is not representative of real world processes and systems as energy cannot be created nor destroyed, following the First Law of Thermodynamics. It has been widely suggested that focusing on *exergy* rather than *energy* is more representative.

3.2.1 Historical aspects of exergy

The concept of exergy can be traced back to Gibbs' concept of "available energy" and "available work" [17], noted as *the available energy of the body and medium* in a reference environment - *medium at constant temperature and pressure*. In the following years and decades, "available work" was further developed, including the necessity for a well defined reference state, and the possible use of exergy studies for increased efficiency in then-inefficient systems was understood. A comprehensive look at the history of the concept of exergy during its early development and its different applications through time can be found in Sciubba and Wall's work [55], which is an excellent addition to classic textbook presentations of exergy, often limited to the thermodynamic aspects.

The wide spread of exergy in the education of future graduates in the 1960s and the need to increase the efficiency of systems and processes following the oil crisis of 1973 have lead to what Sciubba and Wall refer to as an "extraordinary development and expansion of the exergy theory in the 1970s" [55]. This view and development of exergy has had an undeniable effect on the areas explored in terms of applications and the modern view of exergy. Energy conservation and exergy birthed new processes and changes in existing ones, promoting more efficient systems. Exergy is also a large contributor a new generation of process and system design tool for energy demanding applications such as power plants. A large number of studies and publications also focused on the definition and calculation of reference environments for different applications, thus making the use of exergy all the more pertinent and more accurate. Exergy is also used in multiple applications outside the realm of efficiency increase such as environmental impact, thermoeconomics, etc.

Although the idea and theories behind the notion of exergy were made clear starting with Gibbs' work, there was little consensus on the name to be used, several co-habited in publications such as "available energy", "availability", "available work", etc. The spread of the term “exergy” comes from the work of Rant [50] who took a linguist's approach to the problem. As “energy” literally means “internal work” from the Greek *en* - $\varepsilon\nu$ - and *ergon* -$\varepsilon\rho\gamma o\nu$ -, “exergy” with the prefix *ex* - $\varepsilon\xi$- should be used to refer to “external work”. Although the different terms and expressions describing the same concept of exergy were still widely used after Rant's proposal and its acceptance by peers, the practice has died out. There is yet to be a consensus of the notation to be used when addressing exergy.

3.2.2 Modern view and uses of exergy

Exergy is defined as the maximum amount of theoretical useful work that can obtained when a thermodynamic system or flow is brought into equilibrium with a reference environment by means of processes in which the system only interacts with the chosen environment. In other words, exergy is a measure of the potential of the system to cause change as a result of the system not being in stable equilibrium relative to the reference environment.

Exergy is expressed in joules (J) - kg·m^2·s^{-2}. Real systems are characterised by the irreversibilities they present, often named energy losses - an incorrect term as energy cannot be destroyed.

The exergy of a system is commonly split into four contributions: potential exergy (Ex_{Pt}) due to its position, kinetic exergy (Ex_{Kn}) due to its velocity, physical exergy (Ex_{Ph}) due to its pressure (P) and temperature (T) and chemical exergy (Ex_{Ch}) due to its composition, all considered with respect to a reference environment (Eq. 3.1).

$$Ex_{system} = Ex_{Pt} + Ex_{Kn} + Ex_{Ph} + Ex_{Ch} \tag{3.1}$$

The reference environment is defined to be free of irreversibilities, have zero exergy and not be affected by the different impacts thrown at it from the studied systems. Overall it is considered to be in an eternal equilibrium state. It is, of course, not the case of the real world as perfect equilibrium is never reached and there are parts, such as fauna, which are not taken into account in the model. Furthermore the environment changes through time so the model needs to be updated regularly. In some cases, the change can be rather radical, for example the levels of CO_2 have greatly evolved since the pre-industrial era, so studies must indicate what levels they use [11]. Overall, exergy studies greatly depend on the choice of the reference environment, this dependence also means that an exergy study can be tailored exactly to reflect a certain context making it an obvious choice for such applications as the study of thermal power plants. Potential and kinetic exergy are equivalent to potential and kinetic energy. For real world projects, physical and chemical exergies present most interest as they can be used to define accurate efficiencies and improve overall costs.

Further descriptions of the calculation of exergy of processes can be found in I and, among others, [66].

3.2.3 Exergy and environmental assessment

Multiple links can be made between exergy and environmental impact, first and foremost the fact that exergy is a powerful tool to improve the efficiency of processes and systems. A direct consequence of an improved efficiency, especially when it concerns an energy intensive process, is a reduction in the use of raw resources and consequently, in the end, fewer polluting and disrupting emissions and wastes. Throughout history there have been multiple takes on exergy efficiency with three basic forms being based a direct input/output approach (Eq. 3.2), the degree of reversibility (Eq. 3.3) and efficiency based on exergy destruction (Eq. 3.4) [55].

$$\eta_1 = \frac{usefulexergyoutputs}{usefulexergyinputs} \tag{3.2}$$

$$\eta_2 = \frac{exergyoffinalwantedproducts}{exergyinputs} \tag{3.3}$$

$$\eta_3 = \frac{exergylost}{exergyinputs} \tag{3.4}$$

Overall exergy efficiency greatly depends on the studied system and the important aspects which should be monitored. For example, depending on the application, Sorin *et al.*'s approach [60] of calculating exergy efficiency while considering transiting exergy is more representative than Al-Ghandoor *et al.*'s [1] global inputs/outputs approach.

Exergy effiency to promote energetic efficiency of systems is not the only facet of exergy to be exploited for environmental considerations. Starting in the 1970s, multiple ideas for environmental applications blossomed such as "ecological costs" based on exergy and the need to incorporate exergy into resource accounting [76, 66].

All exergy studies are done with a reference environment, which is often considered to be the atmosphere, hydrosphere and lithosphere in general but can be specific to a single location. Emission streams or flows contain, in most cases, exergy as they are in disequilibrium with the environment. Therefore a study of exergy can be viewed as a good basis for environmental evaluation as it can be considered that measuring exergy is equivalent to measuring the potential of the artefact to bring a disturbance to the equilibrium of the environment. As several types of exergy can be calculated, it is important to consider which type is most representative of environmental impacts - the simple approach of assimilating an exergetic emission into the environment to environmental pollution has been shown to be simply a starting point [32, 57]. Exergy of mixing, described in detail below, has been championed as a meaningful representative of environmental impact of material waste emissions [57, 56].

Other views and links between exergy and environmental impact can be made, such as the idea that the destruction of exergy due to irreversibilities can be related to the chaos creation and therefore to the destruction of the pristine natural organisation of the environment [53].

Exergy of mixing.

Exergy of mixing, also named the "composition-dependent component" [66], is computed as shown in Eq. 3.5, for the ith chemical component of a system:

$$Ex_i^m = n_i R T_0 ln\left(\frac{y_i}{y_i^0}\right) \tag{3.5}$$

where Ex_i^m is the exergy of mixing in joules, n_i the total number of moles of the species, y_i the activity of the system in consideration, y_i^0 the reference activity in the appropriate environmental sink, often considered to be the sea, earth crust or atmosphere. *R* is the universal gas constant, here considered to be 8.314 J/mol/K, and T_0 is the standard temperature, considered to be 298.15 K.

Such a definition considers that the chemical components emitted and existing in large quantities in the reference environment have the least potential for harm, at least when they are emitted in reasonable quantities which is not always the case of certain anthropogenic releases (e.g. CO_2). The definition also implies that the exergy of mixing of chemicals which do not occur in nature naturally (e.g. CFCs or other chlorinated hydrocarbons) is infinite, which goes against the principle that the studied systems considered and releasing these chemicals are finite. In essence, these interpretations are true if one considers the environment as having thermodynamically immutable properties , a valid assumption in many cases. In the case of large releases or introduction of new chemicals, the descriptions of the reference environments must be considered dynamically with changes over time.

Examples of potential uses of exergy of mixing can be found in [56], where the exergy of mixing of methane and coal, for the same exergetic overall output, are compared.

Exergy of mixing has been linked with other measures of environmental impact such as environmental pollution costs (EPC), an estimate of total environmental cost, including social or external costs Figure 3.1. For the five pollutants considered in [57], no correspondence can be seen between the total exergy and the EPC of the considered chemicals whereas exergy of mixing appears to be a better predictor.

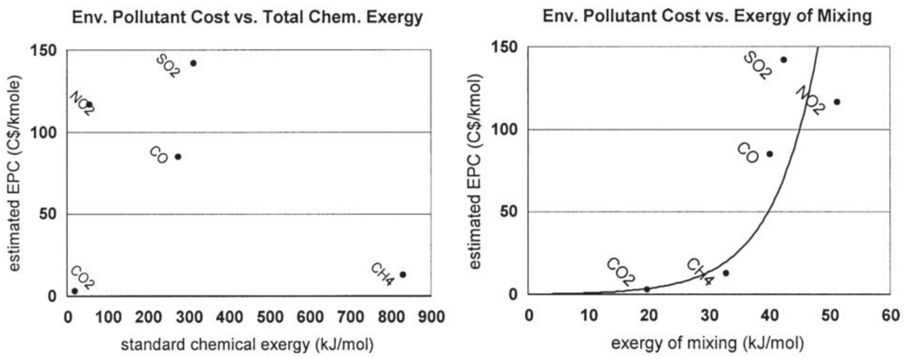

Figure 3.1. Environmental Pollutant Cost (EPC) vs. total exergy (left) and exergy of mixing (right). [57]

3.2.4 Exergy and economic assessment

The strong link between thermodynamics and economy was seen early on, along with the need to define a conversion between the economic and physical world. Lotka [28] rightly points out that it is pointless to assess a system following the First Law of Thermodynamics but rather the efficiency of the system should be modelled. Often the studies of the combination of exergy, essentially an energetic property, and cost, an economic property, are considered under the name of *thermoeconomics*, or sometimes *exergy-economics*, but multiple approaches exist in the study of these two realms.

Valero [74, 75] proposes an "exergy cost" approach identical to Szargut's [66] "cumulative exergy consumption" (CExC), albeit formulated differently, which considers the production chain as a series of elementary processes which can be modeled with their exergetic inputs, outputs and losses. Each process contributes exergy to the chain and therefore anything that is produced, even if it is dematerialised such as electricity, can be modelled and its cost calculated. Valero's method uses a structural matrix of the considered process making the final calculations fast and elegant. Although the *exergy cost* does not deal in monetary units, it can be coupled with the *monetary cost* which takes into account the amount of money consumed to generate a mass and/or energy flow [74].

An augmented approach of *exergy cost* is the general thermoeconomics approach that also considers the full chain of production but with the exergetic inputs being attributed a monetary cost. Although well adapted for large scale energy demanding projects, but essentially adaptable to any project, the thermoeconomics approach can only be effectively applied in the final stages of the design process. Indeed the strong point of such an approach is its compeleteness in the representation of each process of the system.

3.3 Dimensional analysis

Dimensional analysis is commonly used in physics, mechanical engineering, chemistry, etc. and describes the fact that physical laws do not depend on the choice of measurement scales and units. The basic idea behind dimensional analysis is dimensional homogeneity - in other words, the fact that one cannot add up apples and oranges and one also cannot equate apples to oranges. The main purpose for dimensional analysis has long been to model problems for which the exact equations were unknown or too complex to calculate given the available computing power at the time. Today these two hurdles have been overcome in many instances, yet dimensional analysis remains a coherent and useful tool limiting the variables to handle and allowing the user to get a richer knowledge of a phenomenon to study. Perhaps Lord Rayleigh [27] best describes the power of dimensional analysis:

> It happens not infrequently that results in the form of 'laws' are put forward as novelties on the basis of elaborate experiments, which might have been predicted *a priori* after a few minutes' consideration.

3.3.1 Historical aspects of dimensional analysis

The notion of *dimension* has been understood since the early Greek era with the restrictions that faced geometrical operations because of the need for homogeneity in equations. The then definition of *dimension* differed from the modern one as the notions of dimension and direction in space were not separate [2] and therefore imposed much too strict restrictions in geometry. The beginnings of the modern viewpoint of dimensional analysis have been attributed to multiple authors, from Euler's work in the mid-18th century [2] to Maxwell's definition and notation of dimensions in the late 19th century [37], just to name a few. Fourier's work on heat transfer [16] still often retains the title of the first significant contribution to the field and discipline, even though no mention is made of dimensions. Lord Rayleigh [27] proposed the identification and use of dimensionless groups related to any given problem with physical dimensions, which had already been illustrated in his earlier works, his body of works highly influenced later interpretations of dimensional analysis, including the work of Buckingham [5].

Perhaps most famously, dimensional analysis is associated with the work of latter and his publication on a systematic approach to dimensional analysis. Buckingham's theorem, often referred to as the π theorem, represents the entry of dimensional analysis as a scientific method rather than an empirical technique. The 1914 theorem is by far incomplete and multiple works and has been supplemented with the works of Kokar [24] and Butterfield [6], for example, for practical applications of the principle.

Although the fact that dimensional analysis can help with some "back of the envelope" representations of physical systems and phenomena, other uses include scaling up and scaling down of systems as well as categorising phenomena. Reduced scale models in fluid dynamics serve as entry points into the understanding of such dimensionless numbers as the Reynolds number (presented in more detail below) or the Froude number. Their application extends to pre-studies of large structures such as vessels where it is impractical to provide a life size model for tests.

An example of a dimensionless parameter is the Reynolds Number (Eq. 3.6) which has been used on numerous occasions to predict the behaviour of a system based on a scale model.

$$Re = \frac{LV}{\nu} \tag{3.6}$$

where L is a characteristic length, V is the free stream velocity and ν is the kinematic velocity thus providing the dimensional analysis in Eq. 3.7.

$$[Re] = \frac{[length] \cdot [length]/[time]}{[length]^2/[time]} = [] \tag{3.7}$$

The performance of the scale model, for example in a wind tunnel, is the same as that of the full scale model if the two have the same Reynolds

Number. This property has allowed the understanding of many structures while not necessitating large testing facilities and calculation power.

3.3.2 Modern view and uses of dimensional analysis

Buckingham's theorem, or π theorem, is often cited as a starting point in the application of dimensional analysis, it states that any physically meaningful equation involving *n* variables expressible in terms of *k* independent fundamental quantities can be rearranged into an equivalent equation involving a set of *p=n-k* dimensionless parameters that are derived as products of powers of the original variables.

More formally, the theorem states that if a system can be fully described using q_i *n* variables (Eq. 3.8), and they can be rewritten in terms of *k* independent units (Eq. 3.9), then Eq. 3.8 is equivalent to Eq. 3.9.

$$f(q_1, q_2, ..., q_n) = 0 \tag{3.8}$$

$$f(\pi_1, \pi_2, ..., \pi_p) = 0 \tag{3.9}$$

π_i representing *p=n-k* dimensionless parameters generated from the q_i variables and having the following form (Eq. 3.10):

$$\pi_i = q_1^{\alpha_1} \cdot q_2^{\alpha_2} \cdot ... \cdot q_n^{\alpha_n} \tag{3.10}$$

In practice, often dimensionless parameters π_i are written under the form shown in Eq. 3.11 where y is a *performance variable* and x_i are *repeating variables*.

$$\pi_i = y_i \cdot (x_1^{\alpha_{i1}} \cdot x_2^{\alpha_{i2}} \cdot ... \cdot x_m^{\alpha_{im}}) \tag{3.11}$$

The specific defintion of *repeating* and *performance* variables is subject to much debate, thermodynamic textbooks naming *repeating* variables a group of variables that is easily tested by the experimentalist or are the most representative of the system while remaining independent, covering all dimensions and not forming a dimensionless group. No actual guidance over the choice of variables to include in each dimensionless parameter is included in the theorem itself, often leading to impasses and dimensionless parameters irrelevant to the description of the problem.

Augmented approaches to the generation of dimensionless paramters include, for example, Butterfield's table approach [6] which presents an elegant manner of selecting *repeated variables* and always being able to generate dimensionless parameters, or "dimensionless groups". This approach is all the more interesting when there is a large number of variables present to describe a system.

3.3.3 Dimensional analysis in various fields.

Although Buckingham's theorem is often presented as a tool to apply in physics, and especially fluid dynamics classes, the theorem and its augmentations have found applications in multiple fields. Fields dealing with physical dimensions saw the first applications, Fourier and Rayleigh's works, while explicitly using dimensional analysis or not, certainly contributed largely to the expansion of the scientific content.

In the domain of engineering, Taylor's work [67] contributed to the spread of dimensional analysis with a large body of practical examples of applications of the methodology to systems. Today relevant applications can be found in chemical engineering [54], material sciences [7], biology and water treatments [58], etc.

Starting in the 1960s, the fields of application of dimensional analysis expanded outside of those dealing exclusively with physical dimensions. Most notably, DeJong [12] proposed the use of dimensional analysis as a tool in economics. This subject is still widely debated today as there is no consensus on the definitions of dimensions linked to monetary values. Nevertheless, dimensional analysis has always had an appeal in this field as it often deals with problems for which the exact equations are unknown or too complex. Another example of an application in a non-physics field is Ewing's work [14] that considers early on that dimensional analysis can potentially be a useful tool to further the understanding and modelling of certain aspects of social sciences. It is all the more relevant today as new fields of study emerge proposing to incorporate certain aspects of social sciences and economics into the conceptual structure of physics [15].

Furthermore, when the methodology cannot be directly applied, dimensional analysis has been adapted to suit the needs of certain fields. Marinov [31], for example, proposes the *Reversed Dimensional Analysis (RDA)* for psychophysics. The RDA approach considers that sometimes there is no clear cut dimension to work with, such as those dimensions found in physics, but dimensional analysis can still be applied because a dimension can be extracted, or calculated, from data.

3.4 DA-Ex approach

The basis of the DA-Ex approach is the application of the principles presented in Sections 3.2 and 3.3 to an organ or process during a life cycle phase. The first application of the principles is aimed at environmental assessment, as it is at the origin of the motivation for the approach.

DA-Ex approach for environmental assessment

Publication I presents in detail the DA-Ex approach as applied to environmental assessment; Publications II - V also elaborate on the subject. For each stage of the life cycle, an organ is described using the inputs and outputs as shown in Figure 3.2. The organs can be precise or generic models, based on the available information (PVI). The inputs are made up of the exergy of the raw materials (Ex$_{material}$) and the exergy supply (Ex$_{supply}$) necessary to produce the organ or process during the considered phase. The outputs consist of the exergy contained in the desired products (Ex$_{product}$) and useful bi-products (Ex$_{bi-product}$), the emissions to the environment (Ex$_{EnvStandard}$ and Ex$_{mixing}$, calculated using the standard chemical exergy and the exergy of mixing formulas, respectively), the exergy of waste not rejected to the environment (Ex$_{recycling}$) and the exergy lost due to irreversibilities (Ex$_{lost}$). The mentioned parameters are mainly based on definitions proposed by [66] and described in Section 3.2, along with the calculations of the different exergies such as standard chemical exergy and exergy of mixing. Other modelling approaches can be found in literature (e.g. [60]).

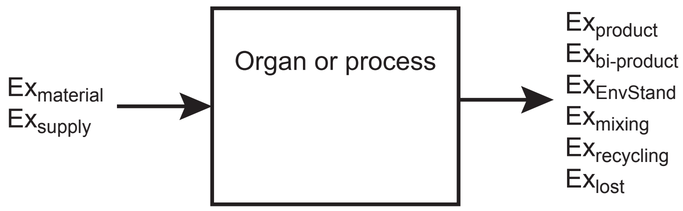

Figure 3.2. Inputs and outputs necessary for the full environmental assessment of an organ with the DA-Ex approach.

Several aspects of exergy have been linked to environmental analysis such as exergy losses, exergy of mixing and the increased energetic efficiency due to exergy studies (see Section 3.2). Given the wide array of variables used to describe a single organ or process (Fig. 3.2) and multiple dimensionless parameters that can be generated, it is essential to consider the final aim of this environmental impact assessment for it to be useful in the early stages of the design process. The three categories of impacts chosen are exergy use efficiency, material and resource use efficiency, and environmental emissions.

Exergy efficiency

Equation 3.12 represents the *Primary Exergy Conversion Efficiency (PECE)* and considers the overall transformation of the exergy from the materials and exergy supply into useful products and bi-products. As an efficiency parameter, a higher the result indicates a more efficient product transformation.

$$\pi_{PECE} = \frac{Ex_{product} + Ex_{bi-product}}{Ex_{material} + Ex_{supply}} \tag{3.12}$$

Material and resource use

Equation 3.13 represents the *Material and Resource Consumption Efficiency (MRCE)* that is based on the consideration of all resources that will be used eventually, it is therefore not limited to the developed product. As the parameter above, it is an efficiency measure.

$$\pi_{MRCE} = \frac{Ex_{product} + Ex_{EnvStandard}}{Ex_{material} + Ex_{supply} - EX_{recycling} - EX_{bi-product}} \tag{3.13}$$

Environmental emissions

Equation 3.14 represents the *Environmental Impact Efficiency (EIE)* based on the exergy of mixing, it is the potential chemical change attributable to the introduction of any pollutant into the environment. Unlike the two parameters above, it is not an efficiency measure and therefore a higher value represents a higher environmental impact.

$$\pi_{EIE} = \frac{Ex_{mixing}}{Ex_{material} + Ex_{supply} - EX_{recycling} - EX_{bi-product}} \tag{3.14}$$

The validation method for the results obtained through this approach is covered in Section 3.4.1.

DA-Ex approach expansion to cost assessment

The expansion of the DA-Ex approach was first considered with value considerations in Publication III. Cost considerations proved easier to combine with exergetical data and Publication IV as well as Publication V expand on the application of the approach to cost assessment through inputs and outputs as shown in Figure 3.3. Unlike for the environmental description, the inputs and outputs cover both the studied organ or process as well as the whole overall system.

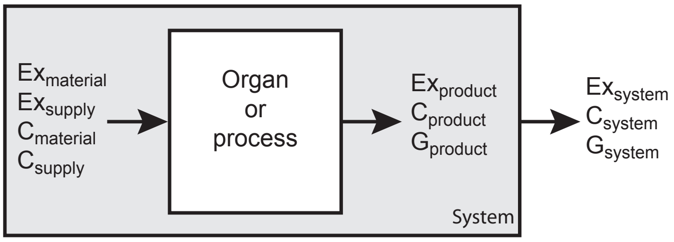

Figure 3.3. Inputs and outputs necessary for the considered cost analysis of an organ with the DA-Ex approach.

At organ level, the inputs considered are the exergy of the raw materials provided ($Ex_{material}$) and of the exergetic supply necessary (Ex_{supply}) as well as the cost of the investments made for the raw materials ($C_{material}$) and energy supply (C_{supply}). The outputs, at organ level, are the exergy of the wanted product ($Ex_{product}$), the cost of the investments made for the final product ($C_{product}$) and the expected gain from the organ or process considered ($G_{product}$). At system level, the outputs considered are the exergy, costs of the investments made for and the gain expected from the whole system (Ex_{system}, C_{system} and G_{system} respectively). To simplify calculations, all monetary costs are converted to euros.

The intended purpose of this assessment is to point out discordances between the costs of the investments of certain parts and their final exergetic value or the gain they represent for the final part. For example in the study of solar thermal panels (PIV), during the chosen life cycle phase there was a discrepancy between the high exergetic content of the casing, thus putting a high stress on the environment, and its low monetary cost in the final structure.

This DA-Ex approach extension to cost analysis does not aim to fully represent the economic situation of the product being designed, but rather it gives the general situation of where the major environmental and monetary costs are and if they correspond. Two main categories of cost analysis are considered - correspondence between the exergetical and monetary costs and the highest cost sinks and sources for gains.

Exergy-cost efficiency

Equation 3.15 represents the *Exergy and Cost* links and correspondence. It takes into account how both the material and resources are used to make the product and how much is invested in them.

$$\pi_{ExC} = \frac{Ex_{product}}{Ex_{material} + Ex_{supply}} \cdot \frac{C_{product}}{C_{material} + C_{supply}} \tag{3.15}$$

Design drivers

Equations 3.16 and 3.17 represent the *Exergy and Cost Drivers* and the *Gain and Cost Drivers* respectively. These two parameters convey the sections of the studied system that benefit from the highest investment, often justified by a high functional importance.

$$\pi_{ECD} = \frac{Ex_{product}}{Ex_{system}} \cdot \frac{C_{product}}{C_{system}} \tag{3.16}$$

$$\pi_{GCD} = \frac{G_{product}}{G_{system}} \cdot \frac{C_{product}}{C_{system}} \tag{3.17}$$

This expansion to the DA-Ex approach has not been fully tested, in part because the original lack of familiarity of the author with the field of cost analysis. Moreover, no appropriate validation method has yet been developed for this aspect of the DA-Ex approach. Further developments proposals for this cost analysis expansion to DA-Ex are described in Section 4.2.

3.4.1 DA-Ex result validation method

The results obtained with the DA-Ex approach for environmental assessment were compared with results from LCA studies performed with the SimaPro software and either the EI-99(H) or CExD methods or both. A description of LCA-based studies and the two methods can be found in Section 2.2.

For each case study, the system was modelled in terms of organs while taking care of noting all hypotheses on the boundaries of the study. The DA-Ex approach was applied after gathering the relevant exergetical data and the results recorded. The system was then modelled in the SimaPro software with the same hypotheses or hypotheses that came as closely as possible to the original ones. Often the differences were mainly in the types of materials used as the exergetical data available in publications did not always correspond to the data available in the ecoinvent database. Either the EI99(H) or CExD, or both, indicator was then applied and results recorded.

As the DA-Ex, EI99(H) and CExD method differ in the way that results are presented, these cannot be compared number to number directly, especially because the DA-Ex approach considers the efficiency of use of exergy and resources while neither EI99(H) nor CExD do. Instead each study was done on different alternatives of concept solutions and these were rated from best to worse in terms of environmental impact.

4. DA-Ex application - case studies

Practical applications of the DA-Ex approach have provided information for new developments in the methodology and have allowed its limits to be tested. Three main studies have been performed, each time increasing in complexity in terms of number of parts and material composition. The first case studies (works I, II) considered metal parts; first comparing two identical parts manufactured with different processes, then comparing two alternative solutions for parts of a novel sand mould. The second study (IV) looked into the assembly phase of solar thermal panels in order to assess the most impacting features. The third study (V) applied the DA-Ex method to different alternatives for cabin insulation of a passenger ferry.

4.1 Case study overview, results and validation

Publication I focused on the study of two alternative manufacturing methods of producing part of a pressure regulator (Fig. 4.1).

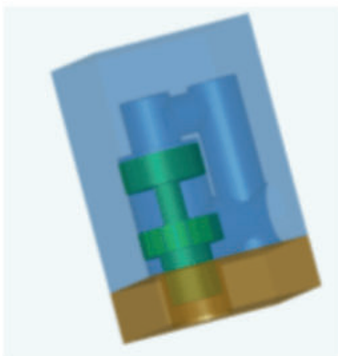

Figure 4.1. Pressure regulator, the foundry part studied is coloured in light brown.

The results of the DA-Ex study show that a part produced through sand casting and milling transforms exergy and uses resources more efficiently than a part produced through milling alone. Due to the high number of emissions from the various processes, the total emission environmental impact metric is higher for the sand casting and milling approach.

Applying Eco-Indicator 99(H) to a similar, but not identical, model showed that a part made by casting and milling has comparatively fewer environmental impacts, or rather in the case of this indicator it causes less damage. On the front of the resources, the result can be called comparable to that obtained through the application of the DA-Ex approach, even though EI-99(H) considers full resource use and DA-Ex its efficiency. The results were diverging for the emission environmental impact, this is due to different system boundaries in both studies. Indeed, the DA-Ex approach did not consider the emissions from energy use outside the processes used in sand casting and milling, this was not the case for the EI-99(H) method.

Publication II considered two alternative solutions for parts of a novel sand casting mould; Figure 4.2 depicts one of the solutions.

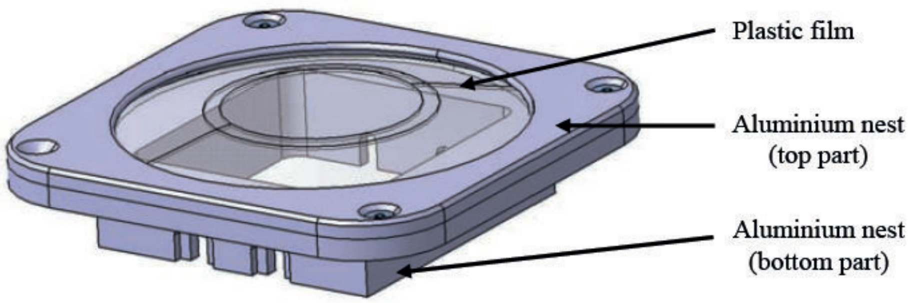

Figure 4.2. One of the alternatives studied of a part of a novel sand casting mould.

DA-Ex applied to the two systems studied in the publication showed that one had a slightly less efficient exergy transformation than the other. The differences in material use efficiency were greater but still to the advantage of the second system. Moreover, the emission environmental impact data was also favourable to the second system.

This second study used the CExD method for comparative results; having learnt from the first study, the system boundaries were set to be identical. The CExD study pointed out the second system as extracting less exergy from nature. This was in concordance with the results from the DA-Ex approach from the point of view that the same system was deemed less impacting overall with the chosen categories and metrics. Given the nature of the CExD indicator and the metrics of the DA-Ex approach, a straight comparison of numbers or impacts is impossible.

Publication IV studied the structure of solar thermal panels, applying both the environmental assessment and cost analysis aspects of the DA-Ex approach.

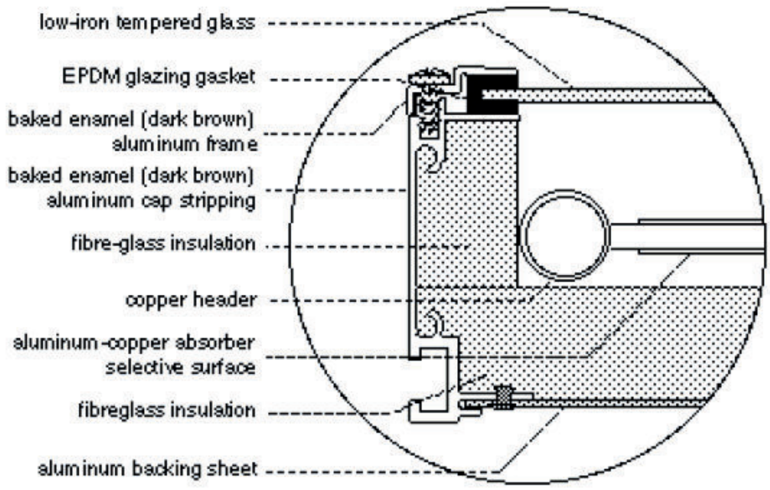

Figure 4.3. One of the alternatives studied of a part of a novel sand casting mould.

Unlike in previous approaches, the modelling was done with orders of magnitude and limited the study to two specific stages, preparation and assembly. Some of the parts of the system were sent to these stages "ready-made", hence they did not effectively participate in any exergy or material use during the preparation stage. The cost analysis expressed expected results such as the fact that using a casing made of aluminium is cheap money-wise but has an important exergetical cost. On the other hand, using high quality fibreglass insulation with lower exergetical cost proved to be a sink in terms of monetary investments. Ideally a solution should be found where there aren't such discrepancies in the design.

No comparative studies were performed for this publication as the accent was put on developing and exploiting the cost analysis facet of DA-Ex following disappointing results with the first proposition found in Publication III.

Publication V presented results from the study of different elements of the cabin of a passenger ferry being developed to be used in the south of France.

First, different types of insulation were considered to be used inside the

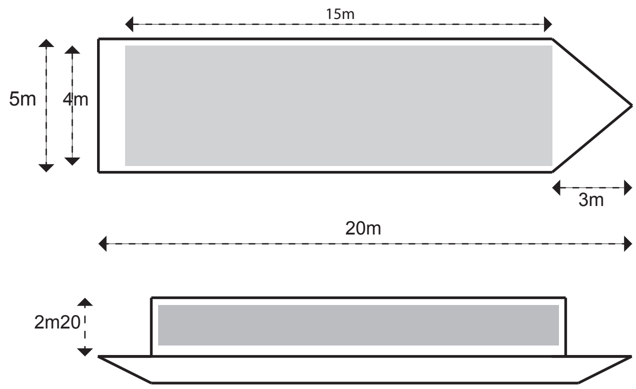

Figure 4.4. One of the alternatives studied of a part of a novel sand casting mould.

cabin. Given the fact that all insulation types require large energetic and exergetic inputs for extraction, the one with the best efficiency for exergy transformation and material use was polystyrene. The associated emissions were much higher, though, than for the other types of insulation. As for the study in I, the results were not conclusive on the boundaries chosen. The study of the types of windows to use confirmed the notion that it's the use phase, not considered in this study, that gives their advantage to triple glazed windows.

The cost analysis showed that in a system that can have more or less window area, windows are an attractive feature that brings up the gain that can be expected from the operation of the whole system. Their cost makes them a less attractive feature, especially when in conjunction with the way they inefficiently transform exergy.

Both EI-99(H) and CExD methods were applied to the model. In the case of windows, both methods pointed to the triple glazed as bringing more environmental damage, given the study boundaries. This was in concordance with the results from the DA-Ex approach. The two methods provided different results, though, for the environmental impact of the different types of insulation. This was due to the fact that they consider different impact categories. The results were also at odds with those of the DA-Ex approach. After careful consideration of the hypotheses made for the characterisation and impact considerations of each approach, all the results proved to make sense. The difficulty remains that the designer must look into the details of all the available methods and indicators to find the most suitable one for his or her needs.

4.2 Discussion

The increasing complexity of each case study and the acquired knowledge and insight after each one have helped develop the DA-Ex approach into an approach that can be applied as any other environmental assessment tool or method. The first applications were limited to well-defined processes and products but the approach has also been applied to artefacts where only the order of magnitude of the data was known. The results obtained were in line with specialists' view on the problem and results from widely used existing tools, where used.

The objectives set during the development (Section 3.1) of the DA-Ex approach were to provide results of comparable quality as those obtained through existing methods and tools, use readily available data, rely on a relatively small database, be applicable during the early stages of the design process, and offer ways to expand the approach to aspects related to sustainability beyond environmental assessment.

The validation approach through comparison with existing methods and tools provides limited results, as seen the different case studies in Publications I, II and V. DA-Ex looks at the efficiency of exergy and resource use as well as exergy of mixing, which concerns mainly emissions. EI-99(H) and CExD have different characterisations with some extreme phenomena appearing, e.g. the importance of water use in CExD, or impact categories that DA-Ex does not consider at all, e.g. damage to human health in EI-99(H). There is, however, a reasonable amount of correspondence in the results and all discrepancies have been studied; this covers the first objective mentioned above.

While the DA-Ex approach is based on easily accessible data, the relevant data is available today but is not centralised. There are no openly accessible databases that would contain information on every material and process used in a study. Thus, currently the user must seek out the data in dedicated publications or industry databases. While this can be a time consuming task, there is a transparency to the data that is not possible with proprietary databases, which represent the majority of those that come bundled in existing LCA software. Through the development of the user base of the tool, it is possible to foresee that the data will become much easier to access, and, as only exergetical data needs to be stored, the database should remain of a modest size.

The DA-Ex approach is still limited by the fact that the artefact studied needs to be decomposed and modelled before it can be evaluated. This is in accordance to the decision making process presented in Figure 2.5. This issue is the same as for methods that fit into the SLCA category and cannot be resolved easily as the model of any studied system is the backbone that the approaches, methods and tools use as a starting point. This limitation has been partially addressed in Publication VI with the use of generic behavioural laws in order to model organs. The use of dimensional analysis makes the approach applicable even if the information in the model is not fully defined. This use also allows the expansion of the framework to other fields linked to sustainability as described in Section 3.2.4.

The current version of the DA-Ex approach partially covers the objectives set at the beginning of the work. Further development and test cases are needed to develop the database, through user base extension, as well as better understand the approach's result accuracy with limited information from artefact models. The study of environmental assessment methods and tools and the development of the DA-Ex approach have pointed out an existent limitation, that was not considered in the objectives, of all approaches - they are not dynamic. They do not consider the systemic responses that occur when an artefact is introduced in a new environment and do not dynamically respond to changes in the system surrounding a studied artefact. For example, rebound effects cannot be seen easily and they can be an important issue in the introduction of products deemed "environmentally friendly". A solution to this limitation is presented in Publications VI and VII and is further developed in the conclusion as perspective for future work.

5. Conclusion

The work presented in this thesis focused on alleviating existing shortfalls of existing tools and methods for environmental impact assessment and mitigation, as to contribute to making more, and better, environmentally oriented decisions during the early stages of the design process. The approach proposed and detailed in this thesis allies exergy and dimensional analysis to form metrics that can help make those decisions. The two pillars of exergy and dimensional analysis were chosen for this task as exergetical data is readily available in publications, the database needed for such an approach would be lightweight as only storing exergetical data, and using dimensional analysis allows the use of orders of magnitude for calculations. The approach can also be expanded to fields other than environmental impact assessment, opening the potential for a method covering multiple facets of sustainability.

The DA-Ex approach for environmental impact assessment has been tested on multiple case studies ranging from simple metallic parts to parts of solar thermal panels. The results are promising as they yield information comparable to that obtained from widely used and accepted methods and indicators implemented in commercial LCA software. The approach has yet to be tested on the full development of a product from the very start of the conceptual phase to the final production. Such a large scale study could provide information as to how the accuracy of the DA-Ex approach evolves as the data about the project is finalised and help improve it. Nevertheless, the approach has been used in real projects such as the choice of insulation of the cabin of a boat (PV) with commendable results.

The works presented in this thesis also highlight the evolution that the DA-Ex approach has followed and the author's attempts at expanding a simple approach aimed environmental impact assessment to other fields. Although the expansion mentioned in Chapter 3 still needs further validating tests, it is crucial to start considering that environmental impacts and their mitigation are not the only issue at hand, but sustainability as whole must be implemented in the early design stages.

As part of further research on the idea of taking sustainability into account during the conceptual design phase and the start of the embodiment phase, development has begun on a systemic approach to the design process.

Future perspectives - DA-Ex, dynamicity, and systems approach to design

Although not considered in the objectives set for the development of the DA-Ex approach, providing support for the design team using a systemic perspective is key for more performant designs. The DA-Ex approach presents, in its current state, an important dynamicity shortcoming that is common to all current environmental assessment and most product development methods - it is the fact that the studied artefact is not studied in the context of the whole system that surrounds it. Many products are developed to be seemingly environmentally "friendly" only to cause great damage when let loose because of unforeseen changes they generate in the whole surrounding system. The first generation of biofuels is a perfect example; biofuels were celebrated as the best approach to wean off fossil fuels but the stir surrounding them caused world-wide grain prices to rise [38], the slow destruction of lands due to monoculture, negative effects on human health [18], etc. Such phenomena are called *rebound effects* and have often been pointed out and studied in economics. From an environmental perspective, rebound effects have been considered and studied in the energy sector, especially whenever energy efficiency schemes are put into place and the observed energy consumption reduction is below that predicted by simple models (e.g. [61]). The underlying causes can be multiple, both causing direct and indirect rebound effects and making them difficult to single out. Evidence of rebound effects linked to engineering design has been mainly documented for large interventions in the fields of energy, heating, and transportation. The impact of the introduction of new mass produced artefacts still remains to be explored and exploited but must be considered as a priority in the case of environmentally conscious designs.

The DA-Ex approach is not systemic, its studies are limited to the artefact considered and, for the moment, it is impossible to take into account the dynamic evolution of the surrounding system. Publication VI considers the dynamicity of a model by implementing its behaviour in response to external variables. This is done through a system dynamics tool and using two basic bricks of the system dynamics language, converters and flows. Publication VII proposes an approach based on value analysis, structural analysis, and system dynamics to help understand the interactions between a system and its environment, select a design focus and strategy in-line with the fundamental goals of the system, and also model and simulate scale effects and impacts that can emerge from the way that a system is used. In both cases, system dynamics play an important role and through this approach the presence of rebound effects should be caught and the consequences of such phenomena analysed. The inclusion of exergy, and possibly the complete metrics proposed by the DA-Ex approach, in this model will be part of future work. Associating an exergetic approach to system dynamics models does not present particular technical issues and there is real potential in this future integration of DA-Ex with the system dynamics approach. Indeed, it is possible to imagine the automation and systematisation of the modelling and simulation processes of complex systems using a limited set of metrics associated with a modelling approach derived from dimensional analysis. The systemic analysis that's currently lacking in DA-Ex would then become possible, and thus the extension of the scope of environmental assessment methods to the early design process phases of complete product service systems and the eco-systems surrounding them. The scope of the design process would be extended by the existence of such a type of dynamic early modelling and simulation approach as the design activities should include the studied system but also the external environment of the system and the interactions of the system with this environment.

Publication VI illustrates the way the dynamic aspects of the behaviour of a model can be studied on the example of the bending of a beam. The approximated behavioural model is obtained through dimensional analysis and then translated into system dynamics language. In the present version of Publication VII, dimensional analysis is used to develop the system dynamics model of a pyrolitic stove eco-system. The system dynamics model equation generation approach already integrates dimensional analysis and more specifically the power law present in dimensional analysis but also in fractal theory [30]. In the article (VII), the authors propose a method to systematise the generation of the system dynamics model and dimensional analysis participates in the generation process of equations governing the system. This proposal is a contribution of the work but will require as such a specific investigation of its scope and generality. The existing analogy between the power law in dimensional analysis and fractals is another interesting aspect to consider. The reasons behind the way this analogy works are puzzling and might become a challenging new field of investigation.

Overall, although artefact design is already considered as a very complex process, it is rarely performed while including a systemic perspective. Nevertheless, this type of consideration must be included in all environmental impact mitigation and environmental assessment analyses. Studying the simple impact of an artefact does not convey the full spectrum of impacts and potentially negative effects can easily be ignored up until they occur in real life when it is too late to take action. For these reasons, the work presented in this thesis in Chapters 3 and 4 has now been further developed to include a systemic perspective and will continue to evolve towards providing more comprehensive and useful support for the design team during the early stages of the design process.

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Publication I

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Study of an exergy method for environmental evaluation assessment in the early design phase using comparative LCA and exergy approach

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Abstract: Environmental evaluation analysis made at an early design stage is an important practical problem because existing approaches such as the LCA method require detailed information about the studied product or service. Consequently, to be efficient such a method requires a product or service located in an advanced development phase. An exergy method offers an appropriate solution for an environmental evaluation analysis at an early design stage. The theoretical model has been validated in previous journal articles. The goal of the present article is to validate the concordance of the results provided by the exergy and LCA approach, as LCA is a widely used approach even though the scientific reliability of LCA techniques has been questioned. This paper addresses the last phase of the validation of the exergy approach by comparing results of a case study analysed through both commercial LCA software and an exergy approach.

Keywords: exergy; environmental evaluation analysis; life cycle assessment; LCA; validation.

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1 Introduction

In the development of a new product, the early stage of the design process poses a major challenge to the engineering team and to the researchers of the product development community because numerous types of requirements involving multidisciplinary and multilevel analysis and synthesis have to be fulfilled simultaneously. In addition, the fast changes in industrial, market and environmental practices have demonstrated the growing importance of early evaluation of various aspects of the life cycle of products or services artefacts. Unfortunately, the knowledge available at this stage of the development process is often qualitative, imprecise and situation-dependent.

In the case of an early environmental evaluation assessment (EEEA), there is an urgent need for simplification and comparability of the metrics. The current situation presents constraints due to the properties of the knowledge described above. This fact represents a fundamental problem for the design activity and specifically for environmental impact analysis and environmental accountancy because repeatability relies less on the methods themselves than on the homogeneity of the product development teams which use them.

This lack is clearly an important motivation for developing a more repeatable method based on generic principles.

The goal of this article is to continue to validate a novel approach dedicated to EEEA. This paper follows two published journal articles which have described exergy as a powerful concept for EEEA. Nevertheless, the validation phase of the exergy approach is not yet fully completed. Indeed the life cycle assessment (LCA) method is widely used and implemented in software. The scientific validity of LCA has been criticised for early design evaluation; however, the results provided seem acceptable when dealing with the detail design phase. The idea of the article is to evaluate the comparative use of LCA and exergy approaches in the case of a detail design phase. We aim to study in a detailed manner the advantages and weaknesses of the exergy approach. This article is the last phase of a scientific validation process of the exergy approach.

The rest of this paper is organised as follows.

Sections 2 and 3 present the background to the need for a new environmental assessment method and the possible solution provided by the concept of exergy.

Section 4 gives a state of the art of the exergy approach by summarising the fundamental finding of Coatanéa (2005), which leads to consider dimensional analysis (Barenblatt, 1979; Matz, 1959; Sonin, 2001) as a central tool for comparison and evaluation of concepts. The section also provides an overview of the LCA approach.

Section 5 presents the case study of the article. Both LCA and exergy are used to treat the problem.

Section 6 is for the discussion and conclusion section. This section summarises the results presented in the article and links it with other works of the research group involved in the writing of this document. This section presents the strong and weak points of the approach. Future research works needed for analysing the problems of aggregating environmental indicators are presented at the end.

2 LCA and functional/system analysis

2.1 Life cycle assessment

LCA is the most commonly used approach by which environmental analysis is carried out during a design process (Allenby, 1997). LCA usually follows a four-step methodology consisting of:

1 scoping

2 inventory analysis

3 impact assessment

4 improvement assessment.

The LCA approach has been criticised as an unreliable scientific method because at each of the four-step methodology a significant scientific limitation can be highlighted (Ayres, 1995; Krozer and Vis, 1998). Indeed, the limitations include difficulties in identifying the boundaries of the system, a lack of adequate inventory data. Moreover, some of the data is unverifiable and may well be erroneous. In addition, widely disparate conclusions can be drawn depending on what information is excluded from the study. Finally, the impact assessment is made in terms that are not directly comparable. However, the life cycle hypothesis underlined in the LCA framework offers a holistic view of design problems, which allows for better-optimised solutions.

LCA forms a descriptive model, for this reason, the data requirement of LCA is extensive. In this respect, LCA is not a design tool because during design process many data are unknown and can only be determined at the end of the design process. Another aspect of LCA is that it has not been created by the design community; consequently it offers very poor support during the design process because of its poor interoperability with common design tools such as CAD tools. These aspects have been emphasised by Millet et al. (2007).

2.2 Functional/systems analysis

System analysis used in thermodynamic analysis share many similarities with functional analysis used in design. Indeed, both analytical approaches require a model that characterises the type of relationships and constraints governing the system and their components. These models are usually the result of analysis made in order to establish links among components. The boundaries of a study can be defined narrowly (e.g., around the system itself) or more broadly (e.g., to include the system and its environment). Therefore, in order to measure the final objective a uniform metric must be expressed. This holistic metric should simultaneously embody multiple other metrics.

Both LCA and system analysis provide a method for a comprehensive environmental analysis. LCA is used as a descriptive model, while systems analysis is used as a prescriptive model. For this reason, the data requirement of LCA may be more extensive than in systems analysis. LCA is therefore more applicable to problems, with an emphasis on examining specific materials, flows and processes whereas systems analysis is more applicable to problems, with an emphasis on examining interrelationships.

3 Environmental metrics

According to Seager and Theis (2004) all sustainable metrics may be characterised in a classification that includes six broad categories:

- financial metrics estimate environmental impacts or ecosystem services in terms of currency
- thermodynamic metrics indicate the resource requirements of industrial activities or services
- environmental (including health and safety) metrics estimate the potential for creating chemical changes or hazardous conditions in the environment
- ecological metrics attempt to estimate the effects of human intervention on natural systems in ways that are related to living things and ecosystem functions
- socio-political metrics evaluate whether industrial activities are consistent with political or ethical goals
- aggregated metrics may combine features or metrics belonging to a variety of other categories or they may group a number of metrics that belong to a single category.

The lack of a uniform metric basis for comparison or expression of different types of impacts or requirements has been pointed out as a shortcoming of the LCA and systems analysis approaches (Ayres, 1995; Ayres et al., 1996). A possible solution to the metric problem is to use the thermodynamic concept of exergy, which gives a more complete vision of the resource and waste accounting (Ayres et al., 1996).

3.1 Exergy as a uniform environmental metric

Exergy introduced by Rant (1956) is defined as the maximum amount of work that can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference environment. Exergy combines the first and second laws of thermodynamics in a way analogous to Gibbs free energy. The advantage of exergy compared to Gibbs free energy or entropy is a system of environmental reference states, first proposed by Ahrendts (1980), which identify the chemical characteristics of three different reference environments for computation of standard exergies: the atmosphere, the ocean and the earth's crust. Exergy is expressed in Joules (J) unit or ML2T-2 using the international system of fundamental quantities with mass (M), length (L) and Time (T), respectively.

Exergy is classified as a thermodynamic metric. Ayres et al. (1996) have proposed to measure environmental impact using simple waste exergy accountancy. This approach can provide only a first approximation of the environmental impact.

A better approach for evaluating the environmental impact may be to focus on the portion of the chemical exergy, which results from material transfers or changes in composition. This approach called exergy of mixing has been proposed by Seager and Theis (2002) for evaluating environmental impact.

3.2 Exergy calculation

Wall (2002) states that exergy is a measure of the quality of natural resources. Jørgensen and Nielsen (1998) emphasise that exergy can be used as an ecological indicator. Ayres et al. (2003) also describe exergy as a measure of the *distinguishability* of a substance or system from its surroundings, which is a measure of its 'distance' from equilibrium.

The following paragraphs give the necessary formulas to compute exergy when the resource consumption is analysed. T_0 and P_0 are the references used for computing the physical and chemical exergy. The chemical exergy is calculated in the paper by using the method proposed by Szargut et al. (1988).

3.2.1 Exergy as a measure of material and energetic resource consumption

Exergy has four basic forms, *kinetic*, *potential*, *chemical* and *physical* (e.g., pressure-volume and heat exchange type of work). From an environmental perspective, both the chemical and the physical exergies are the two exergies of interest.

Higher quality of energy

Forms of energy such as gravitational, electric and kinetic energy can be completely recovered as mechanical work. Therefore, according to the definition of Szargut et al. (1988), exergy and energy are equal for these types of energies. Consequently, work (e.g., mechanical work) and electrical energy are high quality energies.

Degraded form of energy

On the opposite, the variation of exergy associated with a heat transfer between a system and a reference environment is:

$$Ex_Q = \left(1 - \frac{T_0}{T}\right) Q \qquad (1)$$

where

T_0 standard temperature of the reference environment (298.15 K)

P_0 standard pressure of the reference environment (1 atm = 101,325 Pa)

Ex_Q transferred exergy associated with the heat transfer (J)

Q transferred heat (J)

T temperature at the place where heat transfer takes place (K).

Equation (1) shows that heat is a degraded type of energy because $Ex_Q \leq Q$.

Exergy linked to a flow of matter

$$Ex_{Tot} = Ex_{Kn} + Ex_{PT} + Ex_{Ph} + Ex_{Ch} \tag{2}$$

where

Ex_{Tot} exergy associated with the flow of matter (J)

Ex_{Kn} kinetic exergy (J)

Ex_{PT} Potential exergy of the flow (J)

Ex_{Ph} Physic exergy (J)

Ex_{Ch} Chemical exergy (J).

As stated above, the physical and chemical exergies are those of interest from the environmental point of view. The physical exergy is due to the difference of temperature between the flow and the environment as shown in equation (3):

$$Ex_{Ph} = m\left[(h - h_0) - T_0(s - s_0)\right] \tag{3}$$

where

m mass (kg)

T_0 temperature of the environment (K)

h specific enthalpy of the flow (J/kg)

h_0 specific enthalpy of the flow at temperature T_0 and pressure P_0 (J/kg)

s Specific entropy of the flow (J/kg.K)

s_0 Specific entropy of the flow at temperature T_0 and pressure P_0 (J/kg.K).

In practice, the entropy is calculated by using the heat capacity as presented in equation (4):

$$\Delta S = \int \frac{C_x}{T} dt \tag{4}$$

where

C_x is the heat capacity of a fluid at constant pressure (C_P) or constant temperature (C_T) (J/kg.K).

The chemical exergy is the useful work which can be produced when a chemical equilibrium between the flow and the environment is reached. The definition of the environment requires defining at first the reference environment and its reference chemical species (Szargut et al., 1988).

The *standard chemical exergy* of a reference gas, which constitutes the reference atmosphere, is:

$$Ex^0_{Ch_i} = RT_0 \ln \frac{P_0}{P_{00}} \tag{5}$$

where

$Ex^0_{Ch_i}$ standard chemical exergy of the perfect gas (kJ/mol)

R perfect gas constant (R = 8,314 J/K.mol)

P_0 pressure of the environment (Pa)

P_{00} partial pressure of the perfect gas at the reference state (Pa).

However, in many cases, the most oxidised form of an element provides the appropriate reference state in each environment and consideration must be given to the molar concentration of a compound in the specified environmental source. Szargut et al. (1988) describe the principles for computation of the *standard chemical exergy* $(Ex^0_{Ch_P})$ of any compound:

$$Ex^0_{Ch_P} = G^0 + \sum_i \left(\frac{n_i}{n_P} Ex^0_{Ch_i} \right) \tag{6}$$

where

$Ex^0_{Ch_P}$ standard chemical exergy of a compound (J/mol)

G_0 Gibbs free energy of formation of the compound from the elements (J/mole)

n_i the number of moles

Ex_{Ch_i} standard chemical exergy of the ith reactant required to form n_p moles of the product compound (J/mole)

n_i and n_p Stoichiometric balancing numbers of the appropriate chemical reaction.

The formation of ammonia gas from nitrogen and hydrogen provides a simple illustrative example given by Seager and Theis (2002). The chemical reaction is represented below:

$$0.5N_{2(g)} + 1.5H_{2(g)} \rightarrow NH_{3(g)} \tag{7}$$

with $Ex^0_{N_2} = 0.72$ kJ/mol and $Ex^0_{H_2} = 236.1$ kJ/mol (Szargut et al., 1988).

Then:

$$Ex^0_{NH_3} = 16.48 + 0.5(0.72) + 1.5(236.1) = 371 \text{ kJ/mol}$$

The Gibbs' free energy of formation of ammonia gas is given as –16.48 kJ/mol. However, the standard chemical exergy is found to be 371 kJ/mol by substituting thermodynamic data into equation (6).

The Gibbs' free energy is representative of the ideal thermodynamic work required to synthesise pure ammonia from pure elements. On the contrary, the standard chemical exergy is representative of the maximum work that can be obtained under ideal conditions from pure ammonia gas.

For complex substances (i.e., those substances or materials formed by several different pure compounds, e.g., stainless steel such as X2 CrNiMo 17-12-2) standard chemical exergy can be computed by means of the following formula (Seager and Theis, 2002; Abou Khalil, 2008):

$$Ex^0_{Ch_P} = \sum_i \left(n_i \cdot Ex^0_{Ch_i} \right) \tag{8}$$

where

n_i mass fraction of the ith pure substance in the complex substance

Ex_{Ch_i} standard chemical exergy of the ith pure substance (kJ/mol).

Because of the irreversibility expressed by the second principle of thermodynamic, a balance of exergy should be closed by the introduction of a term representing the exergy loss in the system. Some readers might be surprised by the addition of such a term but, unlike energy, exergy is not conserved and therefore the term for exergy loss must be introduced in order to regain balance in the equation (Abou Khalil, 2008; Le Goff, 1979). The exergy loss is extremely useful when considering case studies as it shows where inefficiencies lie (Talbi and Agnew, 2000). The basis for this term comes from the Gouy-Stodola theorem which states that the lost available work is directly proportional to the entropy production (Szargut et al., 1988).

The exergy loss takes the following form:

$$\delta Ex = T_0 \sum \Delta S \tag{9}$$

where

T_0 temperature of the environment (K)

δEx exergy loss due to irreversibility inside the system (J).

Exergy balance equation

The exergy balance takes the following form according to Szargut et al. (1988):

$$\delta Ex = \sum Ex_d - \sum Ex_a + Ex - W \tag{10}$$

where

Ex_d, Ex_a exergy of the input and output matters (J)

Ex increase of exergy in the heat source in contact with the system (J)

W work performed by the system (J).

3.2.2 Exergy as a measurement of the environmental impact

As noted above, a waste exergy approach can provide only a first approximation of environmental impact. In order to overcome this theoretical deficiency, the concept of exergy of mixing (Szargut et al., 1988) can provide a universal, broad-based environmental metric. This is because exergy of mixing focuses on the portion of the chemical exergy, which is solely due to material transfers or changes in composition. It is argued by the authors of this article that it is a measure of the potential chemical change due to the introduction of any pollutant into the environment. Catalytic processes triggered by pollutants are not taken into account in the calculations mentioned in this article. Indeed, the authors consider such events rare in occurrence and their inclusion not vitally important to the subject of this article.

There are two mechanisms by which chemical exergy is converted into work or entropy; heat transfer and mass transfer. The first is manifested in the chemical bond and released during chemical reaction and the second in dilution or dissipation of reaction products throughout the environment.

The exergy of mixing also called composition-dependent component of chemical exergy (Szargut et al., 1988; Abou Khalil, 2008; Le Goff, 1979) is computed for the *i*th chemical species of any reaction as:

$$Ex_i^m = n_i R T_0 \ln\left\{\frac{y_i}{y_i^0}\right\} \tag{11}$$

Ex_i^m exergy of the composition-dependent component in joules (J)

n_i total number of moles of the species

y_i activity in the thermodynamic system under consideration

y_i^0 reference activity in the appropriate environment (sea, earth crust or atmosphere)

y_i activity in the thermodynamic system under consideration. For a mixture gas y_i can be evaluated by:

$$y_i = \frac{p_i}{p_0} \tag{12}$$

where

p_i partial pressure of the gas (bar).

For a liquid in solution, y_i can be evaluated by:

$$y_i = \frac{c_i}{c_0} \tag{13}$$

where

c_i concentration of the liquid specie *i* (mol/l)

c_0 $c_0 = 1$ (mol/l).

y_i^0 is the reference activity in the appropriate environment (sea, earth crust or atmosphere) and can be found for most of the species in the textbook of Szargut et al. (1988).

For instance, if we use the case of combustion of methane CH_4 as an illustrative example, the chemical equation of the combustion is:

$$CH_{4(g)} + 2O_{2(g)} \rightarrow CO_{2(g)} + 2H_2O \tag{14}$$

The exergy of mixing of the exhaust gases coming from the methane (CH_4) is computed below by using equation (11):

$$\begin{aligned} Ex^m_{exhaust-gases} &= Ex^m_{CO_2} + Ex^m_{H_2O} \\ &= 8.314 \cdot 298.15 \left(\ln\left(\frac{1}{3.31 \cdot 10^4} \right) + 2\ln\left(\frac{1}{2.17 \cdot 10^2} \right) \right) \\ &= 38.8 \text{ kJ/mol} \end{aligned} \tag{15}$$

with $y^0_{CO_2} = 3.31 \cdot 10^{-4}$ and $y^0_{H_2O} = 2.17 \cdot 10^{-2}$ (Rant, 1956).

Based on this example, if we create new chemical substances and release these substances in the environment, their exergy of mixing becomes infinite because the initial reference activity of the substances in the reference environment is null. This is simply proved below by equation (16):

$$Ex^m_i \rightarrow +\infty \text{ because } \lim_{y^0_i \rightarrow 0} \ln\left(\frac{1}{y^0_i} \right) = +\infty \tag{16}$$

This conclusion goes against common sense. Consequently, this demonstrates that the definition of the reference environment should be considered from a dynamic viewpoint. Indeed, reference conditions change over time and the reference activities of components should be computed after the complete dissipation of the pollutant of interest.

It is important to notice from the example above that exergy is a cumulative value. This property is used in the following chapter to deal with complex systems.

4 Extended exergy accounting combined with dimensional analysis

At this stage of the presentation, it is necessary to define an approach to use exergy as an efficient environmental accounting tool for early design evaluation. Several attempts have been made to combine exergy and LCA to quantify the environmental impact of industrial processes, such as cumulative exergy consumption (CExC) analysis (Szargut et al., 1988), life cycle exergy analysis (LCEA) (Wall, 2002), exergetic life cycle analysis (ELCA) (Cornelissen, 1997) and extended exergy accounting (EEA) (Sciubba, 2003). All these approaches have been demonstrated to be scientifically relevant, but none of them can be integrated as such in the theoretical framework described in Section 2.

This is due to the fact that none of these methodologies are relevant to analyse design problems in the topological space called metric space. This space is described by a unique metric. This means in practice, that a distance *d* between design solutions can be computed. In fluids mechanics, many examples can be found of this approach (e.g., the Reynolds numbers or Froude numbers).

This transformation of the design space requires three initial fundamental conditions. In the case of exergy, these conditions are easily obtained.

First, a classification space of exergy already exists as it has been briefly described above. In summary, in the case of environmental accounting, there exist two families of exergy: exergy used for analysing the resource consumption and exergy used for analysing the environmental impact. These two families are associated with classes such as chemical and physical exergy. These classes are connected with subclasses such as standard chemical exergy, exergy of mixing for the chemical type of exergy and gravitational, electric, kinetic and heat transfer exergy for the physical type.

Second, a fundamental system of entourage exists (presented in Section 2), which links the concept of exergy with the highly formalised thermodynamic theory.

Third, the system of entourage is countable because it is based on the SI system. Exergy is measured in Joules (J).

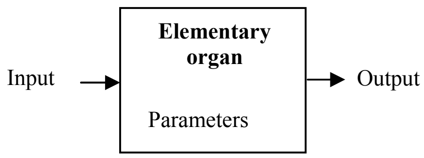
Consequently, in the case of an environmental analysis made by using our unified design framework a metrisation procedure of the design space is feasible. The purpose of the following section is to present the metrisation procedure applied to environmental analysis.

4.1 Metrisation of the design space in the case of environmental analysis

The goal of this transformation is to best achieve the phase of comparison and evaluation of concepts of solutions according to the axiom of separation/recognition of the general design theory. The field of mathematic called topology is in our viewpoint the way to achieve a unification of the design theories. This unification is our ultimate goal.

The transformation of the initial design space into a metric space can be done in two manners. Indeed, dimensionless groups also called Π numbers can be created in two ways. The first, called the top-down approach has been described by Matz (1959), Barenblatt (1979) and Sonin (2001) and uses the Vashy-Buckingham theorem to transform the design space. This approach analyses a design concept globally. The second method is a bottom-up approach which consists of creating Π numbers at the organ level. This approach has been presented by Tomiyama (1980). This method is based on the simple idea that each basic organ, which composes a complex structure, is ruled by a law (or several laws). The law can be organised in the following manner (Figure 1).

Figure 1 An elementary organ and a law for this organ



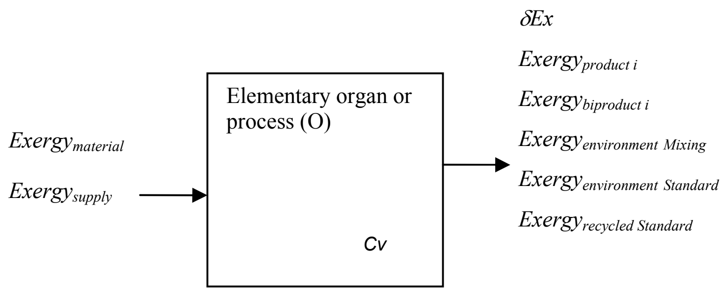
$$\frac{Output}{Input} = f\,(parameters)$$

In the case of the environmental analysis made by using the concept of exergy, both the input and the output represent exergy and they are both are measured in Joules (J). The ratio presented in Figure 1 is consequently dimensionless. In the same manner, the function *f*(*parameters*) (Figure 1) is also dimensionless.

This dimensionless metric is an exergy efficiency of the elementary organ. This is a type of environmental performance. For another type of design performances, we can also build dimensionless groups. This approach can facilitate later a multi-objective optimisation.

According to the presentation of the concept of exergy made in Section 3, different types of inputs and outputs exist. The following figure lists these inputs and outputs.

Figure 2 Type of exergy inputs and outputs of an elementary organ



The inputs to the process are represented in the most general case by the exergy of raw materials ($Exergy_{material}$) and the exergy supply ($Exergy_{supply}$). The outputs consist of the exergy of the desired products and biproducts ($Exergy_{producti}$, $Exergy_{biproducti}$), the exergy rejections to the environment ($Exergy_{environment\ Mixing}$) computed via the exergy of mixing formula, the exergy rejections to the environment ($Exergy_{environment\ Standard}$) computed via the standard chemical exergy formula, the flow of exergy of waste not directly rejected in the environment ($Exergy_{recycled\ Standard}$) and the exergy loss ($\delta Ex$) due to irreversibility.

Several dimensionless numbers can be built if considering material/resource consumption or environmental impact. The two families are presented below.

Material and resource consumption numbers

The 'primary exergy conversion efficiency' (PECE) of the organ or process is computed as the exergetic ratio of the sum of the useful output to the sum of the inputs that concurred to produce it:

$$\Pi_{PECE} = \frac{Ex_{product-i} + Ex_{biproduct-i}}{Ex_{material} + Ex_{supply}} \tag{17}$$

The 'material and resource consumption efficiency' (MRCE) of the organ or process is computed as the exergetic ratio of the output, except the exergy loss, to the sum of the inputs minus the recycled biproducts.

$$\Pi_{MRCE} = \frac{Ex_{prod-i} + Ex_{env-Stand}}{Ex_{Material} + Ex_{Supply} - Ex_{Recy-Stand} - Ex_{biprod-i}} \tag{18}$$

Environmental impact number

The 'environmental impact efficiency' (EIE) of the organ or process is computed as the exergetic ratio of the sum of the inputs to the exergy of mixing.

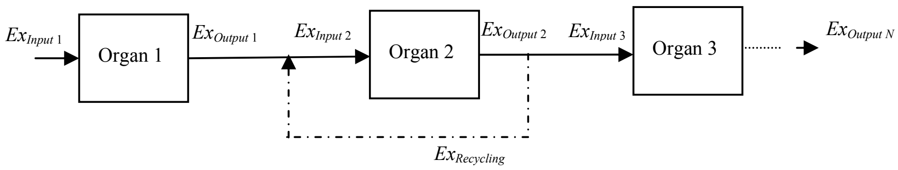
$$\Pi_{EIE} = \frac{Ex_{Env-mixing}}{Ex_{Material} + Ex_{Supply} - Ex_{Recy-Stand} - Ex_{biprod-i}} \tag{19}$$

Π_{PECE}, Π_{MRCE} are thermodynamic metrics, when Π_{EIE} is an environmental impact metric.

4.2 Combination of basic organs for exergy accounting

The section above has presented the exergy accounting in the case of a single organ. The present section defines a simple method to consider separately basic organs of a complex structure during environmental accounting.

Figure 3 A complex structure composed of basic organs



Based on Figure 3, we can write an overall exergy ratio, having the following form:

- Overall exergy ratio (general form):

$$\Pi_{Overall} = \frac{Ex_{Output_N}}{Ex_{Input_1}} = \frac{Ex_{Output_1}}{Ex_{Input_1}} \cdot \frac{Ex_{Output_2}}{Ex_{Input_2}} \cdot \frac{Ex_{Output_3}}{Ex_{Input_3}} \cdots \frac{Ex_{Output_N}}{Ex_{Input_{N-1}}} \tag{20}$$

- Input of the organ 2:

$$Ex_{Input_2} = Ex_{Output_1} + Ex_{Recycling} \tag{21}$$

- Input of the organ 3:

$$Ex_{Input_3} = Ex_{Output_2} + Ex_{Recycling} \tag{22}$$

Then:

- Input of the organ 2 function of the output of the organ 1:

$$Ex_{Input_2} = A.Ex_{Output_1} \tag{23}$$

And in a similar way:

- Input of the organ 3 function of the output of the organ 2:

$$Ex_{Input_3} = \frac{Ex_{Output_2}}{B} \tag{24}$$

With A and B pure numbers bigger than 1, then:

- Overall Pi number as a product of pure numbers and organs Pi numbers:

$$\Pi_{Overall} = \frac{B}{A}\left(\frac{Ex_{Output_N}}{Ex_{Input_1}}\right) = \frac{B}{A}\left(\frac{Ex_{Output_1}}{Ex_{Input_1}} \cdot \frac{Ex_{Output_2}}{A.Ex_{Input_1}} \cdot \frac{B.Ex_{Output_3}}{Ex_{Input_2}} \cdots \frac{Ex_{Output_N}}{Ex_{Input_{N-1}}}\right) \tag{25}$$

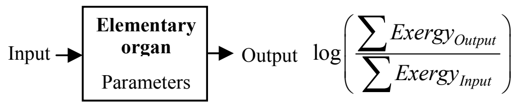
The problem is that, our goal is to make a cumulative environmental analysis starting from the basic organs and ending with the entire structure. In order to achieve this, the idea is to use a decimal logarithm function which transforms equation (25) into a cumulative form, which allows cumulative exergical analysis of a complex system. It should be noticed that the arguments of the function presented in equation (25) are *dimensionless*. Therefore the special function of equation (26) with dimensionless arguments is *derived quantities* with dimension unity too (Sonin, 2001).

- Cumulative form of the accounting:

$$\begin{aligned}\log(\Pi_{Overall}) = \log\left(\frac{B}{A}\right) + \log\left(\frac{Ex_{Ouput_1}}{Ex_{Input_1}}\right) + \log\left(\frac{Ex_{Output_2}}{(Ex_{Output1}}\right) \\ + \log\left(\frac{Ex_{Output_3}}{Ex_{Output_2}}\right) \ldots + \log\left(\frac{Ex_{Output_N}}{Ex_{Output_{N-1}}}\right)\end{aligned} \tag{26}$$

We have proposed here an approach based on exergy and dimensional analysis for the analysis of environmental impact and material/resource consumption. In addition, the method fits with the Axiom 4 of GDT (Tomiyama and Yoshikawa, 1987; Yoshikawa, 1981). This proposal is in our viewpoint an initial step toward the unification of different design theories. The general form of the environmental function for environmental analysis is presented below for a simple organ.

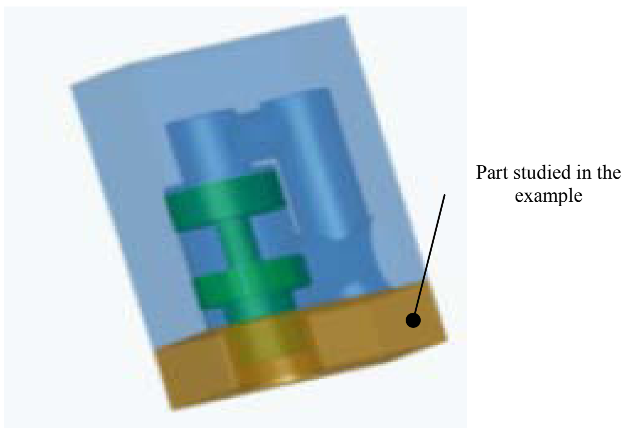
Figure 4 Exergy function for an elementary organ



5 Case study

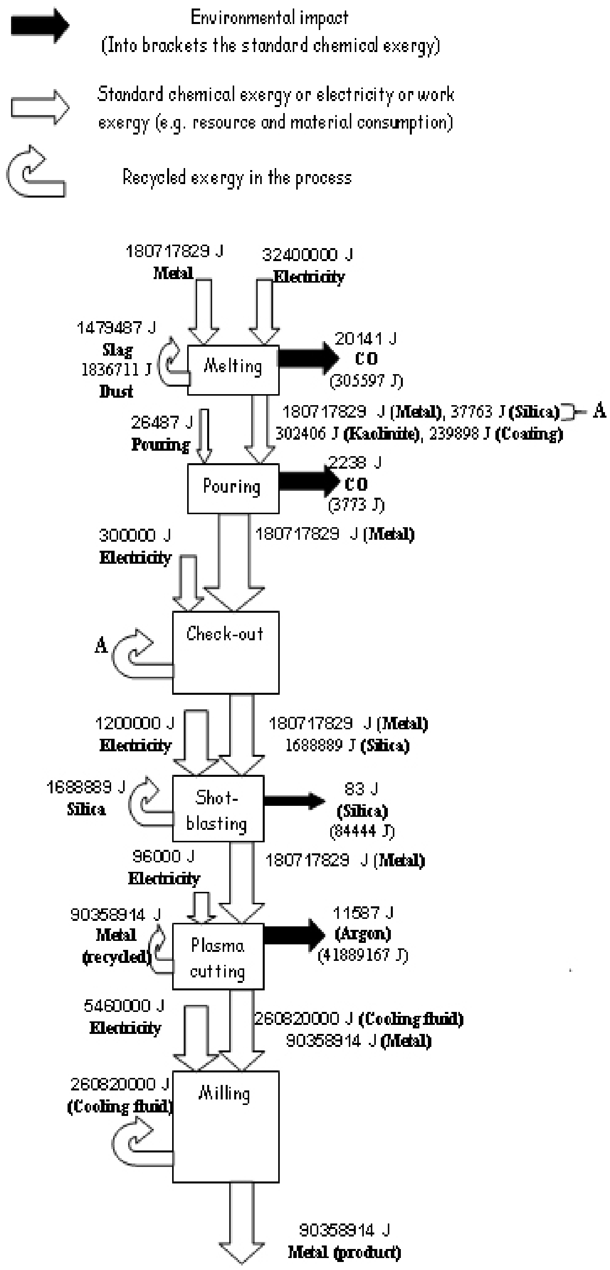
In this case study, we are comparing two manufacturing methods for a part of a fictional pressure regulator (Figure 3). The part can be manufactured by milling from a commercial plate or from a sand casting. The goal is to assess the two manufacturing processes by their consumption of resources.

Figure 5 One concept of solution for a pressure regulator (see online version for colours)



We are using commercial LCA software (SimaPro 7.1) to validate the results obtainable from the EEA with dimensional analysis-approach presented in this article.

Figure 6 Exergy accounting of the sand casting and milling process



In order to ensure comparability of both studies, the boundaries of each process are carefully examined. The algorithm of comparability developed by Coatanéa (2005) is used. The casting and milling process is composed of the following phases – melting, pouring, checkout, shot blasting, plasma cutting and milling. The milling process is composed of a single phase.

5.1 Evaluation by EEA with dimensional analysis

The functional unit used for the study is the production of one part presented in Figure 6. The volume of the part is 729 cm^3. The example studies two production cycles in order to take into account the internal recycling process. The metal selected exhibits in both cases similar mechanical properties and composition. They are both stainless steel. The foundry process is using a steel type GX 2 CrNiMo 18-12. The milling process is using an X2 CrNiMo 17-12-2. The mass of one finished part is approximately 6 kg in both cases. The foundry process requires 12 kg of material per casting and the milling process uses raw pieces weighting 9 kg.

Major hypotheses

This study has been simplified for modelling reasons. Four major hypotheses have been used:

- The exergy consumed and discarded into the environment during the pattern and sand mould manufacturing is not taken into account in the model of this study.
- The exergy consumed and discarded into the environment during the dust's collecting process is not considered.
- The milling process is considered not to discard matter directly into the environment.
- The environmental impact of the electricity production is neglected.

These hypotheses are simplifying the model. Nevertheless, in order to evaluate the impact of these choices, an additional phase can evaluate the impact of these simplifications on the result by completing a sensitivity analysis.

5.1.1 Characteristics of the equipments

Process 1 Casting and milling

The type of furnace used for preparing the steel has the following characteristics:

- Electrical induction furnace with a frequency f = 3,000 Hz. A power of 75 kW and a melting speed of 100 kg/h (Masson, 2005).

The characteristics of the sand mould are:

- type of sand and mass: Silice (SiO_2) (Jasson, 2005): 0.6 kg
- type of binder and mass: Kaolinite ($Al_2Si_2O_5(OH)_4$) (Jasson, 2005): 0.2 kg
- type of coating and mass: ($2SiO_2$, Al_2O_3, $2H_2O$) (Jasson, 2005): 0.16 kg.

The characteristics of the checkout process are:

- electrical energy of the machine (Briard, 2005): 5 kW
- checkout cycle time: 60 s.

The consumption of water is neglected because its contribution is insignificant.

The characteristics of the shot blasting process are:

- electrical energy of the machine (Briard, 2005): 10 kW
- shot blasting cycle time: 120 s.

The characteristics of the plasma cutting process are:

- electrical energy of the machine (Miller Electric, 2007): 3.2 kW
- cutting cycle time: 30 s
- neutral gas consumption (Ar) (Miller Electric, 2007): 129 l/min at 414 kPa.

After the sand casting process, a milling phase takes place. The waste steel produced by the milling process is accounted in the plasma cutting process for simplicity. The characteristics of the process are for a minimal wear's cutting speed (Vc):

- milling time: 2 mn
- power of the machine 13 kW
- flow of cooling fluid emulsion: 7 l/mn
- mass/volume of crude oil no. 5: 0.9
- proportion of crude oil in the emulsion: 0.5.

Process 2 Machining (milling)

The milling process is considered using similar cutting conditions as the ones used in the previous studied process. The characteristics of the machining process are:

- milling time: 8 mn
- power of the machine: 13 kW
- flow of cooling fluid emulsion: 7 l/mn
- mass/volume of crude oil no. 5: 0.9
- proportion of crude oil in the emulsion: 0.5.

Some gases and slag result from the melting and pouring phases. The melting phase produces around 90% of the gases (Duquet, 2005). The main gas resulting from the process is carbon monoxide (CO) some other gases are also emitted (e.g., NOX for example). The proportion of other gases has been considered as negligible for the simplification of this exercise. The production of CO is approximately of 0.16 kg/hr.

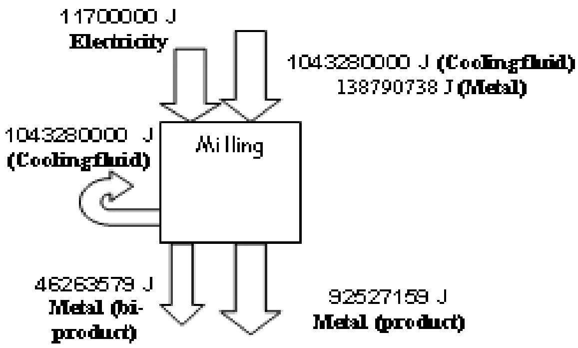
In many cases, the slag is not recycled (Duquet, 2005) so we have also considered the exergy of mixing of slag in this example. The slag is mainly composed of the following compounds (CaO, SiO_2, MgO, Al_2O_3, S). The slag is composed of 55% of CaO, 15% of SiO_2, 5% of MgO, 25% of Al_2O_3, 0.6% of S. The amount of slag produced is 35 kg/t (Masson, 2005).

In addition, the processes of melting and pouring are producing dust (10 kg/t) (Masson, 2005). The dust is composed of the following elements (S, Fe, Mn, Cr, Ni). The proportion of the elements or oxide in the dust are considered to be 0.6% of S, 18% of Cr, 12% of Ni, 2% of Mo, 57% of Fe.

The shot blasting process also produces dust. This dust is composed of silica (SiO_2). The amount of silica used by the sand blasting machine is 800 kg/h (B2). The can state that 5% of the silica is lost in the environment during the shot blasting process in the form of dust. The amount of dust in the checkout process is null because of the type of process selected (closed machine).

The calculations are presented in detail in an earlier article by Coatanéa et al. (2007). The results are summarised in Table 1 and more graphically in Figure 8.

Figure 7 Exergy accounting of the milling process



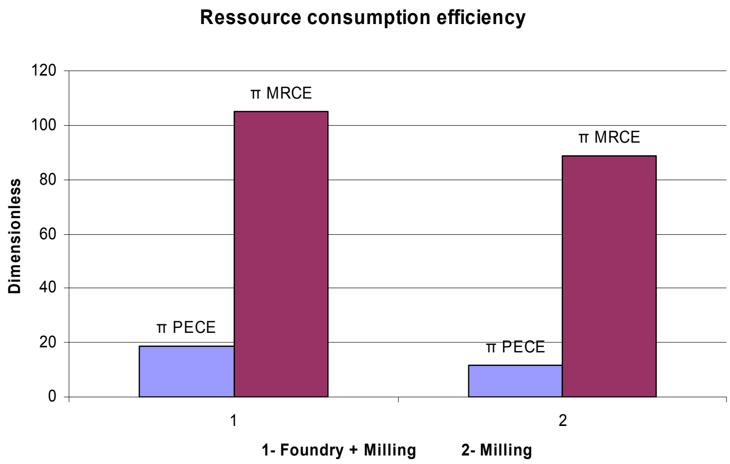
The environmental impact of the processes is low compared with the resource consumption indicators (Figure 8). This does not mean that this indicator is not significant. In our case, we notice that the environmental impact of the production process sand casting-milling is superior to the milling process because the production of gases released (CO mainly) in the atmosphere is significantly higher in the case of the sand casting process.

Table 1 Impact assessment

Production technologies		*Resource cons.*		*Environmental impact*
	Dimensionless criteria	Π_{PECE}	Π_{MRCE}	Π_{EIE}
	Optimisation goal	*Max*	*Max*	*Min*
Sand casting and milling		19	105	0.03
Milling		12	89	0

We propose, in this case study, to complete the analysis using Π numbers (dimensionless numbers) with exergy indicators measured in Joules. These exergy indicators provide us extra information compared to Π numbers. Π numbers are useful as efficiency indicators (i.e., effectiveness of the use of the resources to obtain a certain result) whereas the exergy indicators provide information about the amount of input and output. The following equations provide some of the possible exergy indicators derived from the Π numbers indicators described in Section 3.

Figure 8 Resource consumption efficiency of the two processes (see online version for colours)



Exergy output and input in Joules:

$$Ex_{Useful-Ouputs} = Ex_{product\ i} + Ex_{biproduct-i} \tag{27}$$

$$Ex_{Inputs} = Ex_{Material} + Ex_{Supply} - Ex_{Recy-Stand} - Ex_{Biprod\ i} \tag{28}$$

Table 2 Exergy consumptions and production in Joules

Exergy consumption and production	*Exergy useful outputs*		*Exergy inputs*
Sand casting and milling	Product	90,358,914	126,525,204
Milling	Product	138,790,738	104,227,159
	Waste	92,527,159	

Figure 9 Exergy inputs (see online version for colours)

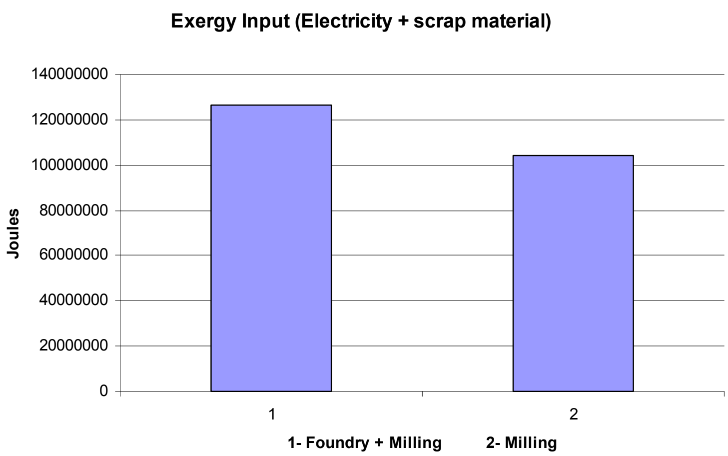
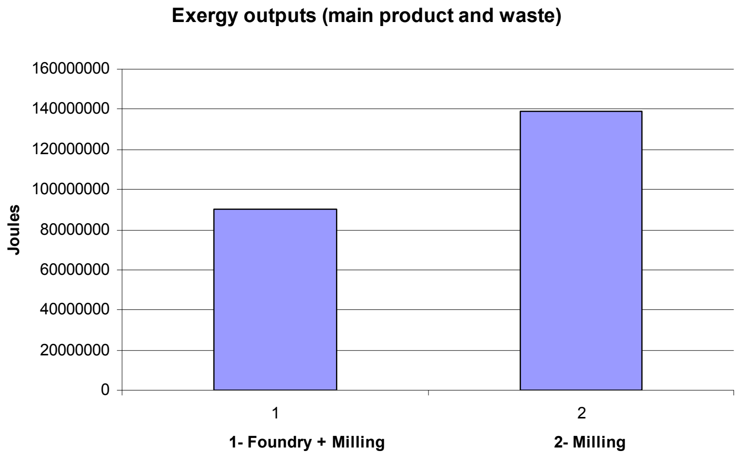


Figure 10 Exergy outputs (see online version for colours)



The exergy input is significantly superior for the sand casting + milling process because the indicator takes into account the electricity used and the scrap material reinjected into the process. Consequently the exergy output is opposite because Process 2 (milling) considers both the machined part and the wasted metal, seen here as a biproduct. All this information should be interpreted with great care about the material consumption of the processes. Nevertheless, the sand casting + milling process seems to be better because the difference between the exergies in Figures 9 and 10 is advantageous for this process.

5.2 LCA approach

5.2.1 Modelling and inventory analysis

As in the exergy approach, the functional unit considered is a steel part with a volume of 729 cm^3. For both the casting and milling and the machining (milling) processes, the steel used is X2CrNiMo 17-12 which is provided in the SimaPro database and is close to the steel used in the exergy approach.

Major hypotheses necessary to compare the LCA with the exergy approach

- Elements such as the cooling fluid are believed to be in a closed loop and therefore are not represented.
- Logistics and transport internal to the processes (inside the plant) are not taken into account.
- All energetic input is considered to come from the same source (Electricity Netherlands ETH1 I).

Figure 11 LCA model of a cast and milled plate

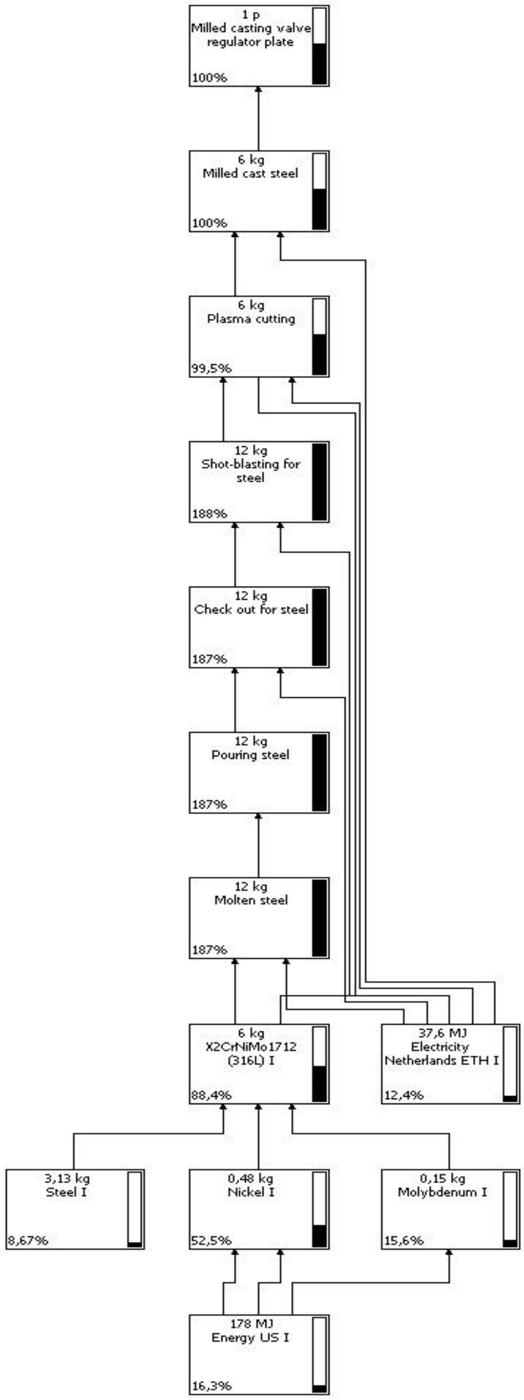
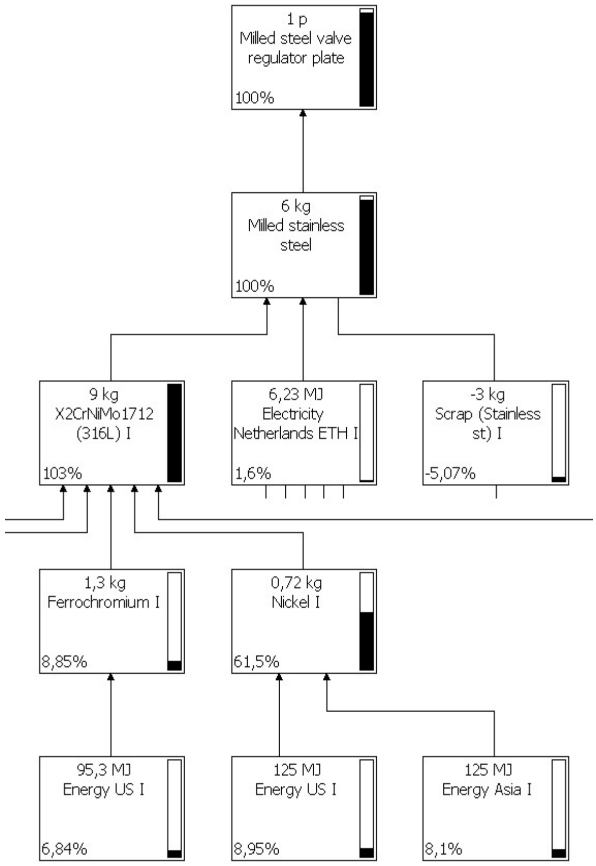


Figure 12 LCA model of a milled plate



5.2.2 Modelling of the processes

The processes were modelled on the details given in Cornelissen (1997) and mentioned in the exergy approach. To include the material and energetic input as well as the biproducts, waste and other outputs, we created a specific product for each phase of the processes (see Figures 11 and 12). The LCA database in SimaPro contains generic, widely used products and processes. To model correctly the different processes we created some products such as slag and a sand mould with basic products already included in the databases. This allowed us to store information for future studies and consider impacts of single products used in the processes.

The main difference between the two processes is the internal recycling that is possible when in presence of a foundry structure. This part of the casting and milling process is shown during the plasma cutting phase. Like in the exergy approach, all the waste steel produced by the milling process is accounted in the plasma cutting phase for simplicity. Moreover, the waste steel after this stage is not considered as scraps or waste but rather as a steel biproduct that can be injected during the melting phase.

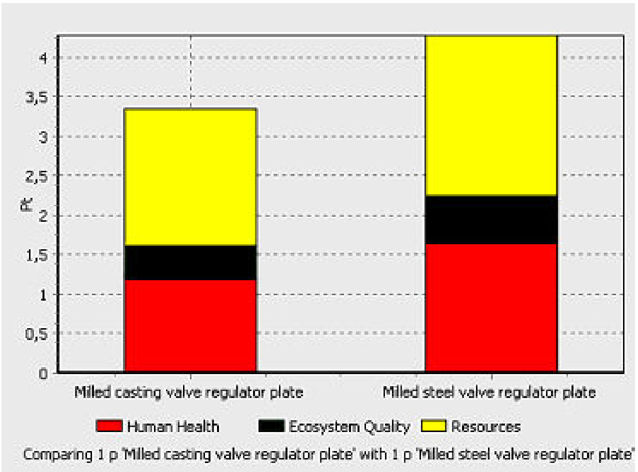
5.2.3 Impact assessment

The two processes were compared using the Eco-indicator 99 (H) method. This method follows a hierarchist archetype, widely accepted impacts are taken into account and they are estimated with a balance between a short and long term perspective. Table 3 and Figure 13 present the different criteria of comparison used in the method. For all three criteria, the plate made by casting and milling has a lower impact than the one only made by milling.

Table 3 Impact assessment

	Process 1	*Process 2*
Human health	1.74	2.05
Ecosystem quality	0.42	0.58
Resources	1.18	1.65

Figure 13 Comparison of the impact of the casting + milling and milling alone plates (see online version for colours)



5.3 Comparison of the exergy and LCA approaches

Both the exergy and LCA approaches use dimensionless indicators to evaluate the impact of a process. The basis for the dimensionless indicators is not the same for the two methods and therefore a direct numerical comparison is impossible. LCA most commonly uses a hierarchist approach whereas the exergy study proceeds in a more egalitarian manner.

The main interest of the exergy approach has been demonstrated through the use of different kinds of indicators the Π numbers and the exergy indicators. This has been made possible because from the very beginning we are using a unique metric which does not require aggregation (if we consider equality in the importance of the Π numbers and exergy indicators). Preferences between the indicators can also be considered but are not treated in this work.

In this aspect, because of the variety of metrics used in the LCA approach, aggregation is made necessary, which increases its lack of scientific reliability. This lack of reliability is due to the necessity to get aggregation factors. Those factors are based on experts' considerations (i.e., EI99). This is not a scientifically coherent approach. This drawback is overcome in the case of the exergy approach.

In both the LCA and exergy studies, the resource consumption impact is less important in the casting and milling process. As said above, in this study, we cannot compare number to number as the two approaches study different aspects of resource consumption. The exergy study looks at the efficiency of the use therefore a part can be made from a large amount of resources but if they are used efficiently, the Pi number will be low. In the LCA study, the resource consumption only gives information on the total amount of resources used at the end. In our study, the part made by casting and milling allows a great amount of steel to be reused; if this were not the case, the resource consumption would be greater.

In the case of the environmental impact study, both approaches seem to provide opposite results. This is due to the fact that the hypotheses used in the case of the exergy approach focus our study mainly on the impact of the manufacturing processes. For example, the use of the electricity or other resources necessary to produce the steel used into the milling process has not been considered in our study. Only the exergy of the mixing of steel has been considered. In the case of the LCA approach, the study is more holistic; this is the reason of this difference. Nevertheless, the results provided with our hypotheses in the case of the exergy study are in agreement with the knowledge of experts in the domain.

A general Eco-indicator 99 (H) LCA study also gives impacts on human health. The exergy approach does not study such numbers.

This study has also demonstrated us that the exergy methodology is much more scalable than the LCA approach. This is an important characteristic for the use of exergy as a design tool for the early design process.

6 Conclusions

There is a need for a more focused and lighter, yet comprehensive method, for environmental evaluation in early design phase, since the reliability and practicability of traditional LCA approach during the conceptual design process is unsatisfactory. The concept of exergy provides a uniform metric for such an evaluation. Using dimensional analysis for exergy calculations, the environmental assessment can be merged into an existing integrated design framework dedicated to conceptual design by using only a limited number of base quantities.

This article has demonstrated that the results obtained with an exergy approach using dimensionless numbers can be compared to those from an LCA study. It is a step further towards the validation of the exergy approach in the EEEA.

The framework presented in this article uses existing information already published in books treating exergy. In addition, the method is not time consuming, the data needed to create exergy Pi numbers can be held in limited databases and could be easily integrated into CAD software. This is a very important aspect because this is probably the most criticised aspect of traditional environmental analysis methods. The last part of the proposed method (e.g., the improvement assessment) has not been used in this example because of the limited format of the article.

Future work will concentrate on extending the exergy approach to different types of requirements in order to compare more data from exergy and LCA studies. The exergy approach will also be integrated in existing design tools such as CAD tools. This is possible because the exergy approach requires a small amount of data and consequently is very portable. We have already developed excel tables allowing us to computerise the exergy calculation process.

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COMPARATIVE STUDY OF ENVIRONMENTAL EVALUATION ASSESSMENT USING EXERGETIC LCA IMPLEMENTED IN EXISTING SOFTWARE AND A NOVEL EXERGETIC APPROACH DURING THE EARLY DESIGN PHASE

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ABSTRACT
Current environmental evaluation analysis methods such as LCA require detailed information about the studied product or process. This leads to uncertain or wrong results when applied during the early design phase. As a result all the design choices must be made before performing such environmental analysis, consequently such methods are not truly design tools. The proposed exergetic approach offers an appropriate solution for an environmental evaluation during the early stages of the design process. A key aspect of this exergetic approach is a combination of a classical exergy and dimensional analysis. In previous works, the exergetic approach has been compared using LCA eco-indicator 99 (H), as the LCA method is a widely used and accepted method. This article aims at further validating the exergetic method by comparing it to the LCA exergetic method implemented in existing, widely spread, software. The comparison of the two approaches is done through a case study which is part of a project that is in the early design stage. This work is a part of the development of a tool that provides a model-based approach of the entire engineering design process.

Keywords: Exergy, environmental evaluation analysis, LCA, validation

1 INTRODUCTION
The knowledge required for a full Life Cycle Assessment (LCA) most often does not match the knowledge present at the early stages of product development. Indeed, during those stages, very few parts are known for a fact which makes a reliable full environmental assessment difficult to obtain.
The development of tools providing repeatable methods based on generic metric aggregating several aspects of the impact assessment is essential for providing correct environmental assessments right from the early stages of product development.
The goal of this article is to further compare the introduced exergetic method to widely implemented methods. It should be mentioned that the introduction of the exergetic approach combined with Π numbers is part of a very ambitious program aimed at developing a model-based approach of the entire engineering design process. Exergy is used as a combined metric derived from the basic metrics of the SI system. Π numbers are part of the Dimensional Analysis Theory [1], [2] and this constitutes a powerful tool to transform the design space into a design space called metric space. This result comes from the branch of mathematics named topology. One fundamental result of topology is that a metric space is the best suited one for comparison [2], [3]. These two elements are part of a model-based project implemented in computer tools and should support more a intensive use of computers in the early phases of engineering design. The present article participates in the construction of an ontology layer dedicated to environmental and life cycle assessments. The global ontology system will be designed using a set of ontology layers mapped together using the Simantics language [4]. Simantics has similarities with Protégé and its ontology language OWL.
Figure 1 describes a potential combination of ontology in simanitcs.
We consider that the above digression is a necessary step to put our research in perspective of our global project involving several researchers.

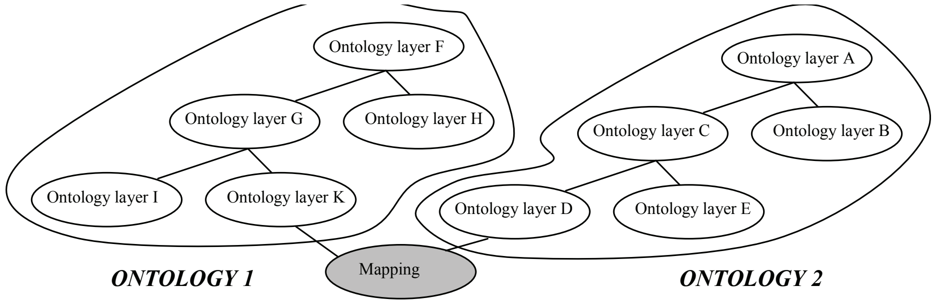

Figure 1: Mapping between ontologies of engineering design

Life Cycle Assessment (LCA) is a widely used environmental impact assessment method, even though its scientific reliability has been criticized. A comparative study between the exergetic method and LCA using Eco-Indicator 99 (H) has been performed in a previous work [5]. Recently LCA has been coupled with exergy in the Cumulative Exergy Demand (CExD) indicator in the software SimaPro 7.1.8. This software is the basis for the comparative study performed in this paper.

The rest of this paper is organized as follows:

Section 2 presents the state of the art of exergy research which started developing in the 1950's with research by Rant [6] and others such as Wall [7].

Section 3 gives an overview of LCA and exergetic LCA implemented in software. The method is based on the research of Bösch *et al.* [8].

Section 4 is a presentation of the exergetic approach developed by Coatanéa [2] using dimensional analysis as a central tool for the comparison and evaluation of concepts. The method is further presented in the case study.

Section 5 presents the case study of the article. Two systems are compared using both exergetic LCA and the developed exergy approach.

Section 6 and 7 contain the comparison and discussion of the results. Section 6 summarizes the results. Future research works for a complete early design phase environmental assessment tool are presented in Section 7.

2 STATE OF THE ART IN EXERGY RESEARCH

Exergy can be regarded as a measure of useful energy by the definition of Rant [6], it is stated to be the maximum amount of work that can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference environment. Wall [7] defines exergy as work, or ordered motion, or ability to produce work as opposed to energy which is motion or ability to produce motion. Exergy is expressed in Joules (J) or ML^2T^{-2} using the international system of fundamental quantities with (M) Mass, (L) Length and (T) Time. Whereas energy is always conserved as per the first law of dynamics, exergy is consumed in real world processes as stated in the second law of thermodynamics [9]:

$$\delta Ex = T_0 \sum \Delta S \tag{1}$$

Ex = Exergy loss due to irreversibility inside the system (J)
T_0 = Temperature of the surroundings (K)
S = Entropy (J/K)

2.1 Exergy as an environmental metric

According to Seager and Theis [10], there are six broad categories of sustainable metrics: financial, thermodynamic, environmental, ecological, socio-political and aggregated metrics. Exergy is classified as a thermodynamic metric rather than an environmental metric. Multiple propositions have been made for environmental metrics such as a simple waste exergy accountancy [11] or exergy of mixing [12].

2.2 Exergy calculation

The formulas on which most exergetic calculations are based can be found in Szargut [9]. Exergy has four basic forms, kinetic, potential, chemical and physical. In the case of an environmental study, only the chemical and physical exergies present an interest.

Physical exergy:

$$Ex_{Ph} = m[(h - h_0) - T_0(s - s_0)] \quad (2)$$

m: mass (kg),
T_0: temperature of the environment (K),
h: specific enthalpy of the flow (J/kg),
h_0: specific enthalpy of the flow at temperature T_0 and pressure P_0 (J/kg),
s: specific entropy of the flow (J/(kg.K)),
s_0: specific entropy of the flow at temperature T_0 and pressure P_0 (J/(kg.K))

Standard chemical exergy:

$$Ex^0_{ChP} = G^0 + \sum_i (\frac{n_i}{n_p} Ex^0_{Chi}) \quad (3)$$

Ex^0_{ChP} : standard chemical exergy of a compound (J/mol),
G_0: Gibbs free energy of formation of the compound from the elements (J/mol),
ni: number of moles,
Ex^0_{Chi} : standard chemical exergy of the ith reactand required to form np moles of the product compound (J/mol),
ni and *np*: stoichiometric balancing numbers of the appropriate chemical reaction.

An approximation of the environmental impact can be made using the exergy of mixing which represents the portion of the chemical exergy due to material transfers or changes in composition. This can be a measure of the potential chemical change due to the introduction of any pollutant in the environment as argued by Coatanéa *et al.* [13].

Exergy of mixing:

$$Ex_i^m = n_i R T_0 \ln(\frac{y_i}{y_i^0}) \quad (4)$$

Ex_i^m : exergy of the composition-dependant component (J),
n_i: total number of moles of the species,
y_i: activity in the thermodynamic system under consideration,
y_i^0: reference activity in the appropriate environment (sea, earth crust or atmosphere).

3 EXERGY APPLIED TO LCA – CUMULATIVE EXERGY DEMAND

3.1 – Presentation of LCA

Life Cycle Assessment is the most commonly used approach during the design process to determine the final environmental impact [14]. LCA is usually performed as a four-step process: 1) scoping, 2) inventory analysis, 3) impact assessment and 4) improvement assessment. During the third stage, an array of impact category indicators such as Eco-Indicator 99 (EI 99), Cumulative Energy Demand (CED) and Cumulative Exergy Demand (CExD) can be used [15].
The LCA software SimaPro describes the four stages as 1) characterization, 2) damage assessment, 3) normalization and 4) weighting. Only the first step is required by ISO standards, not all assessments include the last three steps. As described in the introduction to implementing the LCA software, the results must be thought out and communicated in a careful and well-balanced way as not to cause confusion as to their meaning [16].

3.2 – Shortcomings of LCA

As described in 2.2, exergy can be considered as a thermodynamic metric and research has been done to include exergy in environmental metrics. LCA and other systems analysis methods lack a uniform metric basis which leads to difficult comparisons or expressions of different impacts or requirements [11].

As the method is descriptive, the amount of data necessary to complete a single study is enormous. Moreover, it relies on databases which contain some data that is unverifiable and unreliable. It does not offer support during the early stage of design as all the product components have to be known before an extensive environmental impact assessment can be performed. LCA is also often seen as an external part of the design process as separate software and knowledge is required. Millet et al. [17] discuss the lack of integration of LCA with commonly used design tools such as CAD software.

There are multiple indicators that can be used to evaluate the impact after the life cycle inventory. The results greatly vary when one indicator is used over another one [8]. Each indicator focuses on a different amount of resources and characterizes them differently, for example Eco-Indicator 99 considers that water is an inexhaustible resource.

3.3 LCA combined with exergy

The idea of combining LCA and exergy has been suggested before; Cornelissen [18] proposed to extend LCA with an Exergetic Life Cycle Analysis (ELCA). It is shown that in the case of a zero-exergy process LCA can be replaced with ELCA.

The LCA software SimaPro proposes the Cumulative Exergy Demand (CExD) indicator. It depicts the total exergy removed from nature that was necessary to provide a product, therefore it's the exergy of all the resources required. Bösch *et al.* [8] provide the basis for CExD calculation for 2630 ecoinvent product and process systems. The results are shown for eight impact categories: fossil fuel, nuclear, hydropower, biomass, other renewable, water, minerals and metal.

The CExD method is also the basis for the Cumulative Exergy Extraction from the Natural Environment (CEENE) method which produces more consistent results [19]. It has not yet been implemented in LCA software.

3.4 Discussion of possible results obtained with such a method

The CExD method implemented in SimaPro provides the total exergy that needs to be removed from nature in order to provide a product and that is no longer accessible for future exploitation. The authors of the CExD indicator note that several aspects are not taken into account in CExD such as social demand of a resource or its technical availability or scarcity. As the availability of a resource is not evaluated in the indicator, fewer assumptions are made and create a more reliable database. Results obtained with the CExD indicator were compared with three major indicators, Cumulative Energy Demand (CED), Eco-Indicator 99 and CML 2001. The impact categories of CExD differ from other indicators but Bösch *et al.*[8] concluded that it is a useful LCA component.

4 EXERGETIC APPROACH

4.1 Exergy calculation – dimensionless numbers

In order to evaluate the material and resource consumption efficiency and environmental impact, several dimensionless numbers have been introduced by Coatanéa *et al.*[13] and further developed by Medyna *et al.* [5]. The creation of Π numbers transforms the general design space into a metric space and thermodynamic and environmental metrics as described below.

The concept of exergy requires different types of inputs and outputs:

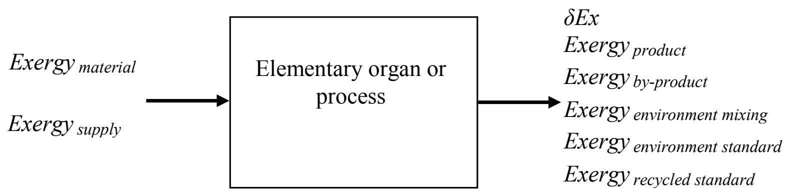

Figure 2: Types of exergy inputs and outputs in an elementary organ or process

The inputs of the process can be represented by the exergy of raw materials ($Exergy_{material}$) and the exergy supply ($Exergy_{supply}$). The outputs are represented by the exergy of the desired products and by-products ($Exergy_{products}$ and $Exergy_{by\text{-}products}$), exergy rejections to the environment computed via the exergy of mixing formula ($Exergy_{environment\ mixing}$), exergy rejections to the environment computed via the standard chemical exergy formula ($Exergy_{environment\ Standard}$), the flow of exergy of waste not directly rejected in the environment ($Exergy_{recycled\ Standard}$) and the exergy loss ($\delta Ex$) due to irreversibility.

4.2 Material and resource consumption numbers (thermodynamic metrics)

The *Primary Exergy Conversion Efficiency* (PECE) is represented by the ratio of the sum of the useful output to the sum of the inputs that occurred to produce it. A high number represents a high efficiency in the overall management of exergy:

$$\prod PECE = \frac{Ex_{product} + Ex_{by-product}}{Ex_{material} + Ex_{supply}} \tag{5}$$

The *Material and Resource Consumption Efficiency* (MRCE) is represented by the ratio of the sum of the output, except the exergy loss, to the sum of inputs, except the recycled by-products. A product that has a high efficiency in its material and resource use will have a high Π_{MRCE} number:

$$\prod MRCE = \frac{Ex_{product} + Ex_{env-standard}}{Ex_{material} + Ex_{supply} - Ex_{recy-standard} - Ex_{by-product}} \tag{6}$$

4.3 Environmental impact number (environmental metric)

The *Environmental Impact Efficiency* (EIE) is represented by the ratio of the ratio of exergy of mixing to the exergetic inputs. As the exergy of mixing represents pollution, a high Π_{EIE} number signifies a high environmental impact:

$$\prod EIE = \frac{Ex_{env-mixing}}{Ex_{material} + Ex_{supply} - Ex_{recy-standard} - Ex_{by-product}} \tag{7}$$

5 CASE STUDY

5.1 Presentation

The case study is performed on two possible systems from a project in the early design phase: the plastic cover of a reconfigurable sand casting mould.

The first system, referred to as *System 1*, is made up of three parts:

- Plastic film – preformed, cut out from a large sheet, volume: $7.987 \cdot 10^{-6}$ m^3
- Aluminium nest (top part) – 45g, machined
- Aluminium nest (bottom part) – 151g, machined
-

The aluminium nest is machined from two aluminium plates with the following dimensions:

- 120mm*120mm*5mm - 195g
- 120mm*120mm*20mm - 780g

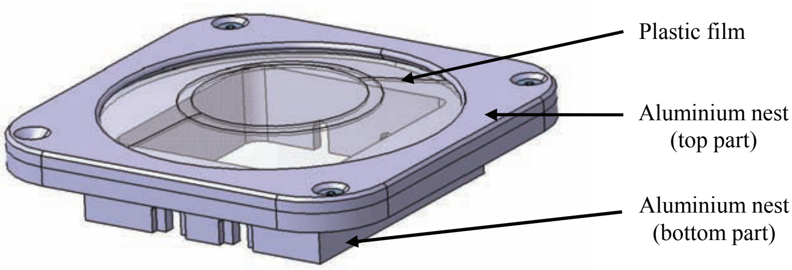

Figure 3: System 1

The second system, referred to as *System 2*, is made up of four parts:

- Plastic film – preformed, cut out from a large sheet, volume: $9{,}4 \cdot 10^{-6}m^3$
- Rubber join – cut-out from a large sheet, volume: $2.265 \cdot 10^{-6}m^3$
- Aluminium nest (top part) – 40g, machined
- Aluminium nest (bottom part) – 398g, machined

The aluminium nest is machined from two aluminium plates with the following dimensions:

- 120mm*120mm*6mm - 234g
- 120mm*120mm*22mm - 975g

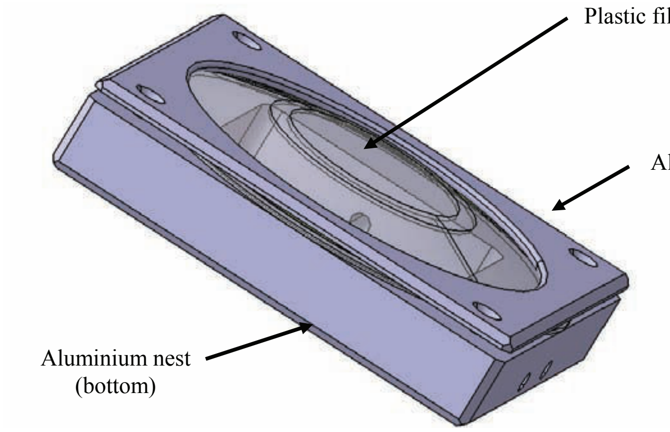

Figure 4: System 2

The machine used for all the aluminium parts is considered to a 15kW milling machine. The times for the milling are as follows:

Table 1: milling times for the aluminium parts

	Weight of raw part (g)	***Total scrap (g)***	***Machining time (s)***
System 1: top part	195	150	300
System 1: bottom part	780	629	1258
System 2: top part	234	194	388
System 2: bottom part	975	577	1154

The goal of the study is to assess the exergetic impact of the two systems using both the CExD LCA and exergetic approach.

5.2 Definition of boundaries

To ensure the comparability of the two studies, the boundaries are thoroughly examined.
The original designs for both System 1 and System 2 included four screws to hold the two parts of the aluminium nests together. In order to limit the amount of materials used and therefore simplify the study, we have chosen to disregard the presence of the screws. Indeed, the four same screws would be used in both systems and would be commercially bought.
The machining process that is used to make the aluminium nests is considered to have a perfect cooling liquid closed loop. The cooling liquid is recycled in its entirety in other milling processes. The material being aluminium, the machining can be done without cooling liquid if the cutting speed is kept low. This paper does not discuss the possibility of other production processes. For an exergetic comparison between a machining process and a process involving casting and milling, refer to [5].

One of the limitations in this study is the description of the materials used. The aluminium alloy used for the making of the parts is considered to be a standard general purpose alloy Al 98.7% Mg 0.6% Si 0.7%. Indeed, the parts discussed in this article are part of a project in development and are made using materials easily accessible and milled. To make the two studies comparable, the data used for the aluminium and steel parts are those provided by the eco-invent databases in SimaPro.
Moreover, the composition of the plastic film and rubber joint posed a problem. We make the hypothesis in the exergetic study that both are made from vulcanized rubber. Indeed the compositions of latex balloons and rubber joints are not easily found as the companies producing them prefer to keep them secret. The SimaPro study uses *Synthetic Rubber, at plant* as it is present in the ecoinvent database. Its composition is not given in the program and therefore cannot be easily used for the exergetic study.
The exergy of the assembly of the parts is not included in this study. The data for the energy necessary for the milling machine is based, for both approaches, on the data in the ecoinvent database for medium voltage energy produced in Finland.

5.3 Exergy LCA applied to the object

5.3.1 Modeling and inventory analysis

The first step of an LCA study is to make an inventory of the parts present in the systems. The inventory for System 1 is represented below in Figure 5. The second system's inventory includes a second part of synthetic rubber.

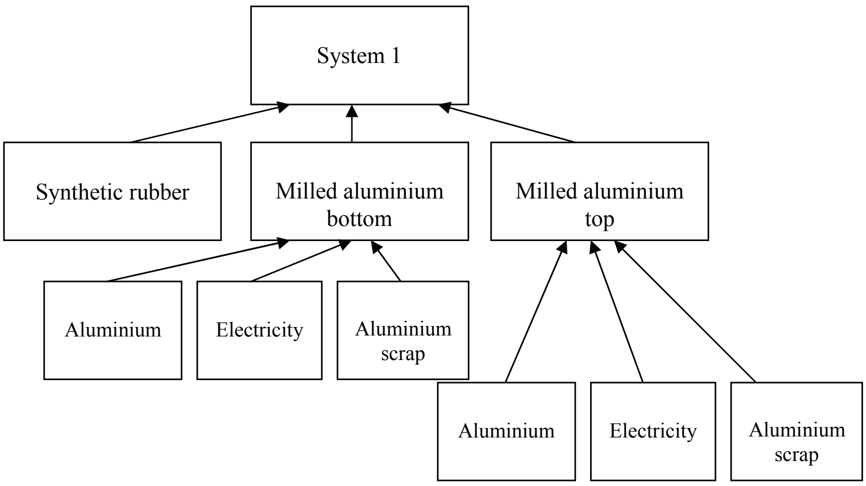

Figure 5: Model of System 1

5.3.2 Impact assessment

The two systems were compared using the CExD indicator. This method evaluates the amount of exergy loss in each category mentioned in the legend of Figure 6.
Table 2 contains the explicit values of the different exergetical impacts. All the categories but the potential exergy are more important for System 1. The most important exergetic impact is deemed to be the water exergy. As stated in [8], the exergy of water contributes on average to 8% of the total exergy demand but, in certain cases, this amount can increase to over 90%. In our scenario, the contribution is of around 94% for both systems. The water importance is due in this case to the important amount of water used in the processing of bauxite ore.

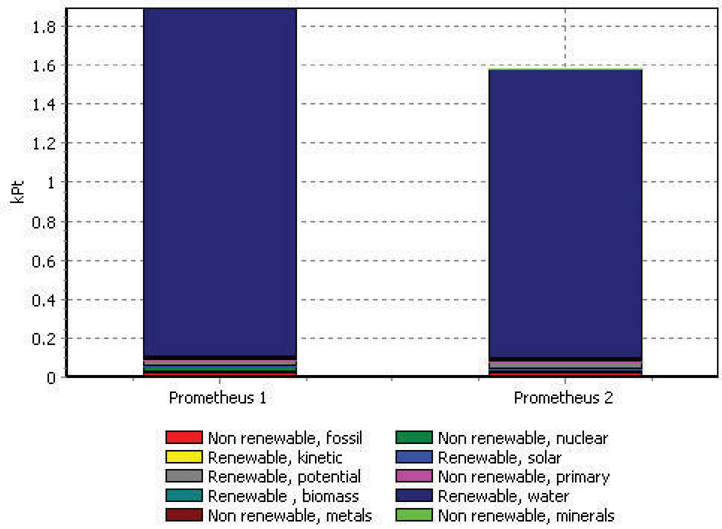

Figure 6: Comparison of System 1 ("Prometheus 1") and System 2 ("Prometheus 2")

Table 2:CExD comparison scores

Impact category	Unit	Prometheus 1	Prometheus 2
Total	Pt	1.89E3	1.58E3
Non renewable, fossil	Pt	23.3	19.3
Non renewable, nuclear	Pt	26.8	22.1
Renewable, kinetic	Pt	0.0389	0.0322
Renewable, solar	Pt	0.000121	0.0001
Renewable, potential	Pt	35.6	38.1
Non renewable, primary	Pt	1.02E-5	8.45E-6
Renewable , biomass	Pt	16.7	13.8
Renewable, water	Pt	1.79E3	1.48E3
Non renewable, metals	Pt	0.0828	0.0685
Non renewable, minerals	Pt	0.0247	0.0246

5.4 Dimensionless Π numbers applied to the object

5.4.1 Modeling and inventory analysis

The plastic film and rubber joint are represented with vulcanized rubber and the aluminium parts are made from an alloy containing Al 98.7% Mg 0.6% Si 0.7%. The density of the rubber is that of an average manufactured rubber, 1522 kg/m^3 [20].

Table 3 contains the data necessary to compute the standard chemical exergy [9]:

Table 3: Molecular mass and standard chemical exergy of single elements

Substance	*Molecular Mass (M)*	*Standard chemical exergy b^0_{ch}, kJ/mol*
Al	26.9815	888.4
Mg	24.312	633.8
Si	28.086	854.6
CH2	14.026	651.46
CH=	13.018	569.95
C=	12.01	473.02
CH3	15.034	752.03

CH-	13.01	549.91
C-	12.01	436.03
S	32.06	642.32

The different exergies indicated in Figure 8 were calculated using the standard chemical exergies in Table 3, the milling times indicated in Table 1 as well as the amounts of CO_2 rejected into the atmosphere as indicated in the ecoinvent database.

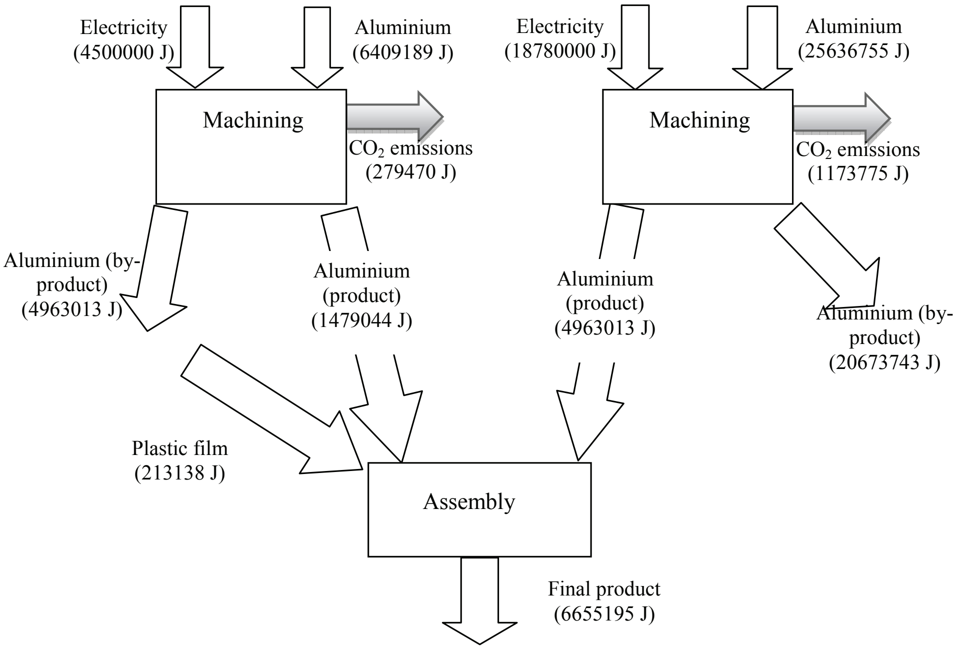

Figure 8: Model of System 1

5.4.2. Impact assessment

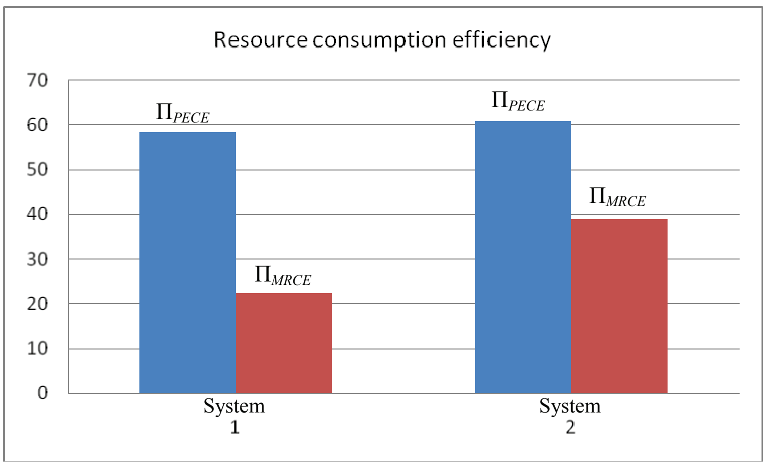

Figure 9: Resource impact assessment

As mentioned in Section 4.3. the Π_{PECE} and Π_{MRCE} numbers represent efficiency. Therefore they should be analysed in the following manner: "*the higher the better*". Therefore System 2 is more efficient from a resource consumption perspective than System 1.

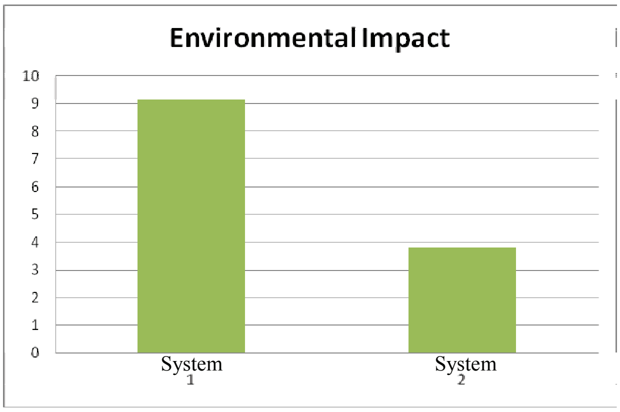

Figure 10: Environmental impact assessment

Π_{EIE} takes into account the exergy of mixing of different emissions of substances produced along with the final product but which are then rejected into the environment. In this study, the rejections considered are those of CO_2 emitted during energy production. System 2 presents less environmental impacts for CO_2 emissions.

6 COMPARISON

The two approaches above yield concordant results. Indeed, the CExD method points out that System 2 leads to a smaller exergy removal from nature to create it than System 1 and the Π number method shows that System 2 uses resources more efficiently than System 1. The two methods cannot be compared number to number because the logic behind them is different.

The first method assessed in this article, the application of the CExD indicator to the ecoinvent database is based on the computation of the total exergy removal from nature to provide a product [8]. The exergy removal measured with the CExD indicator is categorized into eight resource categories fossil, nuclear, hydropower, biomass, other renewables, water, minerals and metal. As it is known since Lavoisier, energy and matter used in society cannot be destroyed but only transformed. The usable energy and usable matter consumed are eventually depleted. The CExD indicator measures the quality of the energy and matter demand, it focuses on the amount of exergy removed from nature and the quality of this exergy. The approach pushes users to optimize the usage of resources of high quality, especially water, but *not to measure the scarcity of resources nor the environmental impact nor the impact of the disposal phase of end-of-life products or elements in the environment*. These three aspects represent in our perspective three rather important drawbacks of the approach that do not take into account two fundamental aspects of exergy, its ability to “close the loop” of life cycle analysis and the possibility to compute exergy of mixing that can be considered a manner of solving the two last issues.

The second approach combining an exergetic approach and Π numbers offers, in our viewpoint, a solution to the three limitations of the CExD indicator. This is due, for the two last points, to the fact that our calculations take into account the exergy of mixing. In addition, the scarcity of resources can be considered by providing the exergy of mixing (Equation (4)) with a reference activity (y_i^0) in the appropriate environment (sea, earth crust or atmosphere) adapted to the concentration of the local environment.

The combined exergetic and Π numbers approach is based on a different philosophy than CExD as it considers that the environment has a certain auto-regenerating capability (for at least some resources). Another difference in the vision of an environmentally friendly behaviour defended by this second approach is the possibility to release processed substances in the environment if they occur naturally in it. The only recommendation made by the authors is to release after reprocessing to ensure that the concentration level of the substance and its chemical form are similar to the local composition and reference activity of the environment. If a substance does not exist naturally in the environment, it should be reprocessed, if possible, into substances existing in the environment. The other alternatives are the destruction or the storage of the substance if no reprocessing solution exists. All these strategies derive logically from this second type of exergetic approach.

Nevertheless, the results of the two approaches are concordant but the scope of the second approach is broader. This is the key point of the analysis which tends to demonstrate once more that the exergy coupled with Π numbers approach provides coherent results.

7 CONCLUSION AND FUTURE WORK

The present article has presented further validation for the use of exergy coupled with dimensionless numbers to complete environmental assessments. The concepts of exergy and Π numbers provide a uniform metric for such evaluations. The concordance of the results obtained with the two approaches studied in this article is a step toward the complete validation of the exergetic and Π numbers approach in the early environmental evaluation assessment. While this study shows a case study of the application of exergy to an engineering problem, future work will include more complex scenarios and will not be limited to products or processes but will be extended to services.

The framework used in the exergetic and Π number study is based on existing information already published in books treating exergy. Moreover, the calculations of the Π numbers do not require many resources and therefore can be easily integrated into other software.

Future work will concentrate on the development of an environmentally oriented design tool for the early design phases. Multiple branches are currently being studied for a further evolution of the tool such as integration of value and decision theory. The final aim is to provide a tool which is light and can be incorporated into other design tools such as CAD software.

As presented above, this research is part of a larger project which will include multiple ontology layers mapped together using the simantics language. Each layer will represent a part of engineering design such as exergy, for environmental purposes, requirements, etc. More than an environmental evaluation tool, the idea is to create a model-based approach for the whole early engineering design process.

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Decision making and value considerations during the early stages of engineering design

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Abstract
Early design is a critical stage in product and service development. The choices made during this period influence the final spread and acceptance of the artefact and therefore must be made in the best possible manner. Different aspects must be taken into account during decision making such as value, risk awareness, environmental impacts, etc. The present work studies value in engineering projects using dimensional analysis and its integration in the decision making framework while putting an accent on value considerations.

Keywords:
Value, decision making, dimensional analysis, early design

1 INTRODUCTION

The first stages of engineering design are crucial for the final product or service. The choices made during the early design stages greatly influence the final cost, representing up to 70% of it. Historically, the final performance of a product was achieved through trial-and-error [1] which is time consuming and all possibilities cannot be assessed through such methods.

The work presented in this paper is part of a larger project which aims at facilitating the decision making process during the early design stages which takes into account such aspects as risk awareness, value, environmental impact, etc. The novelty of the work resides in the use of dimensional analysis and dimensionless numbers.

The notion of value efficiency is important for engineering projects as their viability largely depends on their feasibility as well as on the income they can generate. The proposed methods for measuring value efficiency rely on $\prod$ dimensionless numbers created through dimensional analysis. Dimensionless numbers are commonly used in physical representations yet dimensional analysis can also be applied to economical aspects. The use of dimensionless numbers allows for an easier comparison of models when number to number comparisons are impossible or impractical.

This work is constituted as follows:

The second part presents the state of the art of decision making in engineering design and specifically value considerations. The third section includes a presentation of the decision making model used and the dimensionless numbers developed for value efficiency. The final section includes a discussion on the proposed method and conclusions.

2 DECISION MAKING IN ENGINEERING DESIGN

Engineering design is a complex process which has been described as majorly relying on creativity, analysis, problem solving and so on [2]. The current work does not dwell on the exact definition of the design process but rather considers how to improve it. Methodologies for the early stages of design vary greatly from designer to designer and company to company. A designer's experience, but as well as education, plays a large role in the final outcome of the product [3]. For experienced designers it may be possible to achieve good results very early in the design having considered very few alternatives [4], yet some solutions may get overlooked. Given today's computer power, it is possible to make a great number of models and simulations but that is often time inefficient and resource consuming.

A review of literature related to design methodologies and decision making has been done by Ng [5]. Three major types of decision making aids are established, normative, descriptive and prescriptive, which revolve around step-oriented design methodologies. There are many shortcomings to most decision making aids and effective aids should perform the following functions:

- Allow designers to design in accordance to his or her preferences or natural way
- Enable traceability of minor design decisions
- Easily link to the design requirements

Further recommendations are given about such aspects as the inclusion of the possibility of CAD modeling and time checking.

2.1 Decision analysis and making model

Making decision in engineering design is a hard task because one is not only faced with almost-limitless possibilities but one is also required to think about the interests of many actors, the company, the environment, human values, etc. [6]. Using a decision analysis approach can help a decision-maker, in this case the designer, assess the decisions to make with more objectivity.

Different stages during an engineering project require decisions to be made. The focus of this research is the stage past the requirement specification, when alternatives must be presented to fulfill those requirements. Below is a representation of the decision making model proposed in order to choose the most suitable solution. Many different analysis processes can be found in the literature, the model in Fig. 1 is based on the framework provided by Clemen [7].

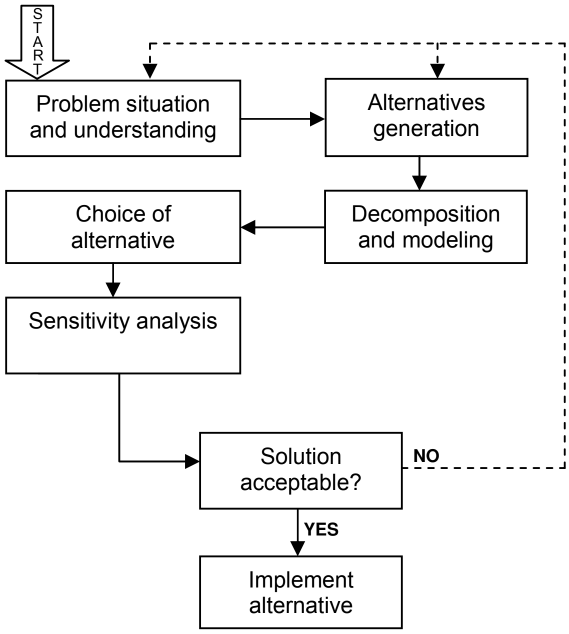

Figure 1: decision making model

Below is a shot summary of the contents of the different stages:

Problem situation and understanding: careful identification of the decision problem as not to address the wrong problem

Alternatives generation: alternatives can be generated through creativity sessions for example. A good examination of the objectives to achieve can provide new alternatives which would not have been generated otherwise, hence the importance of the first step.

Decomposition and modeling: the problem is decomposed into manageable parts and is modeled.

Choice of alternative: provided the model of the decision problem, the designer decides which is the best suited alternative.

Sensitivity analysis: sensitivity analysis performed on the system with the chosen alternative; is the chosen solution still the optimal one even with slight changes to the model? If not, perhaps there is an alternative which will respond well to slight variations in the model. This step is especially important when considering the whole system; a slight change to one component can result in drastically increased or decreased performances of other components.

Implementation of the chosen alternative: once the decision maker is satisfied with the chosen alternative, he or she can implement it.

The present article concerns the third stage of decomposing and modeling the problem in order to make the choice of which alternative is the best suited. There are many aspects that come into play during the modeling and the final aim of the current research project is to focus on three of them as described in the section below.

2.2 Choice influencers

Many models for decision making have already been proposed for engineering projects but they generally only take into account one aspect of a project, as for example Kuo's "Green Fuzzy Design Analysis" (GFDA) which looks at environmental issues [8] which has limitations (1). The goal of the current research is to tackle several aspects which have great importance during the decision making process. The three choice influencers below are presented in the order of development during the research project.

Environmental impacts

Environmental aspects of new products and services are an important factor for many companies and research groups as societies and governments call for more environmentally conscious solutions [9]. The method proposed to assess environmental impacts uses the notion of exergy, useful energy, and was developed by Coatanéa [10] and later further studied by [11] and [12]. This aspect is assessed using dimensional analysis and was the starting point for the development of dimensional numbers outside the scope of environmental studies and physical units. The basics of dimensional analysis are presented in section 3.1. Three Π numbers related to exergy and environmental aspects have been created, the efficiency of use of resources, the efficiency of primary exergy conversion and an environmental impact number.

Value considerations

The development of new projects relies heavily on monetary input. Projects are expected to generate value [13], this value is not necessarily expressed in monetary form, it can also be as improvement in company image for example. In the case of sailing teams, which participate in such races as Vendée Globe, successful new projects result in a well placed boat which receives press and television coverage and therefore shows off the names of sponsors. This in turn pleases the sponsors who, in most cases, choose to continue the sponsorship.

In engineering projects, value is closely linked to physical properties of the different components. Using dimensional analysis, it is possible to link the economical and physical aspects and provide information for simulations and comparisons. Section 3.2 provides details of the calculations.

Risk awareness

Engineering projects contain a certain amount of uncertainty and the actors linked to a project all have different risk awareness towards that project. Risk is a complex aspect which has physical, monetary, cultural and social facets [14]. As all the actors have different backgrounds, their risk perception will be different. For example, the project leader can choose and develop an extremely daring solution which has a slim chance of succeeding on the market, yet the solution is rejected because it does not fit with the company's investment plans which give priority to small incremental innovative solutions. Therefore the time spent developing the rejected solution can be considered as wasted. Capturing the different levels of risk awareness from the start of the project and have them taken into account during the decision making process would limit possible rejection of proposed solutions by one of the actors.

Risk awareness has not been yet incorporated into the presented decision-making model. Future work will include a study the necessity of dimensionless numbers linked to risk and potentially the creation of such numbers.

3 VALUE CONSIDERATIONS IN DECISION MAKING

3.1 Dimensionless analysis

The different aspects mentioned above are not measured with the same units and therefore cannot be compared number to number. In order to facilitate comparisons and understanding, we propose the use of dimensional analysis and dimensionless numbers.

In physics, dimensionless numbers are often used to describe phenomena such as fluid flow, for example with the Reynolds number. The creation and use of those dimensionless numbers is based on Buckingham's ∏ theorem [15, 16].

In economics, dimensional analysis is often used to describe monetary evolutions over a length of time which leads to numbers with units measured in time. Dimensionless numbers are less commonly used than in physics, nevertheless, they exist. For example, economic elasticity is expressed with a dimensionless number.

Dimensional analysis relies on the transformation of design space which uses multiple metrics into a topological space called "metric space" which uses one metric, the dimensionless number. The complete definition of a metric space can be found in Bourbaki [17]. A key aspect of dimensionless analysis using Π numbers is the possibility of interaction between variables, either inside a single Π number or between different Π numbers. The study of these interactions allows a better simulation of a model.

3.2 Value model for engineering projects

In order to comprehend the link between decision-making in engineering projects and value, two approaches have been developed. Potentially only one or both can be useful to fully describe the economic side of projects. In the future, case studies will be performed in order to assess the methods.

"Input/output" economic approach

Engineering projects are made up of multiple parts. The first approach to study value presented first considers each part separately [18].

The general dimensionless number created through this approach is of the form:

$$\prod_i = \frac{\text{monetary output}}{\text{monetary input}} \qquad (1)$$

The total dimension for both the monetary input and output is a monetary unit such as the euro or dollar. The units of individual component of the dividend and divisor must not all be monetary units.

The monetary output is different for each part and is calculated as follows in Eq. 2:

$$\textit{monetary output}_i = (I_{sales} + I_{oth} - E_{market} - E_{other}) \times G_i \qquad (2)$$

where:

I_{sales} : final sale price/income,

I_{oth}: other types of income (e.g. positive image increase),

E_{market}: marketing expenditures,

E_{other} : other global expenditures (e.g. logistics),

G_i : importance of part in project

The last value should of less than 1 for all parts and the total should add up to 1. A priori, all parts should have equal importance. If the designer chooses to, he or she can set specific value for G_i. For example if the part is crucial for the functioning of the product, the value of G_i will be important whereas if the part has more of an aesthetic value, G_i would be closer to 0.

The monetary input is linked to physical data such as the materials needed and the work required to provide the final product. In order to facilitate the calculations, data linked to marketing and promotion is not considered.

Eq. 3 shows an example of the different components which can be found in a ∏ number:

$$\prod_1 = \frac{(P_{sales} - E_{market} - E_{other}) \times I_1}{W_{hours} \times P_{hour} + \sum (Q^j_{mat} \times P^j_{mat})} \qquad (3)$$

where:

P_{sales} , E_{market}, E_{other} and I_i are as above,

W_{hours} : work hours,

P_{hour}: hourly wage,

Q_{mat}: quantity of material needed

P_{mat}: price of material

All the ∏ numbers created represent the efficiency in terms of value of the parts considered.

If ∏ is largely greater than 1, the part creates great income for the company.

If ∏ is close to 1, the company is neither losing nor making profit on the part.

If ∏ is largely inferior to 1, the company is not making any profit on the part and perhaps a new study should be done to see if the value efficiency of the part cannot be increased.

As the ∏ numbers are dimensionless, they can be multiplied to represent the whole product following the product law. A proposal for the combination of multiple Π numbers from different organs has been presented in Medyna *et al.* [11]. This allows an easy estimation of the whole value efficiency of the project, the greater the final ∏, the greater the value efficiency. Such an efficiency study can then be used to compare multiple projects or alternatives inside a project during stage 3 in the decision making model.

Though facilitating comparisons and aiding the decision making process, the proposed method contains a number of shortcomings. First of all, some of the data needed may be erroneous as it is to be estimated before the final sales, such as P_{sales} for example. Should the product not sell, the number of unsold items will diminish the income per item produced. This can be taken into account in E_{other} but it can hardly be predicted before the sales happen. Moreover, more error can be introduced through the estimation of G if the proper weighing method is not used. Nevertheless, it is a starting point to the feasible inclusion of an economic aspect in the early design stage.

Economic drivers in value consideration

Each aspect of a project can be described from a physical point of view, the key of this approach is to link the economical and physical worlds. All physical components will not have the same monetary impacts; the ones with the highest impact are considered cost drivers.

These cost drivers are measured by the cost of providing a given amount of the material or product. The units for this measure are [cost]/[physical units]. Each aspect is then described through a dimensionless number as in Eq. 4:

$$\prod_1 = \frac{[\text{cost}]/[\text{physical units1}]}{[\text{physical units2}]} \qquad (4)$$

For example, if the project requires plastic tubes, the costs associated with those tubes would be:

- Material cost
- Manufacturing cost
- Logistics cost

- Recycling cost
- Other majors linked costs

The costs are estimated per appropriate physical unit, in the case of tube it is length therefore the final expression is in [cost]/[meter].

Having constructed representations for all the cost drivers, it is then possible to estimate the complete monetary impact of the project. This second approach is complementary to the first one and will be further developed through case studies.

4 CONCLUSION – DISCUSSION

The present work aims at facilitating the decision making process during the early stages of engineering design. Value considerations are essential during the decision process as companies and research group aim at generating value and remain viable. The use of dimensional analysis and dimensionless numbers allows for an easier comparison and scaling inside and of engineering projects.

There is a need for decision making aids for the design process and there are multiple options for these aids which already exist but they present shortcomings such as a lack of integration with software which engineers use or a lack of integration with the designers' methods. The dimensional analysis method only considers three choice influencers for the moment but it is possible to envision the development of other aspects if the method is deemed viable and appropriate.

As presented previously, the project of a decision making aid tool for early design is ambitious and encompasses multiple facets. While the general mainframe for decision making has been defined and dimensionless numbers have been defined for environmental impact as well as value considerations, risk awareness will be the subject of future work. Moreover, case studies will be performed for the proposed dimensionless numbers linked to value considerations. Following the completion of the work on the three facets mentioned above, a large scale case study will take place to evaluate the decision making framework.

It is mentioned in section 2 that CAD integration is highly recommended for decision tools for engineering projects. Future work will include the development of software based on the research in order to facilitate its implementation. Given the small amount of data required for the proposed method of dimensional analysis, integration with existing modeling software is possible. An important goal of the software will be to provide a graphical representation of the results to facilitate understanding and comparisons. An interesting graphical representation which could fit Π numbers can be found in CES4 [19].

For the moment the work only concerns aspects after the systems requirements have been set. As the research is done in a research group with members who also focus on the requirement definition stage, a link with even earlier phases of the design process is planned.

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Publication IV

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Environmental and economic evaluation of solar thermal panels using exergy and dimensional analysis

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Abstract

Environmental considerations must now be taken into account more and more during the development of products and processes. As the decisions made during the early phases of development influence a large part of the final structure and cost, a quick and efficient way of evaluating environmental impact is crucial to give solid bases to the decisions. This article presents a framework for an environmental and economic evaluation that uses exergy and dimensional analysis, aimed for these early stages of design. The proposed framework is illustrated through a case study on flat solar thermal panels.

Keywords:

Environmental evaluation; dimensional analysis; exergy; flat solar thermal panels

1 INTRODUCTION

Environmental considerations must now be taken into account more and more during the development of products and processes. As the decisions made during the early phases of development influence a large part of the final structure and cost, a quick and efficient way of evaluating environmental impact is crucial to give solid bases to the decisions.

Engineering projects cannot be mounted only studying a single facet such as environmental impacts or expected added value. Each project involves a combination of aspects that must be taken into account, requiring multidisciplinary work and adapted design aid tools. A large number of these tools though only concentrate on one aspect and require the input of data which is not available during the early stages of design. This problem was the motivation behind the development of an adapted tool, fit for the early stages of design and lightweight in terms of data and calculations.

In order to evaluate environmental impact in a manner that does not necessitate a large amount of raw data and calculations, a framework based on dimensional analysis and dimensionless numbers has been constructed. The use of dimensionless numbers allows easier comparisons and scaling, reasoning by orders of magnitude and the future expansion of the framework to further fields.

The current work presents the developed framework for environmental and economic aspects in Section 2. Its application to the relatively complex system of solar thermal panels is described in Section 3. Section 4 considers the further expansion of the framework and concludes on the results.

2 A DIMENSIONAL ANALYSIS FRAMEWORK

2.1 Dimensional analysis

Dimensional analysis is a powerful tool, which has had numerous applications in physics starting in the 19th century, for example in Fourier's work on heat flow or to represent fluid dynamics with Reynolds number. Dimensional analysis is used from simple error checking of physical equations to obtaining the description of the laws of a system through dimensionless numbers. These, as they are dimensionless, are especially useful for scaled models and comparisons, as they do not depend on the units used.

Dimensional analysis relies on the notion of dimensions that are commonly defined in physics, chemistry, etc. Buckingham's theorem [1] is often considered as one of the first and most important formulations of the bases of dimensional analysis. The application of the theorem and its streamlining have been the subject of multiple publications and works by Butterfield [2] among others. Relevant applications of dimensional analysis outside the traditional fields mentioned above are rare but there are, and have been, multiple research efforts. Works can be found in the fields of economics [3], psychophysics [4], operation management [5], etc.

The framework proposed in the current work uses the bases provided by dimensional analysis for environmental and economic evaluations. As there are multiple design performances that influence an engineering project, the aim is to expand the work in the future and facilitate a multi-objective optimisation of designs.

2.2 System model for the framework

A system can be studied and modelled for dimensional analysis either through a top-down or bottom-up approach. The top-down approach considers the system as a whole first. The bottom-up approach considers each part of the system separately. For the framework, we consider a bottom-up approach where each part is an organ or a process that can be described through one or several laws following the principles of the General Design Theory [6].

Each organ or process is represented in this work as shown in Figure 1, through relevant inputs and outputs.

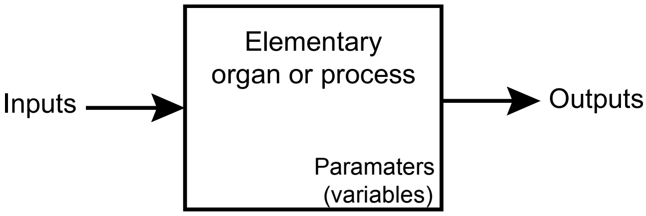

Figure 1: representation of an elementary organ or process.

In order to go from elementary organs or processes to a whole system, it is necessary to combine the dimensionless numbers calculated for each part (Eq. 1).

$$\Pi_{i\,total} = \Pi_{i1} \cdot_{\dots} \cdot \Pi_{in} \quad (1)$$

2.3 Environmental evaluation through exergy

The development of the dimensional analysis framework began as a search for an alternative to existing environmental assessment tools and software (SimePro, GaBi, etc.) which present such shortcomings as a lack of a uniform metric basis for comparison or expression of the different types of impacts. An approach through dimensional analysis creates such a metric space.

The proposed environmental evaluation is based on exergy. The notion of exergy was first introduced as "useful energy" in the 1950s by Rant [7]. Unlike energy, it is both based on the first and second laws of thermodynamics; it can be created and destroyed. The data for exergy is based on reference states and can be found in such works as [8]. Figure 2 depicts the representation of an organ or process through its exergetic inputs and outputs. The inputs include the exergy of raw materials ($Ex_{material}$) and the exergy supply (Ex_{supply}). The outputs include the exergy of the products ($Ex_{product}$) and bi-products ($Ex_{bi\text{-}product}$), the exergy rejections to the environment calculated through the standard chemical exergy ($Ex_{EnvStand}$) and the exergy of mixing (Ex_{mixing}), the waste exergy not directly rejected into the environment ($Ex_{recycling}$) and the exergy lost (Ex_{lost}) due to irreversibility. The explicit presentation and calculations of the notions mentioned in Figure 2 are to be found in [9].

Each organ, as defined in Section 2.2, is represented as shown in Figure 2.

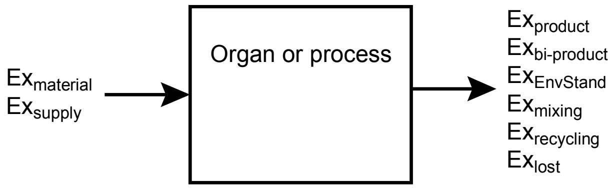

Figure 2: Exergetic inputs and outputs at the level of an organ or process for environmental analysis.

Three dimensionless parameters have been created based on the inputs and outputs indicated for each organ or process. Two of the dimensionless parameters, Π_{PECE} (Eq. 2) and Π_{MRCE} (Eq. 3), are efficiency indicators and the aim should be to increase them, while the third parameter, Π_{EIE} (Eq. 4), is an indicator of emissions and should be decreased.

$$\Pi_{PECE} = \frac{Ex_{product} + Ex_{bi\text{-}product}}{Ex_{materials} + Ex_{supply}} \quad (2)$$

$$\Pi_{MRCE} = \frac{Ex_{product} + Ex_{EnvStand}}{Ex_{materials} + Ex_{supply} - Ex_{recycling} - Ex_{bi\text{-}product}} \quad (3)$$

$$\Pi_{EIE} = \frac{Ex_{mixing}}{Ex_{materials} + Ex_{supply} - Ex_{recycling} - Ex_{bi\text{-}product}} \quad (4)$$

The proposed dimensionless numbers have been tested against a classic LCA Eco-Indicator 99 (H) approach [9] as well as a Cumulative Exergy Demand (CExD) approach [10] for a simple foundry project. The studies were performed on two manufacturing methods for a part of a pressure regulator composed of stainless steel. The results of the exergetic approach were comparable to those found using the LCA EI99 and CExD approaches in terms of environmental impact but could not be compared number to number as the specific impact categories are different for each indicator.

The case study involving flat solar thermal panels in Section 3, and in the long run, photovoltaic panels, is much more complex as a large number of organs is involved and the data is less readily available.

2.4 Economic considerations

Applications of dimensional analysis to economy have been proposed through such works as [3]. There have been a limited number of practical applications using the notion of dimensionless numbers or parameters, restricted mainly to ratios such as debt/GDP. Indeed, most of the economic evaluations done through dimensional analysis generate parameters that rely on a time factor with the final dimension of T^{-1}, $years^{-1}$ for example.

The proposed application of dimensional analysis is both based on economic and exergetic aspects. A previous effort to link the economic and exergetic aspects through dimensional analysis for the purpose of the framework can be found in [11], the current proposition holds the same spirit of seeking cost drivers, but has been reworked. As shown in Figure 3, the data necessary for the economic evaluation both covers the elementary organ or process as well as the whole system.

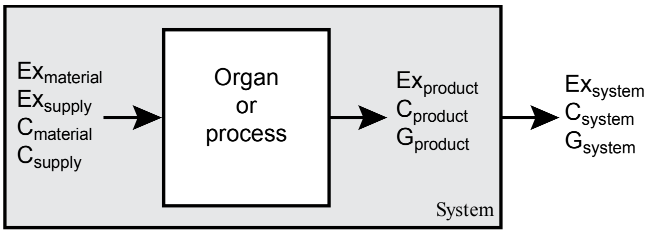

Figure 3 : Input and outputs necessary for the economic evaluation using the dimensional analysis framework.

$C_{material}$, C_{supply}, $C_{product}$ and C_{system} represent the cost of the investments made for the materials, energy supply, final product and for the whole system, respectively. To simplify calculations, all the costs are converted to euros.

$G_{product}$ and G_{system} represent the expected gain from the part considered and from the whole system. For the current calculations, the expected gain is represented in a point system where the expected gain from the whole system is evaluated at 100 points.

The exergetic data ($Ex_{material}$, Ex_{supply}, $Ex_{product}$, Ex_{system}) is the same as for the environmental evaluation, Ex_{system} being the sum of the different $Ex_{product}$ data.

The aim of this economic evaluation is not to give a full overview of every economic aspect of a project but to create and test interactions among dimensionless numbers coming from different fields. In this mind frame, three dimensionless parameters were created to represent the general economic situation of a project. The first parameter, Π_{ExC} (Eq. 5), takes into account both how the material and resources are used to make the product and how much is invested in them. The closest the parameter is to 1, the fewer the losses can be expected.

$$\Pi_{\mathrm{ExC}}=\frac{\mathrm{Ex}_{\mathrm{product}}}{\mathrm{Ex}_{\mathrm{material}}+\mathrm{Ex}_{\mathrm{supply}}}\cdot\frac{\mathrm{C}_{\mathrm{product}}}{\mathrm{C}_{\mathrm{material}}+\mathrm{C}_{\mathrm{supply}}} \tag{5}$$

Two of the dimensionless parameters represent cost drivers, sections of a system which benefit from high investments, generally justified by a high functional importance. Π_{ECD} (Eq. 6) provides information on the raw material and energy investment whereas Π_{GCD} (Eq. 7) focuses on the expected gain to come from the product. Looking at the order of magnitude of the cost driver dimensionless parameters for a single part provides information on whether the costs are well sectioned.

$$\Pi_{\mathrm{ECD}}=\frac{\mathrm{Ex}_{\mathrm{product}}}{\mathrm{Ex}_{\mathrm{system}}}\cdot\frac{\mathrm{C}_{\mathrm{product}}}{\mathrm{C}_{\mathrm{system}}} \tag{6}$$

$$\Pi_{\mathrm{GCD}}=\frac{\mathrm{G}_{\mathrm{product}}}{\mathrm{G}_{\mathrm{system}}}\cdot\frac{\mathrm{C}_{\mathrm{product}}}{\mathrm{C}_{\mathrm{system}}} \tag{7}$$

The current dimensionless parameters do not take into account the costs and expected gain obtained through recycling and bi-product schemes. Should these prove to be important, they can be incorporated into the dimensionless parameters in a similar manner as in the ones for the environmental evaluation.

2.5 Further development of the approach through interactions

The work of Bashkar and Nigam [12] showed the possible interactions between variables inside a single dimensionless number or in multiple dimensionless numbers. When working with multiple disciplines and fields, the number of variables increases and it can be difficult to understand all the implications when one of them evolves. In the example of an environmental and economic evaluation, the complexity of the variables is limited but the proposed framework is being developed in order to be expanded in future works.

The interaction between two dimensionless parameters, given that a common variable exists, is done through partial derivatives (Eq. 8). The evolution can be assessed as the dimensionless parameters are considered constant, a property which also makes similitude studies possible.

$$\left[\frac{\partial y_i}{\partial y_j}\right]^{x_c}=\frac{\partial y_i/\partial x_c}{\partial y_j/\partial x_c}=\frac{-\chi_1\cdot y_i/x_c}{-\chi_2\cdot y_j/x_c}=\frac{\chi_1}{\chi_2}\cdot\frac{y_i}{y_j} \tag{8}$$

given that the two dimensionless parameters are written in the form in Eq. 9 and Eq. 10.

$$y_i=\Pi_i\cdot(x_1^{\beta}\cdot x_c^{\chi 1}\cdot\ldots) \tag{9}$$

$$y_j=\Pi_j\cdot(x_r^{\mu}\cdot x_c^{\chi 2}\cdot\ldots) \tag{10}$$

As an example, the interaction between the exergetic resources and the linked costs is then as shown in Eq. 11 (Ex_{input} represents both the material and energy supply). The result of -1 shows that if the final product stays the same but the material and energy resources increase, the final cost of the product should be decreased for the dimensionless parameters to stay the same and therefore for the project to have the same final outcome.

$$\left[\frac{\partial Ex_{input}}{\partial C_{product}}\right]^{Ex_{product}}=\frac{1}{-1}\cdot\frac{Ex_{input}}{C_{product}} \tag{11}$$

Given the structure of the proposed dimensionless parameters, an interaction between the exergetic input and the gain is observed through the interactions between Π_{ECD} and Π_{GCD} (Eq. 12).

$$\left[\frac{\partial Ex_{product}}{\partial G_{product}}\right]^{C_{product}}=\frac{1}{1}\cdot\frac{Ex_{product}}{G_{product}} \tag{12}$$

The aim of the study of interactions among the dimensionless parameters is to provide a simple way of representing the influences one variable has on others. Figure 4 is an example of a possible representation of the interactions through a graph with some major interactions among the parameters.

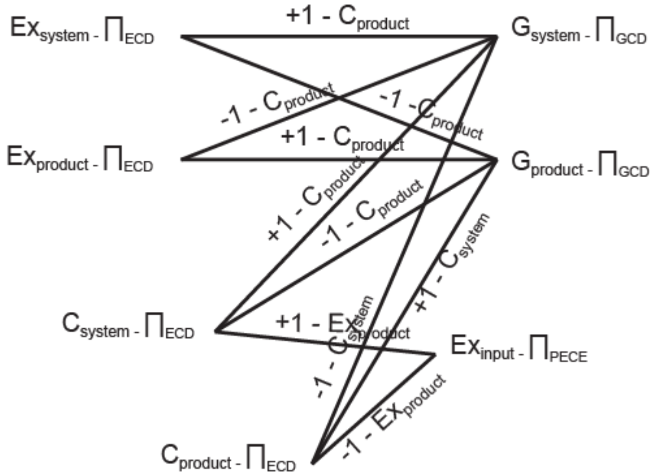

Figure 4. Representation of the interactions among the different dimensionless parameters.

As the number of fields explored through the framework increases, the importance of the representation can be expected to become more complex. The final part of Section 3.3 illustrates the practical application of such a graph.

3 CASE STUDY – SOLAR THERMAL PANELS

The following case study is part of a larger comparative study, using the dimensional analysis framework, of the use of solar thermal panels, photovoltaic panels as well as regular grid electricity in a family home in the Helsinki area. Section 3.1 provides general information on the location of the study and the house considered in the full final study. The information necessary for the present work only concerns the flat solar thermal panels.

3.1 A family home in the Helsinki area

The considered home is a family home built in the Helsinki area in Finland. The average annual solar radiation in the area is of 940 hWh/m^2 but the amount of sunlight greatly varies with the time of year. The months of May, June and July represent the peak of radiation with on average 160 to 170 kWh/m^2 per month whereas the autumn and winter months between October and February only see on average 30 kWh/m^2 per month [13].

The home has a usable roof space of 40m^2, which represents 10m^2 per person for a family of four. Given the size of a single solar thermal panel (1.2m*2.475m) [14], thirteen panels can be installed on the roof. The case study in this is not comparative but rather illustrative; all the calculations are performed for a single panel.

3.2 Solar thermal panels model

The solar panels considered are made of the following organs and processes with the main materials and processes involved indicated in parentheses:

- Glazing (low-iron tempered glass)
- Tubes (copper, cut, soldered)
- Fins (aluminium, cut, glued)
- Insulation (fibreglass, cut, glued)
- Casing (aluminium, cut, soldered)

The study is limited to the preparation and assembly stage performed by the company selling the final panels. Some components are delivered ready to use, such as the glazing, while others need to be prepared as they are easy to work, such as the insulation or casing. The exergetic study takes into account the raw materials and their extraction but not the different energetic inputs and material losses that take place during the production stages before and after the preparation and assembly.

The position of the different parts is shown in Figure 5.

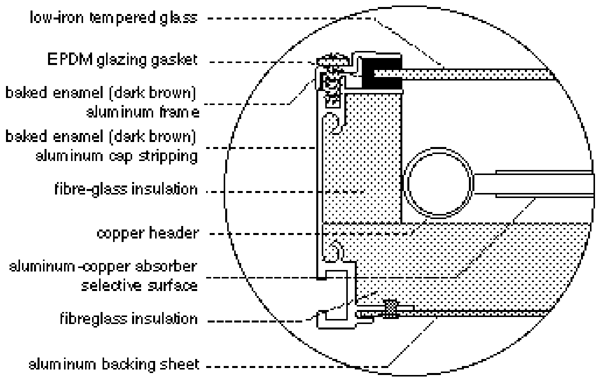

Figure 5. Components and their position on a flat solar thermal panel [14].

For the sake of length, the details of the components of each organ are not specified; the author should be contacted to obtain further information.

3.3 Application of the framework to the panels

Each organ is modelled as shown in sections 2.3 and 2.4 and that is all the necessary data for the calculations. Figure 6 represents the example of the casing for an environmental evaluation. The exergetic data was calculated based on a 3mm aluminium sheet that was cut to the appropriate sizes and soldered to form the final casing. The original aluminium sheets can be cut to only have a 5% material loss, of that material 35% can go directly to a bi-product, 45% is recycled otherwise and the rest is considered irrecoverable scraps.

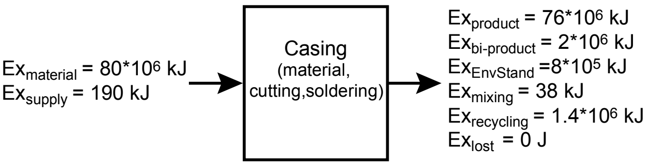

Figure 6. Data collected for an environmental evaluation for the casing of a panel.

	Π_{PECE}	Π_{MRCE}	Π_{EIE}
Glazing	1	1	0
Tubes	0.93	0.98	$\sim 10^{-2}$
Fins	0.90	1 (0.9998)	$\sim 10^{-5}$
Insulation	0.89	0.99	$\sim 10^{-3}$
Casing	0.97	1 (0.999998)	$\sim 10^{-7}$

Table 1. Environmental evaluation dimensionless parameters calculated for a flat solar thermal panel.

Table 1 contains the processed environmental evaluation data linked to the different organs of a panel. As the glazing was acquired ready to use, its resource uses and environmental impacts are considered to be non-existent as its $Ex_{materials}$ is the same as its $Ex_{product}$. The choice of the stage to study also has an impact on the results of Π_{MRCE}, the amount of material which is lost as well as the amount of energy provided to obtain the final part are low. In the studies [9] and [10] the results vary much more given the fact that foundry processes utilise large energetic inputs and produce scraps.

Similarly to Figure 6, Figure 7 shows the data necessary for an economic evaluation for the same casing. Some of the data is same as for the environmental evaluation.

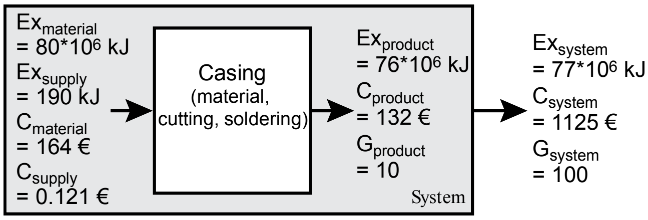

Figure 7. Data collected for an economic evaluation of the casing of a panel.

The results of the input of the data collected into the economic evaluation dimensionless numbers are provided in Table 2. Once again, the result of 1 for the Π_{ExC} is due to the fact that the part is considered to be ready to be used. The order of magnitude of the dimensionless parameters Π_{ECD} and Π_{GCD} are different for all the parts with Π_{ECD} always being lower than Π_{GCD} except for the casing. The results mean that for all the parts except for the casing the relative exergetic content is lower than the expected gain.

	Π_{ExC}	Π_{ECD}	Π_{GCD}
Glazing	1	$\sim 10^{-5}$	$\sim 10^{-1}$
Tubes	0.78	$\sim 10^{-6}$	$\sim 10^{-1}$
Fins	0.72	$\sim 10^{-4}$	$\sim 10^{-2}$
Insulation	0.74	$\sim 10^{-7}$	$\sim 10^{-3}$
Casing	0.75	$\sim 10^{-1}$	$\sim 10^{-2}$

Table 2. Economic evaluation dimensionless parameters calculated for a flat solar thermal panel.

The interactions presented in Section 2.5 show that if the gain linked to a product is increased, at constant product cost, the total exergetic input will decrease while the exergy of the sole product will increase. The information does not provide further input as to which variable should be increased or decreased in order to modify the values of the dimensionless numbers. This aspect must be developed as it responds to a need during the development of artefacts, indeed the dimensionless parameters should not be kept constant, as this would mean that the project is frozen in one state.

4 DISCUSSION - CONCLUSION

Section 3 presented the results for an illustrative study of a flat solar thermal panel with indications on the expected and needed developments linked to the proposed framework. A comparative study of a two or more solutions can provide more information, showing which solution is the best, both on single parts and overall. The next case study covering both solar thermal panels and photovoltaic panels will serve as a basis for such a comparative study.

The tool, in its current state, necessitates, as with other tools, an understanding of the different variables linked to the representations. It is essential for both the initial data gathering and the interpretation of the results. No weights have been added to the calculations making the interpretations simple to understand, should there be a requirement for weighted means, the calculations can be easily adapted.

The goal for the dimensional analysis framework is to provide a lightweight tool for the early stages of design. Currently the calculations are extremely rapid; the gathering of the necessary data for the calculations represents a large portion of the work. The main difficulty resides in the fact that the chemical composition of many components is not known and needs to be approximated. The data on the exergy of chemical compounds is extremely up to date and often covering multiple regions.

4.1 Future development of the framework

The next field considered for the expansion of the framework is risk, defined as the "possibility that a requirement is not met". This field was chosen as risk often plays an important role in engineering projects and there are very few, if any, defined dimensions which are associated with the different aspects. Working with such a notion is expected to provide further material as to the limits of a framework that uses dimensional analysis.

Literature on risk and the given definition shows that the main aspect is the mitigation of risk. Mitigation includes cost and investment notions which could provide the link towards the other proposed dimensionless numbers and come expand the interaction graph presented in Figure 4.

As pointed out in Section 3.3 there is a need to represent the interactions among variables both for constant and variable dimensionless parameters as both have distinct meanings for a project. The expanding nature of the framework also means that perhaps different representations will be explored later on to fully adapt to the needs to designers to facilitate their work, especially during the crucial first phases of development of an artefact.

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Publication V

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IMECE2011
November 11-17, 2011, Denver, Colorado, USA

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EVALUATION OF PARTS OF A BOAT CABIN BASED ON EXERGY - FOCUSING ON ENVIRONMENTAL AND ECONOMIC ASSESSMENTS

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ABSTRACT

Product and process engineering design is a complex problem which relies on multiple fields, and while many design aid tools exist they rarely take into account more than a single field or aspect at a time. This implies that a few tools have to used for a single project, making the engineer, or designer, juggle among them or favouring a single aspect. Many existing environmental assessment tools on the market only focus on environmental aspects, which are extremely important in today's impact conscious context but are not enough to make viable products and processes. Moreover the tools often require precise data which is only known during the late stages of design when it is too late to make any significant changes.

The aim of the current work is to further develop and test a multi-domain modelling framework, for the early stages of product and process design, which primarily focuses on environmental assessment but also takes into account economic aspects and can be expanded to further fields, such as risk. The two bases for the proposed framework are exergy, a measure of useful work that can be, unlike energy, both created and destroyed, and dimensional analysis, a widely used tool in engineering to model problems through dimensional homogeneity. The environmental and economic assessments proposed by the tool are illustrated on the case of insulation of the cabin on a passenger ferry and the environmental results are compared to those from two existing methodologies, Eco-Indicator and Cumulative Exergy Demand.

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INTRODUCTION

Environmental considerations are being more frequently brought into the spotlight during the design of artefacts, as decades of intense industrialized production have left visible marks and the public is made aware of such issues as resource depletion and air and water emissions. Although multiple ”green” design practices, labels, certificates, etc. have been created and are spreading, often they only create an effect of greenwashing, sometimes more resources are spent on promoting the image of being environmentally friendly than resources spent on following environmentally sound practices. It is necessary now to focus on developing science and technology, and ultimately all needed artefacts, that correspond to a sustainable development frame of mind, commonly defined as ”development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [1].

The design of an artefact is a complex process which often involves multi-disciplinary work as well as numerous decisions. The decisions made during the very early stages of the design process have the biggest impact on the final artefact and its final cost [2] and the opportunities for environmental impact minimization dramatically decrease, while their linked costs increase, as the artefact is finalized [3]. Yet the artefact data known during the early stages, such as the materials used and their quantities, are often not as well defined as during the final stages. This makes the use of certain tools such as Life Cycle Assessment (LCA) difficult and the environmental considerations often rely on the previous experience and knowledge of the design team. It is therefore important to provide a means for assessing the environmental impact, robustly, from the early stages.

Moreover engineering projects cannot rely on the study of a single facet, such as either environmental impacts or expected added value. Currently a large number of design aid tools only focus on one aspect which make them inconvenient to use as the design team has to juggle with several incompatible and unconnected tools. In order to remedy the weak points of existing design aid tools, the platform for a design aid tool for engineering projects has been developed based on dimensional analysis and exergy. These two pillars have been picked as they provide bases such as reliable databases and ground for future extensions to other fields for assessments. The design aid tool, from now on referred to as the DA-Ex approach, currently proposes environmental and economic assessments based on the platform.

The purpose of this work is to provide a further example of an application of the proposed design aid tool based on dimensional analysis and exergy and, in this regard, the paper is structure as follows. Section 2 presents the two pillars of the framework, dimensional analysis and exergy, as well as the dimensionless parameters generated to assess the studied system from an environmental and economic point of view. Section 3 focuses on the study of a few parts the cabin of a passenger ferry, the insulation and the windows. First the proposed tool is illustrated and then two existing LCA approaches are also applied. The final section discusses the results of the different studies and puts forward some concluding remarks and provides outlooks for future work.

ENVIRONMENTAL AND ECONOMIC EVALUATION BASED ON DIMENSIONAL ANALYSIS AND EXERGY

The idea for the proposed design aid tool first came into being from considering existing environmental assessment tools and the lack of uniform environmental metrics [4]. Exergy has been proposed as a possible metric as it gives a large vision of resource and waste accounting [5]. The use of dimensional analysis contributes to the creation of a metric space from a general design space and therefore facilitates comparisons [6].

The two pillars of the DA-Ex approach

Dimensional analysis. Dimensional analysis is commonly used in physics, mechanical engineering, chemistry, etc. and describes the fact that physical laws do not depend on the choice of measurement scales and units. The basic idea behind dimensional analysis is dimensional homogeneity - in other words, the fact that one cannot add up apples and oranges and one also cannot equate apples to oranges. The main purpose for dimensional analysis has long been to model problems for which the exact equations were unknown or too complex to calculate given the available computing power at the time. Today these two hurdles have been overcome in many instances, yet dimensional analysis remains a coherent and useful tool limiting the variables to handle and allowing the user to get a richer knowledge of the studied phenomenon.

Perhaps most famously, dimensional analysis is associated with the work of Buckingham [7], although earlier works on the subject exist, and his publication on a systematic approach to dimensional analysis. Buckingham's theorem, often referred to as the π theorem, represents the entry of dimensional analysis as a scientific method rather than an empirical technique and has been adjusted and augmented by others, such as [8] and [9] for example. Coatanea [6] developed a generic approach based on dimensional analysis to transform a design space into a metric space and this approach is used for the generation of dimensionless parameters for the DA-Ex tool.

Dimensional analysis is a classic tool in physics and engineering, especially after the publication of Taylor's work on the subject [10], where the notion of *dimensions* is quite clearly defined as a fundamental physical quantity (e.g. length, mass, time, etc.). The application of dimensional analysis with an exergetic approach to environmental assessment falls into this physics category, with joules (J) - $[M][L]^2[T]^{-2}$ - as main units. Dimensional analysis is sparse in other fields but it can be found in economics [11], social sciences [12], etc.

Exergy. Exergy holds a long history that can be first seen in Gibbs' concept of "available work" [13] although the modern term of *exergy* was not coined until later by Rant [14], as an expression of an "external" quantity as opposed to the "internal work" found in the literal meaning of *energy*. A comprehensive history of exergy and its different applications can be found in [15] and is an excellent starting point to fully understand the importance and interest that exergy has generated over time.

The modern, widely accepted, definition of exergy is *the maximum theoretical amount of useful work that can be produced by a system or flow of matter or energy as it comes into equilibrium with a reference environment*.

The link between exergy and environmental considerations can be made, first of all, through the notion that exergy shows the quality of energy used, this is one of the main aspects of the Cumulative Exergy Demand approach [16], for example. Moreover, through the notion of exergy of mixing, the potential chemical change attributable to the introduction of any pollutant into the environment. This has been proposed as a promising manner of assessing the environmental impact of emissions [17] [18].

Exergy and costs have been linked through thermoeconomics which applies the notion of cost to exergy therefore allying a notion that is originally an economic property to one that is essentially an energetic property. It has mostly found applications in industrial processes where understanding the quality of the energy and the possible improvements can bring cost savings. The work of Valero, for example, has provided a solid theoretical foundation [19]. Although allying exergy and costs, the method developed for the DA-Ex tool is not based on this foundation as most of the applications are in the realm of small engineering project rather than industrial processes.

Dimensional analysis and exergy for a design aid tool

In order to assess the artefact, it is first studied and moddeled in a bottom-up approach where each part, organ or process, of the system is first considered separately. Each single organ and process can then be described through one or several laws following the principles of the General Design Theory ([20] and later works) and can be represented as shown in Fig. 1 through its inputs and outputs.

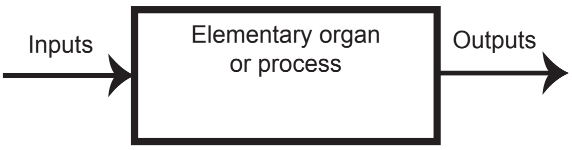

FIGURE 1. REPRESENTATION OF AN ELEMENTARY ORGAN OR PROCESS IN A STUDY.

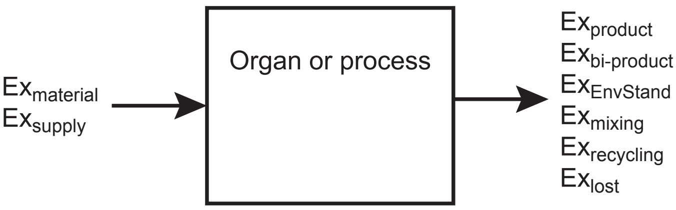

FIGURE 2. INPUTS AND OUTPUTS NECESSARY FOR THE ENVIRONMENTAL EVALUATION.

Environmental assessment. Figure 2 lists the different inputs and outputs necessary to fully describe each organ for an environmental evaluation with the proposed tool. The inputs are made up of the exergy of the raw materials ($EX_{material}$) and the exergy supply (Ex_{supply}). The outputs consist of the exergy of the desired products ($Ex_{product}$) and useful bi-products ($Ex_{bi-product}$), the emissions to the environment ($Ex_{EnvStandard}$ and Ex_{mixing}, calculated using the standard chemical exergy and the exergy of mixing formulas, respectively), the exergy of waste not rejected to the environment ($Ex_{recycling}$) and the exergy lost due to irreversibilities (Ex_{lost}). The mentioned parameters are mainly based on definitions proposed by [21] and further descriptions and calculation of each component can be found in [22]. Examples of applications of the dimensionless parameters can be found in [23], [22], [24], [25].

Equation 1 represents the *Primary Exergy Conversion Efficiency (PECE)* and considers the overall transformation of the exergy from the materials and exergy supply into useful products and bi-products. As an efficiency parameters, the higher the result, the better then exergetic conversion is.

$$\pi_{PECE} = \frac{Ex_{product} + Ex_{bi-product}}{Ex_{material} + Ex_{supply}} \tag{1}$$

Equation 2 represents the *Material and Resource Consumption Efficiency (MRCE)* which is based on the exergy of directly used materials (in the product and direct rejections) which cannot be used for other purposes and will therefore have no further value beyond their use to generate the product or process. As the parameter above, it is an efficiency measure.

$$\pi_{MRCE} = \frac{Ex_{product} + Ex_{EnvStandard}}{Ex_{material} + Ex_{supply} - EX_{recycling} - EX_{bi-product}} \tag{2}$$

Equation 3 represents the *Environmental Impact Efficiency (EIE)* based on the exergy of mixing which is the potential chemical change attributable to the introduction of any pollutant into the environment. Unlike the two parameters above, it is not an efficiency measure and therefore a higher value signifies a higher environmental impact.

$$\pi_{EIE} = \frac{Ex_{mixing}}{Ex_{material} + Ex_{supply} - EX_{recycling} - EX_{bi-product}} \tag{3}$$

Economic assessment. Figure 3 lists the different inputs and outputs necessary to fully describe each organ for an economic evaluation with the DA-Ex approach. Unlike for the environmental description, the inputs and outputs cover both the studied organ or process as well as the whole studied system.

At organ level, the inputs considered are the exergy of the raw materials provided ($Ex_{material}$) and of the exergetic supply necessary (Ex_{supply}) as well as the cost of the investments made for the raw materials ($C_{material}$) and energy supply (C_{supply}). The outputs, at organ level, are the exergy of the wanted product ($Ex_{product}$), the cost of the investments made for the final product ($C_{product}$) and the expected gain from the organ or process considered ($G_{product}$). At system level, the outputs considered are the exergy, costs of the investments made for and the gain expected from the whole system (Ex_{system}, C_{system} and G_{system} respectively). To simplify calculations, all monetary costs are converted to euros.

This economic approach was first considered in [24] and later further developed in [25]. The purpose of this assessment is to point out discordances between the costs of the investments of certain parts and their final exergetic value or the gain they represent for the final part. For example in the study of solar thermal panels [25], during the chosen life cycle phase there was a discrepancy between the exergetic content of the casing and its low cost in the final structure.

The tool does not aim to fully represent the economic situation of the tool but rather to give a general image which can be useful during the early stages of design, especially if there is a large number of elementary organs and processes involved.

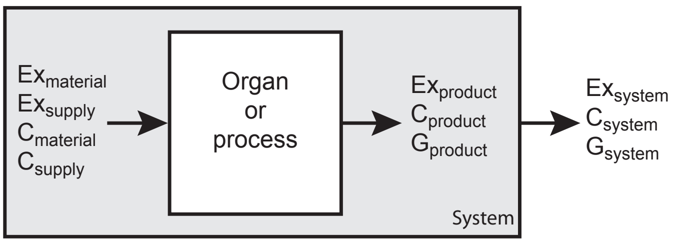

FIGURE 3. INPUTS AND OUTPUTS NECESSARY FOR THE ECONOMIC EVALUATION.

Equation 4 represents the *Exergy and Cost* links. It takes into account how both the material and resources are used to make the product and how much is invested in them.

$$\pi_{ExC} = \frac{Ex_{product}}{Ex_{material} + Ex_{supply}} \cdot \frac{C_{product}}{C_{material} + C_{supply}} \tag{4}$$

Equations 5 and 6 represent the *Exergy and Cost Drivers* and the *Gain and Cost Drivers* respectively. These two parameters convey the sections of the studied system which benefit from the highest investment, often justified by a high functional importance.

$$\pi_{ECD} = \frac{Ex_{product}}{Ex_{system}} \cdot \frac{C_{product}}{C_{system}} \tag{5}$$

$$\pi_{GCD} = \frac{G_{product}}{G_{system}} \cdot \frac{C_{product}}{C_{system}} \tag{6}$$

Expansion possibilities. One of the aims of the proposed tool is to be adaptable for multi-disciplinary work through, using the same dimensional analysis and exergy pillars. The work of Bashkar and Nigam [26] on dimensional analysis and interactions within a single or among multiple dimensionless parameters leads to the possibility of linking the difference assessments and easily modelling the impact of changes in one variable on the whole system. For the moment only two fields are assessed but a future expansion to further fields signifies a large number of variables and such a development could facilitate the understanding of the system.

The next section presents the first results from the application of the DA-Ex tool to the cabin of a passenger ferry.

CASE STUDY - CABIN OF A PASSENGER FERRY

The following study considers the passenger cabin of a real hybrid passenger ferry being developed for public transport inside the roadstead of a southern French city. Multiple sections of the cabin can be designed to minimize its overall environmental impact. The estimated energetic expenditure of cabin auxiliaries such as the heating/cooling system, automatic door system, etc. is of 10-50kW and can represent up to 10% of the total energetic consumption of the boat. The weight of all the equipment inside the cabin and making up the cabin also adds to the inefficiency of the boat as the drag increases with the mass.

Three major areas of the cabin will be considered in the full study - the generation of energy through alternative sources in order to create a self-sufficient environment, the limitation of environmental impact through the use of proper insulation and the organization of the interior to limit wastes.

The generation of energy from alternative sources has potential to create a self-sufficient environment. A considerable problem with installing new systems on a boat is the added weight which creates drag and causes energy losses. Therefore alternatively generated energy must, at least, cover the extra drag created by the weight of the generating system. Prospective solutions include high efficiency photovoltaic cells and systems that use discarded engine heat. The layout of the cabin and the internal air flow can also be optimised to limit the need for extra cooling or heating, for example a double door system that creates an airlock can be installed to prevent energy losses.

This study concentrates of the prospective insulation materials as well as two types of windows.

Model of the cabin

Figure 4 represents a simplified model of the cabin with basic dimensions. The cabin is considered to be, at first, a uniform rectangular shape, 15m in length, 4m in width and 2.20m in height. The windows represent an area of 14mx1.5m along the length of the boat and 3mx1.5m along the width. The roof does not have any windows as it can potentially host an upper deck or alternative energy sources. The area around the windows, the roof and the floor contain insulation materials. In total, there is an area of $60m^2$ for both the floor and the roof, an area of $51m^2$ for the windows and an area of $32.6m^2$ around the windows on the sides.

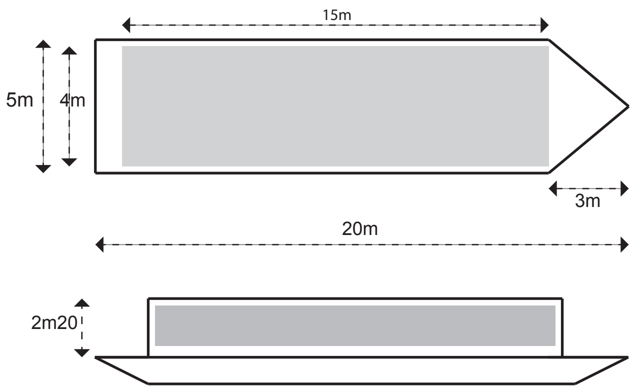

FIGURE 4. SCHEMATIC REPRESENTATION AND DIMENSIONS OF THE CABIN OF THE STUDIED PASSENGER FERRY.

The insulation, where included, is considered to be uniform. The wanted R-value ($m^2 \cdot K \cdot W^{-1}$), due to the insulation, for the sides and roof is 2.5, while it is 1.5 for the floor. These R-values were picked as they provide a decent limitation to thermal losses while maintaining a relatively small wall width. The first results presented in this work consider a constant outside environment

In order to be able to compare the results obtained through the DA-Ex approach and two classic LCA approaches, it was essential to take almost identical data for as closely comparable results as possible. The data for the three materials chosen is shown in Table 1, the area for each material is the same, the thickness was chosen as to have the same R-value. The data was obtained from [27], [28] for the rockwool, [29], [30] for the polystyrene and [31], [32] for the cellulose fibre.

For the windows, double and triple glazed windows were chosen (Table 2). The price of the windows varies with the applications, no quote for double and triple glazed windows for a maritime environment were obtained at the time of writing therefore triple glazed windows are considered to be 10% more expensive (costs start at 5% more than double glazed windows in a normal environment [33]).

The following section presents the results of the studies of the extraction phase of insulation materials and windows with multiple assessment methods - the proposed approach based on dimensional analysis and exergy (DA-Ex), an LCA study using

TABLE 2. DATA FOR THE WINDOWS.

	Double glazed	Triple glazed
Area (m^2)	51	51
Total weight (kg)	1020	1530
U max ($W \cdot m^{-2} \cdot K^{-1}$)	1.1	0.5
Total costs (€)	X	1.1·X

the Eco-Indicator 99(H) (EI-99) approach and an LCA study using the Cumulative Exergy Demand (CExD) approach, both run on the SimaPro 7 software.

Dimensional Analysis - Exergy (DA-Ex) approach

Environmental analysis In order to limit the number of tables of results, the results of the DA and exergetic approach for both the insulation materials and windows are included in Table 3 and illustrated in Fig. 5.

TABLE 3. DA-Ex ENVIRONMENTAL ASSESSMENT RESULTS.

Material	π_{PECE}	π_{MRCE}	π_{EIE}
Rock wool	$8.6 \cdot 10^{-2}$	$1.5 \cdot 10^{-1}$	$2.6 \cdot 10^{-3}$
Polystyrene	$4.1 \cdot 10^{-1}$	$6.2 \cdot 10^{-1}$	$5.9 \cdot 10^{-3}$
Cellulose fibre	$6.9 \cdot 10^{-2}$	$1.4 \cdot 10^{-1}$	$2.0 \cdot 10^{-3}$
Double glazed	$6.5 \cdot 10^{-2}$	$6.9 \cdot 10^{-2}$	$1.4 \cdot 10^{-3}$
Triple glazed	$4.9 \cdot 10^{-2}$	$5.2 \cdot 10^{-2}$	$1.3 \cdot 10^{-3}$

The DA-Ex approach applied to the insulation of the cabin shows that the choice of material is rather ambiguous. Indeed, given the results for π_{PECE} and π_{MRCE}, polystyrene insulation proposes the best exergetic and resource efficiencies, yet it is also this type of insulation which has the highest π_{EIE} and therefore the highest environmental impact calculated using exergy of mixing. The results of the calculations of π_{PECE} and π_{MRCE} might seem surprising but the exergetic supply necessary for the extraction of the raw materials is high for all three types of insulations, while the exergetic contents of the materials themselves are much lower for rockwool and cellulose fibre than for polystyrene, giving therefore an efficiency overall advantage to the latter for the material extraction phase.

For the windows, triple glazed windows have lower exergy

TABLE 1. DATA FOR THE WALLS AND FLOOR.

	Rock wool	Polystyrene	Cellulose fibre
Area (m^2) [R-2.5 + R-1.5]	[92.6 + 60]	[92.6 + 60]	[92.6 + 60]
Thickness (m) [R-2.5 + R-1.5]	[0.10 +0.06]	[0.095 + 0.057]	[0.088 + 0.053]
Total weight (kg)	347	195	433
k ($W{\cdot}m^{-1}{\cdot}K^{-1}$)	0.040	0.038	0.035
Total costs (€)	643	1052	620

efficiency but surprisingly also a slightly lower environmental impact. When considered alone, the exergy of mixing of triple glazed windows is almost twice as high as that of double glazed windows but the exergy of materials and the exergetic supply dampen its impact and create a standard π_{EIE} for windows.

In practice multiple other criteria must be taken into account when choosing the insulation material on a boat, such as the weight, fire resistance, health impacts, etc. as well as careful consideration of all the phases of the life cycle. The study of the other stage of the life cycle should also shed more light on which material to choose.

Economic analysis The overall system studied is only made of two organs, an insulation material and windows, therefore making the applications of Eq. 5 and 6 more complex as certain values are hard to define. The system variables are considered to be averages of the values linked to each organ. The gain was defined for each organ, without considering the studied alternatives, in future work this gain should take into account such aspects as reduction of weight or better thermal resistance for limiting energy losses.

Table 4 summarises the results found for the economic study. These results are also illustrated in Fig. 6 for better understanding. Fig. 6(a) shows that the polystyrene choice has the best ratio of exergy and cost investments, this is largely due to the fact that the exergy ratio is by far the best for the three insulation methods, as seen earlier in the environmental assessment. Fig. 6(b) shows that there is a small relation between the exergetic and gain cost drivers as both window types are cost drivers, indeed this can be explained by the investment that goes into the window area will have a large monetary cost and a large incidence on the efficiency of the cabin.

TABLE 4. DA-Ex ECONOMIC ASSESSMENT RESULTS.

Material	π_{ExC}	π_{ECD}	π_{GCD}
Rockwool	$6.0{\cdot}10^{-2}$	$5.9{\cdot}10^{-2}$	$3.5{\cdot}10^{-2}$
Polystyrene	$3.6{\cdot}10^{-1}$	$2.6{\cdot}10^{-1}$	$5.8{\cdot}10^{-2}$
Cellulose fibre	$5.5{\cdot}10^{-2}$	$2.4{\cdot}10^{-2}$	$3.4{\cdot}10^{-2}$
Double glazed	$3.1{\cdot}10^{-2}$	$2.8{\cdot}10^{-1}$	$7.7{\cdot}10^{-2}$
Triple glazed	$1.3{\cdot}10^{-2}$	$6.2{\cdot}10^{-1}$	$8.4{\cdot}10^{-2}$

LCA - EI99 and CExD results

Eco-Indicator 99(H). The Eco-Indicator 99 methodology contains a large number of standard Eco-Indicator values expressed for commonly used materials and processes and is widely used by designers in order to perform LCA studies and obtain comparable single scores. The approach only weighs three types of environmental damages - human health, ecosystem quality and resources [34]. In this study, the Hierarchist approach was chosen, the calculations are performed using a balanced time perspective.

Table 5 presents the results of the study, all the data is illustrated in Fig. 7. For the insulation materials, polystyrene uses the most resources overall but the damage it poses to the ecosystem quality is the lowest. As in the DA-Ex study there is no clear answer, based on this single phase and constraints, as to which material is best suited for the insulation inside a boat cabin. For the windows, the environmental impact of triple glazed windows in the extraction phase is clearly marked, as compared to double glazed windows.

Cumulative Exergy Demand. The Cumulative Exergy Demand (CExD) approach is also included in the SimaPro 7 software and depicts the total exergy removal from nature to provide an artefact. CExD uses exergy as a means to consider the quality of the energy but does not consider such aspects as availability or scarcity of the a resource, therefore allowing results which differ from other LCA approaches such as EI-99 [16].

The results of the CExD study being given through ten impact categories, separated into renewable and non-renewable re-

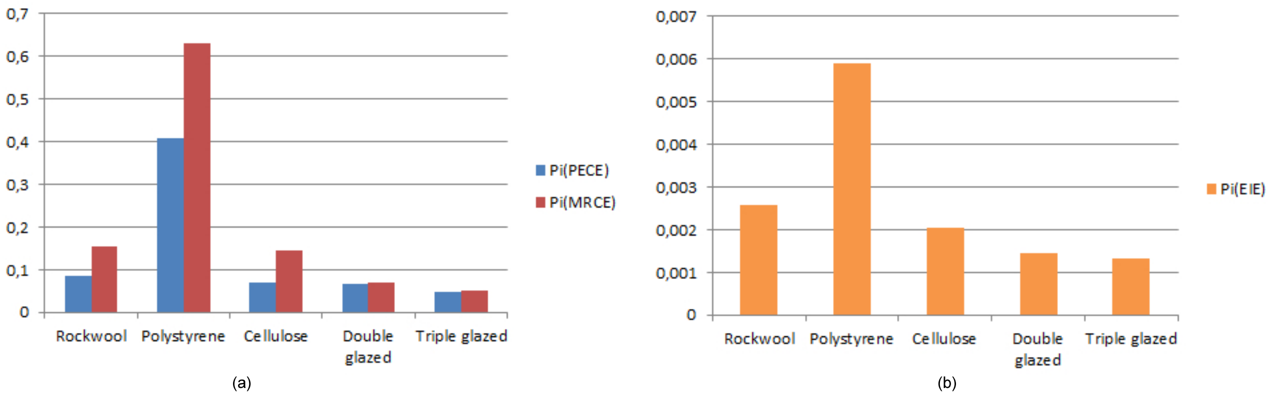

FIGURE 5. RESULTS OF ENVIRONMENTAL DA-Ex STUDY.

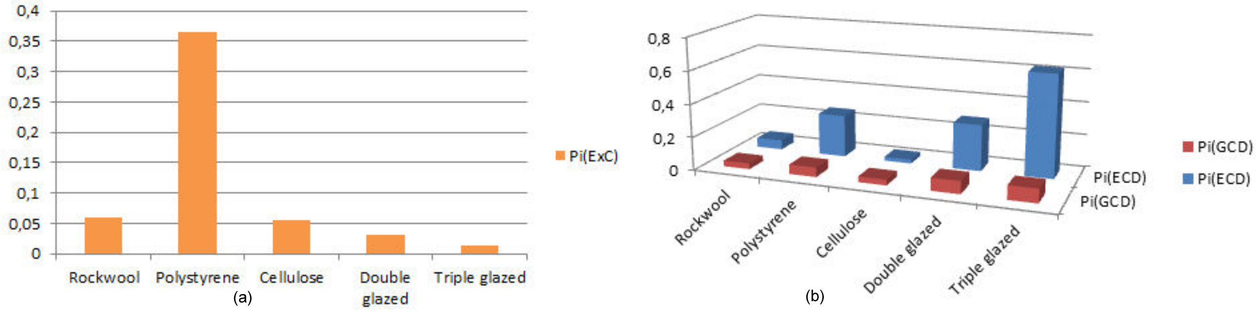

FIGURE 6. RESULTS OF ECONOMIC DA6Ex STUDY.

TABLE 5. EI-99(H) RESULTS COMPARING THE DIFFERENT MATERIALS.

Insulation type	Human Health	Ecosystem Quality	Resources	Total
Rockwool	31.3	2.6	12.6	46.5
Polystyrene	12.9	1.94	59.6	74.4
Cellulose fibre	7.47	2.85	6.51	16.8
Double glazed windows	48.9	7.25	58.8	114
Triple glazed windows	99.1	13.7	107	220

sources, they are not printed here in a table format. Figure 8 portrays the five different materials, the total of the calculated impacts is of $9.6 \cdot 10^3$ points, $5.5 \cdot 10^4$ points and $5.0 \cdot 10^4$ points for the rock wool, polystyrene and cellulose fibre insulation, respectively. For the window types, the total of the calculated impacts comes out to $3.9 \cdot 10^5$ points for double glazed windows and $1.1 \cdot 10^6$ for triple glazed windows.

If considering the single impact view, cellulose fibre is a pertinent choice for cabin insulation but its consumption of water is greater than that of polystyrene, which in turn consumes a large quantity of fossil fuels. Unlike for EI-99 which presented polystyrene as the most impacting material overall, CExD considers rockwool as the most impacting during the extraction phase. The difference between the impacts of the two window types is even more pronounced in this study with water consumption representing a large part of the impact increase.

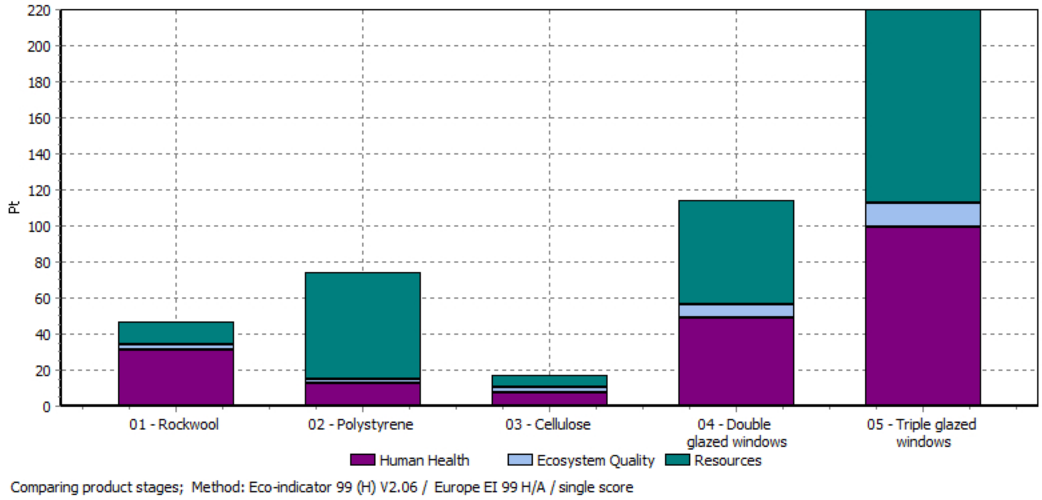

FIGURE 7. SINGLE SCORE RESULTS OF EI99(H) STUDY.

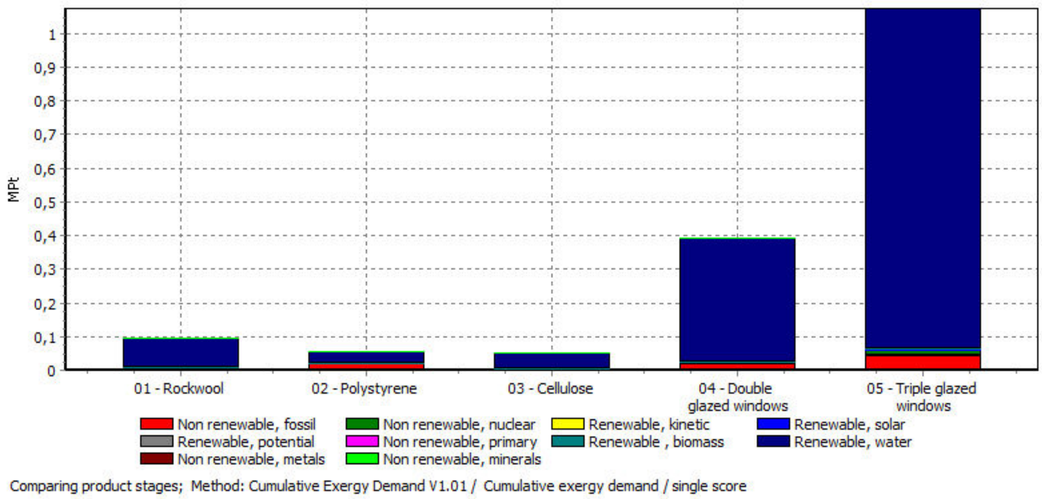

FIGURE 8. SINGLE SCORE RESULTS OF CExD STUDY.

DISCUSSIONS AND CONCLUSION

The current work presented three studies of parts of the cabin of passenger ferry, the insulation of the cabin and the windows, during the material extraction phase. Each of the assessment methods is based on different hypotheses which yielded different results in each case. Overall, for the insulation both the EI-99 and CExD approaches presented the cellulose as the material with least impacts while the DA-Ex approach put it on par with rock-wool in terms of efficiency resource and materials use, largely behind polystyrene. The environmental impact based on the ex-ergy of mixing in the DA-Ex approach also favoured polystyrene, mostly because of the large quantity of exergetic input necessary for the material extraction.

The DA-Ex approach is quite different from the EI-99 and CExD approaches as it considers the efficiency of use of the ma-terials and resources rather than their overall consumption. This approach is especially useful when considering artefacts that present a large embodied exergy. Aspects such as human health are not yet taken into account, therefore making approaches such as DA-Ex and EI-99 complementary to obtain a broader picture of different areas of impacts.

No economic comparison has been made with existing software for this study but such comparative studies are planned for the future expansion of the DA-Ex approach. The field of risk assessment is also currently being considered as a potential assessment field in future developments.

The case of the cabin of a boat is a good example of a system which allies multiple types of potential environmental impacts and multiple sources of environmental impact minimisations. This system will be further developed in the future to include the crucial use phase as well as the end of life of the ferry. Alternative energy sources will also be included in the study as they can potentially increase the environmental efficiency of the cabin.

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Modelling, Evaluation and Simulation During the Early Design Stages: Toward the Development of an Approach Limiting the Need for Specific Knowledge

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Abstract The early stages of the design process are key in the development of products and services. Nevertheless, they are marked by multiple constraints imposed on them, such as, most notably, a limited amount of time available for modelling and evaluating ideas and concepts. The present article develops an approach for modelling, and simulating initial design solutions during these critical early stages. The final objective is to minimize the amount of prerequisite knowledge a designer should have on the artefact being designed in order to propose, develop, and evaluate early models.

First, the current work analyses the conditions necessary to develop a modelling and comparison environment for early design solutions. This is done through mathematical considerations of the design process. In a second part, the work proposes a modelling and simulation approach and develops the machinery behind it. The approach integrates and maps a series of normalized semantic descriptions of functions, generic engineering components and variables, a set of elementary laws associated with these components, and a set of elementary base units. All these elements are used to refine and guide the modelling process. This process is uses the Vaschy-Buckingham theorem followed by an approximation of the generic law describing the general behaviour of elementary components. This combination leads to an approximated model of the behaviour of the studied artefact. The model is further developed by implementing the behaviour in a system dynamics tool using two basic bricks of the system dynamics language, converters and flows. In a final part, the approach is illustrated through the case study of a beam structure.

Keywords: early design, modelling, simulation, evaluation models, dimensional analysis, system dynamics, topology.

1 Introduction

Products and services that we use every day are the result of a multi-faceted and often multi-disciplinary design process. This process is growing all the more complex as artefacts face more and more constraints, from needs to streamline manufacturing to taking environmental issues into consideration. In recent decades, the design process has been the subject of scientific research and, although multiple representations exist, a common backbone of phases stands out – conceptual, embodiment, and detailed design (Motte, *et al.*, 2011). Multiple studies indicate that over 80% of the life-cycle costs of a product are

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committed during the early design phases (e.g. (Lotter, 1986; Hsu & Woon, 1998; Stasinopoulos, *et al.,* 2009)). Indeed, decisions made at the conceptual design stage have a significant influence on such aspects as cost, performance, reliability, safety, or environmental impact of an artefact; a poorly conceived design concept can never be compensated by a good detailed design. In recent years, companies, researchers, and authorities have come to understand that in order to remain competitive and meet increasingly complex customer requirements and demands there are fundamental benefits to properly managing the design process and actively focusing on conceptual design (Pahl & Beitz, 1984; Dardy, *et al.*, 2003; Cross, 2007).

Several methods, tools, and techniques have been developed to support the various phases of design, ranging from design guidelines aimed at specific fields to creativity techniques used to promote innovative solutions. Increasingly, attention has been directed towards the development of support for conceptual-level design activities and of methodologies that can be used during the conceptual stage of the design process. Nevertheless, these attempts remain partially unsatisfactory due to the fact that knowledge during this early phase of a product's life cycle is usually incomplete and approximate (i.e. design requirements and constraints are far from being fully defined). In order to deal with such uncertainty, designers often choose to restrict themselves to narrow, well-defined sub-problems and sub-tasks that should lead to a sound global design but effectively often lead to sub-optimal overall solutions and trial and error approaches (Sydenham, 2004).

The present research work aims to provide an analytical tool for the early stages of the design process that addresses the issues that exist in other methods and tools. In order to be accessible, the practical methodology developed should remain simple while still relying on sound scientific principles. The scope of this article is the conceptual design activity (French, 1999; Yannou, 2000), as represented in Fig. 1, and more specifically Step 3 – the evaluation of concepts of solutions. First, though, some aspects of the refinement of the initial definition of the needs into a functional definition of the problem are considered (Ulrich & Eppinger, 2000; Miled, 2003); this is represented as Step 1 in Fig. 1 – problem clarification and formulation. The focus proper is the creation of a generic modelling and simulation framework that can be applied to the evaluation of different requirements (e.g. functional definition of needs in Fig. 1). This model exhibits similarities with the recursive vision of Zeng (2008).

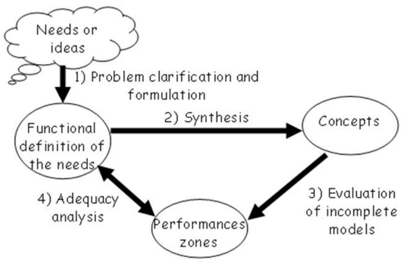

Fig. 1: The conceptual design stage, based on (Yannou, 2000).

The present work is structured as follows. At first, Section 2 demonstrates that a transitional step is needed between the functional representation of the design problem and the synthesis of the initial design concepts. For this purpose, the General Design Theory framework (GDT) and the characteristics of the most appropriate topological structure needed to compare concepts of solutions are considered; a topologic metric space best suited for comparisons between solutions is created. The latter part of Section 2 describes step by step the proposed methodology. This methodology provides the analysis stages needed to develop a representation of concepts of solutions in the form of graph models of a component that can be simulated. Section 3 illustrates the proposed framework using the case study of the selection of the cross section shape of a beam supporting measuring instruments. Finally, Section 4 concludes on the work and future expansions of the methodology.

2 A Graph-Based Representation Based on Dimensional Analysis for System Components

The General Design Theory (GDT) (Yoshikawa, 1981; Tomiyama & Yoshikawa, 1987) is used as the base structure for the present article because, as stated by Reich (1995), "GDT is a notable exception in the domain of design theory in the sense that it is a mathematical theory of design." The main hypothesis of GDT consists in stating that design has a topological structure and therefore geometrical attributes. From this point of view all design is strongly linked to geometry. Nevertheless, the scope of topology is not limited to these geometrical considerations and is broader; it could be seen as an extension of the concept of *continuity* (Reich, 1995; Sutherland, 1975). The major impact of this type of viewpoint is that topology can then be considered as exhibiting the properties linked to the concept of continuity, the four major ones being, according to Reich (1995; Bourbaki, 1966), *distance*, *continuity*, *convergence,* and *transformation*.

The notion of *distance* between two functions or two product concepts is interesting during the selection and evaluation process of conceptual design. It is a metric that can provide insight into such aspects as how close two functions or concepts of solutions are, or how far some concepts of solutions from the expected requirements. *Continuity* guarantees that a small change in the functional description will result in a small change in the product concepts and vice versa. This property also ensures that a mapping is possible between functions and attributes that describe product concepts. *Convergence* oversees that a sequence of small incremental changes in product concept attributes will only cause small incremental changes to their functionality and vice versa. *Transformation* is a property that guarantees that any transformation from a space, model, etc. to another conserves continuity and convergence.

Further continuing along this analogy between topology and continuity, the next step is to define the elementary properties that a design problem should exhibit in order to support these four properties of *distance*, *continuity*, *convergence* and *transformation* when moving from a functional representation to a physical implementation.

The notion of *distance* has been investigated in the research work of Coatanéa (2005). He has established several necessary conditions to obtain a classification space, which is the first step necessary to later form a metric space. This metric space is, according to GDT, the best topological space to compare concepts. The three fundamental conditions necessary for a classification space are:

- a fundamental system of *entourages*,
- a sufficiently detailed fundamental system of entourages in order to ensure *separation*,
- a *countable* fundamental system of entourages,

In a more practical manner, the first condition of metrisation, having a fundamental system of entourages, means that a set of generic engineering concepts is needed. Concepts, in this case, are a set of elements, a detailed presentation for which can be found in Coatanéa (2005). To describe this set of generic engineering concepts, there is a need for a normalized functional vocabulary; a partial reproduction of one is shown in Table 1, as adapted from Hirtz et al. (2002). Furthermore, fundamental types of variables describing a system need to be established. Flow, effort, displacement, and momentum are generic variables used in Bond Graph theory (Top, 1993), to this initial set a fifth type of variables, named connecting variables, is added (Coatanéa, 2005). In physics, for example, a connecting variable is the Young modulus, E.

Table 2 below provides provides an example of generic terms as extracted from the Hirtz taxonomy from the Hirtz et al. taxonomy (2002). Such a table can help name the generic variables involved in a certain technology used to implement a certain type of solution to a design problem. Depending on the field of domain, these generic variables are referred to under different names; Table 3 and Coatanéa (2005) list several examples of such differences.

Table 1: Partial representation of the reconciled functional taxonomy adapted from Hirtz (2002) (entire table available in Coatanéa (2005)).

Domains: Physical, economical, information

Power variables class	State variables class
Generalized effort (e), generalized flow (f), connecting variables	Generalized displacement (q), generalized momentum (p), connecting variables

Open systems mechanisms, command unit mechanisms and signal mechanisms

6 basic organs families associated with elementary organs and laws

Storage mechanisms:
C-organ
I-organ

Dissipative mechanism:
R-organ

Source of effort and flow mechanisms:
Se-organ
Sf-organ

Converting mechanism:
T-organ
G-organ

Distributive mechanisms:
0-organ or Effort junction- organ
1-organ or Flow junction-organ
Fasten link-organ
Rotational link-organ
Prismatic link-organ
Helicoïdal link-organ
Rotational and translational link-organ
Spherical with finger link-organ
Spherical link-organ
Plan link-organ
Linear annular link-organ
Linear link-organ
Point link-organ

Calculation mechanisms:
NO-organ
AND-organ
OR-organ

Table 2: Partial classifications of domains and related names for state variables (adapted from Hirtz (2002)).

Possible Domains	Primary Function	Secondary Function	Tertiary Function	Correspondences
	Taxonomy of the functions			
Physical, informational and economical domains	Branch	Separate		Isolate, sever, disjoin
			Divide	Detach, isolate, release, sort, split, disconnect, subtract
			Extract	Refine, filter, purify, percolate, strain, clear
			Remove	Cut, drill, lathe, polish, sand

A conceptual solution can be implemented using different elementary components classified in fundamental families. The basic set of families is formed by the Bond Graph families (Shim, 2002); it should be expanded using a set of other elementary types of components such as transformation organs (Coatanéa, 2005). The connection between the elementary functions and organs is done via a mapping table, as represented in Table 2. This table not only provides a mapping between generic components but also the nature of the generic variables involved in the organs and the causality between them. The behaviour of the generic organs is governed by generic laws, most of which are derived from Bond Graph theory and Coatanéa's work (2005).

Figure 2 represents an example of a generic law associated with a C-organ (*e.g.* Capacitor organ), a storage organ mechanism.

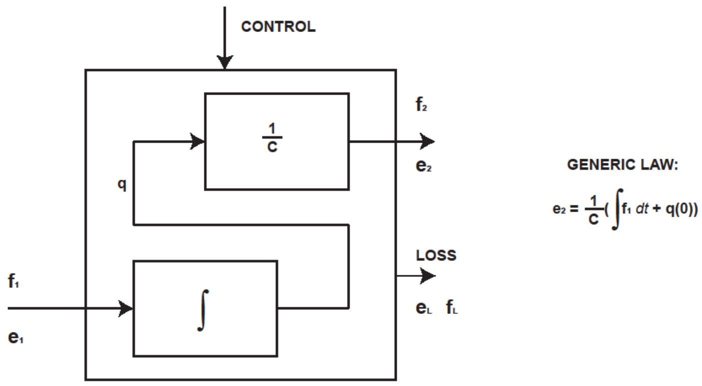

Fig. 2: SADT representation of a C-organ.

Table 3: Classification of elementary variables and organs.

Domain	Energy	Primary fields	Secondary fields	Generalised displacement (q)	Generalised momentum (p)
Physical	Energy	Mechanical translation		Displacement	Momentum
		Mechanical Rotational		Angular Displacement	Angular Momentum
		Electrical		Electrical charge (q)	Flux Linkage (OR) Magnetic flux
		Pneumatic		Volume	Pressure momentum
		Hydraulic		Volume	Pressure Momentum
		Thermodynamic	Heat exchange	Entropy (S)	Temperature Momentum
			Mass flow	Mass	Free Gibbs enthalpy Momentum
		AND Environmental			
			Mechanical Work	Volume	Pressure Momentum
		Magnetic		Displacement	Magnetic momentum
		Acoustic		Volume	Particle pressure momentum
		Biological		Volume	Pressure momentum
		Chemical		Volume	Pressure momentum
		Electromagnetic		Wave length (λ)	Momentum
			Gamma (photon + $\Delta\lambda_1$)	Wave length (λ)	Momentum
			X-Ray (photon + 2 neutrons)	Wave length (λ)	Momentum
			UV (photon + $\Delta\lambda_2$)	Wave length (λ)	Momentum
			Visible (photon + $\Delta\lambda_3$)	Wave length (λ)	Momentum
			Infra-red (photon + $\Delta\lambda_4$)	Wave length (λ)	Momentum
			Radio (atoms, molecules +)	Wave length (λ)	Momentum
		Radioactivity		Displacement	Momentum
			Beta (electron + antineutrino or position + neutrino)	Displacement	Momentum
			Alpha (proton + 2 neutrons)	Displacement	Momentum
Information	Signal	Status	Auditory Olfactory Tactile Taste Visual	Information Charge (Iq)	Information flux Linkage
		Control	Analog Discrete	Information Charge (Iq)	Information flux Linkage
Economical	Monetary	Control	Physical currency Digital currency Exchange	Monetary Charge (Eq)	Monetary flux

Table 4: Mapping between mechanism families, organs, functions, fields, power and state variables.

Classification of mechanisms	Classification of functions		Fields	Power variables type		State variables type	
Basic mechanisms secondary class	Basic mechanisms tertiary class			Effort (e)	Flow (f)	Displacement (q)	momentum (p)
Storage mechanisms							
	C-organ	Provision-store				X	
		Provision-supply		X	X		
		Convert		X (2)	X (1)		
	I-organ	Provision-store					X
		Provision-supply		X	X		
		Convert		X (1)			
		Convert		X (2)			
Dissipative mechanisms							
	R-organ	Magnitude-Change		X	X		
		Convert (1)		X (1)	X (2)		
		Convert (2)		X (2)	X (1)		
Converting mechanisms							
	T-organ	Convert		X(1) X(2)	X(1) X(2)		
		Magnitude-Change		X	X		
	G-organ	Convert	X	X(2) X(1)	X(1) X(2)		
		Magnitude-Change		X	X		
Source mechanisms							
	Source of effort	Provision-supply		X			
	Source of flow	Provision-supply			X		
Distributive mechanisms							
	Effort-junction	Branch		X			
		Channel		X			
		Connect		X			
	Flow-junction	Branch			X		
		Channel			X		
		Connect			X		
	Lock link	Couple-join		X	X	X	X
		Stop		X	X	X	X
	Rotational link	Guide-rotate		X	X		X
	Prismatic link	Guide-translate		X	X	X	
	Helicoidal link	Convert	X Mech. Trans. Mech. Rota.				
	Rotational and translational link	Guide-Rotate and Translate		X	X	X	X
	Spherical link	Guide-rotate		X	X		X
	Spherical link with finger	Guide-rotate		X	X		X
	Plan link	Guide -rotate and translate		X	X	X	X
	Linear annular link	Guide -rotate and translate		X	X	X	X
	Linear link	Guide -rotate and translate		X	X	X	X
	Point link	Guide -rotate and translate		X	X	X	X
Calculation mechanisms							
	NO-organ	Process		X	X		
	AND-organ	Process		X	X		
	OR-organ	Process		X	X		

The second condition of metrisation listed above consists of ensuring that the system of entourages is detailed enough that there is separation between all the concepts of solutions. The property of separation is deeply rooted in GDT (Yoshikawa, 1981; Tomiyama & Yoshikawa, 1987) through the axiom of separation/recognition. In the present work this property of separation is obtained through the set of basic elementary concepts described briefly above, and more extensively described in Coatanéa (2005).

The third condition of metrisation is related to the countable characteristic of the set of concepts verifying the first condition. To be countable a set of concepts should be based on a fundamental system of quantities, taken from the SI system of units augmented by two other basic metrics, one for information content and another for economic exchange (Sonin, 2001; Coatanéa, 2005). Table 5 lists the different elementary metrics that should be used to verify this third condition.

Table 5: Elementary set of metrics.

The seven Base SI quantities and units		
Physical quantity (symbol)	**Base unit**	**Unit Symbol**
Length (L)	meter	m
Time (T)	second	s
Mass (M)	kilogram	kg
Electric current (A)	ampere	A
Thermodynamic temperature (K)	kelvin	K
Luminous intensity (Cd)	candela	cd
Amount of substance (Mol)	mole	mol
The two non-physical quantities and units		
Quantity (symbol)	**Base unit**	**Unit Symbol**
Informational (Sh)	shannon	Sh
Economical (C)	cost	€ or $ or others

A classification space is obtained when the three conditions detailed above are validated. This classification space can be transformed into a metric space using the Vaschy-Buckingham theorem (Barenblatt, 1979; Sonin, 2001) and the machinery introduced Bashkar and Nigam (Bhashkar & Nigam, 1990). This transformation holds the premises for integrating dimensional analysis theory (DAT) (Matz, 1959; Barenblatt, 1979; Sonin, 2001) into the design approach proposed further in this work. It should be noted that the approach developed is compliant with the vision of the design activity traditionally developed in engineering literature (Otto & Wood, 2001; Pahl & Beitz, 1984; NASA, 2007). In both cases, a set of elementary concepts is used to transform and enrich the initial material of any development project (*e.g.* initial needs). It is then progressively refined by turning that material into requirement models that are directly used by engineers to make a synthesis of design solutions. These initial design solutions should be compared and evaluated (Fig. 1) to further develop the most promising ones; this might be very challenging if the solutions are implemented using radically different technologies assessed by different performance metrics.

Nevertheless, even though different technologies can be used to implement a function, the inputs and outputs of each solutions will have similar properties (*e.g.* at the early design stage, the variables and metrics will be the same). Consequently, the difference between different solutions lies in the nature of the technology and what is present inside the *box* describing the solution. Multiple box models exist in system engineering literature (NASA, 2007), such as functional boxes associated with inputs and outputs representing "what is required to be developed" or solution side boxes representing "how the solution is implemented". In this second category, a distinction can be made between a white box, where the contents of the box are known in details, a grey box, where the knowledge is partial, and a black box, where what is inside the box is unknown.

In the context of this work, there is only knowledge on the inputs and outputs (*e.g.* a grey box); ideally engineering designers would prefer to extend this knowledge and move to a white box where the interactions and the architecture of the interactions are known. Figure 3 graphically summarises this idea. In the grey box, on the left side of the figure, an organ has been selected to implement a function. This organ is associated with variables and metrics but the architecture and the interactions have not been defined. The right part of the figure represents a white box where the architecture and interactions have been defined. Developing the linked transformation process is the goal of the following section of this work.

Fig. 3 : Representation of the behaviour model of an organ, C1 and C2 represent clusters of descriptive variables.

The aim of the proposed approach is to provide support in decision making for the design teams during the early stages of the design process. The support comes from possibility of evaluating and comparing different design concepts and their behavioural laws without needing to spend a large amount of time to gather knowledge related to these laws. The final aim of all decision support is to remove as much subjectivity as possible when making a choice as possible (Clemen, 1997), and, overall, multiple other approaches exist to further provide support in the decision making task although they do not tackle the issue of knowledge gathering. For example, the decision-matrix method introduced by Pugh (1991) allows the ranking of complex options in a set and is often used in engineering problems. Zwicky's work (Zwicky, 1969) with morphological analysis also focuses on the choice of relevant solutions; the method is especially interesting in the case of complex systems where no element should be dropped from the study.

2.1 Moving from a list of variables to a model of the interrelation of these variables

The present section develops a concrete approach helping transform an initial list of variables associated to a box in the Fig.3, and the associated metrics, into a model of the interactions between these variables. Such a model represents the behavioural law of the organ under consideration. Section 3 illustrates this approach with the case study of a beam structure.

The fundamental tool of the approach and making the transformation possible is the Vaschy-Buckingham theorem. This theorem is used for the metrisation of the classification space (Matz, 1959; Barenblatt, 1979; Sonin, 2001) and is presented below.

Let $y = \sum_i a_i x_i$ be a law. Then all $a_i x_i$ must have the same dimension as y. If a_i is a dimensionless constant, then x_i must have the same dimension as y. This is the principle of dimensional homogeneity. If the system of fundamental quantities needed to represent a specific law is in the form of three basic quantities, namely length L, mass M, and time T, and if $[y]$ is the dimension of the variables, it is then a combination of the three basic dimensions and has the form:

$$[y] = C_1 \cdot L^{\alpha_1} M^{\alpha_2} T^{\alpha_3} \quad (1)$$

In this form, the constant C_1 and the exponents α_1, α_2, and α_3 are dimensionless numbers. It follows from the product theorem that every law which takes the form $y_0 = f(x_1, x_2, \dots, x_n)$ can take the alternative form shown in Equation 2.

$$\prod\nolimits_0 = f(\Pi_1, \Pi_2, \dots, \Pi_n) \tag{2}$$

Π_i are dimensionless products and this alternative form is the final result of dimensional analysis. It is possible to represent any law between variables as the combination of dimensionless numbers. A dimensionless number is a product that takes the following form:

$$\prod\nolimits_i = y_i \cdot \left(x_1^{\alpha_{i_1}} x_2^{\alpha_{i_2}} x_3^{\alpha_{i_3}}\right) \tag{3}$$

$\{x_1, x_2, x_3\}$ are repeating variables, $\{y_1, \dots, y_n\}$ are performance variables (Bhashkar & Nigam, 1990) and $\{\alpha_{ij} | 1 \leq i \leq n - r, x_2, x_3\}$ are exponents.

The Vaschy-Buckingham theorem, also known as the Π theorem, is a universally used tool in the context of dimensional analysis. Nevertheless, it does not provide any specific guidance related to the two following choices: the selection of the repeating and performance variables, and the determination of the unique number of governing dimensions (D_{min}). That selection can be especially tricky in the case of complex problems and can lead to impasses; Section 3 includes an example of such a scenario.

An approach for making the appropriate choices has been proposed by Butterfield (Butterfield, 2001) and developed into an algorithm, it is summarized in Table 6. The approach can be elaborated as follows. V is the list of independent variables assumed to govern the system. $R \in V$ contains the variables selected from V, which have distinct dimensions other than 0. P are the variables not in R, which have been placed in this group because the dimensions of some of these variables repeat the dimensions of the variables in R. O are variables which have zero dimension. D is a possible set of m independent variables of basic or composed dimensions. Q is a set of variables selected from R, from which a dimensionless group cannot be formed. Q forms the repeated variable list. The array $(m \times m)[A]$ is the outcome of the process of selecting variables to form dimensionless numbers; it should be checked that $[A]$ is non-singular (*i.e.* $det(A) \neq 0$ or rank of [A] is m). The number of components of D to be D_{min}.

Nevertheless, Butterfield's approach remains unsatisfactory from an engineering point of view. Indeed, the list Q is often not unique and consequently different models, all equivalent dimensionally, can be formed for the same problem. In order to avoid selecting a set of variables Q that will lead to models that are inconsistent from engineering and scientific viewpoints, a simple heuristic can be applied. This heuristic states the following:

When several sets of variables can be selected in Q, the modeller should locate and choose the variables that he or she can influence and that are not imposed as constraints.

In practice, this means that if the length L is imposed by some requirements to the designers inertia I is a variable that can be acted upon in the design, then I should be selected over L.

Table 6: Table for the selection of repeating and performance variables (adapted from Butterfield (2001)).

<table>
<tr><td colspan="2" rowspan="4"></td><td colspan="9">V</td></tr>
<tr><td colspan="5">R</td><td colspan="2" rowspan="2">P</td><td colspan="2" rowspan="2">O</td></tr>
<tr><td colspan="3">Q</td><td colspan="2">S</td></tr>
<tr><td>v_1</td><td></td><td>v_m</td><td></td><td>v_O</td><td></td><td>v_p</td><td></td><td>v_n</td></tr>
<tr><td rowspan="5">D</td><td>d_1</td><td colspan="3" rowspan="5">A (mxm)</td><td colspan="6" rowspan="5">B(mx(n-m))</td></tr>
<tr><td></td></tr>
<tr><td></td></tr>
<tr><td></td></tr>
<tr><td>d_m</td></tr>
</table>

The process presented above leads to the final formulation of the design problem in the form of a set of dimensionless numbers similar to the form of Equation 2. Π_0 is the dimensionless number containing the dependent variable of the problem and the other Π numbers on the right side of the equation contain the problem's independent variables. After generating such an equation, the traditional approach, in qualitative physics, consists in using the machinery introduced by Bashkar and Nigam (1990) to reason qualitatively about the phenomenon under consideration. The goal of this work is different; it is to generate an approximated model of the phenomenon in order to simulate it quantitatively via a system dynamics approach. As such, this forms the novelty of the work and the next section presents the approach developed for the generation this approximated model.

2.2 Generation of the approximated model

In order to generate an approximated model of the phenomenon under consideration, there is a need for supplementary information to transform the dimensionless numbers in the form of Equation 2 resulting from the transformation process described in the previous section. The necessary information comes from a limited set of generic laws associated to organs. As shown in Figure 3, based on the work of Coatanéa (2005), a design solution can be associated with a functional vocabulary and its mapping through a generic organ. This means that if a solution to a design problem is a beam, and if this beam is associated to a function that is to support a mass, then the function and the solution can be mapped with a generic organ named C-organ (C for Capacitor). The generic organ (see Figure 3) is associated with the generic law:

$$e_2 = \frac{1}{C}\left(\int f_1 \cdot dt + q(0)\right) \qquad (4)$$

In this law, $e_2$is the effort, f_1 is the flow, q is the momentum and $\frac{1}{C}$ groups all the other factors. In order to present and illustrate the approximation method, the example of the beam problem, further developed in Section 3, will be used. The variables describing this problem set in the form of Equation 2 result in:

$$\frac{d}{I^{1/4}} = f\left(\frac{F_1}{EI^{1/2}}; \frac{L}{I^4}\right) \qquad (5)$$

The effort e_2 in the generic equation is equivalent to the force F_1 in the dimensionless numbers in the right side of the equation. The flow f_1 corresponds to the displacement d of the beam.

By simple inspection of the variables in Equation 5, the behavioural law of a beam, based on the generic law for a C-organ, can take the form:

$$F_1 = \frac{1}{C_1} d \tag{6}$$

C_1 includes all the variables other than F_1 and d.

This generic form can then be transformed into Equation 7, which shares similarities with the form found in Equation 5.

$$\frac{F_1}{C_a} \cdot C_b = \frac{d}{C_c} \tag{7}$$

By inspecting and separating the dependent variable d from the other variables forming the independent set of variables, it is possible to generate Equation 8, where C is a dimensionless constant.

$$C \frac{d}{I^{1/4}} = \frac{F_1}{EI^{1/2}} \cdot \frac{L}{I^4} \tag{8}$$

The final form of the law then takes the form:

$$d = \frac{L}{CEI^{1/2}} F_1 \tag{9}$$

It should be noted that a similar principle can be applied to other generic organs listed by Coatanéa (2005). Furthermore, the method can be applied individually to single organs forming a more complex system and the system's behaviour can then be obtained by integrating the elementary laws together. To be able to integrate such elementary laws in a simple manner, this work proposes to use system dynamics as a modelling language. The next section presents the modelling principles to use in order to develop system dynamic models; in this article, the principles are applied at an elementary level but they remain the same for an application at a higher level.

2.3 Generation of a system dynamics model

The mapping principle between the elementary variables presented in Table 3 can be summarized using Table 7.

Table 7: Mapping between elementary variables and system dynamics basic bricks.

	Flow 	Stock 	Converter 
Power variables			
Effort	X		
Flow	X		
State variables			
Displacement		X	X
Connecting variables		X	X

For simplifying the modelling, when either a *stock* or a *converter* can be used, the representation of a *converter* will be systematically selected. In practice, this means that in the example of a beam problem, displacement, momentum, and connecting variables such as *Inertia* (I) or *Young modulus* (E) will always be modelled using converters.

The aim of a system dynamics model is to be simulated quantitatively. Thus, the user of the approach must select quantitative values, for the different variables, with appropriate units and magnitudes. Magnitude considerations will be added to the approach in future work.

3 Beam Shape Selection Problem: Case Study Illustrating the Proposed Method

The following case study does not discuss or include a description of the qualitative step that allows the transformation from a design problem to a design solution. The synthesis of solutions is not part of the contribution of this research work. Rather, the objective of this case study is limited to the demonstration that the practical framework developed in Section 2 can be used to gradually model design solutions. This framework provides the possibility of later developing a new type of support software for modelling and simulating design concepts during the early stages of the design process.

The present case study is organized in the following manner. A brief description of the design problem is followed by the presentation of three initial early solutions. All three belong to the same family of solutions to the problem and simply differ on the nature of their cross sections. A model of the solutions is then developed based on the step by step integration of the concepts presented in the previous section. This model is compared to a model widely available in literature and is implemented through a system dynamics approach. Finally, follows a discussion on the validity of the model and the possibility of applying the proposed approach to more complex problems.

3.1 Description of the design problem

The design problem consists in developing a technical solution able to support a heavy measuring device at a height of 3m on the external wall of a building (Fig. 4). All vertical movements of the measuring device should be minimised as it is supposed to be calibrated on a reference target on the adjacent wall. Furthermore, the ground below the measuring device should remain free of any kind of construction; therefore no support mast can be built. There is also an economic constraint, the final cost of the solution should be also minimized.

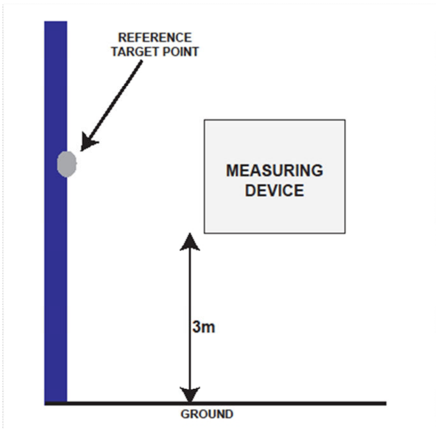

Fig. 4: Representation of the design problem.

It is supposed that the design team has developed three potential solutions, and, for simplification purposes, all solutions are considered to be based on the same principle of a beam. Future work will apply the similarity principle embedded in the first part of the proposed modelling technique (*i.e.* in the Vaschy-Buckingham theorem) in order to compare solutions based on radically different principles.

Figure 5 illustrates the developed solutions as part of the early stages of a design process. They only differ by their cross sections and the aim is to compare them from the point of view of requirements. For this purpose, a step by step construction of the problem model is proposed below, based on the approach developed in Section 2. If supported by a computer tool, the need for experienced modellers would be greatly reduced and, thus, this aspect will be a main focus for future work.

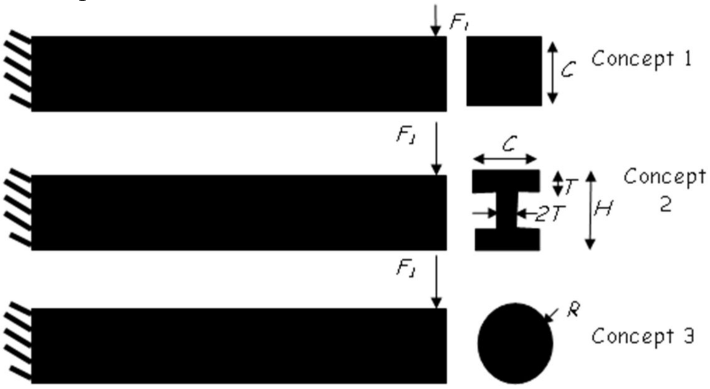

Fig. 5: Concepts of solution for a beam loaded with effort which causes bending

3.2 Progressive refinement to attain a model of the design solutions

The beam can be represented (Fig. 6) using a functional vocabulary based on the normalized vocabulary from Hirtz et al. (2002). The main function of the beam is represented as a black box.

Fig. 6: Functional structure of a beam.

Once the functional description of the solution has been established, the potential generic organs that can be used to implement the function can be determined based on Table 4. In the present case, a C-organ can be used. The selection should be made based on the functional vocabulary description but also the solutions that have been proposed. The selection of a generic organ indicates a list of elementary variables that should be used to describe this organ (see Tables 3 and 4). These variables are divided into three groups, power, state, and connecting variables. In the case of a beam, the taxonomy developed in Table 3, and further in the work of Coatanéa (2005), indicates that it can be described using the state variable of displacement $\boldsymbol{d}$ due to the bending effort and the connecting variables of the Young modulus ($\mathbf{E}$), Inertia ($\mathbf{I}$), and length of the beam ($\mathbf{L}$). Figure 7 shows the SADT diagram with these four variables and the input power variable $\mathbf{F_1}$.

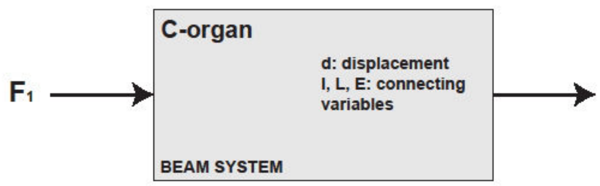

Fig. 7: SADT representation of the beam.

Table 8 summarises the list of variables selected as well as the metrics associated to these variables.

Table 8: List of attributes and quantities involved in the problem

Functions	Comment	Beam concept list of attributes and quantities: Power variables type	Connecting and comparison variable types	State variables type
STORE	System	Effort (F_1) in (MLT^{-2})		
and	input	velocity (v_1) in (LT^{-1})		
CONVERT	C-organ			d bending displacement in L
			A section of the beam (L^2)	
			I inertia of the beam (L^4)	
			L Length of the beam (L)	
			E Young modulus ($ML^{-1}T^{-2}$)	
	C-organ output	Effort (F_2) in (MLT^{-2})		
	and I-organ input	Linear velocity (v_2) in (LT^{-1})		

According to the C-organ generic law, A, I, L, d, F_1, and E are variables of interest for the analysis of how the proposed concepts can meet the requirements of supporting the mass of the measuring instrument while inhibiting the harmful effect (Altshuller, 1984) of bending. The three basic dimensions involved are L, T, and M. d depends on the five other variables and while it is a complete set, as required, it is not an independent set. Indeed, once A is specified, I follows, and therefore one must be excluded. If I is kept in the set, the following relationship expresses d in terms of a complete set of independent variables:

$$d = f(I, L, F_1, E) \tag{10}$$

d is the dependent variable and the set I, L, F_1 and E are the independent variables. Note that the choice of a complete, independent set for this problem is not unique. There are four independent variables and one dependant variable, thus a total of five variables (n); there are three base units (m), and it is therefore theoretically possible to form N=n-m=2 dimensionless groups. Table 9 presents the clustering of variables based on the Butterflied algorithm (Butterfield, 2001). It is mainly used to select a valid set QxD ensuring that the matrix is not singular. The choice of the set Q is not unique and, in this case, the choice has been made based on the application of the heuristic developed in Section 2. The full interest of this heuristic is shown at a later stage of the methodology.

Table 9: The first step of the selection of the performance and repeating variables.

<table>
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<tr><td></td><td></td><td colspan="2">Q</td><td colspan="2">S</td></tr>
<tr><td></td><td></td><td>E</td><td>I</td><td></td><td></td><td>F₁</td><td>d</td><td>L</td><td></td><td></td></tr>
<tr><td rowspan="3">D</td><td>L</td><td>-1</td><td>4</td><td></td><td></td><td>1</td><td>1</td><td>1</td><td></td><td></td></tr>
<tr><td>T</td><td>-2</td><td>0</td><td></td><td></td><td>-2</td><td>0</td><td>0</td><td></td><td></td></tr>
<tr><td>M</td><td>1</td><td>0</td><td></td><td></td><td>1</td><td>0</td><td>0</td><td></td><td></td></tr>
</table>

Q is the set of repeating variables and P forms the set of performance variables. The matrix formed by QxD is non-singular. According to Equation 3, is then possible to generate three dimensionless numbers, Π_1, Π_2, and Π_3.

$$\begin{cases} \Pi_1 = F_1 E^{-1} I^{-1/2} \\ \Pi_2 = d I^{-1/4} \\ \Pi_3 = L I^{-4} \end{cases} \tag{11}$$

According to the Vaschy-Buckingham theorem, the dimensionless numbers are related in the following manner:

$$\Pi_2 = f(\Pi_1; \Pi_3) \tag{12}$$

$$\frac{d}{I^{1/4}} = f\left(\frac{F_1}{EI^{1/2}}; \frac{L}{I^4}\right) \tag{13}$$

The beam studied in this case study can be compared to a kind of spring than can be classified in the C-organ family of the Bond Graph theory (*i.e.* Capacitor organ). Such an organ is represented by a generic law shown in Equation 4. The bending, or behavioural, law of the beam takes the general form of Equation 6. Consequently, it is possible to consider that the combination of the three dimensional numbers of the problem takes the form shown in Equation 9, with C being a dimensionless constant. Thus, the final form of the associated law is:

$$F_1 = C\frac{EI^{1/2}}{L}d \tag{14}$$

If the goal is to calculate the displacement d due to bending, the equation is easily transformed into Equation 10 as seen in Section 2.2.

For comparison, Equation 15 shows the law found in textbooks for such a beam problem, with C_1 being a constant.

$$F_1 = \frac{C_1 EI}{L^3}d \tag{15}$$

If, once again, the goal is to calculate the displacement due to bending, the following expression is obtained:

$$d = \frac{L^3}{C_1 EI}F_1 \tag{16}$$

Both Equations 14 and 15 (*i.e.* the reference equation) are valid from a dimensional point of view. Equation 14 is generated through the approach developed in Section 2. Equation 15 is the reference equation found in literature (Boresi, *et al.*, 1993). When comparing the two equations, it is possible to see that Equation 14, and therefore also Equation 10, minimises the negative effect of the length of the beam on the increase of the displacement. Nevertheless, the impact of the length on the displacement can still be evaluated using this approximated form. Moreover, the two laws are comparable in terms of taking into account the impact of a variation in the shape of the cross section and, therefore, it can perfectly be evaluated with the proposed approach. Consequently, it can be concluded from this short analysis that a novice designer can use the approximated law of the bending of the beam to support the selection of a design solution.

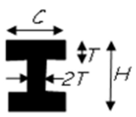
Table 10 summarises the results from this initial modelling stage. The results are based on the hypotheses that the mass of the measuring device e is 2000 kg, the gravitational constant is 9,81 m/s^2, both C and C_1 are taken equal to 1 as they do not affect decision making at this stage, the Young modulus is in the range of 200 GPa (approximately the value for steel).

It should be noted that, at this stage, it is possible to see that a permutation between the two variables *I* and *L* in the sets *Q* and *P* of Table 8 leads to the following law:

$$d = \frac{I}{C_1 E L^5} F_1 \tag{17}$$

Such a law shows that an increase in the length of a beam limits its bending while an increase in inertia increases it. The opposite is obviously correct. Therefore, the example of this permutation tends to demonstrate that the heuristic presented in Section 2 supports the development of approximated laws respecting physics and reference laws.

Table 10: Evaluation of the different concepts of solutions using the approximated law and the reference law.

	Figure		Dimensions (m)	Section (A) (m^2)	Inertia (I) (m^4)	$d_{evaluated}$ (m	d_{ref} (m)	
Concept 1		C	0,45	0,2	3,33E-03	1,77E-04	7,95E-04	
Concept 2		C	0,45	0,2	3,42E-03	1,72E-04	7,75E-04	**Selected concept of solution**
		H	0,45					
		T	0,20					
Concept 3		R	0,25	0,2	3,18E-03	1,85E-04	8,32E-04	

The next step consists in modelling the approximated law in system dynamics language. Figure 8 depicts the form of the model used.

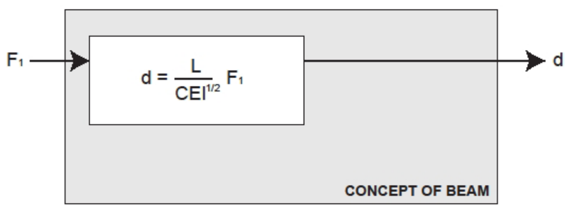


Fig. 8: Representation of the law of the beam

The mapping between the variables of the approximated law and the components of a system dynamics model can be done according to Table 11. In short, power variables are mapped with flow in system dynamics, while state and connecting variables can be mapped either with stocks or converters. Nevertheless, as indicated in Section 2.3, for modelling simplicity, state and connecting variables are systematically mapped with converters. Indeed, a mapping with stocks greatly limits modelling as stocks only accept connections from flows located before or after them in a given model.

Table 11: Mapping between beam problem variables and SD components

	Flow	Stock	Converter
Power variables			
F_1	X		
d/dt	X		
State variables			
d			X
Connecting variables			
E			X
I			X
L			X

In the case of a beam problem, an approximated law has been established above. The modelling is done by systematically selecting converters over stocks for state variables. Using a system dynamics approach, the influence of any of the independent variables can be simulated. As there are dedicated software, this type of simulation is easily achieved and can provide useful information on the validation of each variable. In the rest of the case study, the variable simulated is inertia *I*.

Figure 9a depicts the systems dynamics model obtained with the mapping proposed in Table 11. Figure 9b is a representation of the dynamic input law for the inertia of the system and the resulting bending of the beam can be seen in Figure 9c. In practice, the variation in inertia may not be explicitly known but the simulation of the model (Fig. 9a) allows the testing of different inertia properties and the evaluation of their impact on the displacement *d* and therefore the bending of the beam.

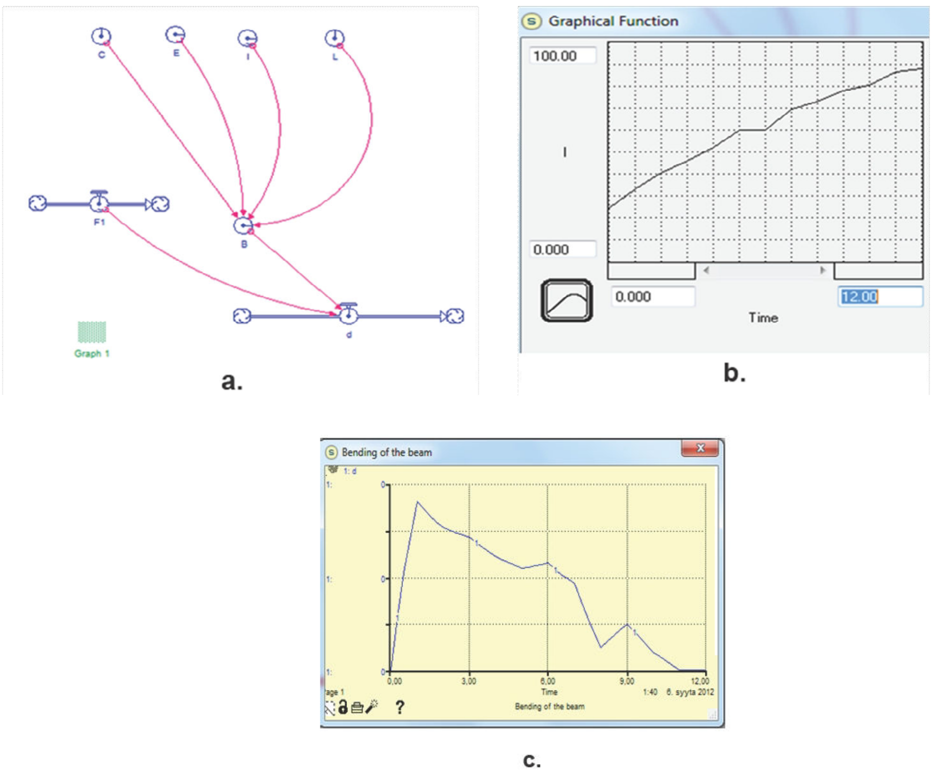


Fig. 9 (a-c): System dynamics model and effect on the displacement due to dynamic changes in inertia.

Overall, the example of the displacement of a beam yields a simple model but it efficiently illustrates the approach developed in this research work. This approach will be taught in Master's level classes in the upcoming months in order to develop its usability.

4 Discussion - Conclusion

The early stages of the design process highly influence the final outcome of projects but they are marked with immense time constraints, concept designs must be elaborated and evaluated in order to pursue the most promising ones. The design team cannot afford to waste time on seeking specific knowledge related to a design concept. The present article proposed an analytical approach that allows designers to evaluate and compare design concept solutions without seeking the specific behavioural laws that govern these concepts. The approach is based on multiple successive steps. First, the design activity is described in mathematical terms. Solutions are conceptualised as functions, organs, and mappings between these functions, organs, base metrics and units, forming "grey boxes". This conceptualisation leads to a cluster of variables and metrics that describe the problem. The second stage of the approach is to move away from a "grey box" to a "white box". The interrelations between the variables and metrics are modelled based on the Vaschy-Buckingham theorem, Butterfield's work, and a heuristic proposed by the authors. From this interrelation model, an approximated model, or behavioural law, is extracted. There is no need for any specific knowledge to obtain this law, the designer simple should model the concept and apply the proposed approach. As a final part of the work, the approximated law is modelled using system dynamics to better understand the dynamic influence of the different variables on the system. The application of the full approach is illustrated on the case of a beam displacement problem under bending conditions.

The contributions proposed in this work are as follows:

- A mathematical analysis of the early design process justifying the use, by engineering designers, of intermediate abstract concepts to move gradually from an initial description of needs to initial solutions,
- A practical method of combining these concepts for operational use,
- A method for modelling the behaviour of early design solutions and representing models in the form of a graph representation and a set of clustered descriptive attributes of the design problem,
- A demonstration of the method, with results that are in line with existing computational methods used for selecting the best cross section shape in the case of the bending of a beam.

The focus of the article has been on the evaluation and comparison of concept designs based on similar technological solutions. The implementation the comparison of concepts that use radically differing technological solutions is to be included in future versions of the approach. Indeed, the function fulfilled by each solution is the same and, at the early design stage, the input and output variables are similar or even identical. The behavioural laws will be different based on what is in the "box" (i.e. technological solution) but the influence of the input variables can be compared. In the future, the approach will also be included in software in order to make it easier to use and more accessible. Its further validation and applicability will also be tested in Master's level engineering design classes.

The mathematical bases for the approach have been largely discussed in Section 2, nevertheless, certain concepts should be explored further. The term "sufficiently detailed", used in the conditions necessary to form a metric space from a classification space, refers to the granularity level needed to reach in order to describe and study concept designs in a manner that would make their evaluation and comparison pertinent. This term is not analysed in mathematical terms in this article and remains to be tackled in future work.

The present work was centred on the notions of function and organ to describe design concepts, both are widely used and accepted in the engineering design field, as well as systems engineering.

Nevertheless, certain authors claim that the concept of function does not grasp all the situations that can be encountered in artefact design. For example, some designs consider the notion of affordance, described as "action possibilities latent in the environment" by Gibson (1977, Norman, 1988), and it can present functions that were not intended by the original design team. Moreover, the evaluation of the approximated law with the proposed approach is done through tangible and quantifiable metrics. The framework reaches its limits when human perception comes into play.

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Publication VII

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EARLY DESIGN STAGE SUPPORT USING A SYSTEMIC PERSPECTIVE: SUSTAINABLE DESIGN OF A PYROLITIC STOVE ECO-SYSTEM

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ABSTRACT

Early design is a strategic stage of the development process. The intense decision making taking place during this phase considerably affects the quality of the final design outcome. In the case of eco-design, the early stages are also where the biggest positive impact can be generated from following an adequate global design strategy. The authors of the present article claim that a fundamental qualitative shift can be gained from the systematic integration of a system oriented approach during the first phases of the eco-design process. Indeed, widely adopted eco-design methods such as Design for Environment (DfE) guidelines and Life Cycle Assessment (LCA) studies are fundamentally incapable of considering systemic effects despite the huge consequences that might emerge from global interactions. The present article proposes an integrated approach supported by the combined use of value analysis, structural analysis and system dynamics in order to achieve three fundamental goals that can increase the quality of the outcome of early stages of the eco-design process: understand the fundamental interactions between the system to develop and its environment, select a design focus and strategy supporting the fundamental design goals of the system, model and simulate scale effects and impacts emerging from the different possible uses of the system.

This work contributes to the field of eco-design research by integrating tools traditionally employed in prospective and system analysis and shifting their application from being purely analytical to being design focused. The authors claim that the approach is scalable and applicable to other design domains. The approach is demonstrated using the case study of a stove using biomass as a fuel source.

1 INTRODUCTION

Design is a complex multi-stage activity that involves the strategic selection and clarification of the main problem to solve, the generation of solutions, the selection of the solution with best potential and the development of tangible products and services implementing this solution. The design process is recursive by nature and the early design phases integrate, in a nutshell, the three first phases of the overall design process. Figure 1 depicts a representation of the early design activity (Yannou, 2000). The main tasks of an engineering designer during these stages, which play a large role in the success of the design process later on, consist in being able to understand from a holistic perspective the future interrelations between the system to develop and its environment. The designer has to extract from this complexity the main problem to solve, the set of fundamental interactions that will later really influence the system behaviour and its success. The difficulty of these tasks is increased by the fact that engineering design is becoming more and more complex. In modern design approaches, increasing importance is given to the end user and a great deal of effort is put in modern design methods to satisfy to user needs and to ensure that the developed products and services will be accepted. This is done in order to ensure a competitive advantage over competitors. Other important design goals that can benefit from a holistic analysis are environmental and sustainability design requirements. At the moment, existing approaches used to assess environmental impact (e.g. Life Cycle Assessment based methods) are static and do not consider systemic effects. Nevertheless, numerous practical examples and theoretical analyses, especially in energy economics, have demonstrated that complex interactions can lead to emerging behaviours such as rebound effects, which refers to systemic responses to the introduction of new technologies that increase the efficiency of resource use. These responses tend to offset the beneficial effects of the new technology or other measures taken. In other terms, it is not sufficient to develop eco-friendly products, design methods should also be able to design the eco-system and interactions or uses associated with these new products.

The present article proposes tools to support this systemic analysis during the early eco-design stages. The goal of the article is twofold. First, the authors provide an approach for modelling the environment and selecting the set of most important influential and influenced parameters. Second, the authors develop a method to systematically transform a value analysis model into a system dynamic model that can be simulated using a new proposal made by the authors to generate more systematically the equations controlling the behaviour of a system. This approach should be associated with a method supporting the generation of use and interaction scenarios, as well as a design strategy for a network of expected and non-desired interactions. These last aspects are not developed in this article but will be developed in an upcoming work from the same group of authors.

This rest of the article is built as follows. Chapter 2 develops a state of the art analysis presenting the main concepts that support structural and system dynamics. Chapter 3 presents the approach proposed by the authors using the case study of an environmentally sustainable pyrolytic stove. An innovative solution is modelled to counteract non-desired uses of the bi-product produced by the stove. Chapter 4 discusses the advantages and limitations of the approach.

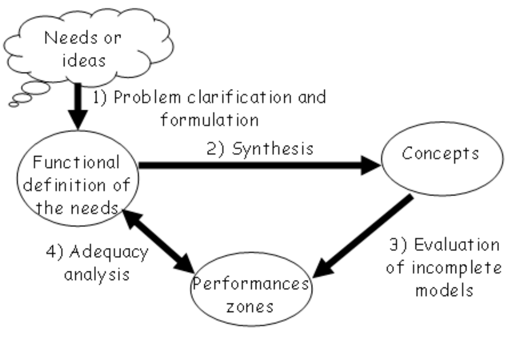


Figure 1: Key phases of the early design activity

2 SCIENTIFIC BACKGROUND

2.1 Why is it difficult to integrate computer-aided methods at the early design stages?

Design is often seen as a problem solving activity. The authors of the present article consider, in addition, that discovering the problem to solve is an initial task often obliterated in design literature. The present work considers that it is of upmost importance and a required initial condition of every good design. Before going to the core of the contribution of this article, it is necessary to briefly describe what makes the design activity so specific. This may also help clarify why computer-aided approaches are slow to penetrate the early design stage process.

When analysing the manner in which scientists and designers solve similar problems, Cross (Cross, 1984) states that: "The scientists tended to use a strategy of systematically exploring the problem, in order to look for underlying rules which would enable them to generate the correct or optimum solution. In contrast, the designers tended to suggest a variety of possible solutions until they found one that was good or satisfactory. The evidence from the experiments suggested that scientists problem-solve by analysis, whereas designers problem-solved by synthesis. Scientists use - problem-focused – strategies and designers use –solution-focused- strategies". Another differentiation can be made between the two problem solving approaches through use of a different point of view. The traditional scientific approach is descriptive because scientists try to understand how things are, whereas designers tend to adopt a prescriptive perspective. They need to define "how things ought to be in order to attain goals and to functions" (Simon, 1996). Yoshikawa (Yoshikawa, 1989) has classified design activity philosophies in three schools, integrating the difference between problem and solution-focused strategies.

1-The semantics school: The central proposal of this school is that every object of design can be seen as something that transforms three forms of inputs - *substance, energy, information*- into three outputs similar to each input, but having different states. The difference between the inputs and the outputs is called functionality. The initial requirements are usually given in terms of functionality, which can be in turn decomposed into sub-functionalities. The resulting sub-functionalities are implemented using particular physical phenomena that realize the transformations.

2-The syntax school: This school is associated with the effort made to give some formalism to the design process and special attention is paid to the procedural aspects of the design activity, rather than on the design object itself. The static aspects of design are neglected and the dynamic or temporary aspects are forming the centre of the attention. This is done through a process of abstraction which is considered as the premise for improving the universality of design. The process can be combined with the semantics aspect, therefore also emphasizing the static aspects of design to achieve a more sophisticated design methodology.

3-Past experience school: Adherents of this school suggest that a universality of design, which is the target of most design methodologies and theories, is contradictory to practical usefulness, and that the creativity of designers may be blocked if design methodologies are adopted. Emphasis is placed on the significance of case histories of previous design, in order to obtain all knowledge to be learnt for improving one's design ability. This view is closely related to the idea that the ability to design should be acquired through experience. The past-experience school exhibits an interesting characteristic in the sense that it provides a kind of compass in order to direct the design flow in the direction of good or appropriate solutions more quickly and efficiently. In this respect, the TRIZ methodology (Altshuller, 1984) (Savransky, 2000) fits well with the past-experience school; it grasps its positive aspects by integrating past experience knowledge into a methodology by describing the underlying design rules of a collection of old successful patents.

The authors claim that it is possible to combine the positive aspects of each of these schools by combining a functional analysis with an effort to formalize some of the concepts used in this article, but also by consciously selecting pragmatic viewpoints to develop the analysis and design focus in certain directions. The present article aims at combining these three perspectives.

Another aspect of this article is the early design stage. The early design phases have been seen by the different schools as an important stage of the process because of its important impact on final results. Consequently, numerous practical methods or tools have been developed by adherents of the different schools. The most well-known methods and standards supporting the early design process are Value analysis (Miles, 1961), norms, Quality function deployment (QFD) (Akao, 1966), Pugh concept selection method (Pugh, 1990) or morphological matrix (Zwicky, 1969), design structure matrix (DSM) (Kreimeyer et al., 2011). Modelling languages such as SysML (Friedenthal, 2008) or OPM (Dori, 2002) are also attempts to go in the direction of more formalized descriptions of problem and solutions, and to keep track of all actions during the early design process (see Figure 1). Nevertheless, despite the numerous tools and methods, several central issues have yet to be tackled. Notably, there is flagrant variation in the use of computers during the development process phases. Several design tasks taking place during the early stages are purely manual when the later phases of the development process are much more computer-aided. In addition, little support is provided for dealing with the analysis and understanding of complexity and non-linearity resulting from the interrelations taking place in systems and systems of systems. In the same manner, few tools support the disambiguation, clarification and ranking of the fundamental design problems that have to be solved. Several potential reasons might explain this situation. First, the viewpoints and perspectives underlying the different methods might be difficult to integrate in a unified approach. Second, for the tenant of the procedural aspects of the design process, as well as the tenant of the past history school, the main focus of design research is not to introduce computer-aided tools at the early stage. It might even be seen as limiting the creativity of designers. Third, the nature of the design problem at the early stage is characterized by the ill-definition of the problem. Developing computer-aided tools for this purpose will require the integration of this fuzziness in computational methods and it is a challenging task. The present article tries to provide support for eco-design tasks by considering value analysis (Miles, 1961) and transversal approaches derived from the fields of prospective (Godet, 1994) and system dynamics (Sterman 2000). The authors view traditional eco-design methods, such as LCA, as analytical methods instead of real design methods.

The central idea of this article is that every good design is first grounded by the discovery and clear description of a set of central problems to solve and also from an ability to extract the most significant factors from the complexity emerging from a problem description. In addition, dynamic effects caused by systemic reasons can generate rebound effects, described earlier in this article. Approaches or methodologies developed for unveiling systemic environmental effects are not used, to our knowledge, in early eco-design. In addition, methods supporting the design and simulation of systemic counteracting methods at very early stages should be considered as precious eco-design support.

Following this general background information on the subject, the article presents in the next section, to readers perhaps not familiar with the field of prospective, a method named, in this field, structural analysis (Godet, 1994).

2.2 Structural analysis

"Structural analysis enables one to describe a System by using a matrix which interconnects all the System components. This method permits analysis of the relationships and identification of the main variables." (Godet, 1994). The aim of structural analysis is to highlight the structure of the relationships between the qualitative variables, whether quantifiable or not, characterizing the system under study. Structural analysis is based on Leontiev's input-output matrices from the theory of graphs (Leontiev, 1986). Structural analysis has been traditionally used in two main areas: - in decision-making for searching, identifying key variables and interactions in order to achieve the selected objectives, - in forecasting for searching for the key variables and potential changes in behaviour that can influence the future.

The representation of system interrelationships can be done in several manners. System dynamics is an advanced approach to describe such relations. System dynamics models give a visual representation of the interdependencies between the different variables in a system. Such models show which variables influence each other, and how they affect, directly and indirectly, other variables. They also show whether feedback loops are self-reinforcing or self-correcting. The system dynamic approach is useful when quantitative relations can be described; nevertheless this is not always possible at an early stage. For this purpose, direct interrelationships can be represented in the form of adjacency matrixes, also referred to as a Design Structure Matrix (DSM) in the field of engineering design (Kreimeyer et al., 2011). DSMs are used for multiple purposes in engineering design such as modularisation and clustering of systems (Eppinger et al. 1994); the specific use described above is seldom emphasized and constitutes a novelty in this type of engineering applications.

A DSM displays the relationships between system components and variables in a visual and analytical way. DSMs can be used in several ways, for example, it is possible to extend the basic relationship between variables by including measures of the degree of the dependency (Browning, 2001). Figure 2 shows an example of a model with numerical dependency values between different variables. The values can either be negative or positive depending on the type of dependency; the dependency range is fixed in this example to be in the range of 1 to 4 (Table 1).

Table 1 Dependency strength range

1	Weak influence
2	Avarege influence
3	Strong influence
4	Very strong influence

Dependency values can also be presented as 2^0, 2^1, 2^2 and 2^3 instead of 1,2,3,4 (Browning, 2001). By representing the dependency values with 2^n, where n = {0, 1, 2, 3}, the strongest dependency levels in the model are highlighted, thus making the relevant variables easier to unveil. The downside of using exponential values is that they have a negative impact on the sensitivity of the model. A shift from a strong influence to a very strong influence has more influence on the sensitivity of the results if exponential values are used instead of linear ones.

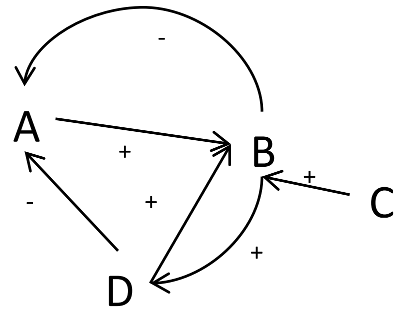


Figure 2: Dynamic system model with dependency values

The dependency values from the dynamic model in Figure 2 can be transferred into the DSM shown in Table 2. From this DSM, the variables with the strongest influence can be picked, as well as the one that is the most influenced. The column furthest to the right shows the absolute influence of variables. In the case presented in Table 2, variable D is the most influential. It influences both variables A and B and the addition of the single dependency values results in it having the strongest absolute influence. The bottom row of the DSM shows to what extent each variable is influenced in total.

Power ^1	A	B	C	D	Absolute influence
A	0	2	0	0	2
B	-3	0	0	1	4
C	0	1	0	0	1
D	-2	4	0	0	6
Is influenced	-5	7	0	1	

Table 2: Design structure matrix

The matrix in Table 2 describes the direct relationships between the variables in the dynamic model. Raising the power of the matrix allows a deeper analysis of the relationships in the dynamic model (Godet 1994). Multiplying the matrix by itself raises it to the power of 2 (Table 3), making it possible to study the indirect influence of the variables, e.g. in Figure 2 variable B is connected to variable A through variable D. The model in Table 3 shows that the value of the relationship is (+1).(-2) = -2.

Power^2	A	B	C	D	Absolute influence
A	-6	0	0	2	8
B	-2	-2	0	0	4
C	-3	0	0	1	4
D	-12	-4	0	4	20
Is influenced	-23	-6	0	7	

Table 3: DSM raised to the power of 2

As shown in Table 4, more distant relationships between variables appear each time a matrix is raised. DSMs also provide an interesting tool for identifying conflicting loops in a dynamics system model, these conflicting relations can be found by inspecting the columns and rows of a DSM. For example, a node can be influenced in an opposite manner by two other nodes. In Figure 2, B is influencing A negatively and D positively, if both A and D are two desired effects then there is a contradiction.

Table 4 Order of relationship

Power of matrix	Order of relationship
$Matrix^1$	direct relationship
$Matrix^2$	secondary relationship
$Matrix^3$	third relationship in order
$Matrix^4$	fourth relationship in order
etc.	etc.

Raising a DSM to the power of 3 or 4 can be used to investigate deeper level of relationship and also to locate more easily the fundamental influences and dependencies. This is done by summing up the rows and columns of the raised matrices. The example in Figure 3 shows how raising the power of a DSM highlights the most influential and influences variables. In the figure, A influences B and only B, it is not influenced by any other variables. B influences C and is influenced by C and A. C is only influenced by B. All these aspects are summarized in Table 5. Table 6 is summarizing indirect second level interactions.

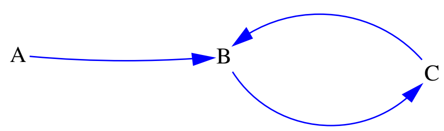


Figure 3: Dynamic system model example with three variables

Table 5: DSM matrix representing direct interactions of the graph of Figure 3

	A	B	C	Influencing
A	0	1	0	1
B	0	0	1	1
C	0	1	0	1
Influenced	0	2	1	

Table 6: Matrix raised at power 2

Power 2	A	B	C	Influencing
A	0	0	1	1
B	0	1	0	1
C	0	0	1	1
Influenced	0	1	2	

The central aspect of the structural analysis used by the authors of this article is the method used for highlighting the impact of indirect interrelationships based on the development of a network of direct interrelationships (Duperrin and Godet, 1973). Nevertheless, the reader should remember that other fundamental practical steps are involved in the structural analysis method. The steps are the following:

- Listing of the variables.
- Representation of the direct interrelationships within the structural analysis matrix,
- Processing of the matrixes for extracting the key variables,

These steps will be followed in the case study.

Starting from this initial method, the results can be used to assess the stability and controllability of a dynamic system. This is a more advanced use of structural analysis method described in the following section.

2.2.1 Influence-Dependence chart

The global behaviour emerging from the interactions among the different variables of a system can be analysed using an influence-dependence chart (Godet, 1994). The charts shown in Figure 4 are divided into four quadrants:

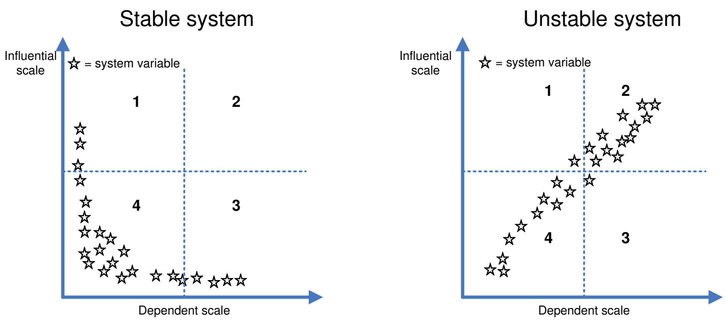
- Quadrant 1: Influential variables. These variables have a high influence and a low dependency. They condition the rest of the system. Influencing and selecting the values of these variables by design choices should help to pilot the system to design in a desired direction.
- Quadrant 2. Relay variables. These variables are both highly influential and highly dependent. They are considered unstable; any action taken on them will have repercussions on other variables. The presence of such type of variables in a system is creating problems to control the system behaviour and might be source of non-desired and unpredictable systemic effects. An unstable system is a system in which relationship links are widespread. Any influence on a relay variable in a system generates a cascading process on other variables. A system which is unstable is complex to define, as the variables are themselves dependent of influencing parameters.

- Quadrant 3: Resultant variables. These variables have a low influence and are highly dependent. They are variables located at the end of a causal relation chain. If they are performance variables of a system, the goal is to influence them. Different strategies can be considered to influence these variables. First, the influence variables, especially if they belong to quadrant 1, should be carefully tuned. Second the network of influence should be designed to promote expected values and behaviour of these variables.
- Quadrant 4: Low influence, low dependency variables. These variables are relatively autonomous and don't determine the future of the systems on a large scale. If performance variables belong to this quadrant it means that there is limited possibility to adjust the behaviour and values of these variables. These variables in a first approximation can probably be removed from the initial analysis of the system at early design stage.

The charts presented in Figure 4 are similar to the chart presented by Godet (Godet, 1994), each chart contains four regions instead of the five used in the original work (Godet 1994). The reason for only having four sections is that potential instabilities are coming from quadrant 2. From this perspective, the addition of a central quadrant does not define an interface region that would be of fundamental interest for the analysis. Quadrant 2 is filled with relay variables. Variables influenced by influential variables are located in quadrant 1. They influence variables located in quadrant 3.

In order to achieve the ideal situation where a system is stable, the variables should be clustered close to the horizontal bottom line and towards the left edge (quadrants 1, 4 & 3) of the chart (Figure 4a).A system with variables close to the chart's main diagonal is unstable (Figure 4b) (Godet 1994). Two aspects need to be considered during the analysis of the distribution of points in a chart. First the global shape of the cloud should be checked in order to determine if the system is closer to being stable or unstable. Second, any points in quadrant 2 should be examined in order to understand the fundamental reasons explaining the presence in this quadrant. If possible a design approach should be considered in order to modify the network of interaction in order to modify the location of such type of variables in the graph.

Figure 4 Stable vs. unstable system



The strategy leading to a more stable system consists in modifying the design of the network of influences of a product or system in order to transform any existing relay variables into more stable variables, thus moving them to quadrant 1, 3 or 4. There is also, in our viewpoint, a potential use of this structural analysis tool when combined with system dynamics to develop a rapid evaluation of risks associated with variables of a system.

2.2.2 Sensitivity analysis

Several levels of uncertainties can be defined in the construction of the model of a system and in the constructions of the interactions existing with the environment. Uncertainties in the models developed in this article can be classified in different categories: parametric uncertainty, parametric variability, and model inadequacy. The first refers to uncertain inputs or parameters of a model. For example in the structural analysis, the presence of the appropriate parameters or the absence of important parameters is belonging to this level of uncertainty. Parametric variability refers to uncontrolled or unspecified conditions in inputs or parameters. This uncertainty is affecting more the system dynamic model of this article. Indeed, the range of value of parameters as a well as the nature of the value of the parameters are susceptible to influence greatly the results of a system dynamic simulation. Model inadequacy relates to the fact that no model is perfectly modelling the interactions. In the case of this article this type of uncertainty is affecting both the structural analysis model and the system dynamic models. Do we have the proper links between variables and are the links properly described?

Each uncertainty lowers the robustness of the conclusions that can be drawn from one of these two models. A sensitivity analysis tests the robustness of the conclusions and the uncertainty in the assumptions.

The robustness of the conclusions that can be derived from a dynamic model can, to a certain extent, be assessed by means of a sensitivity analysis.

Overall, three major types of sensitivity analysis have been defined in system dynamics literature: numerical, behaviour mode, and policy sensitivity (Sterman, 2000).

- Numerical sensitivity exists when a change in assumptions changes the numerical value of the results.
- Behaviour mode sensitivity exists when a change in assumptions changes the patterns of behaviour generated by the model.
- Policy sensitivity exists when changes in assumptions reverse the impacts or desirability of a proposed system.

In the context of the present paper, numerical sensitivity can be tested using the integrated functionalities of the modelling software STELLA® used by the authors. Indeed, a numerical sensitivity module exists and provides possibility to test the numerical sensitivity. Behavioural sensitivity is associated in system dynamic models with changes in the nature of the links between basic modules of the models. It can also occur if equations piloting the behaviour of stocks, flows or converters are changed. In the case of the study conducted in this article, such type of behavioural sensitivity has been conducted rapidly but more extended analysis will be done in future work.

Policy sensitivity analysis emerges if the use of the stove generates negative effects that question the development of such a type of stove. Some such non-desired effects emerge in the study developed in the following case study. Structural analysis can be used to analyse policy sensitivity for key variables extracted using the structural analysis. Indeed, a certain level of uncertainty exists related to the direct influences between variables. This policy sensitivity can be conducted by modifying direct influence links when direct influence is uncertain. Nevertheless, when the direct influence is not evident the uncertainty lies more often in an ambiguous description of the variables of the model. Clarifying the parameters used in the model is important and this work has been done in the present article's case study by using a value analysis approach.

Extracting the most influencing factors of a problem is a very good starting point at early design stage. Nevertheless, being able to bring a level of simulation to test feasibility of design hypotheses and the risk of potential systemic effects generated by multiple interactions are important to verify at early design stage. This is why the following section is presenting a short analysis of different simulation methods that can be considered at early design stages.

2.3 Several modeling and simulating approaches for systems

Three major methodologies have been developed in literature to build dynamic business simulation models, System Dynamics (Newman, 2003), Discrete-event modeling, and Agent-based modeling. The first two rely on a system-level (top-down) view of the phenomena under consideration. Agent-based modeling, a more recent development, is a bottom-up approach where the modeler focuses on the behavior of individual objects linked to the studied phenomena. Emerging phenomena can be studied with the Agent-based modeling approach as they appear from the interrelations of individual phenomena. The System Dynamics method assumes a high level of abstraction and is primarily used for strategic level problems. The Discrete-event approach is a process-centric modeling method and is mainly used at operational and tactical levels. Agent-based models are more generic and can be used at all levels. Agents can represent companies, consumers, projects, ideas, vehicles, pedestrians, robots, animals, biomass, etc...

The Agent-based approach is the most recently developed in this field and it has found applications in different domains from biology to computing science (Jennings et al., 1998).

The method considered in this article is the system dynamics because the early design process is a phase of the design process where choices are strategic for the final success or failure of a development program. The level of abstraction at early design level is high and the expected results are general rather than specific. This is the reason why the present article is specially focusing on system dynamics.

2.4 Dynamic system modeling

This article considers the case of a stove that, at term, could be disseminated at the scale of a country, or even at level of a continent or worldwide, if successful. The development of such stove is implying system level analysis due to the potential large scale phenomena involved. For this reason, the authors have selected a modeling and simulation approach able to integrate systemic aspects. Among the three approaches described above aimed at system oriented problems, the System Dynamics modeling approach is used in this article due to the strategic aspects of the decisions making process as

well as the possibility to study the mapping rules between value analysis modeling approach and systems dynamics modeling language.
Regarding the two other modeling approaches briefly described in the previous section, there is no sufficient existing individual data to use an Agent-based approach at this stage of the development process. A Discrete-event approach is not relevant in this work as the studied phenomena cannot be yet represented through a stable process. Indeed, the aim of this article is to provide insight on the impact of design decisions and therefore the design of the phenomena is not finalized.

The system thinking paradigm can be used for problem discovery and problem solving through the analysis of the dynamic aspects of a system. This is achieved by viewing a problem as a conjunction of multiple interacting factors, outcomes or events, all potentially contributing to further development of unintended consequences. The system thinking paradigm is characterized by the following fundamental principles (Le Moigne, 1977):

- Each system is defined according to the explicit and implicit intentions of the modeler,
- A system is a part of a super system,
- There is relativity and contingency of the causality principle,
- The study of the behavior and of the objectives is the most important aspect,
- Analyzing the objectives of a system involves the analysis of the environment of a system,
- The scope of the analysis of systems is consciously limited in his scope and a clear viewpoint is selected. The choices should be clearly explicated and justified.

In a system dynamic perspective causal loop are playing an important role (Sterman, 2000) (Gharajedaghi, 1999). Three different types of loops exist, positive, balanced and negative loops. A positive feedback loop is a loop where the system is self-reinforcing. In the case of Figure 5, the + signs indicates that the more chickens there are, the more eggs there will be and, in the same manner, the more eggs there are the more chickens there will be.

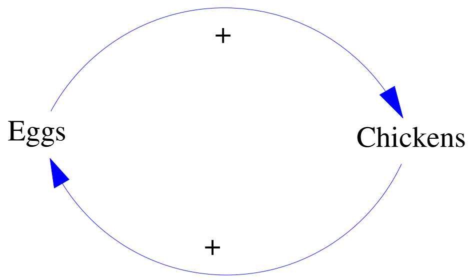


Figure 5 Positive feedback, or self-reinforcing, loop

Figure 6 shows an example of a balanced feedback loop, or self-correcting loop. An increase in chickens will lead to more road crossings (+), which will then lead to a decrease in the chicken population (-).

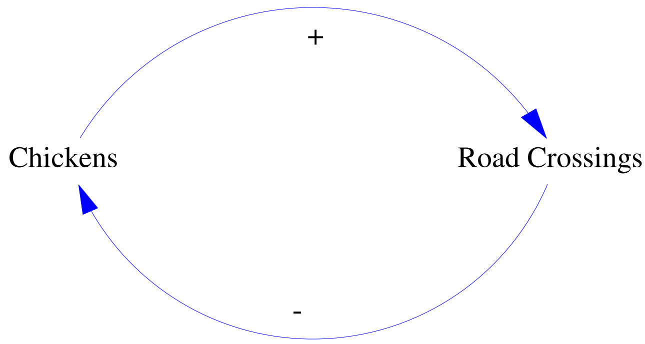


Figure 6: Negative feedback, or self-correcting, loop

These two loops can be combined into a multiple loop system (Figure 7). Depending on the type of system, there can be numerous loops, positive, negative and balanced. The dynamics of all the systems arise from the interactions among the different variables and from the existence of loops (Sterman 2000).

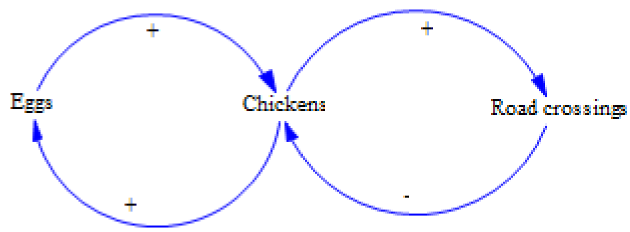


Figure 7: Multiple dynamic loop system

The strength of the relationship between two variables can either be described qualitatively using polarity signs, as in the figures above, or through numerical values or equations. Depending on whether the relation is positive or negative, conflicts emerge. These conflicts or contradictions play an important role in product development and specification processes. Solving them is often the central goal of any design task. The authors claim that system dynamic models form an excellent method for locating design contradictions and performing further studies of their influence. A systematic discovery of contradictions is forming a fundamental tool that can support the design strategy. This aspect is not developed extensively in this paper but constitutes an interesting research idea that the authors would like to develop further in future contributions. Usually the next level of analysis following the causal diagrams described before in this section is the stock and flow diagrams. Stock and flow diagrams are differing from causal loops diagrams by the constitutive analogy existing with fluid dynamics. Stock and flow diagrams are also offering a level of simulation not existing in causal loops diagrams.

In stock and flow diagrams, the basic language for modelling is based on the concepts of stocks, flows, converters, sink, and sources. A stock represents a level, a condition, or attribute of a variable at a given time. Stocks can also be used to represent buffers or delays. A stock, in general, is a term for any entity that accumulates or depletes over time, for example, delay, buffer, transit time, conveyors.

A flow represents activities or things in motion. A converter represents constants, conversion tables, conditions or restrictions affecting the behaviour of the system (Gharajedaghi 1999). Converters might also be elements that are outside the borders of the studied system but nevertheless interact with the system. A source is representing some inputs in the system. A sink is representing the output of a system. The basic bricks of the language are linked through dynamic relations as shown in Figure 8.

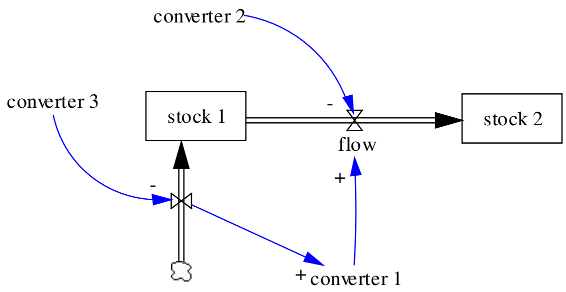


Figure 8 Stock, flow and converter

Having summarized the language and some potential uses of the approach for modelling purposes, the next section introduces the expanded structural analysis that forms the core contribution of this article. In the proposed method, the Design structure matrix or Adjacency matrix from linear algebra (Newman, 2003) is used to process complex networks.

The case study developed below is integrating elements of the structural analysis and system dynamics but associated with functional and value analysis and also root need analysis. The methodology is introduced step by step using a case study facilitating the exemplification of the method. The readers should not lose the fundamental perspective of this article which is not only to analyse a design problem using system oriented tools but also to take benefit of these tools to direct the design effort into a promising direction.

3 INTRODUCTION OF THE METHOD: CASE OF A PYROLITIC STOVE

This chapter is presenting the initial analysis and design work related to a pyrolitic stove. The goal is at first to clarify the scope, objectives and needs associated with this development.

As stated in section 2.4, the goal of the present article is to support early design decisions via use of systemic tools associated with more traditional engineering design methods.

The problem studied in this article is related to the unsustainable use of wood biomass as the main energy supply for households in developing countries. Indeed, biomass still remains the highest energy source for the developing nations. Over 60% of household energy supply comes from biomass (Legros et al., 2009). Studies have shown that about 25% of the greenhouse gas emission is due to utilisation of biomass fuel (Mc Kendry, 2002). In this context, the traditional three stone fires still remains the predominant biomass combustion method in several areas of the world such as Africa, India, and South America Asia. This type of use of the biomass associated with the nature of the combustion process is source of several acute problems. Important deforestation due to unsustainable use of this biomass, massive emission of CO_2 as well as the existence of acute respiratory illnesses (ARI) amongst women and children mainly. A report by World Health Organization (Legros et al., 2009) indicates that 1.6 million people lose their lives annually due to ARI. All these problems are interrelated and to be solved requires actions in different domains.

Efficient biomass conversion technology and reduced indoor air pollution are therefore key issue in addressing energy crisis and more efficient use of biomass. An inefficient use of combustion method for cooking and warming is source of increasing deforestation, increasing emission of greenhouse gases and increasing death rate due to respiratory illnesses for the most fragile part of the population. The impact of using inefficient combustion methods is consequently affecting locally the users but also globally the entire eco-system. Tackling such type of issues is not only a matter of technology development but also a systemic problem involving education, change of cultural habits, usages of natural biomass resources and affordability of new efficient stoves. In order to solve the major problem of unsustainable use of biomass and global warming, several viewpoints need to be considered conjointly. For example the necessity of understanding the interactions between pyrolitic stoves and the environment are important.

There is also the need to design an ecosystem associated with the usages of stove in order to avoid rebound effects that might offset the benefits of a better design of the machine.
For this reason, the aim of this chapter is to model and analyse different levels of effects and influences that are emerging from the introduction of more efficient pyrolitic stoves. There is also a need to consider a potential extension of the initial needs to include an analysis of the usages of biomass, and bi-products generated by the combustion (Ponge et al., 2006).

In such type of project it is not sufficient to develop a new machine, it is also necessary to promote global positive effects on health and development of local communities as well as on sustainable use of biomasses and carbon sequestration.

The study is decomposed in three main phases; first a functional and value/cost analysis is used during the initial phase of the analysis to obtain a representation of the needs, value inductors and cost inductors associated with the system under study. The second phase of the analysis consists of using a structural analysis in order to extract from the systemic complexity the main influencing factors (Lefebvre, 1982). Then the initial needs are questioned and an ideal need is proposed involving potentially the integration of new aspects belonging to the eco-system of the stove. The contributions of this article can be classified in three parts. First, the coherent integration of value and functional analyses with structural analysis in order to extract fundamental design factors from set of value and cost inductors. Second, a critical analysis of the scope of the needs is conducted based on a structural analysis leading to the consideration of needs associated to the eco-system of the machine under design.

The potential non-desired impacts as well as the desired impacts are listed at this stage and different design conflicts are highlighted. Third, a system dynamic analysis is conducted based on the discovered conflicts and potential emerging systemic effects are examined.

The next section is developing a root-cause analysis of the different needs associated with the design problem. This section is helping to underline different levels of objectives associated with the initial needs. The goal is then to start defining the scope of the study.

3.1 **Initial needs associated with the stove development**

Two fundamental associated issues are underlying the need for development of a stove, the deforestation problems in certain area of the world and the significant amount of CO_2 emission due to usage of biomass for cooking and heating purpose. In order to clarify the scope of the study and evaluate the complexity level of the design, it is necessary to describe explicitly the different levels of objectives associated with the project. The authors of this article have decided to use the method popularized by Sakichi Toyoda the founder of the Toyota Company (Asian Development Bank). He has developed the method of the 5 Why's to highlight sources of problems. The usage of 5 Why's method is wide spread especially in different lean methodologies to solve problems, improve quality, and reduce costs. The Why's method is applied below in Figure 9 but only for 3 levels of Why. Two initial starting problems are defined and they both lead to high level needs, reducing the usage of wood for cooking and heating purpose and diminishing CO_2 emissions. The analysis of the Figure 9 tends to show that the main five fundamental reasons for the problems to occur are the poor combustion efficiency due to the combustion in open air and with low temperature reactions, the usage of big pieces of woods, the quality of the biomass and the massive usage of charcoal produced from wood as a combustible. There is consequently needs to promote a new combustion process if possible in a closed volume, to increase the reaction surface of the biomass as well as the temperature of the reactions. There is also a need to improve the quality of the biomass as well as promoting a plan to modify the habits of using charcoal for cooking and heating purpose.

The problem is not only limited to the design of a new type of stove but there is also a need to promote other type of usages of stove and cooking and heating habits. Charcoal is a bi-product of the combustion process and an innovative idea needs to be considered in order to use charcoal for another purpose than combustion purpose.

In order to evaluate lately the solutions that are designed at system level to prevent the problems to happen or to minimize the negative consequences, there is a need for defining performance criteria at each level of problems and answers presented in Figure 9. The performance criteria are listed in Table 7. This list form an initial set of variables that will be used to generate a model of the phenomenon later in the approach.

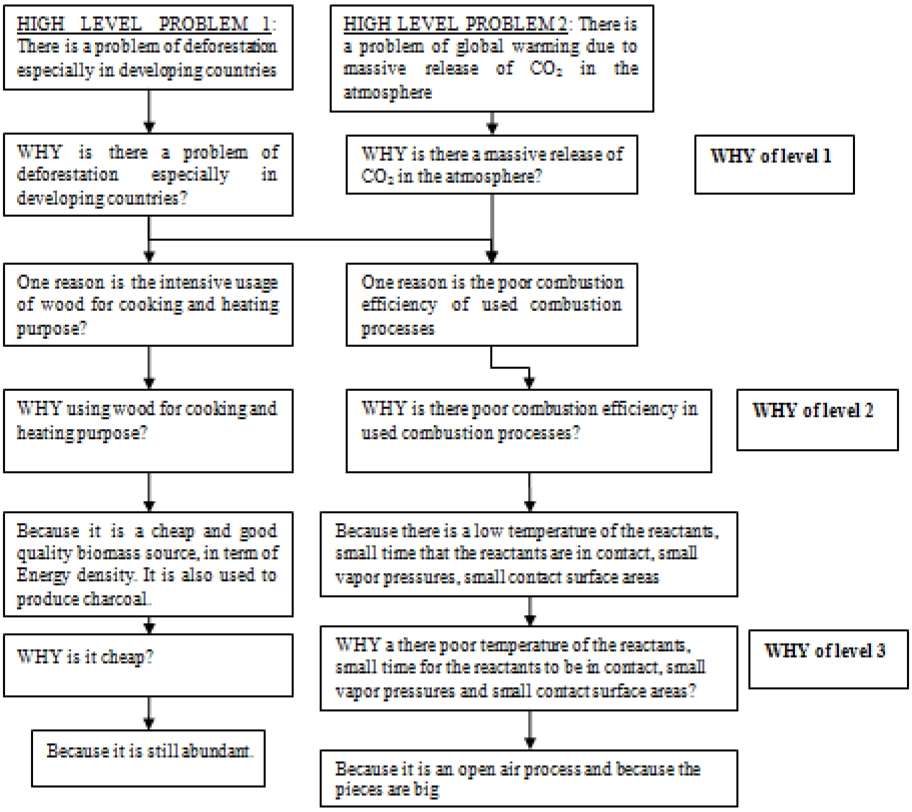


Figure 9: Root cause analysis of the case study problem

Table 7: Performance evaluations metrics for the system

Problems and answers	Performance evaluation metrics
Deforestation and CO_2 release	Wood stock (m^3), Carbone capture (Tons)
Combustion efficiency, Energy density	Heat/mass of biomass ratio (%), mass of biomass/mass of char coal ratio (%)
Low temperature of the reactants	Temperature in the stove (°C)
Small time for contact between the reactants	Time of contact in the stove (s)
Small contact surface	Average contact surface of the biomass (mm^2)
Small vapour pressure	Pressure inside the stove (bar)

The next section develops the functional, value and cost analysis with the aim to define a list of initial requirements for the stove as well as describing the eco-system of the stove.

3.2 Functional, value and cost analysis

The functional, value and cost analysis is supported by a set of graphical tools derived from the APTE method (Apte) and from Coatanéa (Coatanéa, 2005). The diagrams are allowing the representation of the elements of the environment potentially interacting with the stove as well as different types of functional interactions between the stove and these elements. When the functional interactions are listed, it is becoming possible to list cost and value inductors that will help the performance evaluation of the different required functions. Two types of functional interactions are defined at this level, the service and constraints that the system that will be developed should fulfil. A service function is a function provided by the system and creating interaction with two elements of the external environment. A constraint function is only imposing a limitation in the association with one element of the environment and the system (Coatanéa, 2005).

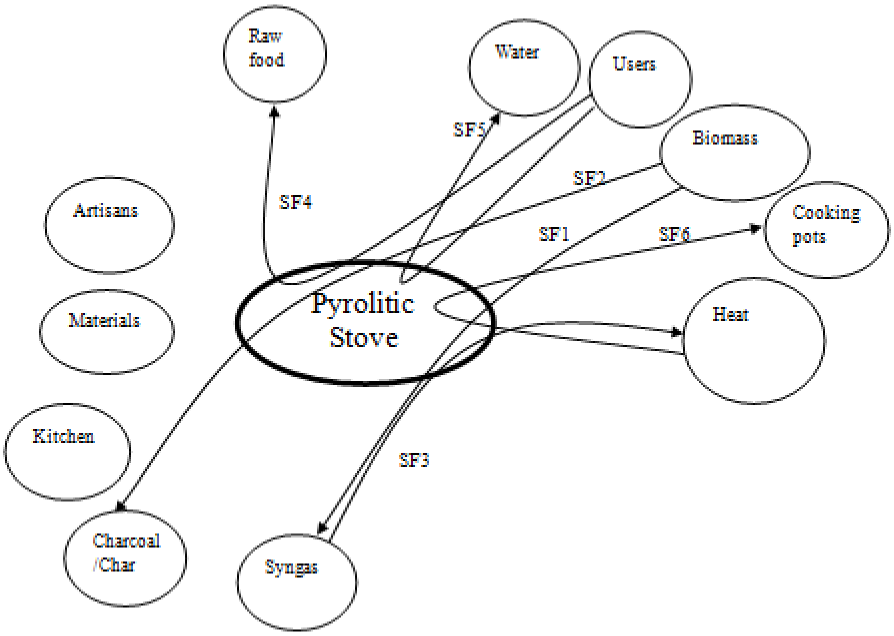


Figure 10: Environment of the pyrolitic stove and service functions provided by the pyrolitic stove

The services that the stove is expected to achieve. They include:

SF1: - To transform biomass into syngas
SF2: - To produce charcoal from biomass
SF3: - To combust syngas in order to generate heat
SF4: - To help user to cook row food
SF5: - To help user to warm water
SF6: - To transmit heat to cooking pots

The main service functions provided by the stove are defined above. It is interesting to notice that the arrows can be oriented. The meaning of this orientation is the existence of a cause-effect relation. For example, the first service provided by the stove is to transform biomass into syngas. The input is the biomass which is transformed by the pyrolitic stove into syngas.

After analysing the services provided by the stove, there is also a need to search for the constraints that the machine that will be designed should fulfil. This is a second type of functions.

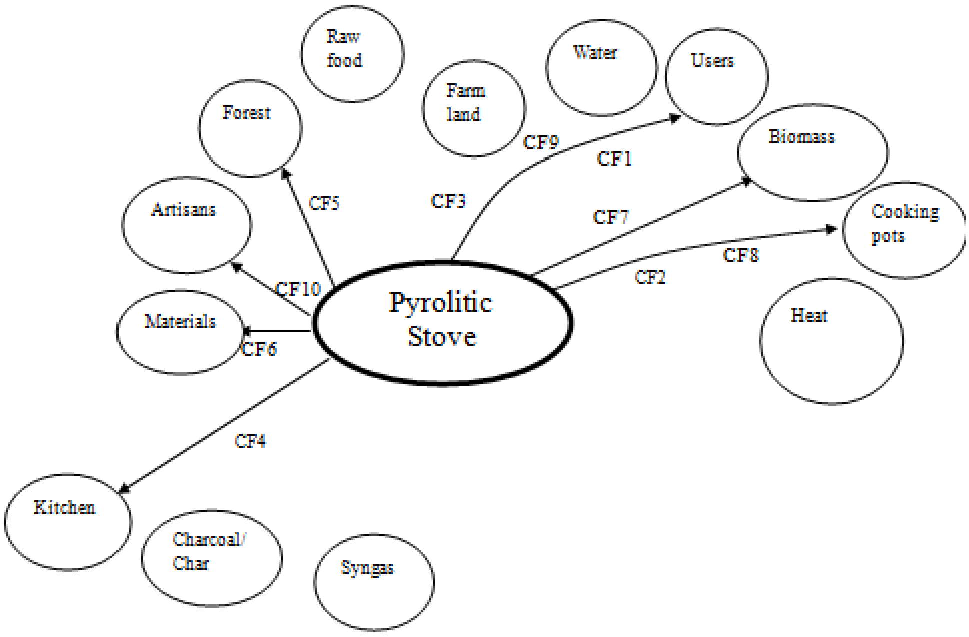


Figure 11: Constraint functions that should be fulfill by the pyrolitic stove

A list of constraints functions is defined below. This list is not exhaustive. A constraint function is a function linking the machine or device of interest with only one element of the environment.

CF1: - To avoid on burns by hot surfaces for users
CF2: - To support safely cooking pots
CF3: - To be affordable to users
CF4: - To reduce indoor air pollution in kitchen
CF5: - To reduce the use of wood resource
CF6: - To be manufactured using locally available materials and local machineries
CF7: - To be able to use variety of biomass feed stocks
CF8: - To be used with different size and shapes of cooking pots
CF9:- To be easy to operate or use by semi – literate people
CF10: - To be manufactured by local artisans

This initial part of the approach has been dedicated to the search for the basic list of services and constraints that the stove has to fulfil. In the following stage of the approach the functions have to be characterized by a set of value inductors and cost inductors. Those inductors are describing the properties of the functions in order to later evaluate the performances of the machine to be developed and of the system associated to the machine. The value inductors are metrics developed in order to answer to the question: How to measure the performance and added-value of the function under analysis?

A cost inductor is a metric developed to evaluate different aspects of the cost generated by a certain function. A cost inductor is providing an answer to the question: How to measure the costs generated by the function under analysis?

The table below is presenting the set of functions, value and cost inductors.

Table 8: Partial list of functions, value and cost inductors

Functions	Value inductors	Target	Cost inductors	Target	Existing contradictions between identical value and cost inductors
SF1: - To transform biomass into syngas	H:C ratio of biomass	Target	volume concentration of CO (ppm)	minimize	
	O:C ratio of biomass	Target	volume concentration of NO (ppm)	minimize	
			Smoke emission (l)	minimize	
			Volume stove (m^3)	minimize	
			Heat losses through system surface (C°)	minimize	
			Moisture level of biomass (% water w/w)	Target	
			Stove weight (kg)	minimize	
			Particulate emissions (ppm)	minimize	
SF2: - To produce charcoal from biomass	ratio charcoal/Char	Maximize	*Other cost similar than for SF1*	*Same than for SF1*	
	Ratio coal produced/mass of biomass (%)	Maximize			
SF3: - To combust syngas in order to generate heat	Temperature (C°)	Target	Heat losses through system surface (C°)	minimize	
	LHV of syngas (Kj/m3)	Maximize	volume concentration of CO [ppm]	minimize	
	Time required to cook food (e.g. min/kg cereal)	minimize	Volume stove (m^3)	minimize	
			volume concentration of NO (ppm)	minimize	
			Smoke emission (l)	minimize	
			Stove weight (kg)	minimize	

The initial needs associated with the stove can be summarized in form of a causal graph in which the initial features or characteristics covered by the need are integrated in a group representing the initial need.

3.3 Structural analysis

Table 8 above summarises a set of variables describing the problem. This set is expended by taking into account the variables describing the environment. From this elementary set of variables, functions and elements of the environment describing the future stove system, it is important to consider the causal relations existing between the elements. This is the role of the adjacency matrix presented in Table 9.

Table 9: Partial representation of the adjacency matrix (or DSM) representing the direct influences

		Overall and stove performance metrics 1								Environment of the stove									
	Direct Influence on →	Wood stock (m^3)	Carbone capture (Tons)	Heat/mass of biomass ratio (%)	Mass of biomass/mass of char coal ratio (%)	temperature in the stove (^oC)	time of contact in the stove (s)	average contact surface of the biomass (mm^2)	pressure inside the stove (bar)	Type of Biomass	Singas	Charcoal	Heat	Row food	Water	Cooking pots	Users	Kitchen atmosphere	Local artisans
Overall and stove performance metrics 1	Wood stock (m^3)	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0
	Carbone capture (Tons)	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
	Heat/mass of biomass ratio (%)	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Mass of biomass/mass of char coal ratio (%)	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	temperature in the stove (^oC)	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
	time of contact in the stove (s)	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	average contact surface of the biomass (mm^2)	0	1	1	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0
	pressure inside the stove (bar)	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Environment of the stove	Type of Biomass	1	1	1	1	0	1	1	0	0	1	1	1	0	0	0	0	0	0
	Singas	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Charcoal	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Heat	0	0	1	1	1	0	0	1	0	1	1	0	1	1	0	0	0	0
	Row food	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Water	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Cooking pots	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
	Users	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0
	Kitchen atmosphere	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
	Local artisans	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0

From this adjacency matrix a causal graph can be derived this graph in order to be simulated needs to be transformed later into a flow graph using the basic language of flow, stocks, converters, source and sink. There is consequently a need to map the set of elementary variables, functions and elements of the environment presented in the table above with the basic elements used in the stock and flow diagrams.

The mapping will be done later in the development of this case study but before it is important to rank the important variables and to select the most important ones of them.

This is done by raising the power of the DSM matrix of Table 9 several times and by adding both the columns and lines. The

Table 10 is presenting a part of this DSM table.

Table 10: Partial representation of the DSM raised to power 4

	Indirect Influences level 4→	e performance metrics 2													SUM
		Temperature accepted in contact surfaces (C°)	Contact surface with pots (m²)	time to warm water (t)	Mass of insulating material (kg)	cost of purchasing ($)	Volume of wood used for warming at 100°C, 1l of water (m³)	cost of material and machinery	Volume of local material (m3)	number of different biomass that can be used (n)	Ratio of cooking pots diameters	Level of usage easiness (qualitative) (Level)	Level of manufacturing complexity (qualitative) (level)	Number of different tools needed (n)	
Overall and stove performance metr	Time needed for adjusting the temperature (t)	9	2	30	11	9	39	9	2	5	0	27	0	0	492
	Transfer efficiency (J)	50	13	156	61	80	173	56	17	13	6	142	5	4	2410
	Temperature accepted in contact surfaces (C°)	[redacted]	1	10	3	6	11	1	1	0	2	7	1	1	134
	Contact surface with pots (m²)	23	[redacted]	70	33	30	91	26	11	9	4	69	3	3	1162
	time to warm water (t)	0	1	[redacted]	0	0	2	0	0	0	0	2	0	0	24
	Mass of insulating material (kg)	33	17	110	[redacted]	69	125	51	20	13	10	107	9	7	1789
	cost of purchasing ($)	12	6	26	14	[redacted]	27	14	8	1	6	26	4	4	393
	Volume of wood used for warming at 100°C, 1l of water (m³)	30	5	101	39	47	[redacted]	28	9	7	3	85	2	1	1547
	cost of material and machinery	8	7	20	12	21	19	[redacted]	8	2	5	25	4	3	328
	Volume of local material (m3)	15	10	33	17	35	32	23	[redacted]	3	9	37	7	5	525
	number of different biomass that can be used (n)	5	2	12	3	6	13	1	1	[redacted]	2	9	1	1	158
	Ratio of cooking pots diameters	3	2	17	4	8	17	4	0	0	[redacted]	15	0	0	231
	Level of usage easiness (qualitative)	5	1	10	3	6	11	1	1	0	2	[redacted]	1	1	134
	Level of manufacturing complexity (qualitative)	3	4	7	3	14	5	9	3	2	3	11	[redacted]	1	132
	Number of different tools needed (n)	1	2	1	2	3	1	2	2	0	2	2	2	[redacted]	31
SUM		828	282	2607	1032	1336	3050	966	333	304	166	2428	136	104	

From this numbers represented in the columns we can derive how a variable is influenced, from the lines it is providing information about how influential is a variable. It is then possible to represent and rank the variables by influenced and influential levels. It is also possible to define a threshold level for the cumulative set of variables representing 80% of the influence and influential levels.

Figure 12: Influenced variables and their ranking

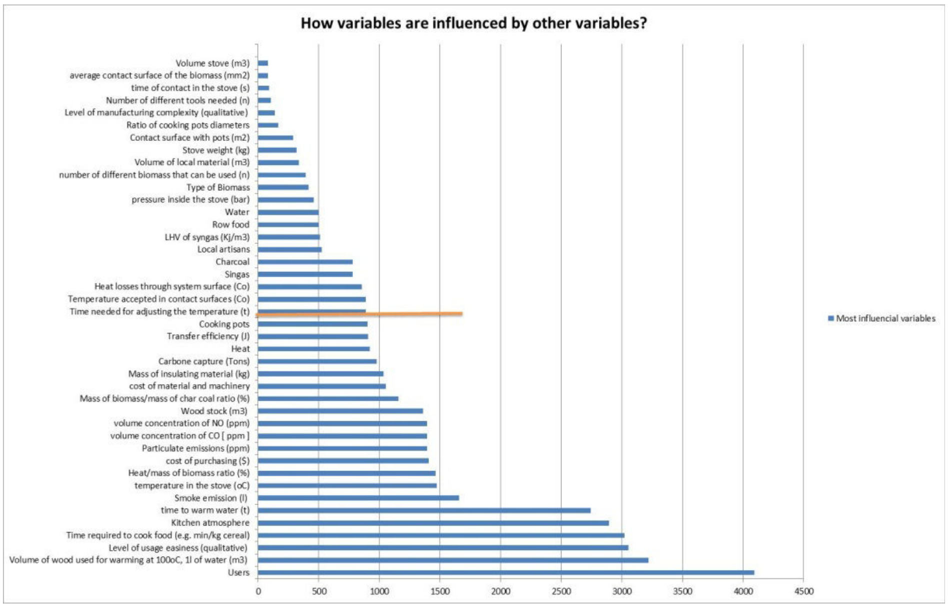
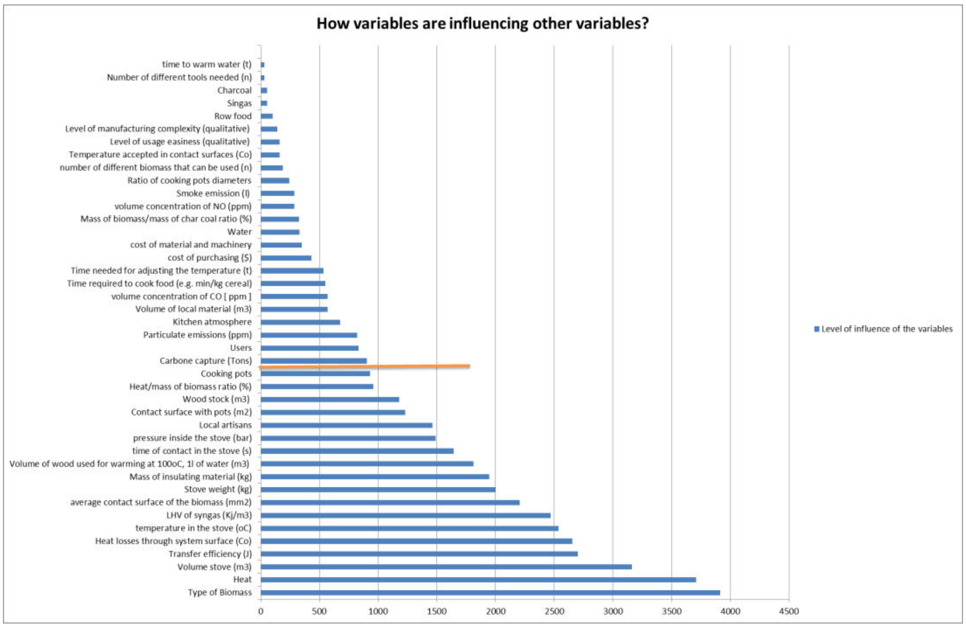


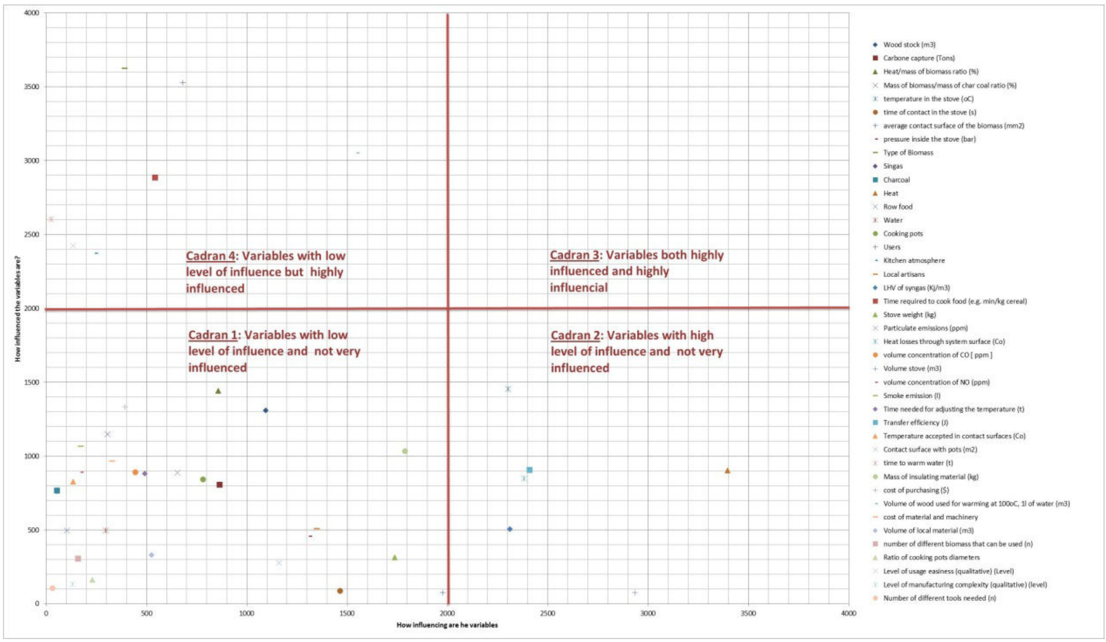
Figure 13: Influential variables and their ranking



The limit of the 80% has been defined in this case by using a simple Pareto principle (80-20) (Pareto et al., 1971).

It is also possible to represent in Figure 14, the influenced/influential graph providing useful information about the stability of the system that we want to model. In our case it seems that no variables are present in the cadran 3 in Figure 14 which means that the system is a-priori stable. This is forming initial useful information.

Figure 14: Influenced/influential graph



After having established this list of key variables and having made this initial analysis of the system, the next step of the analysis consists in generating a system dynamic model. This is done in the following chapter.

3.4 System dynamics analysis

The structural analysis part of the case study has consisted of selecting a limited set of most influencing and most influenced parameters. All the elements are belonging to three categories in our classification, value inductors, cost inductors and element of the environment. The design project has set some goals on the value and costs inductors. The cost or value inductors have to be minimized, maximized or set to a target value. They have been defined in the Table 8 presenting the list of functions and associated value and cost inductors. The elements of the environment such as the wood stock have to be protected and consequently the usage of wood has to be minimized. The goal of the system dynamic model that the study is establishing now is to be able to generate a simulation model that can support the early evaluation of the value and costs generated by different design alternatives. The model can be used to test different design alternatives involving the stove and the service system and eco-system associated with it.

The design alternatives can be tested using a design of experience strategy. This article is simply developing the system dynamic model allowing the simulation process and the design of experiment to take place. The present article is not mapping directly the impact of value and cost inductors directly on the service and constraints functions that should be fulfilled by the stove and the potential usages that can be make of it and of its bi-products. These two last phases will constitute the focus of a future article.

The pyrolitic stove is producing mainly heat, fumes and charcoal. The fumes are not desired and constitute a cost associated with the generic service function to generate heat. The heat is a desired effect of the stove and constitutes a value inductor of the pyrolitic stove. The charcoal is considered to be a bi-product of the stove. From the perspective of users in developing countries it can be seen as an added value of the stove because charcoal can be directly used to generate heat or be sold to other users. Nevertheless this usage of the charcoal is cause of extra release of gases in the atmosphere. This usage is offsetting the positive impact generated by the development of a more efficient combustion process in such type of stove. Consequently, the present system dynamic model should be used to test potential design option of the service system associated with the stove that can avoid non-desired usage of the stove. It should be especially analysed the potential alternative usages of the charcoal produced by the stove to counteract direct usage of the charcoal for heating purpose or selling of the charcoal for heating purpose.

One idea modelled in this system dynamic model consists of using charcoal has a natural fertilizer. Indeed when charcoal is mixed with grinded stones and soils it constitutes a potentially very efficient fertilizer. This natural fertilizer is then diminishing or replacing usage of chemical fertilizers that are source of important costs (i.e. both monetary and environmental costs) for farmers. The associated costs of the production of this natural fertilizer (processing cost of the mixture charcoal, grinded stones) have to be compared with the cost of chemical fertilizers. This is the role of such type of early system dynamic model to analyse the dynamic and initial conditions that can support the development of such type of innovative usage of charcoal. The feedback loops can also be studied and the effects of replacement of wood biomass by biomass generated from waste of farming products such of cereals, leaves, grass, etc…).

The development of a system dynamic model is implying the mapping between the three categories of variables defined before in the study (i.e. cost inductors, value inductors and elements of the environment) with the concepts of Stock, flow and converters used to represent system dynamics models.

These concepts of Stock, Flow and Converters have been defined before in this article, nevertheless we need now to map them with the concepts of cost and value inductors and elements of the environment. This is done first by defining the scope of the system dynamic model. The scope of the model is defined by the types of problems that have to be analysed in priority during this early design stage. As seen at the beginning of this section the pyrolitic stove is producing heat, fumes and charcoal. We would like ideally to maximize the production of heat, have no fumes and develop a carbon sequestration process. If possible the charcoal sequestrating the carbon should also provide another additional function which is acting as a fertilizer. This is indeed one possibility offered by charcoal particles when combined with soil and stones.

The consequences for our model are the following, the selected set of value and cost inductors containing the keywords heat, carbon capture, charcoal, biomass, wood, smoke, emissions as well as their synonyms should be classified in the categories *Stock* or *Flow*. Otherwise the parameters not directly parts of the main modules of the model which are in the initial model the stove direct behaviour, the charcoal usage and the agricultural fertilizing and growing process are classified in the category *Converters*. The Table 11 below is summarizing the mapping of the influenced and influential variables in system dynamics components.

Table 11: Mapping between DSM selected parameters and system dynamic elementary bricks

MOST INFLUENCED VARIABLES (FROM HIGHER TO LOWER)	NAME	STOCKS	FLOWS	CONVERTERS
Users	Element of the environment	X		
Volume of wood used for warming at 100oC, 1l of water (m3)	Cost inductor	X		
Level of usage easiness (qualitative)	Value Inductor			X
Time required to cook food (e.g. min/kg cereal)	Cost inductor			X
Kitchen	Element of the environment			X (no direct influence on the behavior of the stove)
time to warm water (t)	Cost inductor			X
Smoke emission (l)	Cost inductor			X
temperature in the stove (oC)	Value Inductor	X (2 separate stocks)		
Heat/mass of biomass ratio (%)	Value Inductor	X (Biomass)	X (Heat)	
cost of purchasing ($)	Cost inductor			X
Particulate emissions (ppm)	Cost inductor			X
volume concentration of CO [ppm]	Cost inductor			X
volume concentration of NO (ppm)	Cost inductor			X
Wood stock (m3)	Element of the environment	X (direct influence on the behavior of the stove)		
Mass of biomass/mass of char coal ratio (%)	cost and value Inductors	X (2 separate stocks)		
cost of material and machinery	Cost inductor			X
Mass of insulating material (kg)	Cost inductor			X
Carbone capture (Tons)	Value Inductor	X		
Heat	FUNCTION		X	
Transfer efficiency (J)	Value Inductor			X
Cooking pots	Element of the environment			X

MOST INFLUENCIAL VARIABLES (FROM HIGHER TO LOWER)	NAME	STOCKS	FLOWS	CONVERTERS
Heat	FUNCTION		X	
Volume stove (m3)	Value Inductor			X
Transfer efficiency (J)	Value Inductor			X
Heat losses through system surface (Co)	Element of the environment		X	
temperature in the stove (oC)	Value Inductor			X
LHV of syngas (Kj/m3)	Value inductor			X
average contact surface of the biomass (mm2)	Value Inductor			X
Stove weight (kg)	Cost Inductor			X
Mass of insulating material (kg)	Cost inductor			X
Volume of wood used for warming at 100oC, 1l of water (m3)	Cost inductor	X		
time of contact in the stove (s)	Cost inductor			X
pressure inside the stove (bar)	Cost inductor			X
Local artisans	Element of the environment			X
Contact surface with pots (m2)	Value Inductor			X
Wood stock (m3)	Element of the environment	X (direct influence on the behavior of the stove)		
Heat/mass of biomass ratio (%)	Value Inductor	X (Biomass)	X (Heat)	
Cooking pots	Element of the environment			X

It should be noticed that the mapping is offering freedom. The converter category is the most used because the connections rules are easier to apply on this component category.

Stocks and Flows are only used to represent the fundamental modules of the model. In the initial model three modules have been implemented, *a stove behaviour model*, *a charcoal use model* and *a fertilizing and growth model*. It appeared quickly that *a usage and purchasing model* was necessary to connect coherently the 3 initial modules. For this reason extra variables needs to be added to the initial model and are forming a fourth module dealing with adoption and purchasing. The added variables are represented table below.

Table 12: Added variables for a purchasing and adoption module

EXTENTION OF THE INITIAL MODEL	NAME	STOCKS	FLOWS	CONVERTERS
Vegetable production rate	Element of the environment		X	
Chemical Fertilizers	Element of the environment			X
Crop and vegatable production	Value inductor	X		
Number of stove in use	Value inductor	X		
Purchasing rate	Value inductor		X	

The implementation of the system dynamic model is then requiring to define the interconnections between the components and to generate the equations of the model. The interconnections are directly taken from the initial Design Structure Matrix of Table 9 containing only the direct. Using this table and the extended set of variable from Table 12 it is possible to generate the system dynamic model of this study.

Figure 16 shows this model. The last step consists of generating the equations of the model. This is done in this article by proposing a new heuristic method based on the dimensional analysis theory (Butterfield, 2001). Usually the generation of equations is requiring an extensive search for existing knowledge and equations. In this article, the authors are proposing a heuristic minimizing this search process and fitting to a fast evaluation process at early stage. The heuristic is associating dimensional homogeneity principles, dimensional analysis theory, and summation-subtraction principles. The rules of the heuristic are defined below.

Rule 1: If several parameters are influencing a component of the model and if they have same dimensions then they are summed or subtracted.
Rule 2: If the dimensions of different components influencing another component are different then they are combined using the product theorem
Rule 3: The principle of dimensional homogeneity should apply. If the dimensional homogeneity cannot be found with the variables of the problem, a constant should be created to ensure this homogeneity.
Rule 4: The Pi theorem is applied to generate the rules.

The application of these rules can be summarized using the following small example of a fluid flowing through a pipe. The principle can be generalized.

The variables associated to the fluid flowing in a pipe are all classified in the category converter and are the following, v is the mean velocity of the object relative to the fluid (SI units: m/s), L is travelled length of the fluid (m), μ is the dynamic viscosity of the fluid (Pa·s or N·s/m² or kg/(m·s)), ρ is the density of the fluid (kg/m³). The fluid property is a converter named *Re* and influenced by all these parameters.

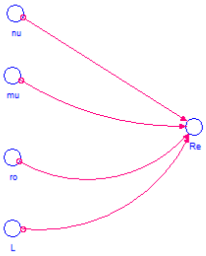


Figure 15: Example of a fluid through a pipe

The equation of Re can be defined using the Pi theorem (ruel 2 and rule 4) because the 4 variables can form a dimensionless combination in Re. The equation of Re can then be expressed in the folling form.

$$Re = \rho^{\alpha}.\mu^{\beta}.L^{\gamma}.\gamma^{\delta}$$

The exponents of the equation are computed in order to ensure the dimensional homogeneity of the equation (rule 3). The final equation is then.

$$Re = \frac{\rho L \gamma}{\mu}$$

This model is not taking into account the weight that might exist between the importance of different factors but it is not important at this stage where only the dynamic emerging behaviours and sensitivity analysis of the key parameters are really useful.

The rule 1 is applied when two components have a similar dimension and when summation or subtraction rules should be used. The interpretation of the signs is not defined in our heuristic but is based on the judgment of the user of the approach.

Using this simple heuristic it is possible to generate rules governing the model.

Nevertheless the rules are offering a way to compare the importance of different links coming to a component but these rules are generating rather rough models that might be limited in some cases. This specific study will be done in further paper.

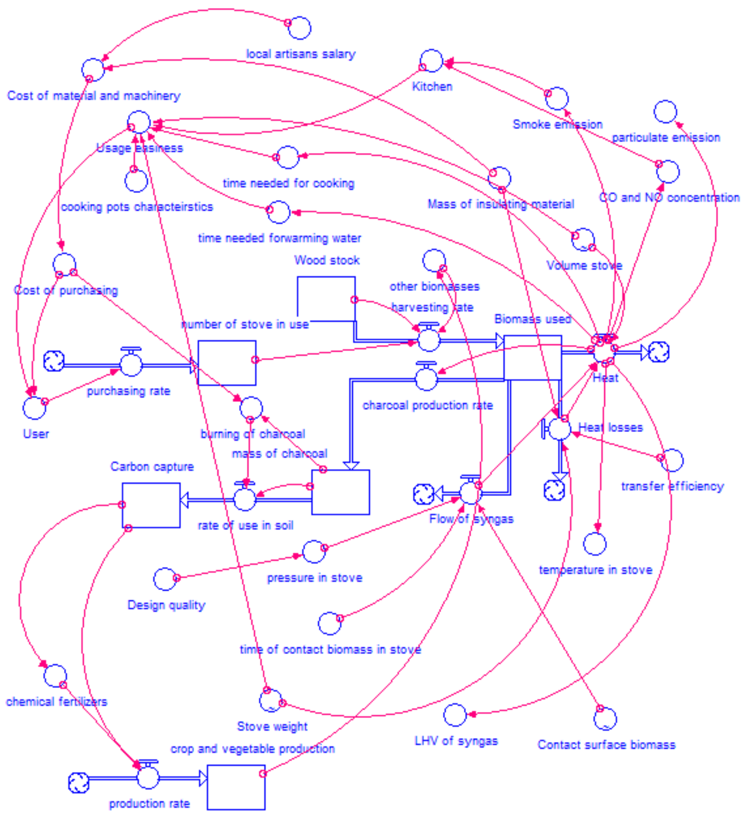


Figure 16: System dynamic model

A sensitivity analysis is also developed on such type of model using the sensitivity analysis method implemented in our modelling and simulation tool.

The Figure below is showing the control panel of the sensitivity analysis module in relation with our model.

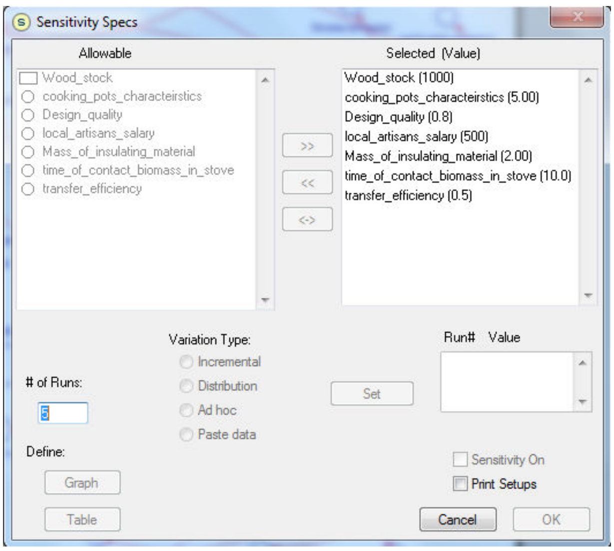


Figure 17: Sensitivity analysis module

The model has been simulated using this sensitivity approach and several early conclusions can be drawn concerning the initial design hypotheses.

The initial fundamental hypothesis was that the introduction of technical improvements in the combustion process of stove used in developing countries can be sufficient to tackle the sustainability issue associated with the massive usage of wood in some areas.

The simulation and the sensitivity study tend to demonstrate that it is not the case if such type of heating process will be generalized. It seems that this heating process is in large scale developing a too big pressure on the existing wood stock. Second conclusion, the scare wood resources in the usage of such type of stove will promote the usage of the bi-product charcoal for burning instead of a usage as a fertilizer. This is also a negative impact of the unsustainable usage of wood. Other aspect, the delay in creation of charcoal and in increasing crop and vegetable production has also negative consequences because they impose an over exploitation of wood stock during a temporary period. The scarcity of wood stock is also generating supplementary cost levels for the user of stove that can also direct them toward the usage of charcoal for food or use of traditional three stones fire places.

in order to tackle the sustainability issue it can be considered two main solutions, first a quota of pyrolitic stove can be considered. This solution seems not to be really sustainable either and will introduce risks of social tensions, social differences and difficulty to enforce the rule that are probably not manageable in long run. Another more realistic solution will consist of considering also other sources of heat generation such as biogas or solar energy systems. It is most probable that a combination of these heating sources is necessary to ensure a sustainable pressure on the wood stock.

As a conclusion of this initial study, the design of a pyrolitic stove seems to be a good manner to increase farm productivity by using the charcoal in an innovative manner. Nevertheless the approach seems not to be sufficient to tackle the sustainability issue of the wood stock.

4 DISCUSSION

The article above has been an attempt to develop a system oriented approach that can be used at early design stage to steer and design a value system. The interest of the approach is first its ability to extract a set of fundamental parameters that are the main inductors for performance control and analysis. Second the approach is providing a concrete manner to generate a system dynamic model that can be used to test some of the initial design hypotheses that have been stated in the Figure 9 . The heuristic developed for generating this model is generic and might be applied to various case studies. The present focus has been the environmental early assessment of a pyrolitic stove and its usage. The approach when applied to environmental design is offering in the viewpoint of the authors a fundamental advantage which is to design and bring a certain level of testability for very early solutions and their possible usages and operational limitations. This is a forming a fundamental advantage compared with existing Life Cycle Assessment (LCA) methods that can be used late in the development process and that are not offering possibilities for really designing new solutions. The LCA methods can be considered as an assessment tool but not really as a design tool. The present approach is offering the possibility to analyse the design problem, to design new solution systems for the fundamental problems emerging from system interactions and to visualize and simulate system behaviours.

The last part of the process which is not described in this article and which should be the final design functionalities required from such type of method is the possibility to generate new design scenarios and to test them using the system dynamic modelling approach developed in this article. This part will be developed in a future article. The basic idea is to systematically search for potential connections that may emerge between variables of the model. The goal is then to develop strategies to stop or limit non-wanted interactions and to promote desired-interactions.

Other aspect not fully tackled in this article is the selection of initial conditions used to simulate the system dynamic model. This aspect is complex and might generate different emerging behaviours. This article is presenting an innovative approach toward value development and analysis of sustainability conditions at early design stage. The potential impact of such type of work is enormous to improve the quality of design. The authors also consider that the method can by nature be applied to totally different domains.

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FIGURES AND TABLES

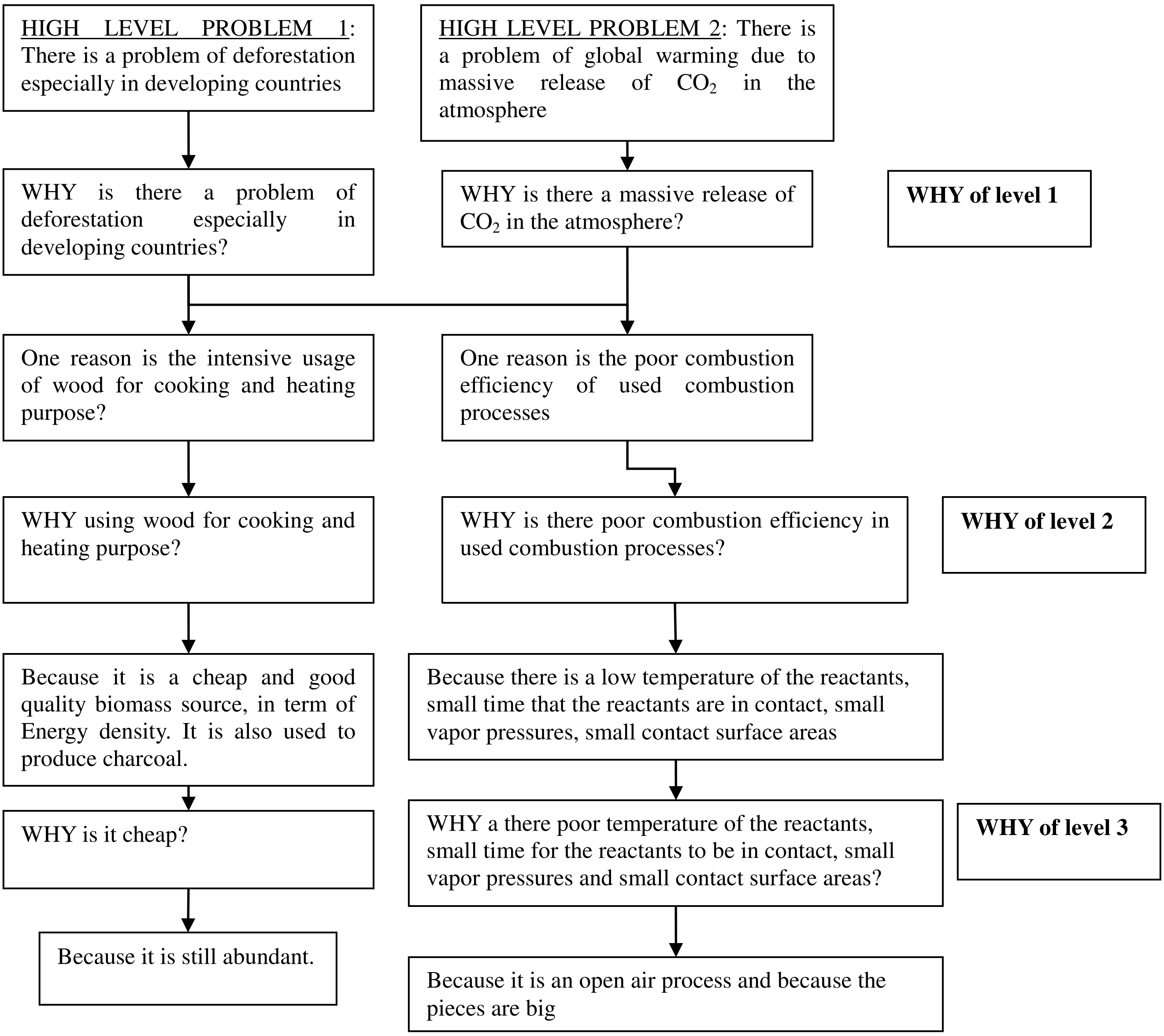


Table 13: Performance evaluations metrics for the system (to be developed)

Problems and answers	Performance evaluation metrics
Deforestation and CO_2 release	Wood stock (m^3), Carbone capture (Tons)
Combustion efficiency, Energy density	Heat/mass of biomass ratio (%), mass of biomass/mass of char coal ratio (%)
Low temperature of the reactants	Temperature in the stove (^oC)
Small time for contact between the reactants	Time of contact in the stove (s)
Small contact surface	Average contact surface of the biomass (mm^2)
Small vapour pressure	Pressure inside the stove (bar)

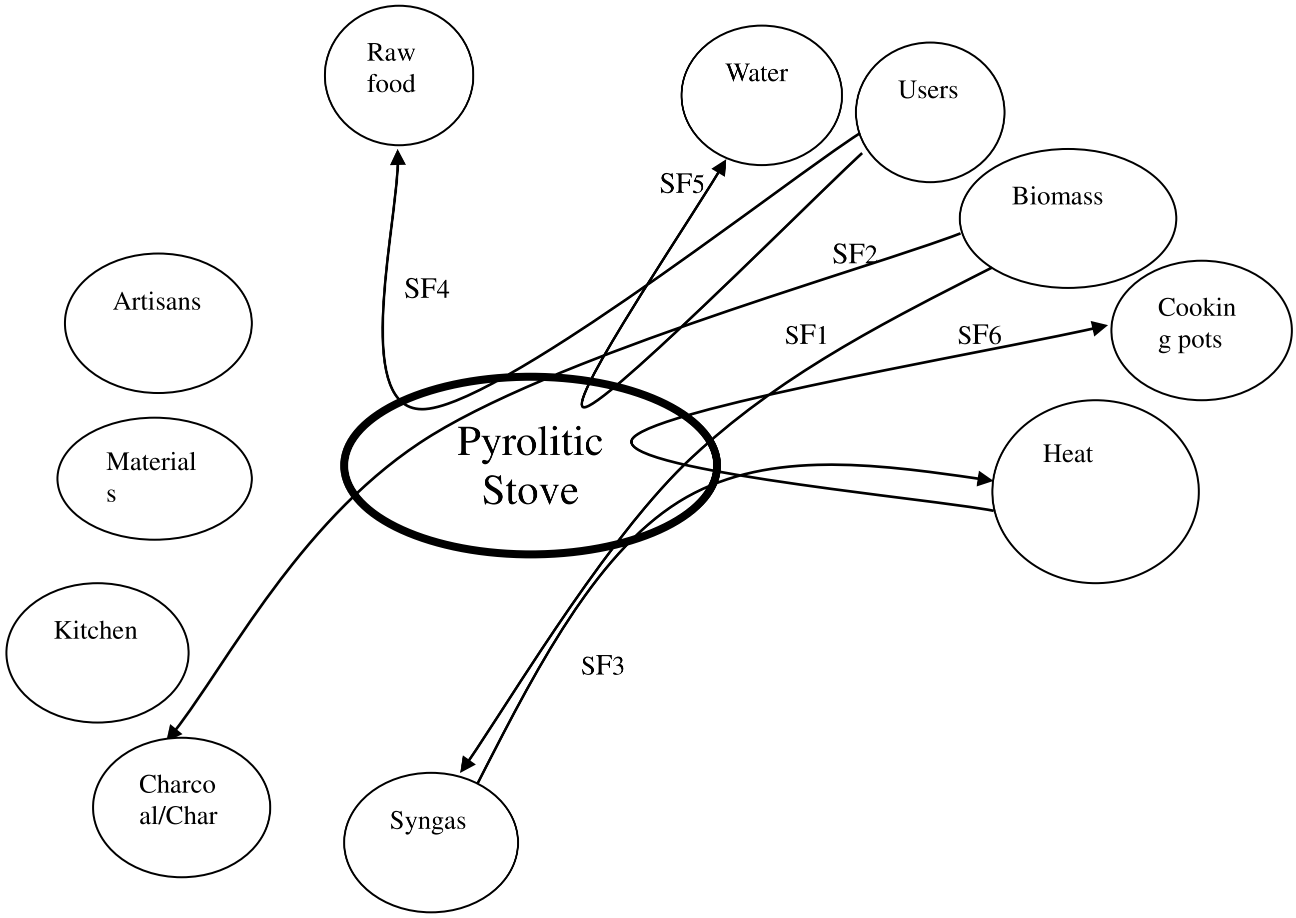


Figure 18: Environment of the pyrolitic stove and service functions provided by the pyrolitic stove

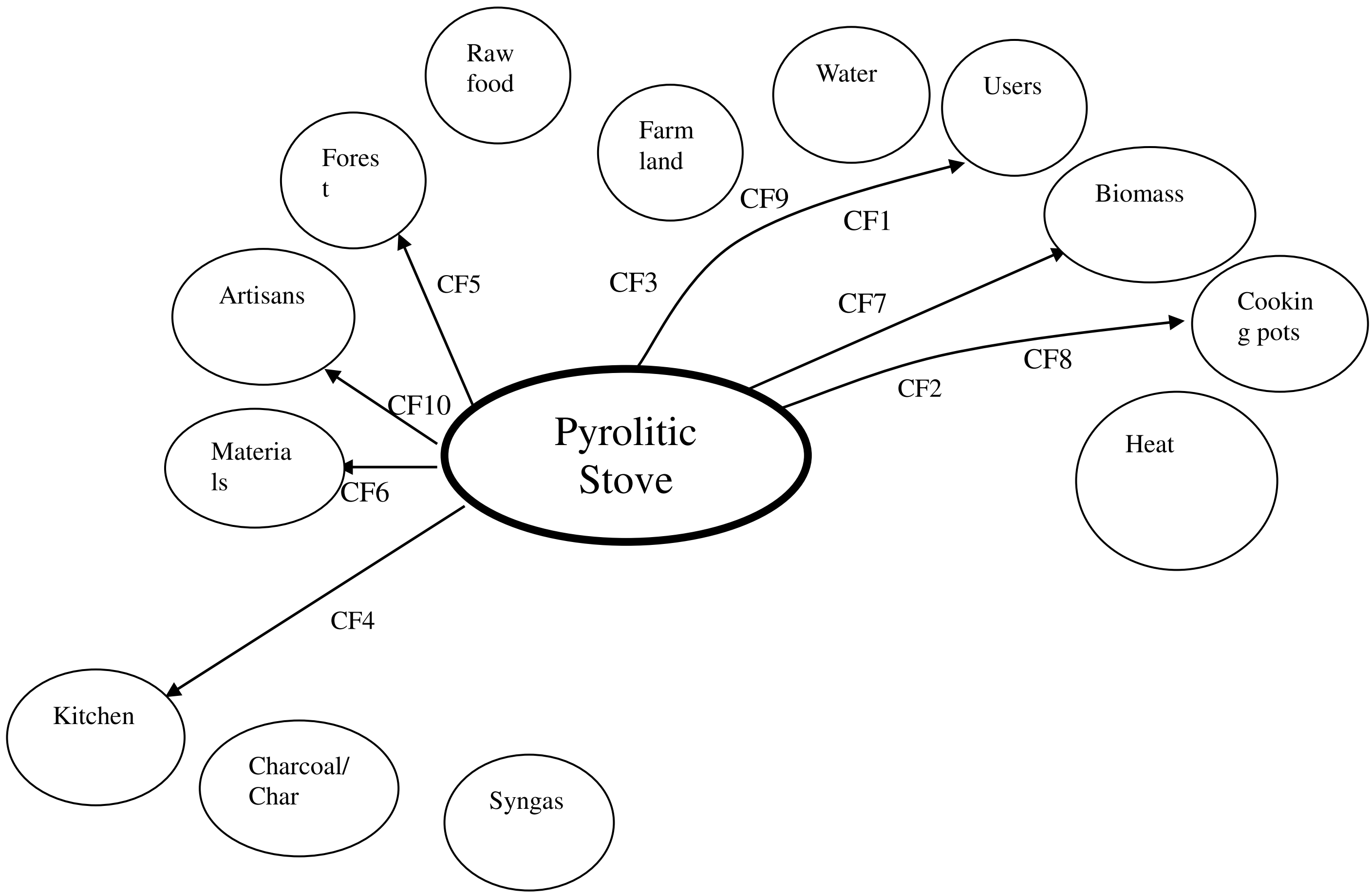
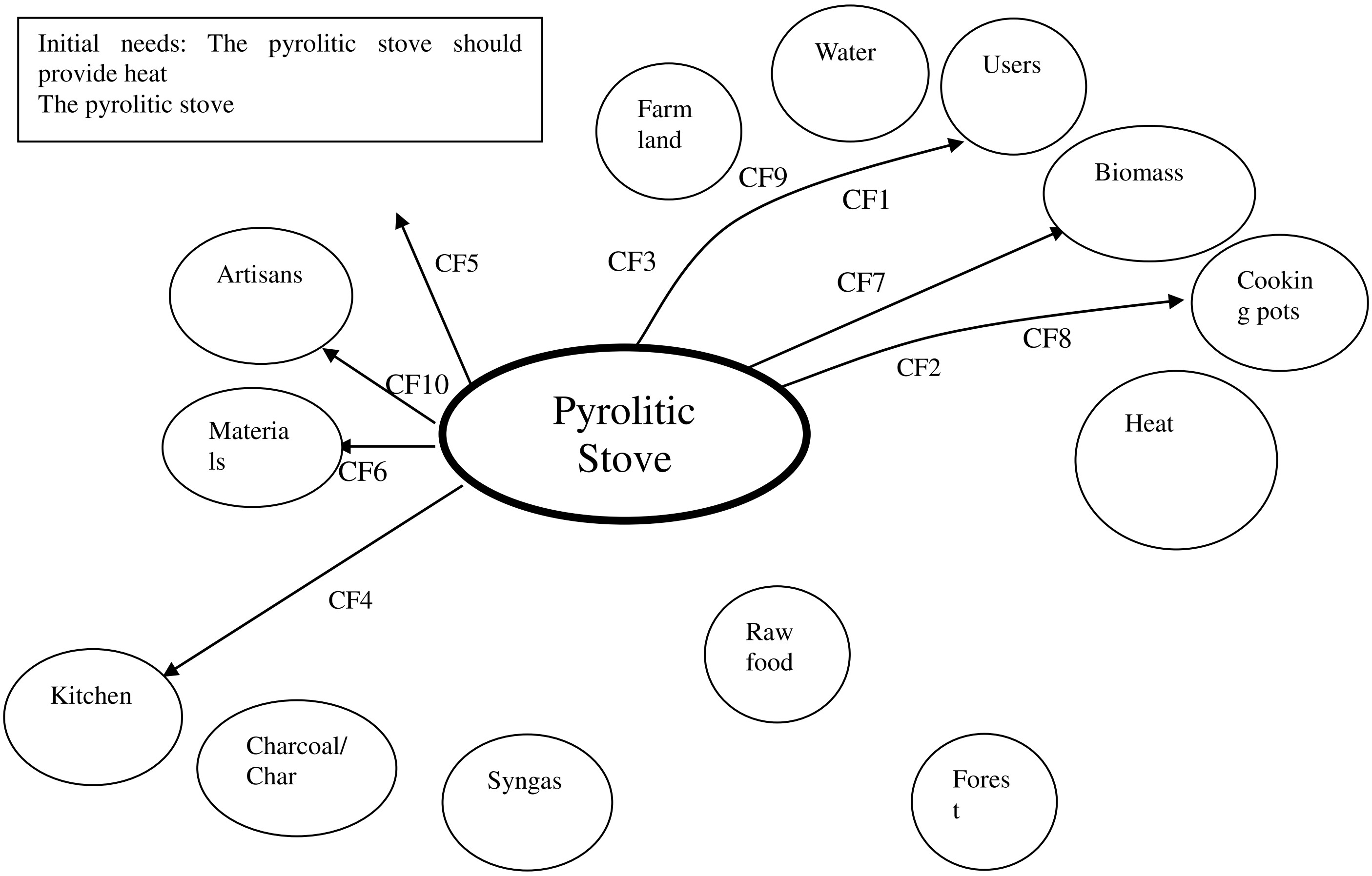


Figure 19: Constraint functions that should be fulfill by the pyrolitic stove

Table 14: Partial list of functions, value and cost inductors


Initial needs: The pyrolitic stove should provide heat
The pyrolitic stove
Water
Users
Farm land
CF9
CF1
Biomass
Artisans
CF5
CF3
CF7
Cookin g pots
CF8
CF10
CF2
Materia ls
Pyrolitic Stove
Heat
CF6
CF4
Raw food
Kitchen
Charcoal/ Char
Syngas
Fores t