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A Constraint-based Approach to Sustainable Design and Development

Helen Liang, Glen Mullineux, Geoff Hammond
Innovative Design and Manufacturing Research Centre
Department of Mechanical Engineering
University of Bath
Bath, BA2 7AY
UNITED KINGDOM
H.Liang@bath.ac.uk

Abstract
Integration of sustainable design solutions is a current issue at the forefront of any business that claims to have corporate and social responsibility. Sustainable design and development stems from the idea of sustainability which is an increasingly well known ideal but with an application and resulting definition that can differ across the many different industrial disciplines. Sustainability and indeed sustainable design becomes a complex problem due to the many interlinking factors that evolve around three key principles of people, planet and prosperity.

This paper reports a research programme that aims to establish a generic interpretation of sustainability and how the complex problem of sustainable design can be effectively and efficiently tackled using a constraint-based approach. The paper discusses how different aspects of sustainability and sustainable design affect design process thinking and examines their effect on project management including a discussion of current tools such as life cycle assessment, information modelling and integrated resource management that are widely used. There is also an introduction into a newly formed concept which involves the application of a function specific constraint modeller in order to manage sustainable design and development.

Keywords: Sustainable design, integrated resource management, computer aided design, constraint modelling.

Introduction
Sustainability, in its own right, can be considered as a newly founded discipline that has evolved most prominently within the last two decades. Indeed, the term “sustainable” is increasingly used by industrial players who claim high standards of practice as part of their corporate and social responsibility. However this is suspected to be more than questionable in many cases. These suspicions are founded partly on the lack of definition and complex nature of sustainability even within the academic and scientific arena and are also due to the lack of complete and formally established tools and methods.

The complexity of sustainability itself goes much deeper than first meets the eye. Sustainable design and moreover sustainable development can be a long and arduous process which is considered as the journey towards the goal of sustainability. However, as can be seen from published literature, it has been accepted that sustainability is generally based on the foundation of three key factors: people, planet and prosperity [1]. These cover the breadth of sustainability with the onus of sustainable design based upon the planet, and this is analogous to ecodesign and the environmental aspects within design and development.

Due to the level of complexity, managing effectively the elements of sustainable design has become the focus of research detailed in this paper. Although current tools exist under the scope of computer aided design, the majority of these have not been specifically developed to encompass the full range of elements within sustainable development. It is therefore the aim of the research programme to investigate methods of using the constraint-based approach that is detailed here, in order to manage the inherently complex nature and interlinking disciplines of sustainable design and development.

Interpreting Sustainability and Sustainable Design and Development

Although the general nature of sustainability is easily understood, it took an astounding four years to establish even the most widely accepted definition in the late 1980's Brundtland Report entitled "Our Common Future". The report proposes that "sustainable development meets the needs of the present generation without compromising the ability of future generations to meet their own needs" [2].

As a result of the Brundtland Report, additional models of sustainability have been developed in order to further define the concept. The most dominant model bases sustainability on the foundations of people, planet and prosperity. These cover generic aspects of society, environment and economics which are considered as the "triple bottom line" of a sustainable business. This often forms the basis for a company's claim of high standards in corporate and social responsibility. However, the terms of people, planet and prosperity and the consequent expressions of "society, environment and economics" are themselves considered confusing and non-self explanatory [3]. Attempts to remove such confusion have led to other models such as the so-called prisms of sustainability, shown in Figure 1. These models seek to avoid ill-defined terms whilst creating measurable indicators of sustainability to provide a holistic and satisfactory description [4].

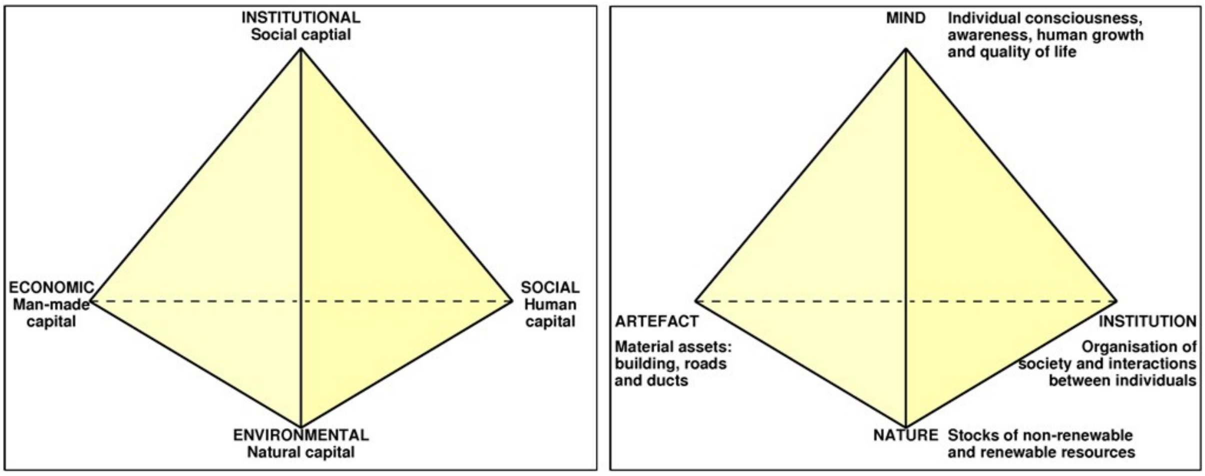

Figure 1. Prisms of sustainability

Within an industrial setting, the more holistic models, such as those detailed in Figure 1, are overlooked as they can seem overly complex. In some cases, a particular focus and hence an element dedicated to natural resources is added to the three existing baseline factors of people, planet and prosperity. The different models of sustainability only emphasise the lack of formal definitions within the emerging discipline and the numerous interlinking aspects that must be considered in design processes. From literature [3][4], it is seen that many aspects from models or definitions are in essence no different. In Figure 1, The “Environmental” and “Nature” points on the prisms represent equivalent sustainability factors.

The generic interpretation used in this paper is that sustainable development is the optimum development and contribution to society, environment and economics without compromising future needs working towards a goal of sustainability.

Sustainable Design and the Design Process

Consideration of sustainability and therefore sustainable development has its effect on the design process. It is therefore necessary to consider sustainable design and its integration into the design process which is represented in Figure 2. The design process itself seems to be the subject of much research and is well documented. It can best be defined as the “organisation and management of people and the information they develop in the evolution of a product” [5]. The process may be carried out in a series of individual or combination of consecutive and or concurrent events. Many models of the design process have been proposed (e.g. Pahl and Beitz) but most are variations on the six main activities shown in Figure 2 [6].

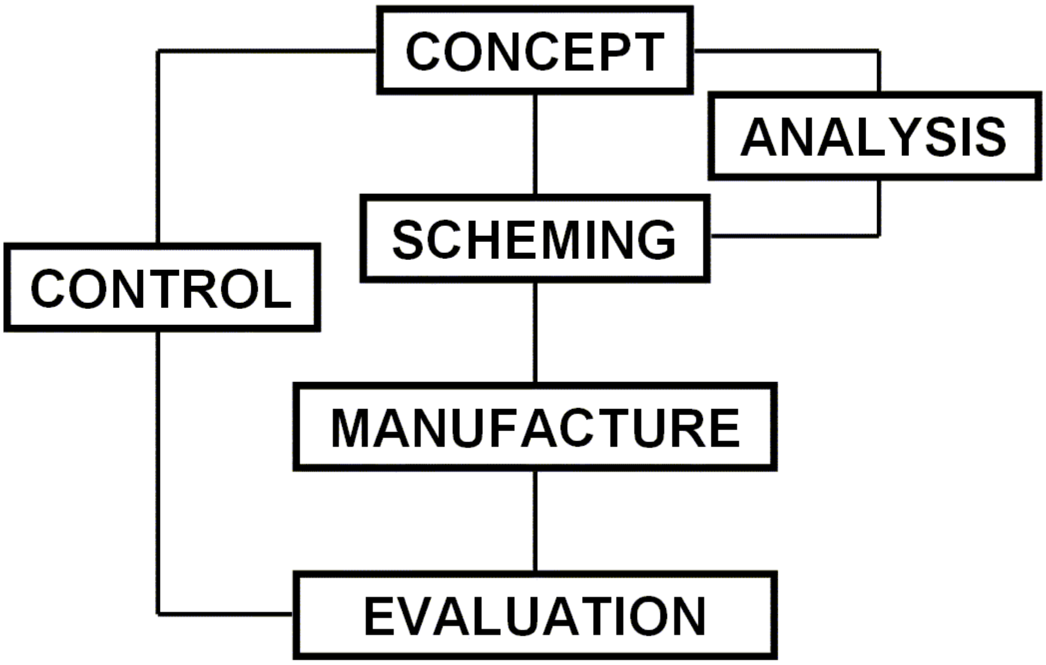

Figure 2. The design process

Research into the design process is based on continuing endeavours to improve the effectiveness of design decisions to reach an optimum solution. More recently, design has rapidly evolved as an activity primarily driven by economic factors such as profit, cost and time to market. It is now an activity also driven by environmental factors. Furthermore, the incorporation of social and environmental considerations in design is continually increasing due to the recent concerns related to sustainability and sustainable development.

The integration of environmental considerations into product design and development has led to the inception of *ecodesign* in which design decisions are based around the effects on the planet including factors such as energy consumption or depleting natural resources. It is therefore unsurprising that the onus of sustainable design and development has so far been placed upon the environmental dimension. Development of low environmental impact products, processes and systems is preferable during the initial concept stages of the design process. This demands knowledge of methodologies in design for the environment at the early concept stage. The need to understand the ecodesign methodology before executing the process applies to sustainable design and development which should also be implemented at the concept design stage of the design process.

The addition of sustainability as a consideration into design is effectively considered as a factor in the search for an optimal design solution. When incorporated into the design process, the elements of sustainable design add a significant number of considerations. This requires management of new and additional information knowledge within an already data rich process. Although there are no well known sustainable design process models, methods of sustainability appraisal have been developed under the influence of legislation such as the 2001/42/EC European Directive on the assessment of the impact and effects of certain plans and programmes on the environment. This has been largely specific to the civil engineering and construction sector.

Industry commonly labels design objectives as *key performance indicators (KPIs)* that often relate to targets and measures for success. Such indicators stem from the requirements of a product design specification and can be both qualitative and quantitative. Therefore, it is possible to objectively measure the effective level of sustainability within a design by creating a framework that appraises and evaluates key performance indicators. A sustainability appraisal framework is most likely to be effective when used at the early concept design stage. The application of such a framework is currently prominent in the civil engineering and construction industry in which sustainability has a big impact on the design process and the end result. Sustainability in this sector will involve key performance indicators such as land, buildings, people, transport, energy, water and waste management.

Methodologies and Support for Sustainable Design and Development

Examining sustainable design and its effects on design process has an impact on methodology and the tools and techniques that are inherently used. In conventional design, c*omputer aided design (CAD)* tools and systems have provided designers with increased capabilities. They have evolved to comprise three dimensional models with parametric capabilities that integrate data management, planning and manufacturing facilities [7]. Given the current interest, “intelligent CAD” systems are evolving to allow industries to assess quick measures of cost and energy and hence to help to reduce these.

The application of such CAD based tools is commonplace within industry and has led to the development of information modelling used specifically by the architecture, engineering and construction industries [8]. Specific to such consultancies, *building information modelling (BIM)* is software that generates CAD models for coordinated design and integration with mechanical, electrical and plumbing services [8]. It is also easily and readily accessible within globally distributed teams.

The advantage of such information modelling is that it allows design information to reside within one central model and can be used by all disciplines within a design team, without duplication of information. Models created are viewed with a graphical user interface, and information can be directly and readily extracted for documentation purposes. Most important, however, is the ability of the model to provide information ready for technical analysis such as finite element analysis or computational fluid dynamics with a simple application programming interface. This feature of information modelling provides a high level of interoperatability and semantic knowledge transfer. This contributes to the effective management of people and information to help develop good and sustainable design solutions that cover various design objectives.

Although these CAD tools and techniques provide effective results and offer savings in time, they have not been specifically developed to encompass the full scope of sustainable development. In some cases the qualitative and social aspects of sustainability are neglected. It is also the case that plug-ins, for example, those that provide energy analysis or computation of material and resource quantities, have been developed independently and do not always interface with different information modelling software.

Life cycle assessment (LCA) is an appraisal methodology that has evolved through the ecodesign discipline and is accepted and used throughout industry. The methodology examines the energy and resources used for production, transportation, through-life use and disposal of a product. In effect a "cradle to grave assessment". In examining the environmental impact, improvements are made and often result in both environmental and economic savings. Although initially a time consuming exercise, the development of CAD support for the methodology has led to the development of software and therefore tools which can instantaneously chart the energy use and effects of each design decision for optimal results in the concept and scheming phases of the design process.

Constraints and Constraint Modelling as a Computer Aided Design Tool

In the same way that CAD tools have been created for LCA methodologies, there exists potential in the use of constraints and constraint modelling for supporting sustainable design and development. In design work, there are many constraints imposed upon what is possible. They are *declared restrictions* that stem from client or stakeholder demands, some from physical laws and others from legislation or guidelines. Constraints naturally arise in other areas of design and various constraint-based techniques have arisen in recent years. There has been much interest in constraint-based graphics and CAD systems where constraints are used to ensure that geometric entities maintain in the appropriate relationships to each other [9]. Particular application areas have used constraints as a means for dealing with forms of parametric design [10].

A constraint can in some instances be regarded as a relationship between some of the design parameters. It corresponds to a region of design space in which the constraint is satisfied. Different constraints correspond to different regions and a fully satisfactory design solution is one which lies in the intersection of all the regions, as suggested in Figure 3. If the design problem is over-constrained then the intersection is empty and the part of the skill of the designer is in deciding which constraints can be relaxed without jeopardising the entire design.

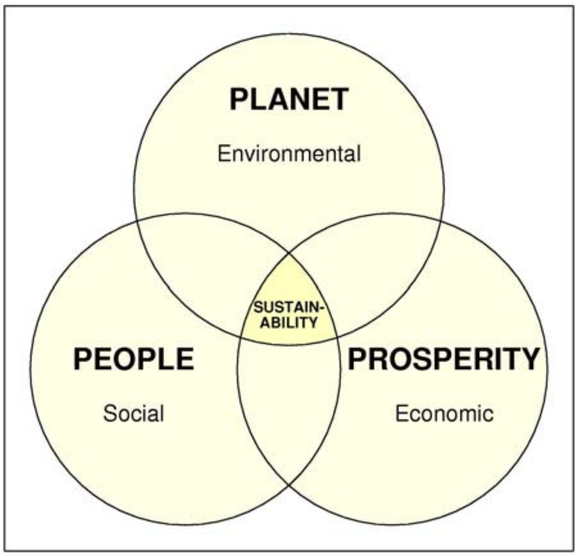

Figure 3. Design and solution space for optimised sustainable development

If constraints are available and their validity can be tested, there are several approaches that can be used. The simplest is *constraint checking*. Here each constraint is tested in turn using the current design parameters and any violations are reported. The next level is *constraint satisfaction*. Here computer support is essential and software is used to vary the design parameters in order to try to make all the imposed constraints true. In *constraint optimisation* the aim is to satisfy the imposed constraints and also optimise one or more measures of performance. For example, in machine design, constraints may be specified to ensure the parts assemble at any stage of the operating cycle. The design parameters are the sizes, positions and orientations of the parts. Then constraint checking is seeing if the parts assemble correctly. Constraint satisfaction may involve adjusting the positions and orientations of the parts so that they assemble at various stages of the operation. This allows a simulation of the operation to be obtained. Constraint optimisation is used to simulate and also to try to adjust sizes so that one or more performance measures are improved.

A constraint modelling software environment has been created [11]. This allows a user to specify design parameters and the constraints between them. It then uses optimisation techniques to vary selected parameters to search for configurations which satisfy the constraints. The constraints are regarded as expressions in the parameters which are zero when they are true: their actual values are a measure of falseness. A state of minimum falseness is sought. This has the advantage of finding some form of best compromise solution even when the imposed constraints are in conflict.

One approach with complicated designs is to use constraints to model individual elements. These are then brought together as a single collection of constraints and additional ones introduced to specify how the elements interrelate. This naturally creates a more complex system of constraints. Constraint checking is of course still possible, but automatic constraint satisfaction can become more problematic. This can be eased by taking simpler (perhaps heuristic) representations of the elements, at least in the initial stages of exploring the design space. This allows some indication of the sensitivity of the design to changes in parameters to be appreciated. More realistic constraints can be introduced as replacements once an approximate feasible design has been achieved.

Integrated Resource Management Methodology

A methodology that is currently emerging to support sustainable design and development is *Integrated Resource Management (IRM).* This is the focus of the research work reported in this paper. IRM seeks to integrate and manage the interlinking factors of social contribution, environmental integrity and economic prosperity of design solutions. Its use is predominantly applicable within the civil engineering and construction sector where designers seek solutions for the development or regeneration of sustainable communities.

IRM is a method that encompasses the full scope of sustainable development. A successful example of its early application can be seen in the case study of the Municipality of Heidelberg, Germany. The municipality initially faced the challenges of unemployment, unaffordable housing and shifting demographics that threatened the sustainability of the community. The reaction was to develop a plan that integrated the management of the many and varied methodologies for sustainable development. Techniques such as "environmental budgeting", which draw parallels to financial budgeting, were employed to manage the natural resources as economically as artificial resource, namely money [12].

Creating a consistent framework provided a structured approach to the problem which aimed to improve and maintain sustainable living within the municipality. The use of an IRM methodology completed the solution strategy allowing the successful consideration and management of financial, human and natural resources. This holistic approach is not only the essence of sustainable development, it is also mandatory.

Heidelberg is an example where IRM has been applied to improve the social aspects of a community whilst considering both ecology and economy. Better social living has been achieved whilst reducing environmental factors such as carbon dioxide emissions and residual waste. However, the success of the project is arguably dominated by the collaborative efforts of the community to draft, develop, apply and maintain the IRM framework. It is also an example where the IRM methodology can be used in an iterative manner as analysis is continuously carried out for existing and future scenarios within one consistent framework. The case study provides support for the application of the IRM methodology in managing many interlinking factors and devised key performance indicators (KPIs) for sustainable development.

A Constraint-based Approach to Integrated Resource Management

Within sustainability appraisal frameworks, such as Heidelberg, there exist objectives that are associated with key performance indicators. These are likely to be many interlinked indicators and correspondingly the objectives can be interrelated and even contradictory. Using some objectives as constraints on feasible solutions and other as targets, allows the creation of an optimisation problem with constraints. In this way it seems that there is a constraint modelling approach which can work alongside methodologies such as IRM for sustainable design and development. This adds to existing constraint-based approaches for conceptual and life-cycle design [13] [14]. For IRM, the approach has capabilities to continuously manage and capture the complex interactions of multidisciplinary key performance indicators as an appraisal and even optimisation tool for sustainable design methodology.

Investigating a Constraint-based Approach to Sustainable Design and Development

As previously suggested, constraint-based approaches deal with the limitations imposed by design constraints and seek to improve or optimise various performance measures. This suggests that such an approach is possible with relation to the IRM methodology. The limitations imposed by acceptable values of some of the KPIs imposes constraints upon what is allowable, and the desire to improve the values of other indicators means that these can act as suitable performance measures. Thus exists the opportunity to create a new methodology around IRM and generate appropriate tools that benefit both sustainable design and development and the general design process. Investigation into such a constraint-based approach is beginning with a focus on tools for the civil engineering and construction sector.

Preliminary work is examining the IRM methodology and investigating the use that has been of KPIs as reported in the literature and practical industrial case studies. These studies will be used to identify the constraints that emerge between key performance indicators and how these constraints can be used to produce optimal solutions. A constraint modelling approach will then be developed and applied with IRM methodology. Case studies and trials of an IRM constraint modeller will be carried out to investigate user interaction, benefits, drawbacks and possible limitations of the approach.

Conclusions

It has been seen that there exists an opportunity to create a design methodology and constraint-based approach to sustainable design and development. Sustainability as a discipline encompasses many variables which are shown to be effectively managed using integrated resource management. Key performance indicators obtained from design objectives and project specification translate into constraints, providing in effect, an optimisation problem for many interlinking variables.

It is intended that the research will provide a methodology to capture complex interactions between design objectives in the form of key performance indicators. These will be specified by the civil engineering and construction sector with a focus on sustainable design and development. However, it is anticipated that the research outcome will provide a general application for any design discipline.

The constraint-based approach can provide a methodology and the constraint modelling technique can form a sustainability appraisal tool. Its primary function will be an information exchange and informed decision making tool that brings together the interlinking disciplines of sustainable design and the multidisciplinary experience of those working to achieve sustainability.

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