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CONSTRAINT-BASED MODELLING: A PARADIGM FOR SUPPORTING DESIGN IN PRACTICE

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1. Introduction

The process of designing an artefact involves a large number of interdependent tasks which relate either to the artefact or the processes and systems by which it is to be developed and produced. These characteristics make design processes challenging to model and a number of process models have been proposed over recent years, as identified by Ding *et al.,* [Ding et al. 2009]. Notwithstanding this it is generally accepted that design processes moves through four phases: task clarification, conceptual design, embodiment design and detailed design. Encompassed in these design models, Pahl and Beitz [Pahl and Beitz 1996] identify three distinct types of activities:

- *Original design:* which involves elaborating or developing an original solution principle for an artefact not already in existence, although the task may be the same, similar or new, where the term task encompasses the required function of the solution.
- *Adaptive design:* which involves adapting a known system or the modification of an existing artefact (the solution principle remaining the same) to a changed task. Here original design of various parts or assemblies is often required.
- *Variant design:* which involves varying the size and/or arrangement of certain aspects of the chosen system, the function and solution principle remaining unchanged. No new problems arise as a result of, say, changes in constraints.

At a fundamental level each type of design activity can be considered to involve some form of problem solving where a solution is sought that best achieves a set of requirements or goals given a variety of constraints and the available set of elements or alternatives [Simon 1969]. Within the three design activities noted by Pahl and Beitz, McMahon observed four modes for change through incremental development of designs that have been based on established design principles [McMahon 1994]. As with Simon, McMahon argues that design involves searching for solutions within a feasible 'design space', with the process being guided by the design requirement. During this process the artefact is described in terms of design parameters; *explicit attributes*: shape, dimension, material etc. and evaluated using the artefact's performance parameters; *implicit attributes*: strength, reliability, efficiency etc. The modes of change proposed by McMahon are:

1. *Design space exploration*: in which design parameters are varied in order to find values that satisfy a requirement;

2. *Modification of the feasible design space*: as materials, manufacturing processes and other aspects of the artefact are changed so the design space will change, allowing the performance of the artefact to change;

3. *Improvements in understanding of design attribute relationships*: the ability to exploit the design space fully depends on the knowledge of the relationship between design parameters and performance parameters; and,

4. *Change in product design specification*: this effectively is a change in the objective function used in searching the design space and will lead to a different choice of design parameters in order to meet the different requirements.

While the models proposed by Pahl and Beitz, Simon and McMahon are different (process, activity or tasks) many of the individual elements within their models are remarkably similar. This similarity concerns both the terminology employed (e.g. goals, problem solving, constraints, design space and design parameters) and their relationships to the four phases of design (requirements, concept, embodiment and detailed design). What may differ is the starting point, order of activity and the notion of what constitutes new design. These commonalities and indeed similarities with other design process models perspective and descriptive, reinforces the proposition that design as it is practiced is most closely represented as a collaborative constrained problem solving activity. Where information is generated and discussions are undertaken [Hicks et al. 2009]. It is further proposed that the constrained problem-solving activity and the interaction between (problem-solving, collaboration, information gathering and decision making is essentially a Constraint-Modelling (CM) process, where the full definition of CM is adopted. This indicates the identification of the problem to solve elicitations of constraints, determination of objective, the conceiving of solutions to resolve constraints and where appropriate, best meeting of objectives.
It follows that the contribution of this paper is to examine the appropriateness of CM as a supportive paradigm of design in practice exploring in detail the relationship between McMahon [McMahon 1994] modes of change, and CM, and the relations between CM, collaboration, information gathering and decision making proposed by Hicks *et al*. In order to explore these relations, a range of industrial engineering examples are considered. Prior to this an overview of the process of modelling with constraints is given and a generalised model of design with constraints is presented.

2. Constraint theory

In Simon's 1969 works it was argued that design problems can be described as sets of 'bounding' constraints or requirements on the artefact to be designed. He states that design is purely a problem of optimization; maximizing or minimizing an objective or goal within a region of alternatives circumscribed by constraints. In other words, the constraints and the objective are initial conditions for design, and optimizing produces the solution through a form of evolution.

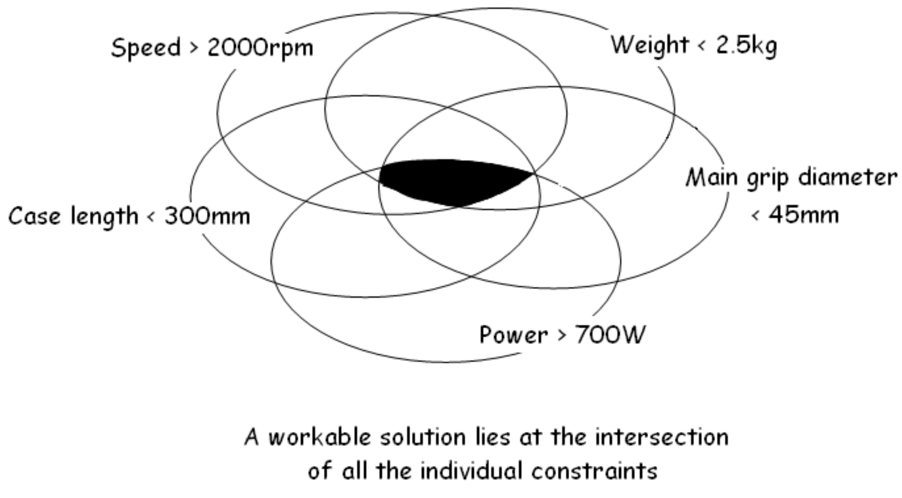

Figure 1. Constraint rules illustrated as sets

Elaborating on this, when a designer first encounter a task, the precise rules which should be applied are ill-understood and only evolve as the design progresses. What is often apparent initially are the constraints which bound a subset of feasible designs. A fully acceptable design lies at the intersection of all these subsets (cf. Figure 1). If the intersection is empty, then the skill of the designer is in deciding which constraints can be relaxed [Mullineux et al. 2005]. Constraint approaches aim to represent what is to be achieved rather than how it is to be achieved. These objectives or goals are represented as 'constraint rules'. These represent both the explicit and implicit relationships and objectives between the design parameters, which must be satisfied if the design is to fulfil all of the requirements. These constraints may include function, performance and physical requirements of the design and also constraints imposed by resources. In this manner the design of the artefact is not process led but goal orientated.

3. The process of modelling with constraints

The process of modelling with constraints involves five specifics aspects: the constraints, objects, parametric (constraint) model, Solution approach (numerical or computational methods) and the solution method (architecture (coding) structure).

- ***Constraints:*** When modelling with constraints, the constraints can be the internal relationships (of the parametric model), the bounds on a parameter (implicit or explicit) and the relations between parameters (implicit or explicit).
- ***Objects/ entities:*** These are the parts/ components/ elements which could be geometric or mathematical (algebraic).
- ***Parametric model:*** Core to the process is the creation of a parametric model. Here each object has parameters associated with it (objects can even be geometry). These parameters can be changed by the user or search strategy/ technique as necessary to create the desired part. Associated with the parameters are the explicit parameters relations (algebraic) and constrained relations.
- ***Solution approaches:*** There are three distinct methods of modelling with constraints. They are constraint monitoring (or constraint checking), constraint satisfaction, and constrained optimization [Lin and Chen 2002]. Constraint monitoring uses constraints passively to check whether a decision satisfies all constraints. Constraint satisfaction uses constraints actively to derive some values of variables based on given input values of other variables. Constraint monitoring and constraint satisfaction methods do not have the notion of finding the 'best' solution. Constrained optimization, on the contrary, aims at finding the best solution from the alternatives to maximize or minimize the objective functions (or utility functions) subject to constraints.
- ***Solution method:*** A variety of search algorithms can be readily applied within constraint-based design, most commonly used examples are: simulated annealing, generic algorithms, Tabu search and direct search (derivative and non-derivative based). In design many problems are unconstrained and it is often useful to combine algorithms, such as employing the global search strength of genetic algorithms with the localised search strength of simulated annealing. Other approaches employ strategies of search, one example being the application of sensitivity analysis to identify critical constraints, then employing search strategies only to resolve these [Medland and Matthews 2009].

While at the start of a modelling process these five aspects maybe only partially understood, building the understanding is an intrinsic part of the modelling process and in particular iidentifying the constraints is fundamental to characterizing the problem and presents the issues that need to be resolved which are critical for designing.

4. Designing with constraints

The process of designing with constraints is a multi-faceted exploration of the potential design space until a viable or best compromise solution is obtained. The process of designing with constraints is presented in Figure 2; a simplified description of the approach follows. From the design specification the initial set of constraints are elicited. The next stage is the construction of the parametric constraints model, associated with this model are the internal constraints (e.g. shape consistency, connectivity between objects) the external constraints (e.g. design solution performance requirements) and the objectives of the process; normally generated from the design specification. The initial stage in the 'resolving' of the model is to check for any constraint violations. If violations exist, various modes of response can be employed, the designer can try changing the start point of the search algorithm; change the search method or strategy (e.g. trying for constraint satisfaction not optimization). If violations still exist, then the next approach is to refine the model (modify the rule set), and again investigate the application of different strategies. If after this process a design solution cannot be sought then the final option is to modify the solution space, this can be achieved by relaxing or tightening the constraints (modifying the design space). Once the model has been produced, the order in which different approaches and strategies are applied is related to the outcome or design knowledge the designer requires. This is explored further in the next sections with particular reference to McMahon's four modes of change.

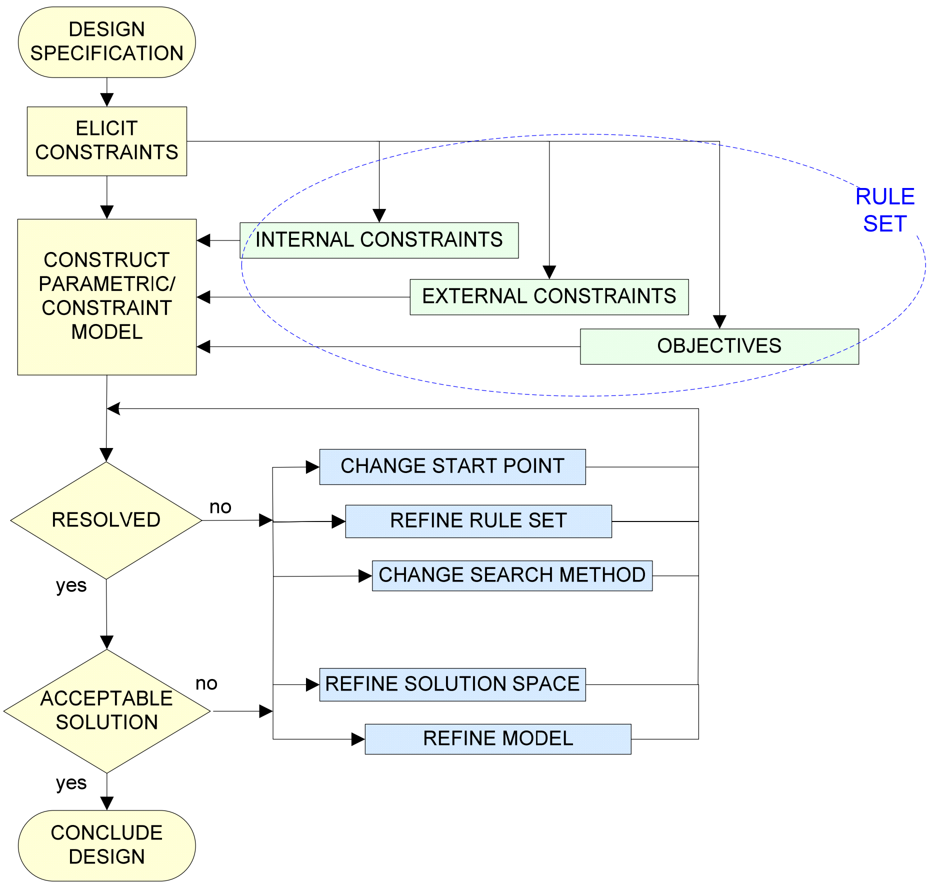

Figure 2. The process of designing with constraints

5. Constraint modelling in design

During the process of validating a concept, a design decision is triggered whenever constraint(s) are violated or new design considerations are introduced. The designer's knowledge of the solution space increases as various alternatives are explored. In McMahon (1994), the design space is described by bounds on the legitimate values of the design parameters and of the performance parameters. The designer's understanding of the attribute relationships between design parameters and performance parameters, or the ability to estimate or calculate these, are important aspects of the design activity. In this section the constraint modelling process is explored and its relationship to the modes of change are described by the use of case studies, along with the knowledge and understanding generated.

5.1 Design space exploration

As previously stated, all design work explores in some way the feasible design space; indeed potential designs outside the feasible space are likely to be considered, and it is hoped rejected, during typical design activities. When modelling with constraints the design parameters are varied in order to identify designs of improved performance [Medland et al. 2008]. The process is performed using a variety of search methods and algorithms [Lin and Chen 2002]. Selection involves the identification of design configurations and parameter values that satisfy particular design requirements.

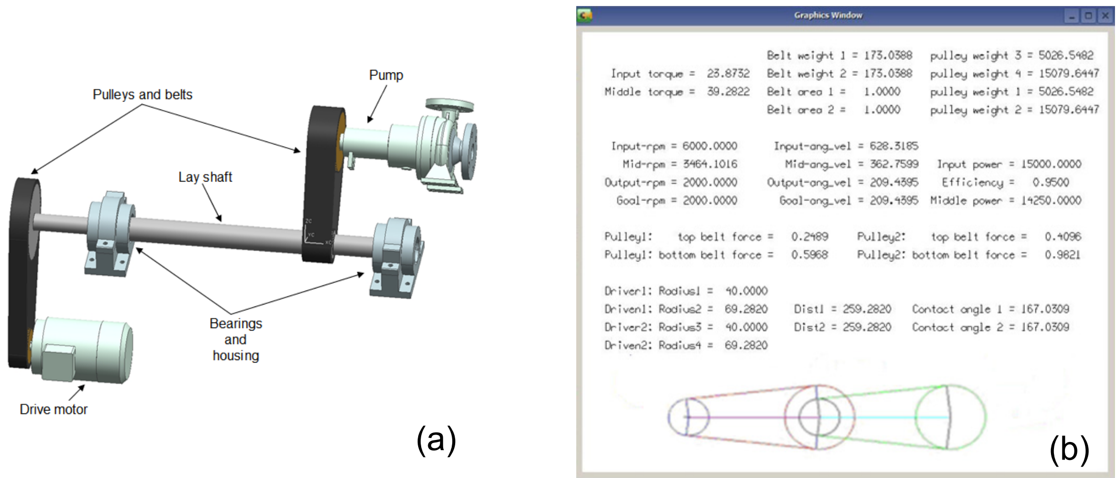

Figure 3. Mechanism design space exploration

By way of an example of design space exploration, consider the primary drive for a machine involving a motor via a lay shaft. The first demand on the shaft is a pump (as shown in Figure 3). The problem is one of packaging, where a finite space for the system is given, and the optimal position of the bearings and along with the dimensions of the pulleys and shaft are required. A constraint-based parametric model is produced. Constraints relate to the allowable values of performance and to materials and individual components. A combination of genetic and direct search algorithms are employed as the search methods and each viable solution recorded. The result of the search produces not only an optimal result for the dimensions of the shaft and pulley, positioning of bearings and pulleys, but also provides an understanding of the design space. The process also offers the potential to explore solutions which seem to fail when measured against the design specification, the parameters from such failed solutions can be plotted in the form of a multi-dimensional failure mode map [Matthews et al. 2007]. This process presents the designer with knowledge of why a solution fails; it can also reduce levels of uncertainty if a derived solution sits near the theorectical edge of the design space.

5.2 Modification of the feasible design space

Modification to the feasible design space essentially involves processes such as the identification of alternative parts, materials or manufacturing processes that allow the design space to be modified. It is related to the selection issue in that such modification often becomes possible as information relating to the new materials and manufacturing processes becomes available. It is rare that a single constraint is modified at one time. There is usually uncertainty in our understanding of the design space.

To illustrate this an example of the design of a product family of bicycles is considered. Here, design objectives were firstly collected and a list of design knowledge describing the requirements/specification generated. The product design specification (design objectives) totalled more than 30 and relates to both the rider and the bicycle. These extend from necessary performance needs and physical restrictions, for example ‘pedal not hitting the ground’ and ‘foot not going through front wheel’, to styling considerations that limit the range and sizes of the wheels. This design knowledge is transformed into a series of constraint rules that relate to a constraint model of the bicycle and the rider (cf. Figure 4).

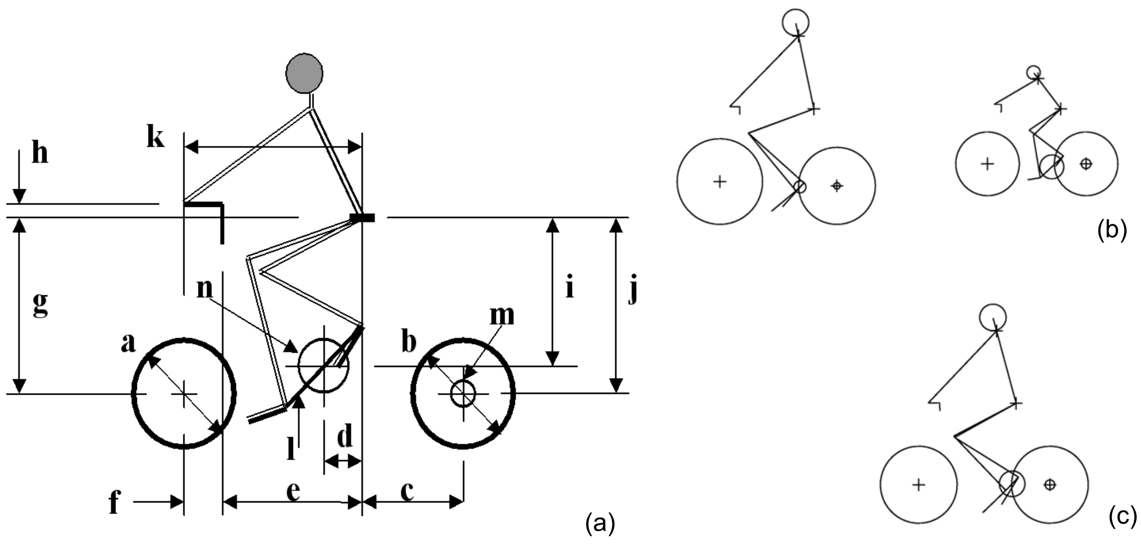

Figure 4. Modification of the feasible design space

To achieve the design objectives, a global solution is sought for the constrained problem for various sizes of rider. Part (b) of Figure 4 shows two variants for different sizes of rider. In these solutions everything has been varied in order to satisfy the constraint set. However, in practice it is desirable to use a number of standard components. These can be included by either fixing the values of certain design parameter so by restricting their range of permissible values to within a bounded interval or even a list of values, such as sprocket sizes. In part (c) of the Figure a solution obtained using standard components for the wheels and the sprockets is shown. When developing a product range or family it is often desirable to explore strategies for minimal change. This is made possible by investigating the sensitivity of the design solution to changes in the design variables [Medland and Matthews 2009]. Dominant or critical design variables may then be altered to best achieve the desired effect with the minimal change to the solution.

5.3 Improved the understanding of design attribute relationships

If the solution principle, design space and requirements specification are fixed, the design may also change by exploiting an improved ability to describe, model or predict the relationships relating the performance parameters of the artefact to the design parameters. For example, improved analytical techniques may allow a more precise calculation of stresses in a component, and perhaps reduced factors of safety (reserve factors) may be used in stress analysis. The understanding may for example also come from empirical results from experiments, from the application of computer-based techniques, from examination of historical competitive product data or from other techniques.

To illustrate the use of improved understanding within a constraint-based model, the investigation of a fluid power circuit, containing a hydraulic pump, a 5-port valve and a cylinder is considered. Here specified constraints govern how the hydraulic cylinder and a 5-port control valve operate. These constraints relate the internal pressures and flows to the configuration and motion. Considering these constraints together with constraint on the pressure and flows between components enables the system to be simulated and reverse engineered. This gives a larger group of constraints which can be used to generate knowledge of how a valve can be used to control the motion of the piston. The natural extension to this is to put these constraints together to inform the designer about a system's behaviour. In this case different valve models can be interchanged to provide modified system performance.

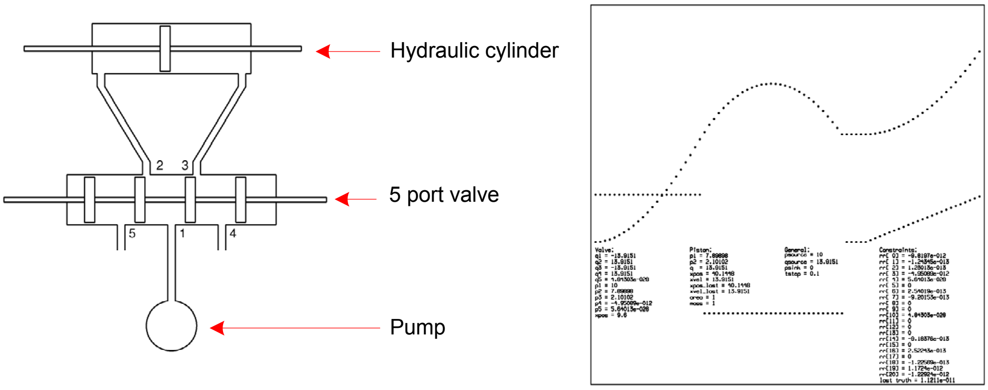

Figure 5. Improved understanding of design attribute relationships

5.4 Changes in the product design specification

The search of the design space is driven by the product design specification, which determines the objective function (actual or implied) by which the relative merits of different design proposals are judged. The product design specification also determines a number of the constraints that bound the design space. For example, specification of the intended manufacturing facility determines a number of constraints on the dimensions of the artefact, on the materials that may be used and so on.

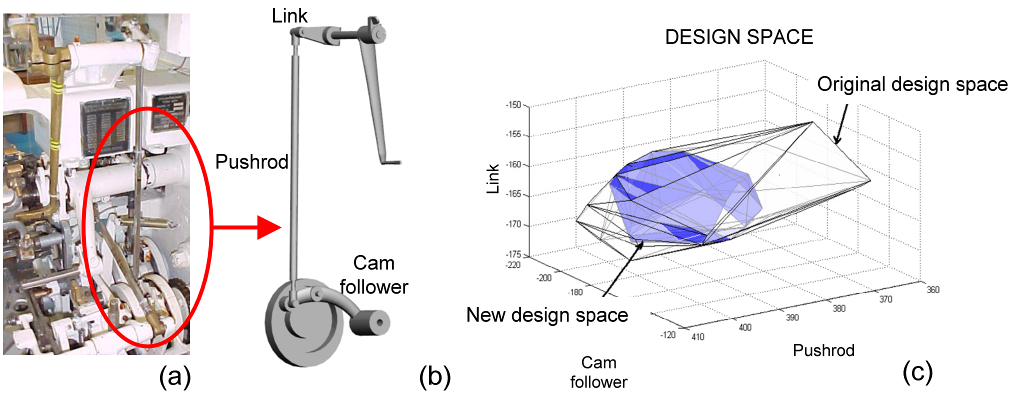

Figure 6. Changes in the product design specification

By way of an example, consider the redesign of an ejection mechanism from a confectionary wrapping machine (cf. figure 6a). The producer needed to wrap a candy bar with dimensions larger dimensions than the system was originally designed for, would it be possible? A constraint-based model was constructed of the machine, of which the ejection mechanism is shown in Figure 6 part b. The mechanism has topological hard constraints, defining its function and behaviour. The position of the pivot points for the cam follower and the pushrod to link are fixed. The length of the ejection arm is constrained, as the product is held centrally in the gripper jaws and the index position for ejection is fixed. Initially the cam profile is not evaluated for modification. This leaves the four links as the option to produce the configuration to process the new and old product. A search strategy based on "direct search" was employed to explore the limits of each element, while operating under functional and performance constraints. Once a constraint is violated the values of each object are recorded. Using these values the multi dimension design space can be plotted.

6. Constraints in the wider design activity

As noted in section 1, four interrelated activities need to be undertaken in producing a successful design outcome. These have been identified by Hicks *et al.,* [Hicks et al. 2009] as:

1. *Problem-solving:* problem formulation, goals, convergence and divergence;
2. *Decision making:* alternative evaluation and choice, action choice and control, design rationale and collective decisions;
3. *Collaboration:* communication and sharing of information between individuals and teams; and,
4. *Information transformation:* the consumption and generation of information during the design process. Their interrelationship are presented in Figure 7.

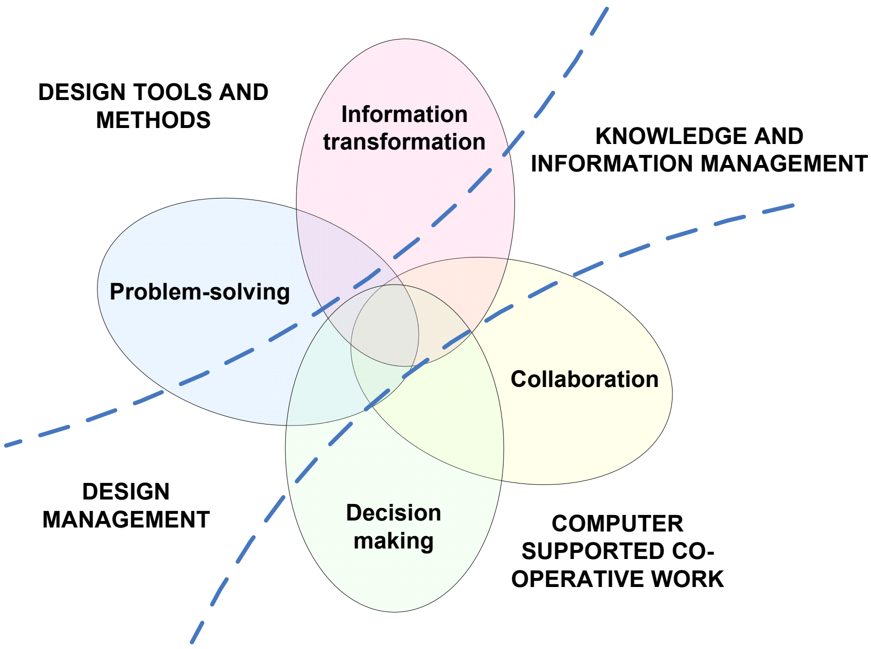

Figure 7. Core activities of design [Hicks et al. 2009]

While much of the previous sections discussion concerns the problem solving dimension of design, the relationship between CM and the wider design activity are now considered.

Problem solving: since the work of Simon, all researchers and practioners working with CM concur that viewing the design activity as constraints assists problem solving. Whether this comes from the exploration of the design space as shown in the example presented in section 5.1 or by the use of heuristics in the forms of search algorithms or that of constraint networks. In these approaches conflicts can be resolved, or limits of a design concept identified.

Decision making: the identification of design capability limits shows the designer when they need to consider new concepts (when to be creative). In particular the decision making process involves:

- exploring the influences of design parameters to assess their influence and importance
- the weighting of constraints to determine trade-offs
- capturing instances of constraint sets which explicitly represent design changes and rationale

Collaboration: in the generation of new technological products complex interactions are found between the technologies being employed, the diverse skills of the disparate design teams (spreading from materials scientists and manufacturing engineers, to business partners) as well as technical conflicts within the design of the artefact itself. Here they draw upon the skills and experience of their individual disciplines and can be unaware of potential problems being generated in other areas. Such interactions are seen to greatly increase when the objective is to create a family of products for a wide range of potential applications. It is only when such a conflict is identified by another member that it can be discussed and resolved. Within such a design team conflicts can often occur as members concentrate upon their individual responsibilities. It has been shown that CM offers the opportunity to clusters sets of rules relating to individual technical aspects of the design requirements, which can then be formed into networks that can be solved interactively within the constraint modelling environment [Medland *et al.* 2009]. Core to any collaborative approach is the development of a consistent terminology. As many design approaches theories and models are domain specific, so are their terminologies. It is arguable that constraints aid collaborative design as constraints present a commonality of terminology across domains. All designers understand limits whether these are presented as equalities and inequalities.

Information transformation: with increasing knowledge intensity in modern design and development, the capture of experiences and knowledge about previous designs is becoming more and more important so that previous work can be reused to speed new design processes and avoid unnecessary errors. When considering the design process as being constraint-oriented, the constraints become the rationale driving the design to the final characteristics and specifications of the product. Their evolution reflects the decisions made in the design process. Thus capturing the constraints and their evolutions to be associated, processed and retrieved, offers the potential to present understandings of why design decisions are made; why solutions are abandoned, why solution directions were not tried.

7. Conclusion

This paper has shown that there are similarities between design models and in particular McMahon's modes of change and the activities given by Hicks *et al*. It also proposes that constraint modelling reflects design in practice and in particular the wider definition has been argued. Core elements of modelling with constraints are highlighted and the overarching process of designing with constraints is presented. The potential of constraint modelling to support design in practice, particularly the four modes of change is shown by the way of case study examples.

The wider potential of constraint modelling as a paradigm for design practice is also explored through consideration of how it supports discussion making, problem solving, information transfer and collaboration. This reveals how constraint sets and evolution of constraint sets provide the interface between these four dimensions presented by Hicks *et al.* The constraint-based view can be argued presents a more holistic and intuitive approach and the basis for a more integrated model of design in practice.

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