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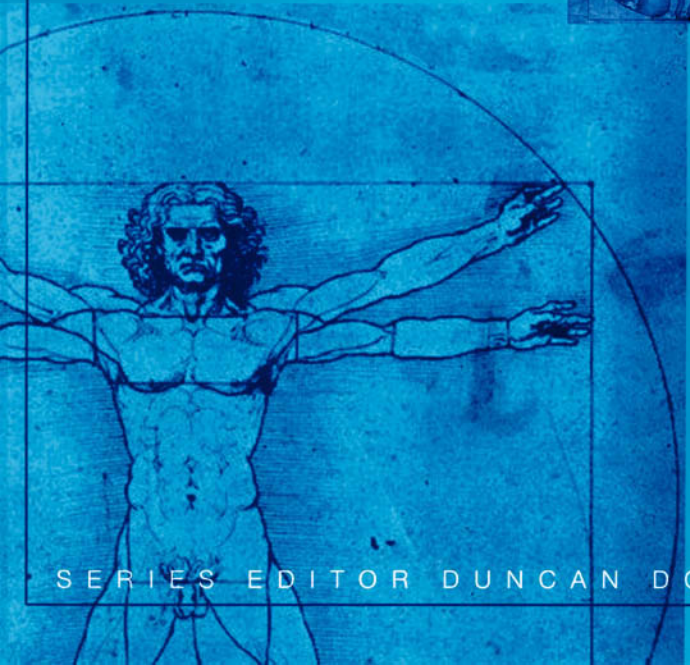
Constraint-Aided Conceptual Design

ERS 9

B O'Sullivan



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Constraint-Aided Conceptual Design

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B O'Sullivan

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About the Author

Dr Barry O'Sullivan received his primary degree in Production Management from the University of Limerick in 1994 and his PhD in Computer Science from University College Cork (UCC) in 1999. Between October 1998 and September 1999, he was an assistant lecturer and post-doc researcher in the Department of Computer Science at University College Cork. He was co-founder of a UCC campus company called Suntas Technologies in 1999. This company commercialized a constraint processing technology to support the analysis of printed circuit board designs. In October 2000 he was appointed to a permanent position in UCC as a College Lecturer in the Department of Computer Science.

Dr O'Sullivan has acted as reviewer for a number of international conferences and journals. He has also been involved in the organization of several international workshops and conferences. He has published widely in the field of constraint processing for engineering design. Over the past number of years he has also been an invited speaker to many universities, research labs, and companies in both the US and Europe on the same topic.

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This work is dedicated to my mother, for always being there; to my wife, Linda, for all her love and support; and to the memory of my grandparents, Frank and Mary Conroy, who would have been proud to have held this book.

I would also like to extend my deepest thanks to the other members of my family: my father, Noel; my brother, Brian; my sister, Carmel; and my brother-in-law, Anthony. They are a constant reminder of what is truly important in life.

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Contents

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Series Editor's Foreword

The nature of engineering research is such that many readers of papers in learned society journals wish to know more about the full story and background to the work reported. In some disciplines this is accommodated when the thesis or engineering report is published in monograph form – describing the research in much more complete form than is possible in journal papers. The Engineering Research Series offers this opportunity to engineers in universities and industry and will thus disseminate wider accounts of engineering research progress than are currently available. The volumes will supplement and not compete with the publication of peer-reviewed papers in journals.

Factors to be considered in the selection of items for the Series include the intrinsic quality of the volume, its comprehensive nature, the novelty of the subject, potential applications, and the relevance to the wider engineering community.

Selection of volumes for publication will be based mainly upon one of the following: single higher degree theses; a series of theses on a particular engineering topic; submissions for higher doctorates; reports to sponsors of research; or comprehensive industrial research reports. It is usual for university engineering research groups to undertake research on problems reflecting their expertise over several years. In such cases it may be appropriate to produce a comprehensive, but selective, account of the development of understanding and knowledge on the topic in a specially prepared single volume.

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ERS6	*Strategies for Collective Minimalist Mobile Robots*
ERS7	*Tribological Analysis and Design of a Modern Automobile Cam and Follower*
ERS8	*Automotive Engine Valve Recession*

Authors are invited to discuss ideas for new volumes with Sheril Leich, Commissioning Editor, Books, Professional Engineering Publishing Limited, or with the Series Editor.

The ninth volume comes from the National University of Ireland and is entitled

Constraint-Aided Conceptual Design
by
Dr B O'Sullivan

This is the third volume in the Series to include the word 'design' in its title, reflecting the importance of, and current interest in, the subject of design. The design process remains one of the enigmas of engineering. The difference between an engineer and a scientist is often said to be the creative ability of the former to design equipment, processes and systems to achieve stated objectives. Yet not all engineers are good designers.

The process of 'creative design' results in a solution, or solutions, which meet desired objectives within a framework of specified constraints. There is rarely a 'unique' solution to a design problem. Indeed, a multitude of solutions might well emerge and additional factors are then invoked to determine the selected design. Such factors might be aesthetic appeal, cost or ease of manufacture, life-cycle performance, and the total cost of maintenance.

In this volume Dr O'Sullivan of the Department of Computer Science, University College, Cork, shows how powerful computational systems can be used to address these problems and to rationalize the total design process. The text represents a fascinating illustration of the impact of computers and computing strategies upon conceptual design. It is based upon his PhD thesis submitted to the National University of Ireland, Cork, in 1999 and it represents the first contribution to the Engineering Research Series from that country. The text is a further illustration of the developing impact of computing upon traditional engineering processes and will be of interest to engineering designers and computer scientists alike.

Professor Duncan Dowson
Series Editor
Engineering Research Series

Author's Preface

The product development process is concerned not only with the design of products, but with how these products are manufactured, distributed, and serviced. Engineering conceptual design can be defined as that phase of the product development process during which the designer takes a specification for a product to be designed and generates many broad solutions to it. Each of these broad solutions is, generally, referred to as a 'scheme'. Each scheme should be sufficiently detailed that the means of performing each function in the design has been fixed, as have any critical spatial and structural relationships between the principal components. While it is generally accepted that conceptual design is one of the most critical phases of the product development process, few computer tools exist to provide support to designers working in this stage of product development.

In this book a thesis is presented which argues that constraint processing offers a rich basis for supporting the human designer during engineering conceptual design. A new perspective on the conceptual phase of engineering design is presented, upon which a constraint-based approach to supporting the human designer is developed. This approach is based upon an expressive and general technique for modelling: the design knowledge that a designer can exploit during a design project; the life-cycle environment that the final product faces; the design specification which defines the set of requirements that the product must satisfy; and the structure of the various schemes that are developed by the designer. A computational reasoning environment based on the notion of constraint filtering is proposed as the basis of an interactive design support tool to assist a human designer working in the conceptual phase of design. Using this interactive design support tool, the designer can be assisted in developing models of proposed schemes which satisfy the various constraints that are imposed on the design.

The primary contribution of the work presented in this book is that it provides a novel approach to supporting the human designer during the conceptual phase of engineering design. The approach presented here not only addresses the issue of modelling and reasoning about the design of products from an abstract set of requirements, but it also demonstrates how life-cycle knowledge can be incorporated into the conceptual design of a product and how alternative schemes can be compared.

B O'Sullivan
University of Cork, Ireland

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Acknowledgements

This book is based on my PhD dissertation, which was submitted to the National University of Ireland, Cork. I would like to extend my warmest gratitude to my PhD supervisor, Professor James Bowen, for his help and encouragement while I carried out the research presented in the dissertation. In particular, I would like to thank him for the time he spent helping me to present my research and thesis in the form of that work.

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I would like to thank Maurice O'Brien, Pat Doyle, and Mel Conway of Bourns Electronics Ireland, for their assistance with the industrial case study carried out at their company.

I also wish to acknowledge the support of the European Commission and their funding of the 'Concurrent Engineering Design Adviser System' (CEDAS) project (Esprit Project 20501) and the integration in Manufacturing and Beyond (IiMB) Subgroup for Design Co-ordination (Esprit Working Group 21108). My involvement in these activities was a very valuable source of inspiration for the research presented here.

Dr Barry O'Sullivan
University College Cork
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Chapter 1

Introduction

This chapter briefly introduces the research presented in this book. The influence of conceptual design on the remainder of the product development process and on the final product is presented. The research objective and scope of the work is defined. A formal statement of the thesis is presented. The major contributions of this work are outlined in general terms. The chapter ends with a description of the architecture of the book and a guide to reading it.

1.1 Engineering design and product development

Engineering design[1] is concerned with the development of detailed specifications for products which provide a technical function. It is a demanding process that requires expertise in many different fields such as science, engineering, and often art. Product development is concerned not only with the design of products, but with how these products are manufactured, assembled, distributed, and so on. A typical product life-cycle is illustrated in Fig. 1.1. In this figure it can be seen that design can be considered to be a phase of the life-cycle of a product.

Over the past few years, a good deal of research has been carried out in the fields of design and product development. This is due to the recognition that product development has become the battleground upon which industry can achieve competitive advantage [1]. Improving the product development process increases efficiencies in operational areas within an organization, such as manufacturing and assembly. The benefits include shorter development and manufacturing lead-times, increased product life-cycle revenue, reduced engineering change-order costs, and less development waste.

[1] In the remainder of this book, the term 'design' will be used as a shorthand for the phrase 'engineering design'.

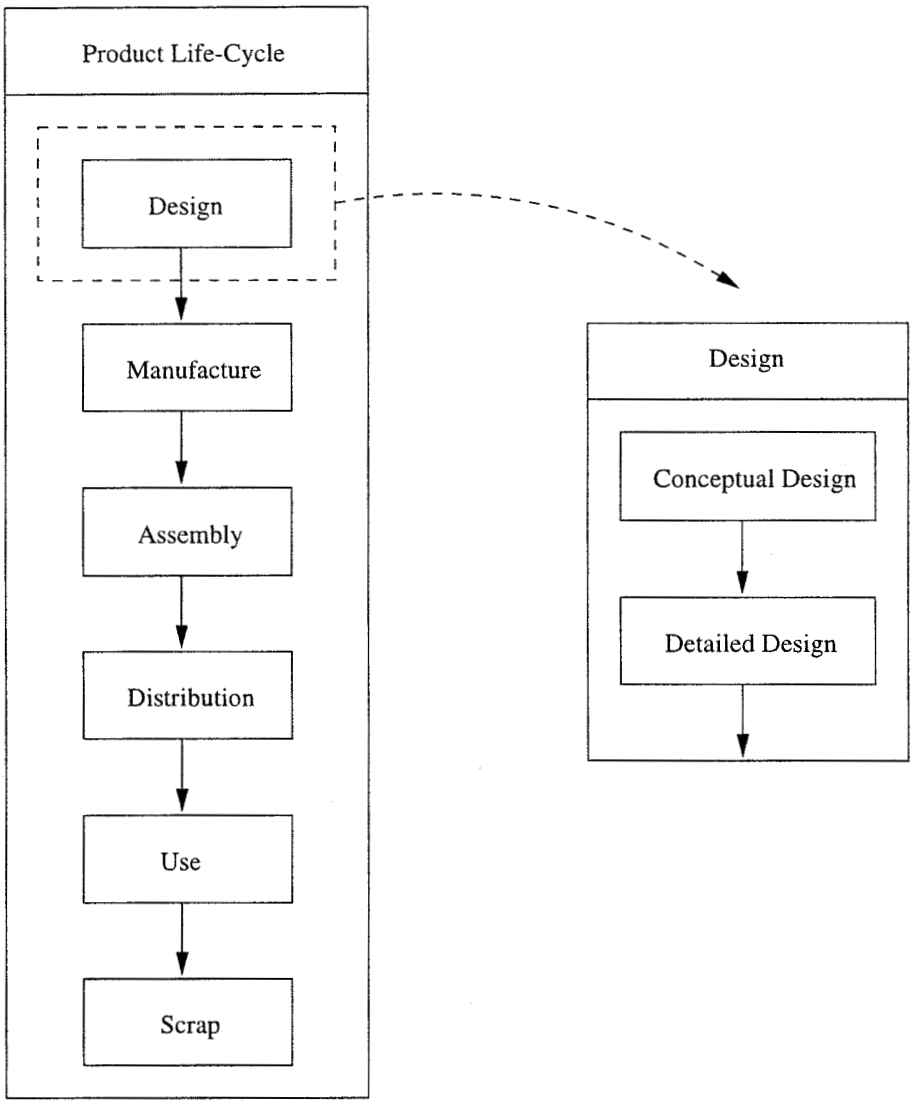

Fig. 1.1 Engineering design and the product life-cycle

In an effort to increase the effectiveness and productivity of design, several approaches to incorporating knowledge of the downstream phases of the product life-cycle have been developed. The most commonly used of these approaches is *Design for X (DFX)* [2, 3]. The 'X' in DFX can be interpreted in a number of ways [4]. For example, 'X' could be interpreted as either a *life-cycle process*, such as manufacturing or assembly, or a *design property*, such as quality or cost; it can also be interpreted as meaning a *set* of these processes or design parameters. The objective of DFX is the optimization of the design of a product from the perspective of the life-cycle process(es) or design parameter(s) referred to by 'X'. DFX techniques have been successfully applied to the design of products in industry [2]. The improvement in the competitiveness of many companies has been due to the use of DFX during product development.

Due to the level of sophistication and customization expected by customers in today's markets, the amount of knowledge required for bringing a product to market has become vast. Consequently, modern approaches to product development advocate integration among the various phases of the product development process. This model of product development has given rise to several approaches that support multi-disciplinary decision making and design, such as Integrated Product Development [5], Concurrent Engineering [6] and Design Co-ordination [7].

1.2 The topic of this research

The thesis presented in this book is concerned with the development of a constraint-based approach to supporting engineering conceptual design. Engineering conceptual design can be regarded as that phase of the design process in which the designer takes a specification for a product to be designed and generates many broad solutions to it. Each of these broad solutions is generally referred to as a *scheme* [8]. Each scheme should be sufficiently detailed that the means of performing each function in the design has been fixed, as have any critical spatial and structural properties of, and relationships between, the principal components.

It is generally accepted that conceptual design is one of the most critical phases of the product development process. It has been reported that up to 80 per cent of a product's total cost is dictated by decisions made during the conceptual phase of design [9]. Furthermore, poor conceptual design can never be compensated for by good detailed design [10].

The cost of a product is a complex function of the elements from which it is configured and the various processes required to design, manufacture, assemble, and service it. During design, human designers have an ideal opportunity to tailor the design of a product to the particular life-cycle processes that face the products which they develop. Therefore, major cost advantages can be gained through ensuring that, during conceptual design, the decisions which are made are informed by data relating to the product being designed and the life-cycle processes required to produce and deliver the final product.

Although the many benefits of effective conceptual design have been recognized, very few computational tools exist that provide support to the human designer working in this stage of the design process. The majority of those tools that do exist are found mostly in research laboratories in universities around the world. Additionally, many of the tools that are available do not *assist* the designer in the task of design, but *dominate* the entire design process. However, designers may be inhibited by the design policies of their company, or may be required to carry out design tasks in a particular order due to the design tools being used. While the design policies of the company should be supported, indeed enforced, by good design tools, the designer should be allowed to perform design tasks in any order. It is the primary objective of this research to address this need for interactive designer support during conceptual design. A more precise statement of the goals of this research is presented in Section 1.3.

1.3 The goals of this research

In the discussion of engineering design and product development presented so far, the importance of conceptual design has been highlighted. The benefits of providing support during the conceptual phase of design are well known. Thus, there exists a real justification for developing approaches to supporting the designer during this phase of design.

The Galileo constraint programming language [11–13] has been widely used to develop design adviser systems for supporting integrated approaches to design, such as Concurrent Engineering [11] and post-design verification [12, 13]. It has been shown that Galileo offers an appropriately rich basis for developing design adviser systems for these aspects of the *detailed* phase of design. It is believed that Galileo can also provide an appropriately rich basis for supporting *conceptual* design. Therefore, the objectives of the work presented in this book are as follows:

1. to investigate whether constraint-based reasoning can be used as a basis for supporting conceptual design;
2. to determine if the expressiveness needs of conceptual design motivate the introduction of new features into Galileo.

These goals have been used to form a central thesis, which will be defended in this book. This thesis is presented in Section 1.4.

1.4 A statement of the thesis

To achieve the goals presented in Section 1.3, the approach adopted in this research is to attempt to use constraint processing to provide a basis for the modelling and evaluation of a set of alternative schemes for a product. In this approach, constraint processing is used to ensure that all design concepts are consistent with respect to the various restrictions imposed by the design specification and by the product life-cycle.

Thus, the thesis which is presented and defended in this book can be stated as follows:

'It is possible to develop a computational model of, and an interactive designer support environment for, the engineering conceptual design process. Using a constraint-based approach to supporting conceptual design, the important facets of this phase of design can be modelled and supported.'

1.5 Contributions of this research

The research presented in this book contributes to the state of knowledge in the fields of constraint processing and computer-aided engineering design. The research addresses many important issues in product development, such as computer support for a primarily abstract and creative phase of design, constraint processing in early-stage engineering design, computer-assisted evaluation of alternative schemes, and the use of DFX concepts during conceptual design. The research provides a unique insight

into how constraint processing techniques can be used to support conceptual design. The concept of the function-means tree [14] was extended and used as a vehicle for interactively developing alternative constraint-based models of a product having particular properties, while providing a particular functionality. The use of Pareto optimality within the constraints paradigm to actively prune uninteresting parts of the design space during design is also novel. From a design perspective, this research represents a novel approach to interactively supporting designers during conceptual design. The interactive nature of the approach advocated here ensures that the utility of the designer's expertise, knowledge, and creativity is never compromised.

1.6 Structure of this book

This book comprises six chapters and four appendices. The remainder is structured as follows:

- **Chapter 2** reviews the background literature relevant to the thesis presented in this book.
- **Chapter 3** presents the theory of conceptual design upon which the thesis presented in this book is based.
- **Chapter 4** describes a constraint-based implementation of the conceptual design theory presented in Chapter 3.
- **Chapter 5** demonstrates the approach to supporting conceptual design that is presented in this book, on two design problems: a toy design problem, related to the design of a transportation vehicle, and an industrial case-study.
- **Chapter 6** presents a number of conclusions and recommendations for further study.
- **Appendix A** presents an overview of the Galileo language.
- **Appendix B** presents the Galileo implementation of the various generic design concepts that are used as a basis for supporting every conceptual design project.
- **Appendix C** presents all the Galileo code used in the toy design problem related to the design of a transportation vehicle.
- **Appendix D** presents all the Galileo code used in the industrial case-study carried out in association with Bourns Electronics Ireland.

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Chapter 2

Background

This chapter reviews the background literature relevant to the thesis presented in this book. The literature on conceptual design research is reviewed from three perspectives: first, with a focus on the approaches to modelling design problems, design knowledge and design solutions; second, with a focus on the various design reasoning techniques which have been advocated; third, a number of trends in conceptual design research are identified and discussed. Constraint processing techniques have been applied to many aspects of the engineering design problem. This chapter also reviews the literature on the application of constraint processing techniques to engineering design. It will be shown that, while constraint processing has been applied to many aspects of design, there is considerable scope for research into using constraint processing techniques to support the conceptual phase of design. Finally, this chapter reviews the concept of Pareto optimality. The principle of Pareto optimality is used in this research as a basis for assisting the human designer to compare alternative schemes that satisfy a design specification for a product.

2.1 A review of conceptual design research

Conceptual design has been defined as that phase of design which takes a statement of a design problem and generates broad solutions to it in the form of, what are generally referred to as, ‘schemes’ [1]. A scheme should be sufficiently detailed that the means of performing each major function has been fixed, as have any spatial and structural relationships of the principal components.

While conceptual design is regarded as the most demanding phase of design on the designer [2], it also offers the greatest scope for improvements in the design of the product [1]. It is the phase of design where engineering science, practical knowledge, knowledge of production methods and commercial expertise must be brought together,

and where the most important design decisions are made. It is widely acknowledged that up to 80 per cent of a product's total cost is dictated by decisions made during the conceptual phase of design [2]. Furthermore, the effects of poor conceptual design can never be rectified by good detailed design [3]. Most errors in design, as opposed to those made during production, are due to the use of a flawed conceptual design [4].

In Chapter 1 the role of conceptual design in the product development process was discussed. While in many theories of design there is no explicit mention of a conceptual phase of design, all theories recognize the need to synthesize preliminary solutions to the design problem. It is these early synthesis activities that can be regarded as conceptual design.

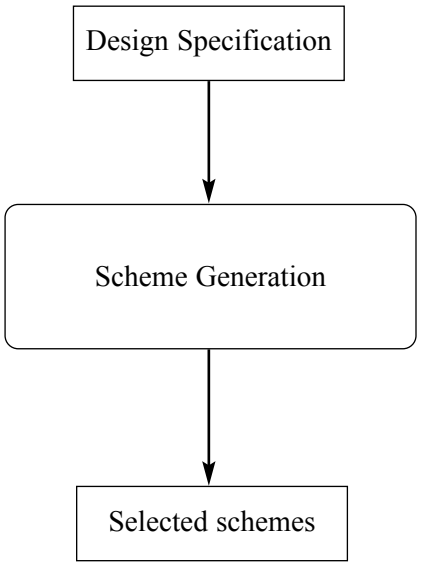

Fig. 2.1 A simple perspective on the conceptual design process

A simple perspective on the conceptual design process is illustrated in Fig. 2.1. A design specification can be regarded as a set of requirements that the product must satisfy. The output of the conceptual design process is a set of schemes for products that have the potential to satisfy the requirements described in the design specification. This set of schemes has been selected from a larger set of alternatives that have been considered during conceptual design. These schemes will be further developed during later stages of product design. A more detailed view of the conceptual design process is presented in Fig. 2.2.

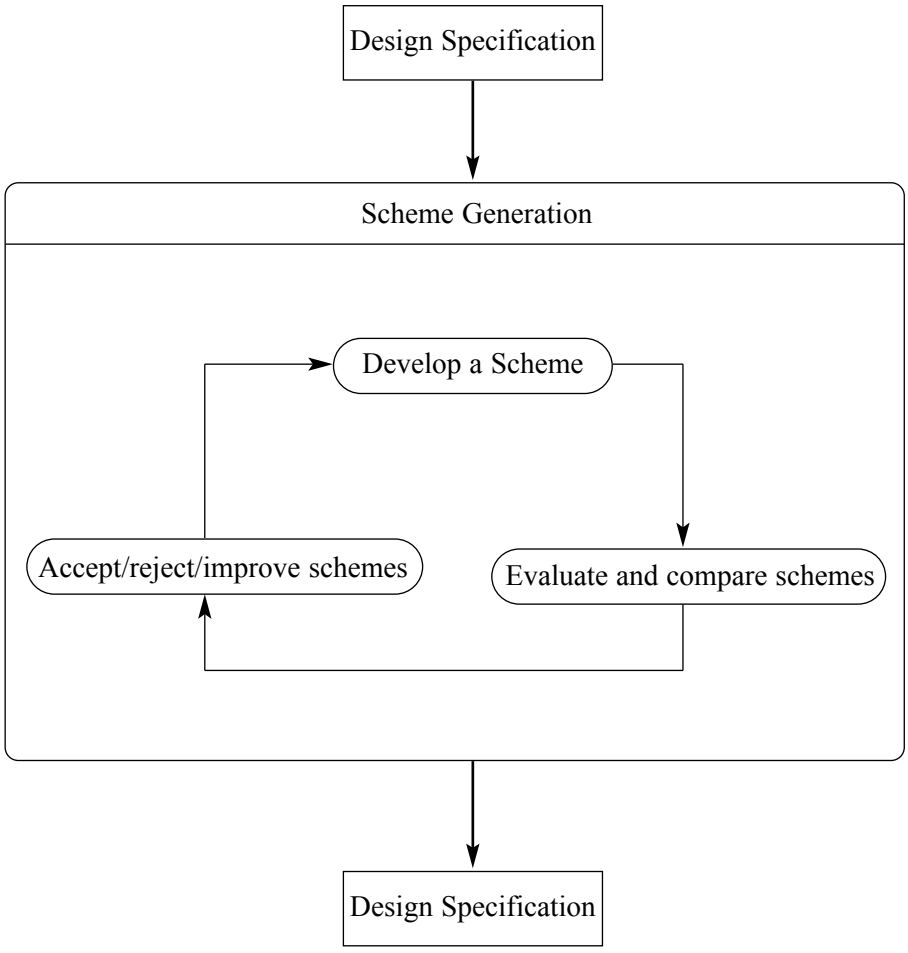

Fig. 2.2 A more detailed view of the conceptual design process

From Fig. 2.2 it can be seen that conceptual design is an iterative process during which the designer generates a set of alternative schemes for a product based on a design specification. The design specification will contain a set of requirements that the product to be designed must satisfy. Based on these requirements, the designer begins an iterative process of scheme generation. During this process the designer will develop a scheme that is intended to satisfy the design specification. The designer will then evaluate the scheme against the design specification and compare it to those schemes that have already been developed. As new schemes are generated, the designer may decide to accept, improve, or reject from the existing pool of schemes. One of the primary objectives at this stage of design is to avoid prematurely selecting one scheme without considering as many other schemes as possible. This model of conceptual design is consistent with all of the 'textbook' descriptions of the process that exist in the literature [5–8].

2.1.1 Modelling for conceptual design

In the design theory literature it is recognized that modelling, both the product design and the design knowledge from which the design is developed, is one of the most difficult issues to address [3, 9]. A number of approaches have been proposed that attempt to address this issue. These approaches can be classified as:

- function-based modelling;
- domain representations;
- grammars and ontologies;
- geometry-based methods;
- knowledge-based methods.

These will now be reviewed.

Function-based modelling

Since designs exist to satisfy some purpose or function [10], knowledge of functionality is essential in a wide variety of design-related activities, such as the specification, generation, modification, evaluation, selection, explanation, and diagnosis of designs. Generally, function can be regarded as the abstraction of the intended behaviour of a product. A number of researchers have integrated the role of function into complete theories of design [5, 11, 12].

Formalizing the representation of functional design requirements is essential for supporting conceptual design using a computer. Two approaches to representing function have been reported in the literature [13]. These involve representing functions as either verb–noun pairs [14] or as input–output transformations, where inputs and outputs can be energy, materials or information [6]. The former approach is often referred to as the *symbolic function* model while the latter is often referred to as the I/O *function* model [15].

It has been reported that, while the I/O function model is more systematic than the symbolic function model, the former is the more flexible of the two approaches [15]. The symbolic function model has been widely used [14, 16, 17–21]. However, the I/O-based approach has also been widely advocated [22–24]. One of the major advantages of the symbolic function model is that designers can define a function at quite a high level of abstraction. Furthermore, by describing the intended functionality in this way, the designer is not biased towards developing a product with a particular physical structure.

The term ‘synthesis’ is used in design to refer to the process of developing a physical realization for an abstract notion of a product. For example, developing a configuration of parts from a functional specification of a product can be regarded as an instance of synthesis. Many approaches to design synthesis based on function have been reported in the literature [15, 18, 21, 22, 25, 26].

Function–means modelling is based on the notion of a *function–means tree* [28]. A function–means tree describes alternative ways of providing a top-level (root) function through the use of means. A means is a known approach to providing functionality. Two types of means can be identified in a function–means tree: principles and entities. A principle is defined as a collection of functions which, collectively, provide a particular functionality; it carries no other information than the lower-level functions to be used in order to provide a higher-level function. An entity represents a part or sub-assembly. The function–means approach has been adopted by several researchers as a basis for supporting synthesis [12, 25]. Indeed, from the earliest stages of the development of the thesis presented in this book, a similar approach has been adopted [17, 26].

Another approach to design synthesis based on function is known as Function–Behaviour–State modelling [21], which has been proposed as an approach to minimizing the subjectivity of function in design [21]. This approach is based on a distinction between two types of relationships: *function–behaviour* relationships and *behaviour–state* relationships. Function–behaviour relationships are used to relate functions to behaviours. For example, the function 'to make a sound' can be provided by behaviours such as 'something striking a bell'. In order to support synthesis, behaviour–state relationships are used to describe all possible behaviours of an entity.

Some researchers have adopted a 'Function–Behaviour–Structure' (FBS) approach to supporting synthesis based on function [18]. This approach uses the relationships between the physical structure, behaviour, and functionality of existing designs to provide a basis upon which designs for new products can be developed using analogical reasoning. Integrating new production technologies has been addressed using a generalization of the FBS approach called 'Function–Behaviour–Process–Structure' modelling [26].

The interpretation of function as a transformation between inputs and outputs is the basis for systems such as the DICAD-Entwurf system [15] and the FuncSION system [22, 27]. In these, a functional model of a product is developed from a set of IO function units. These units can be configured in a particular way to develop a complete functional description of a product based on the transformation of flows through the design. Among the advantages of the IO approach is that it is a formal approach to conceptual design. However, the disadvantages are that it is not very flexible and is often limited to particular design domains, such as the design of mechanical mechanisms.

Domain representations

Many European design researchers regard the design of mechanical systems as a progression through a two-dimensional space [11]. This space is illustrated in Fig. 2.3. One dimension of this space relates to the designer's understanding of a solution to a design problem – defined as a progression from an abstract to a concrete understanding. The second dimension relates to the specification of the design solution – defined as a progression from a simple to a detailed specification of the solution.

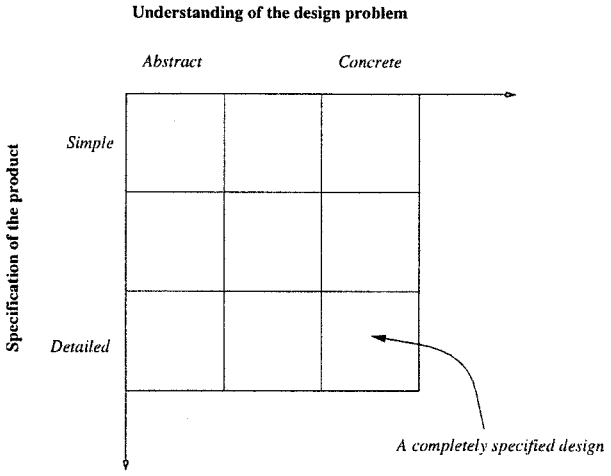

Fig. 2.3 The progression of a designer's ideas through the design process

When developing a design for a product there are several perspectives that a designer can have on the emerging design. For example, the 'Theory of Domains' defines four perspectives, called domains, of a mechanical system design [11]. These four domains are:

- the *process domain* – describes the transformation that takes place in the product;
- the *function domain* – describes the functions to be provided in the product and the relationships between them;
- the *organ domain* – describes the interfaces between the entities that provide the functions;
- the *part domain* – describes the parts and structure of the product.

Another approach to supporting design synthesis based on the maintenance of consistency between a number of views of a product model is the 'Artifact Model' approach [28]. This approach is based on the premise that a sufficient level of support can be offered to a designer through the use of three product viewpoints: a function view, a solution view and a state view [28]. These views collectively provide a complete model of the state of the product being designed and the design activities that were performed by the designer.

Grammars and ontologies

Grammatical approaches to design effectively define a design language [29]. There are two main categories of design grammar: *shape grammars* [30] and *graph grammars* [31]. Grammars have been developed as a mechanism for specifying a set of designs in terms of the transformations that can be used to generate that set [30]. For example, shape grammars are often used in CAD systems to ensure the validity of the geometric model of the product [31, 32].

The use of design grammars during conceptual design has been widely reported in the literature [3, 33]. Designs generated from shape grammars may often need to be modified before they are considered in further detail. The refinement of designs

generated from shape grammars has been reported in the literature [29, 34]. Some grammar-based approaches to conceptual design attempt to ensure the validity of designs in terms of the design specification, which may change during design, and in terms of the constraints inherent in the life-cycle of the product. For example, the issue of ensuring that the designs generated using grammars are manufacturable has been addressed [35]. In addition, predicting the variety of possible designs that can be generated using a given grammar has also been addressed [36].

Instead of developing ad-hoc design languages, many researchers have directed their efforts at developing a common design ontology. An ontology is a set of common terms and concepts that are general enough to describe different types of knowledge in different domains, but specific enough for application to particular design problems [3]. The YMIR ontology has been proposed as a domain-independent ontology for the formal representation of engineering design knowledge [37]. Design ontologies have been used as the basis for many general-purpose approaches to addressing some critical aspects of product development, such as the evaluation of designs using design norms [38].

Geometry-based methods

Most modern CAD systems are geometry-based. In other words, when using a conventional CAD system, the designer focusses on the dimensions and spatial relationships between design elements. However, during conceptual design the various alternatives that are created and compared by a designer are generally created from a non-spatial perspective and lack detailed geometric structure [39]. That is not to say that consideration of geometry is irrelevant at the conceptual design stage. In order to satisfactorily evaluate an engineering design concept, it is often important to consider all critical geometric and spatial relationships that are relevant.

The ‘minimum commitment principle’ is well known in engineering design. This principle states that no decision should be made beyond what is necessary to ensure the quality of the current solution [40–42]. This principle has been used as an approach to creating geometric models of design solutions at the conceptual stage of design in which only the most critical details of the product are modelled [42]. This ensures that the designer has maximum scope later in the design process to make decisions about the specifics of a particular design.

The use of features as carriers of function in design has been an important area of research for a number of years [43–45]. A feature is considered to be ‘a region of interest in a part model’ which provides some function [46]. Since features provide function and are generally described geometrically, feature modelling for conceptual design is a specific application for geometry-based modelling. Many sophisticated approaches for supporting feature modelling for conceptual design in both two and three dimensions have been reported [43]. Representing features for use in collaborative product design environments has also been reported in the literature [44]. In these approaches features are represented by different views – each view relating to a particular discipline represented in the product development team.

Some researchers have combined parametric geometry, features, and variational modelling into integrated design representation schemes for conceptual design [47].

Knowledge-based methods

During conceptual design, a designer exploits a considerable variety of knowledge to effectively generate a set of good design concepts. A designer will typically exploit information relating to function, technologies for providing function, cost information, and life-cycle knowledge. To represent the variety in the knowledge required by designers, flexible modelling paradigms are required. Knowledge-based methods, developed by a number of researchers, are capable of modelling many aspects of the design problem that are relevant to the conceptual stage of design.

While there exist domain-specific knowledge-bases for domains such as vehicle design [48, 49] and the preliminary design of tall buildings [50], more general approaches have also been reported. For example, a knowledge-base known as the 'Design Model', which provides a basis for enhancing the design process by providing the designer with a means for communicating a broad range of design knowledge derived from the multiple disciplines involved in the design process, has been reported [51]. Two of the more well-known knowledge-based systems for conceptual design are the QPAS system [52] and the Scheme-builder system [23,53].

The use of databases of known design solutions has become very common in conceptual design [54–58]. These databases have the flexibility to store vast amounts of data relating to many different aspects of the design domain of interest to the designer.

Many other knowledge-based design approaches have been reported in the literature [27, 38, 59–65]. Among the approaches taken are the use of model-based representations, analogical knowledge-bases, and concept libraries for modelling complex collections of design knowledge. These systems address different aspects of the knowledge requirements of conceptual design and general engineering design.

2.1.2 Reasoning techniques for conceptual design

Based on the modelling techniques presented in Section 2.2.1, many approaches to supporting reasoning during conceptual design have been developed. Design reasoning techniques form the basis for computer-based design support systems. Computer-based design tools can provide the human designer with various levels of support, from fully automated design generators through to post-design verification environments [66].

A review of the literature on reasoning techniques for conceptual design is presented here. The review is structured according to the predominant reasoning mechanisms for conceptual design which have been reported in the literature. The following categories will be used here:

- adaptive methods;
- case-based reasoning;
- other knowledge-based approaches.

Adaptive methods

Adaptive search is a collective term that describes those search and optimization techniques with operational characteristics which are heuristic in nature [67]. The term 'adaptive search' relates to search techniques, such as genetic algorithms, evolutionary search, simulated annealing, and hill climbing. In general, adaptive search techniques have been used as a basis for automated design applications. The goal of these applications has been improving the features of existing designs through the optimization of variables defined within the system [68]. Of the many adaptive search methods that exist, genetic algorithms [69] have been most widely used to support reasoning during conceptual design; thus, the emphasis in this section will reflect that.

Genetic Algorithms (GAs) have been used to generate candidate solutions to particular types of design problems. The design of optical prisms and other solid objects has been reported in the literature [70, 71]. The use of GAs in general engineering is a considerably more difficult problem due to the possibility of the existence of constraints on what constitutes a valid design. The use of problem-specific knowledge both to enhance the search power and to ensure that only valid designs are generated has been reported [67, 72]. In automatically generating design solutions, GAs are often used in conjunction with other techniques, such as backtracking, constraint propagation, and heuristic-based methods [73].

A number of other adaptive methods have been used to support reasoning in conceptual design. These include neural networks and machine learning [68, 74–77].

Case-based reasoning

Case-based Reasoning (CBR) is a relatively new approach to decision automation [56]. CBR is based on the premise that humans generally solve new problems by modifying solutions to previously solved problems, which are stored in a case-base. When a new problem is being addressed, the case-base is searched for solutions to similar problems that can be used as a basis for a solution to the current project. Failed searches form the basis for a new case. It is in this way that the case-base can be extended over time.

Many successful applications of CBR have been reported in the literature. DOMINIC is a multi-domain parametric design system in which general design goals are explicitly represented in term of design parameters [78, 79]. KRITIK is a case-based design system for the conceptual design of physical devices [59].

A number of CBR systems have been developed for the conceptual design of structures. Among these are the analogical reasoning system STRUPLE [80], and the architectural design systems CADSYN [81] and ARCHIE [82]. CADRE is an architectural design system that can support reasoning about topologies and spatial relationships [83].

The development of a distributed conceptual design system based on using CBR over the worldwide web has been reported [56–58]. This work is of considerable interest since an approach to supporting design through a combination of Internet, multimedia and CBR technologies is a very promising approach to supporting distributed Concurrent Engineering.

Other knowledge-based approaches

A number of knowledge-based reasoning systems for supporting conceptual design have been reported in the literature. These systems have been developed to support conceptual design in a number of specific engineering domains such as the preliminary design of buildings, creative elementary mechanism design, and early-stage design of machine systems.

A knowledge-based expert system called TALLEX has been developed for supporting the preliminary design of buildings [50]. This system is based on the integration of symbolic and numerical processing. The knowledge-base for this system is based on a set of IF/THEN rules that provide the inference mechanism with the information needed to support the designer during the design process.

The creative design of elementary mechanisms has been addressed from a knowledge-based system perspective [65]. Explanation-based learning has also been used to support the acquisition of conceptual design knowledge through an analysis of the structural features of designed objects [62].

The HIDER methodology enables detailed simulation models to be used during the early stages of design [84]. HIDER uses a machine learning approach to develop abstractions from these detailed models. These abstractions are used as a basis for formulating a multiple objective optimization problem, which is used to generate a set of 'optimal' conceptual designs for a product. The designer is supported in interactively exploring the design space by managing trade-offs between design objectives.

Constraint-based approaches to supporting engineering design have been reported in the literature. These will be reviewed separately in Section 2.2.

2.1.3 Trends in conceptual design research

Over the past number of years, industry has needed to become more effective in bringing new products to the market. There is an increasing demand from customers for customized products. In order to achieve manufacturing and field-maintenance economies in this sort of competitive environment, modern manufacturers must strive for minimum lead-time, a minimum number of dedicated machine tools and considerable flexibility to react to changes in market demand for their products. In response to these market characteristics, manufacturers have invested heavily in maximizing the degree of flexibility of their facilities while minimizing lot sizes, minimizing manufacturing and delivery lead-times, and maximizing the quality and variety of products available to their customers. In terms of product design, the effect has been that manufacturers must have extremely efficient product development processes. Concurrent Engineering and Integrated Product Development have been applied in industry although they are macro-approaches to addressing the problem, and the detail of their implementation is largely unreported.

In the field of engineering design, and in particular conceptual design, there are a number of issues that have emerged as areas which can offer significant competitive advantage to companies. The following have attracted the most attention from industry and academia as critical issues to be addressed:

- design reuse;
- modularity and configurability in product design;
- the design of product families;

Each of these issues will be discussed in a little more detail here.

Design reuse

One of the most difficult aspects of conceptual design is that it can be regarded as a problem-solving process aimed at addressing an abstractly defined problem. Conceptual design is often performed in a free-form manner, which can result in a designer developing a solution that comprises many novel elements. This can have a considerable effect on the manufacturability of a product and can cause many difficulties in managing its re-design, if this becomes necessary at a later date. The reuse of design knowledge in new design projects is an attempt at minimizing the non-standard content in the designs for new products.

Many companies have tried to increase the degree of commonality between different products by re-using libraries of preferred parts and technologies [85]. It is now becoming commonplace for companies to attempt to structure their design knowledge in a form that can be readily used by designers who develop new solutions to new problems. The DEKLARE project (ESPRIT project 6522) developed a methodology for generating specialized computer-based re-design support systems by capturing the design knowledge used in a company [86]. This approach has also proved useful in supporting the design of new products since designers can use known technological approaches in their product designs.

A number of methodologies have been put in place to assist industry in building databases of design knowledge. The ‘PS Methodology’ has been proposed as a practical approach to rationalizing past designs for their effective reuse in future design projects [87].

Modularity and configurability

Many industrial approaches to increasing the efficiency of product design focus on two issues: modularity and configurability. Modularity in product design relates to the use of modules in structuring a product. Configurability in product design relates to the composition of parts or modules to satisfy some set of design requirements. These two issues have been receiving considerable interest from industry and academia, since they offer a methodology for managing the complexity of product design.

A module is a physical element of a technical system which has a clear and explicitly defined interface, is totally self-contained, provides particular known functionalities, and exhibits a well-understood behaviour. A product can be regarded as modular if it is composed of a set of modules. Adopting a modular approach to product design can yield significant benefits for the design process, such as reduced design lead-time and limited product complexity [88]. Using a modular approach to product design facilitates an 'engineer-to-order' approach to manufacturing since specific customer requirements can be realized by modifying and composing a set of predefined modules.

A number of surveys reporting the experiences of industrial companies who exploit modularity in product design have been carried out [89, 90]. Due to the importance of modularity in product design a new technique for supporting product structuring called 'Modular Function Deployment' has been proposed [91]. This technique provides a basis for supporting the design of modular products from the gathering of customer requirements, through conceptual design, to the final design of a fully modular product.

Product configuration management has become a crucial product development success factor in a number of industries. Configuration design can be regarded as the activity of combining a set of predefined components and their relationships in a certain manner so that the resulting design satisfies a set of design requirements [92, 93]. It has been reported that configuration is a critical factor in a number of industries [94]. A number of extensive reviews of the field of product configuration design exist in the literature [95]. An open question in the field of configuration relates to the problem of re-configuration [96, 97]. The need for approaches that can cope with the re-configuration of an existing configured design is becoming more critical.

Product family design

Modern manufacturing companies are facing an ever-increasing demand for customized products to be manufactured and delivered within ever-shortening lead-times. In many industries, the design of families of products has been an attempt at managing market demands while maintaining competitiveness [85]. Competitiveness in many industries requires efficient design and delivery of large numbers of product variants [98]. Product variants can be regarded as members of a product family. During the research presented in this book, some work in the area of a product family design has been carried out, although it is not presented in this publication. In that research, a product family was regarded as a collection of products that are similar from some given perspective [99].

The effective design of product families requires that designers can quickly develop product designs that are based on a common, well-defined set of design elements. The use of modular design techniques is obviously relevant, as indeed is the use of configuration. The key to successful product family design is the use of a small set of well-understood modules whose interfaces are well defined [100].

2.2 A review of constraint processing for design

Most decisions that are made in daily life involve considering some form of restriction on the choices that are available. For example, the destination to which someone travels has a direct impact on their choice of transport and route: some destinations may only be accessible by air, while others can be reached using any mode of transport. Formulating decision problems in terms of parameters and the restrictions that exist between them is an intuitive approach to stating these types of problems. These general restrictions can be referred to as 'constraints'.

The fact that constraints are ubiquitous in many decision problems has given rise to the emergence of many popular problem-solving paradigms based on the notion of constraints. These techniques have been widely reported in the literature in such research fields as Operations Research (OR) and Artificial Intelligence (AI).

Some of the most popular approaches to solving problems comprising a set of constraints defined on a set of parameters stem from the constraint processing paradigm. Constraint processing is concerned with the development of techniques for solving the *Constraint Satisfaction Problem* (CSP) [101]. A large number of problems in AI, computer science, engineering and business can be formulated as CSPs. For example, many problems related to machine vision, scheduling, temporal reasoning, graph theory, design, design of experiments and financial portfolio management can be naturally modelled as CSPs.

One of the major advantages of the constraint processing approach to solving decision problems is that all that is required is an appropriate formulation of the CSP. There is no need to specify an approach to solving it since constraint processing techniques can be readily used to solve a problem formulated as a CSP.

2.2.1 Constraint processing for the phases of design

In Chapter 1 the process of product design was discussed. In Fig. 1.1 it was shown that this process could be divided into two phases: conceptual design and detailed design. Constraint processing techniques have been applied to a variety of aspects of the product design process in recent years. In the following, the literature reporting constraint-based research for phases of the product design process will be presented.

Constraint processing and conceptual design

Research related to constraint-based approaches to supporting conceptual design has been on the increase. However, most of this research does not address the synthesis problem; the vast majority has focussed on constraint propagation and consistency management relating to more numerical design decisions.

One of the earliest works in the field of constraint management for conceptual design was carried out at MIT [102]. The research resulted in the development of a computer tool called 'Concept Modeller'. This system is based on a set of graph processing

algorithms that use bipartite matching and strong component identification for solving systems of equations. The Concept Modeller system allows the designer to construct models of a product using iconic abstractions of machine elements. However, a number of issues are not addressed by this work. Among these issues is the dynamic nature of conceptual design. During conceptual design constraints may be added or deleted at any point. In addition, the system does not address the issue of design synthesis, nor does it address the comparison of alternative solutions to a design problem. However, Concept Modeller demonstrated that constraint processing did offer a useful basis for supporting designers working through particular aspects of the conceptual design problem.

Based on the earlier work on Concept Modeller, a system called 'Design Sheet' has been developed [103, 104]. This system is essentially an environment for facilitating flexible trade-off studies during conceptual design. It integrates constraint management techniques, symbolic mathematics and robust equation-solving capabilities with a flexible environment for developing models and specifying trade-off studies. The Design Sheet system permits a designer to build a model of a design by entering a set of algebraic constraints. The designer can then use Design Sheet to change the set of independent variables in the algebraic model and perform trade-off studies, optimization, and sensitivity analysis.

Some researchers have used the Dynamic Constraint Satisfaction Problem as a basis for managing conflict during the preliminary phases of engineering design [105, 106]. Traditional conflict resolution techniques in constraint-based models of the design process use *backtracking* and *constraint relaxation*. Some researchers focus on differentiating between types of assumptions that are made by designers during design. Variations on this type of approach have also been proposed for managing conflict in collaborative design [107].

The use of autonomous agents to solve CSPs for conceptual design has been reported in the literature [108]. The motivation for the work is the support of spatial layout generation. The constraint specification used in the work facilitates a high-level representation and manipulation of qualitative geometric information. The search engine used in the proposed system is based on a genetic algorithm. The issue of constraint consistency is not addressed in the work. In addition, important design issues such as synthesis are not considered. However, it is realized that the primary focus of this work is the use of autonomous agents to solve CSPs.

The use of constraint logic programming for supporting reasoning about dynamic physical systems has been reported [109]. This work combines a constraint logic programming approach with bond graphs to assist in the development of a simulation model of a system in the form of a set of differential algebraic equations. The approach can be used for identifying causal problems of a bond graph model of a dynamic physical system.

Constraint processing and detailed design

The later phases of design are concerned with developing a subset of the schemes generated during the conceptual design phase into fully detailed designs. In the design literature, two later phases of design are generally identified: embodiment design and detailed design [6]. The embodiment phase of design is traditionally regarded as the phase during which an initial physical design is developed. This initial physical design requires the determination of component arrangements, initial forms, and other part characteristics [110]. The detailed phase of design is traditionally regarded as the phase during which the final physical design is developed. This final physical design requires the specification of every detail of the product in the form of engineering drawings and production plans [110]. In reality the boundaries between the various phases of design are quite fuzzy. Therefore, the constraint processing literature for supporting the later phases of design will be reviewed as a whole. However, the constraint processing literature relating to configuration will be reviewed separately in Section 2.2.2. This is to reflect the fact that there exists a clearly identifiable body of literature on constraint processing and configuration design.

The CADET system has been developed at the Cambridge University Engineering Design Centre (EDC) as a computer tool for supporting embodiment design [111]. CADET is an acronym for Computer-Aided Embodiment Design Tool. This system is capable of assisting the designer to formulate and satisfy large sets of algebraic constraints. It comprises a generic database of components that can be used to develop a constraint-based model of the geometry of the product being designed. The CADET system uses simulated annealing as the basis for its constraint satisfaction algorithm for solving the constraint-based representation of the geometric product model [112]. Recent research at the Cambridge EDC has focussed on the development of tools that can assist a constraint-driven design process based on the CADET system [113].

A constraint-based knowledge compiler for parametric design in the mechanical engineering domain called MECHANICOT has been proposed [114]. This system is based on the assumption that the design process can be modelled as a CSP. The purpose of the tool is to generate knowledge-based systems for parametric design of mechanical products by using knowledge compilation techniques. The MECHANICOT knowledge compiler is useful for supporting the reuse of design knowledge and can be used for producing design plans.

Many constraint-based systems reported in the literature have been developed for supporting reasoning about purely geometric aspects of design for use with CAD systems [115–118]. However, these systems have been developed to address aspects of the design process which are too specific to geometric CAD to be reviewed in depth here.

2.2.2 Constraint processing for configuration

The use of constraint processing techniques for supporting configuration design has been widely reported in the literature. Configuration can be regarded as a special case of engineering design. The key feature of configuration is that the product being

designed is assembled from a fixed set of predefined components that can only be connected in predefined ways [119]. The core of the configuration task is to select and arrange a collection of parts in order to satisfy a particular specification. The growing interest in configuration systems is reflected by the level of interest reported from industry [120]. The role of constraint-based configurators has been reported in a number of reviews [95].

The configuration problem can be naturally represented as a CSP. In general, a configuration problem can be formulated as a CSP by regarding the design elements as variables, the sets of predefined components as domains for each of the design elements, and the relationships that must exist between the design elements as constraints. Constraints can also be used to state the compatibility of particular arrangements of components and connections.

One of the earliest works in the field of constraint-based support for configuration was based on dynamic constraint satisfaction [93]. The key characteristic of Dynamic Constraint Satisfaction Problems is that not all variables have to be assigned a value to solve the problem. Depending on the value of particular variables, other variables and constraints may be introduced into the network. Inspired by this approach, the use of constraint processing for configuration problems in complex technical domains has been reported [121, 122].

A general constraint-based model of configuration tasks represented as a new class of non-standard constraint satisfaction problem, called the Composite CSP, has been proposed [119]. The Composite CSP unifies several CSP extensions to provide a more comprehensive and efficient basis for formulating and solving configuration problems. In the Composite CSP approach, variables in the problem can represent complete sub-problems in their own right. This approach provides a useful basis for supporting abstraction in configuration whereby the product can be viewed, recursively, as a larger component aggregated from a set of parts.

A number of variations on the standard configuration problem have been highlighted by industry with a number of constraint-based solutions being proposed in the literature. Among these are: reactive and interactive configuration [123]; reconfiguration [97]; and the management of configuration complexity through abstraction [124].

2.2.3 Constraint processing for integrated design

Design is a complex activity which requires a variety of knowledge to enable a product to be successfully designed and developed. The phase model of design is often considered to imply that design is carried out as a sequential process. However, this is not generally how design is performed in industry. Modern approaches to product development, such as Concurrent Engineering [125], Integrated Product Development [126], and Design Co-ordination [127] attempt to maximize the degree to which design activities are performed in parallel. One of the most common techniques used during

the design phase of product development is to use knowledge of the life-cycle of the product being designed to assist designers in making well-informed decisions at as early a stage in product development as possible. This is generally known as Design for X (DFX) [110].

A number of researchers in the constraint processing community have developed constraint-based technologies that support integrated approaches to product development [66, 128, 129]. These technologies can be used to support collaborative design by facilitating the use of DFX knowledge during the design process.

Constraint-based approaches to supporting Concurrent Engineering have been very successful, although these systems generally focus on the design of a product in the detailed stages of design. The inter-dependencies between design and manufacturing have formed the basis for the development of design adviser systems which can evaluate the manufacturability of a design and generate re-design suggestions to alleviate any problems that may exist. The 'manufacturing evaluation agent' is a computer-assisted Concurrent Engineering technology that identifies cost-critical tolerances in the design and generates cost-reducing design suggestions [130]. The purpose of the system is to help focus the designer's attention on the specific aspects of the design that influence manufacturing cost.

A more general approach to supporting Concurrent Engineering using constraints has been adopted in developing the Galileo constraint programming language [128, 129, 131]. The Galileo language is based on a generalization of the Predicate Calculus. A program in Galileo is a declarative specification of a constraint network. Constraints may be atomic, compound, or quantified sentences in the predicate calculus. An interactive run-time environment has been developed for the Galileo language [128]. Using this system, a Galileo program becomes fully interactive. At run-time users, who can be regarded as designers, can declare additional parameters and constraints. Alternatively, users may ask questions about the consequences of the existing constraints. A constraint network in Galileo can be divided into various, possibly overlapping, regions that correspond to the perspectives of the various members of a product development team. Each perspective can be presented in a variety of interface styles, including spreadsheets and simple feature-based CAD [132].

The use of Pareto optimality in managing conflict in collaborative design systems has been reported [107]. The same principle has also been reported as part of the research presented in this book [133]. Indeed, there is also a recognized need for assisting the design team co-ordinate the design activities that must be carried out. The use of constraint processing for assisting in the co-ordination of design activities has also been reported [66].

Constraint-based approaches to supporting the use of DFX knowledge during design have been widely reported in the literature. Among these are techniques for supporting the evaluation of design norms during the design process [38]. A design norm can be regarded as a statement of good design practice stated in the form of a quality standard

or a code of good design practice. The constraint logic programming language CLP ($\Re$) has been used to support the design for test of active analog filters [134]. Models of active circuits are developed in CLP ($\Re$) and these models are then used to support fault diagnosis of the designed circuit. The constraint programming language Galileo has been used to develop design adviser modules for use with electronics CAD systems which critique a design against a set of user-specified life-cycle guidelines [129, 131].

2.2.4 Constraint processing and design domains

Constraint processing techniques have been applied to the design of a wide variety of design domains, such as mechanical system design, electronics design, and structural design.

In the field of mechanical design, constraint processing techniques have been applied to the validation of features [135] and the general design of mechanical parts [136]. The automated generation of constraint-based design expert systems for mechanical design has also been reported [114].

In the field of electronics design, constraint programming techniques have been widely used to support the verification of both expected and observed functionality of electronics systems. For example, constraint programming has been used to support model-based diagnosis of analog circuits [137]. Many modern electronics CAD systems are marketed as having constraint-based editors built-in to allow designers to specify customized relationships that must be maintained during design. Amongst these CAD systems are the electronics systems from such vendors as Zuken-Redac [138], Mentor Graphics [139], and Cadence Systems [140].

Structural and architectural design have also been reported as application domains for constraint processing. The design of bridges has been used as an application domain for constraint processing research into issues such as dynamic constraint satisfaction [141] and conflict management during preliminary phases of design [106]. Constraint-based approaches to floor-planning have also been reported [142]. The layout planning problem has been studied in depth by researchers in the constraint processing community [143].

2.3 Pareto optimality

A design specification defines the various requirements that a product must satisfy. Many of these requirements are categorical in the sense that they must be satisfied by every scheme that the designer considers. Sometimes, however, a design requirement will merely specify some preference about some aspect of the design. For example, a requirement may state that the mass of the product should be as small as possible. These preferences play a critical role in the evaluation of schemes. There may be many preferences defined in the design specification, related to many aspects of the product and its life-cycle. These design preferences can be regarded as defining a constrained multiple objective optimization problem.

Pareto optimality [144], which takes its name from the economist Vilfredo Pareto, is an economics technique for identifying solutions to a multiple objective optimization problem; the principle has been in use since 1906. The principle of Pareto optimality can be used to assist the designer in making decisions about the details of a design that will result in a Pareto optimal concept being developed [17, 145].

In contrast to a single objective optimization problem which produces a single optimum (or a set of equivalent optima), multiple objective optimization produces a set of non-dominated (Pareto optimal) solutions [84]. A set of non-dominated solutions is characterized by the property that every solution in the set is either better than every other solution to the problem, with respect to at least one of the objectives, or is at least as good as every other solution on all objectives.

Interest in the principle of Pareto optimality has resulted in the development of a number of techniques for solving multiple objective optimization problems. Among such techniques are the 'Method of Weighted Convex Combinations' [146], goal programming [147], multi-level programming [148], and Normal–Boundary Intersection [149]. Recently, a number of researchers have begun to apply the principle of Pareto optimality to a wide variety of problems in design [17, 68, 84, 133, 144, 150]. Indeed, in this book, the principle of Pareto optimality will be used to assist in the evaluation and comparison of alternative schemes that are intended to satisfy a design specification.

The principle of Pareto optimality is illustrated in Fig. 2.4 (adapted from [84]). In this figure the points *X*, *Y* and *Z* represent the *Pareto optimal set* of solutions to a multiple objective optimization problem involving two conflicting objective functions, both of which are to be maximized.

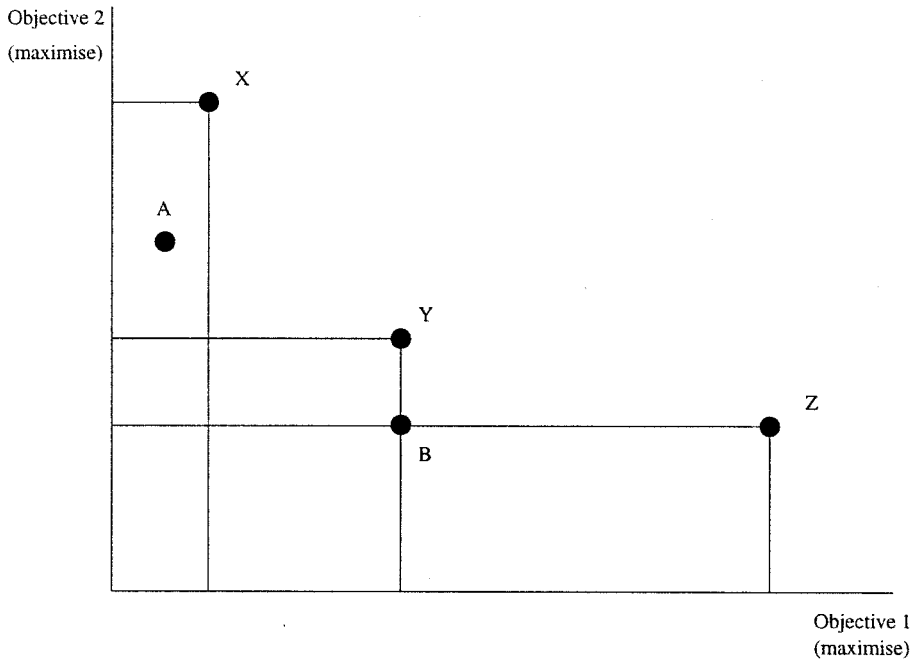

Fig. 2.4 The Pareto optimal set of solutions to a multiple objective optimization problem

The point *X* is not dominated by any other solution since there is no solution better than it in terms of *Objective 2*. The point *Y* is not dominated by any other solution since there is no solution better than it in terms of both *Objective 1* and *Objective 2*, simultaneously. The point *Z* is not dominated by any other solution since there is no solution better than it in terms of *Objective 1*. Two dominated solutions are shown in Fig. 2.4; these are points *A* and *B*. Point *A* is dominated by point *X* because point *X* performs better than point *A* on both *Objective 1* and *Objective 2*. Point *B* is dominated by both points *Y* and *Z*; it is dominated by *Y* because *Y* performs better than *B* on *Objective 2* while it does just as well on *Objective 1*; point *B* is dominated by *Z* because *Z* performs better than *B* on *Objective 1,* while it does just as well on *Objective 2*.

Formally, given the set *S* of candidate solutions to a multi-objective optimization problem the Pareto optimal set P_s can be defined as

$$P_s = \{s_i | s_i \in S, not\_dominated(s_i, S)\}$$

The predicate *not_dominated*(s_i, *S*) means that a candidate solution s_i is not dominated by any other candidate solution in *S*. Thus,

$$not\_dominated(s_i, S) \Leftrightarrow \forall s_j \in S, \neg dominates(s_j, s_i).$$

A solution, s_1 *dominates* another solution, s_2 if s_1 *improves_on* s_2 with respect to any objective and s_2 does not improve on s_1 with respect to any objective. Thus

$$dominates(s_1, s_2) \Leftrightarrow improves\_on(s_1, s_2) \wedge \neg improves\_on(s_2, s_1)$$

The predicate *improves_on* (s_1, s_2) can be defined as follows,

$$improves\_on(s_1, s_2) \Leftrightarrow \exists \langle F, I \rangle \in O, better\_than(F(s_1), F(s_2), I)$$

where O is the set of objective functions, each objective function in O being a pair, $\langle F,I \rangle$, where F is a function and $I \in \{minimal, maximal\}$; the predicate *better_than* is defined as

$$better\_than(x, y, maximal) \Leftrightarrow x > y$$
$$better\_than(x, y, minimal) \Leftrightarrow x < y$$

Later in this book it will be shown how the *dominates* relation is used to compare schemes that are being developed by the designer. A scheme which is dominated by another can be regarded as being Pareto sub-optimal and must be either improved or discarded.

2.4 Summary

This chapter reviewed the relevant background literature for the thesis presented in this book. The literature on conceptual design research was reviewed from three perspectives. The literature was first reviewed with a focus on the approaches to modelling design problems, design knowledge, and the design solutions. The literature was then reviewed with a focus on the various design reasoning techniques that have been advocated. Third, a number of trends in conceptual design research were identified and discussed.

This chapter also reviewed the literature relating to the application of constraint processing techniques to engineering design. It can be seen from the literature review presented in this chapter that there have been a wide variety of approaches adopted by the constraint processing community in addressing the problem of support for the human designer. However, it should be noted that much of this research addresses either well-structured aspects of the design problem or more parametric phases of design. There is a particular lack of constraint processing research in the area of designer support during conceptual design which addresses the critical aspects of the process such as design synthesis and the evaluation and comparison of alternative schemes for a product. As noted in the previous chapter, successful conceptual design adds significantly to the potential for overall successful product design. It is this need that is a primary motivation for the research presented in this book.

Finally, this chapter reviewed the principle of Pareto optimality. This will be used in this research as a basis for assisting the human designer compare alternative schemes that satisfy a design specification for a product.

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Chapter 3

Theory

Conceptual design is an extremely demanding phase of the design process. Designers must often combine imagination and technical expertise to serve satisfactorily a design problem; thus, in order to assist a designer during conceptual design, a computer needs to be capable of supporting both the technical and non-technical aspects of the process. Conceptual design can be regarded as a process that translates a specification for a product into a set of broad product concepts, known as 'schemes'. During conceptual design, a set of alternative schemes is developed for the product by applying design knowledge that is known to the human designer. In this chapter a theory of conceptual design is presented. This theory was developed as a result of conversations with design researchers and a review of the design research literature. The theory was then used as the basis for the constraint-based implementation presented later in this book.

3.1 A perspective on conceptual design

Engineering conceptual design can be regarded as that phase of the design process during which the designer takes a specification for a product to be designed and generates many broad solutions to it. These solutions are generally referred to as 'schemes' [1]. Each scheme should be sufficiently detailed that the means of performing each function in the design has been fixed, as have any critical spatial and structural relationships between the principal components [1]. The task of developing even a single scheme for a design specification requires the application of expertise from a wide variety of technical and non-technical disciplines. Also, designers are often required to use imagination and creative flair in order to develop satisfactory schemes.

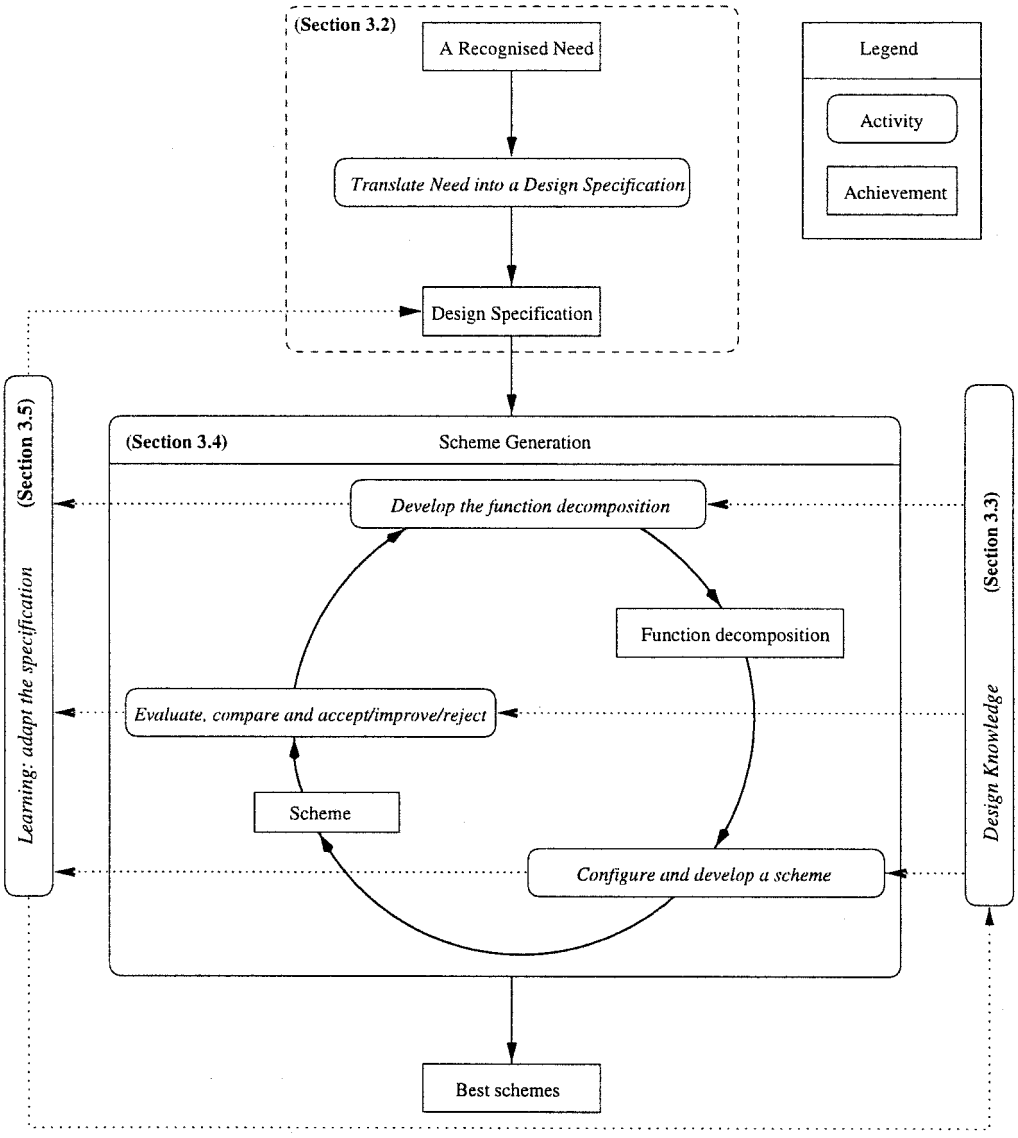


Fig. 3.1 The model of the conceptual design process adopted in this research

The model of conceptual design adopted in this research is based on the fact that, during the conceptual design process, a designer works from an informal statement, comprising an abstract functional requirement and a set of physical design requirements, and generates alternative configurations of parts that satisfy these requirements. Central to this exercise is an understanding of function and how it can be provided. Figure 3.1 graphically illustrates this model of conceptual design. While this model is based on a well-known approach to conceptual design [2], the detail is novel. In particular, the approach to developing schemes is based on an extension of the function–means tree. This extension, called the function–means map, has been developed as part of the research presented in this book [3]. Various parts of the model presented in Fig. 3.1 are annotated with section references. Each section reference points to the section of this chapter which offers a detailed discussion of that part of the

conceptual design process which has been marked. One section reference pertains to a number of aspects of the model of the conceptual process illustrated in the figure. The scope of this section reference is denoted by a dashed box.

From Fig. 3.1 it can be seen that the conceptual design process can be regarded as a series of activities and achievements. The achievements and activities relate to the development of the design specification and an iterative process of scheme generation. The process of scheme generation involves the development of a function decomposition which provides the basis for a configuration of parts that form a scheme. This scheme is then evaluated and compared against any schemes that have already been developed. Based on this comparison, the designer will choose to accept, improve, or reject particular schemes. The process of scheme generation will be repeated many times in order to ensure that a sufficiently large number of schemes have been considered. The roles of design knowledge and learning are also illustrated in Fig. 3.1, using dotted lines. Design knowledge is used during the process of scheme generation, during which the designer may develop a greater understanding of the design problem being addressed. This learning may affect the design specification for the product or the design knowledge used to generate schemes.

In the remainder of this chapter a detailed discussion of the theory of conceptual design as used in this research will be presented with reference to Fig. 3.1.

3.2 The design specification

From Fig. 3.1 it can be seen that the conceptual design process is initiated by the recognition of a need or customer requirement. This need is analysed and translated into a statement which defines the function that the product should provide (referred to as a functional requirement) and the physical requirements that the product must satisfy. This statement is known as a *design specification*. A number of techniques exist for generating a design specification from a perceived need. The most well known of these techniques is Quality Function Deployment (QFD) [4]. The formulation of the various requirements which comprise the design specification can be regarded as the first major achievement of the conceptual design process.

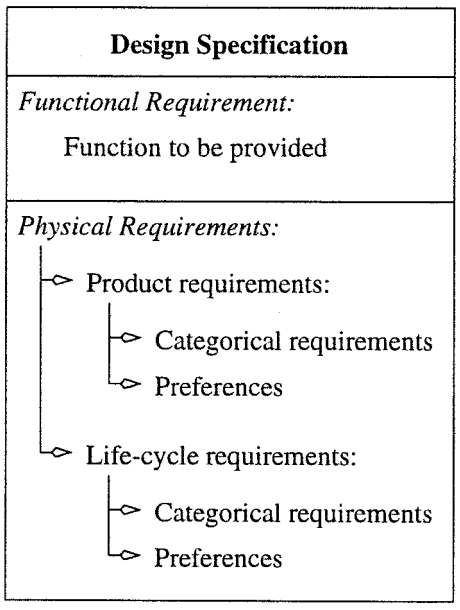


Fig. 3.2 The contents of a design specification

The contents of a design specification are illustrated in Fig. 3.2. The design specification contains a set of requirements that the product must satisfy. Two categories of design requirement can be identified: *functional* requirements and *physical* requirements. A design specification will always contain a single functional requirement; it may also contain a set of physical requirements. The nature of each of these requirements will be discussed in further detail in the following sections with the aid of the example design specification for a transportation vehicle presented in Fig. 3.3.

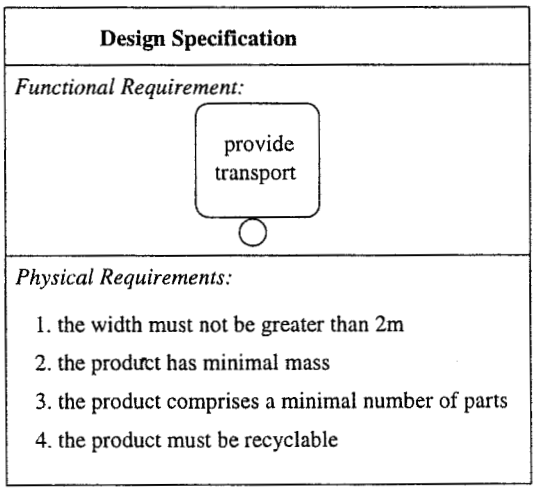


Fig. 3.3 An example design specification for a transportation vehicle

3.2.1 The functional requirement

The functional requirement represents an abstraction of the intended behaviour of the product. For example, in the design specification presented in Fig. 3.3, the functional requirement is that the product can fulfil the function '*provide transport*'. At this stage, there is no association made between the function that is to be provided and the physical mechanism that provides it. The designer's task is to find a physical configuration of parts that satisfies the functional requirement. A design specification should never be more specific about the intended behaviour of a product, for example, by specifying several functions – that would be far from ideal since it would indicate a decision made unwisely early, about the means for providing the required functionality. In this research the design specification will always contain only a single functional requirement. This gives the designer greatest scope to search for schemes for the required product.

In some cases the product specification resulting from an analysis of a market need may be couched in terms of a *set* of functions. However, before design commences, this set of functions should be re-stated in terms of a single, more abstract, function from which the designer can begin to develop schemes. This re-statement of a set of functions in terms of a more abstract parent function can be treated as the basis for developing a new design principle which is then used to structure the scheme[1].

3.2.2 Physical requirements

As stated earlier, the designer's task is to develop a complete physical configuration of parts which satisfies the functional requirement specified in the design specification. However, since the design specification also contains a set of physical design requirements, the physical solutions developed by the designer must not only provide the required functionality but must also satisfy these physical requirements. In Fig. 3.2 two classes of physical requirement can be identified: product requirements and life-cycle requirements. A product requirement can be either a categorical requirement, which defines a relationship between attributes of the product, or it can be a preference related to some subset of these attributes. A life-cycle requirement can be either a categorical requirement, which defines a relationship between attributes of the product and its life-cycle, or it can be a preference related to some subset of these attributes. Each of these classes of physical requirement are explained further here.

Categorical physical requirements

These describe relationships between some subset of the attributes that define a product (a product requirement), or between some subset of the attributes that define a product and its life-cycle (a life-cycle requirement). For example, in the electrical domain, the current, resistance, and voltage related to a resistor would be regarded as attributes of the resistor, while Ohm's Law defines a particular relationship that a resistor must satisfy, namely that the voltage is equal to the product of the current and resistance.

[1] Design principles will be presented in Section 3.3.3.

This is an example of a product requirement. On the other hand, a life-cycle requirement might forbid the use of particular materials in the design of a product because of an environmental issue or might specify that products to be manufactured using a particular process must have a particular geometry.

The design specification illustrated in Fig. 3.3 contains a categorical product requirement that the width of the transportation vehicle be no greater than 2 metres. This implies that it must be possible to compute the width of the product in order to check that this requirement is satisfied. There may be many ways of computing the width of a product, depending on the components involved and the manner in which they are configured. The functions used to compute the width of a product would be part of the knowledge of the particular company designing the product.

The design specification illustrated in Fig. 3.3 contains one categorical life-cycle requirement, namely that the product be fully recyclable. The meaning of this life-cycle requirement is, again, part of the design knowledge of the organization designing the product.

The example categorical physical requirements just discussed are quite simple. However, in general, these requirements can, of course, be arbitrarily complex.

Design preferences

Often it may not be possible, or appropriate, to define a categorical relationship over some subset of attributes of the design or its life-cycle. For example, it may not be appropriate to stipulate that the mass of a product be less than a particular number of kilograms, but rather that the mass should be as small as possible. Therefore, a design specification will often contain one or more *design preferences*.

A design preference is a statement about the designer's intent regarding some aspect of a product or its life-cycle. For example, a design preference may relate to the value associated with a particular attribute of a product or its life-cycle. A preference for an attribute may be that its value be maximal or minimal. However, design preferences may also be stated about any other aspect of a scheme, such as preferences on the use of particular components or relations over several product or life-cycle attributes.

The design specification illustrated in Fig. 3.3 contains two design preferences, namely that the product have minimal mass and comprise a minimal number of parts. The functions used to calculate the values of these design attributes are, generally, part of the design knowledge of the organization designing the product.

3.3 Conceptual design knowledge

During conceptual design, the designer must reconcile the functional and physical requirements for a product into a single model of the product. This means that the designer must synthesize a configuration of parts which satisfies each of the functional and physical requirements in the design specification. To do so, the designer needs

considerable knowledge of how function can be provided by physical means. Often this knowledge exists in a variety of forms. For example, a designer may not only know of particular components and technologies that can provide particular functionality, but may be aware of abstract concepts that could also be used. For example, a designer may know that an electric light-bulb can generate heat or, alternatively, that heat can be generated by rubbing two surfaces together. The latter concept is more abstract than the former. In order to effectively support the human designer during conceptual design, these alternative types of design knowledge need to be defined and modelled in a formal way. In Fig. 3.1 it can be seen that design knowledge is used: to develop the function decomposition and the configuration of parts for a product; to form a scheme; and to evaluate and improve the schemes that are generated. The various aspects of the design knowledge used during conceptual design will be discussed in the remaining parts of Section 3.3.

3.3.1 The function–means map

The notion of the *function–means tree* has been proposed by researchers from the design science community as an approach to cataloguing how function can be provided by means [5]. The use of function–means trees in supporting conceptual design has attracted considerable attention from a number of researchers [6, 7]. In general, the level of interest in the use of functional representations in conceptual design has increased in recent times [8], showing growing confidence in the potential of approaches incorporating such techniques.

In this book, a generalization of the function–means tree called a *function–means map* is used to model functional design knowledge. The early developments of the concept of the function–means map have been reported in literature available on the research presented in this book [9, 10]. A function–means map can be used to reconcile functions with means for providing them. In a function–means map two different types of means can be identified: a means can either be a *design principle* or a *design entity*.

A design principle is a means which is defined in terms of functions that must be embodied in a design in order to provide some higher-level functionality. The functions that are required by a particular design principle collectively replace the function being embodied by the principle. The functions that define a design principle will, generally, have a number of *context relations* defined between them. These context relations describe how the parts in the scheme that provide these functions should be configured so that the design principle is used in a valid way. Design principles are discussed in greater detail in Section 3.3.3.

A design entity is a physical, tangible means for providing function. It is defined by a set of parameters and the relationships that exist between these parameters. Design entities are discussed in greater detail in Section 3.3.4.

Before a more detailed discussion of design principles and design entities is presented, the notion of function embodiment will be discussed.

3.3.2 Embodiment of function

As the designer develops a scheme every function in the scheme is embodied by a means. In this section the icons used to describe the embodiment of functions will be presented.

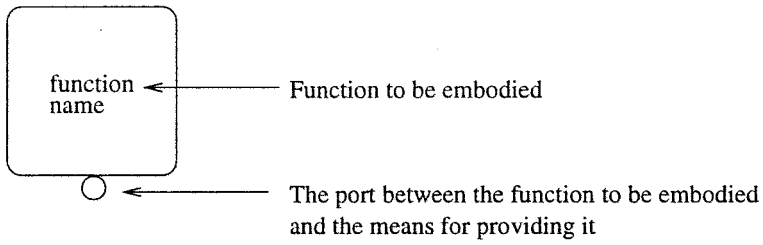


Fig. 3.4 The icon used to represent a function to be embodied

In Fig. 3.4 it can be seen that an embodiment icon is defined by a function that is to be embodied and a port which will be connected to a means that is to be used to embody the function. This port is referred to as the 'means port' of the embodiment icon. In Fig. 3.4 no means has yet been selected for this embodiment since the port is an empty circle.

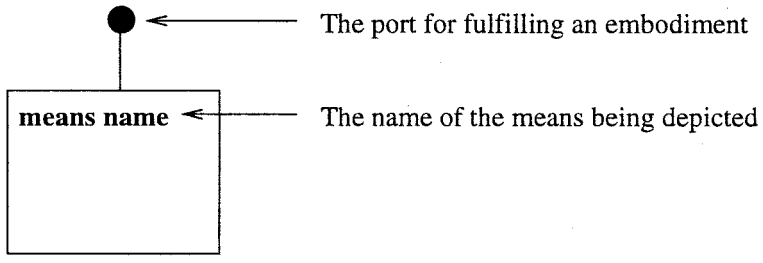


Fig. 3.5 The icon used to represent a means

In Fig. 3.5 it can be seen that a means icon is defined by the name of the means being represented and a port which can be connected to the means port of an embodiment icon to indicate that the means is being used to provide the function being embodied. Two types of means are available: a design principle and a design entity. The detailed representation of these different means will be presented later in this chapter.

In Fig. 3.6 an example of embodying a function with a means is illustrated. In this example a function *provide light* is embodied using a means called *bulb*. This is indicated by 'plugging' the port of the means icon into the port of the embodiment icon for the function. While, in this example, there is a one-to-one mapping between a function and a means, this may not always be the case. A means will often be able to provide more than one function in a design.

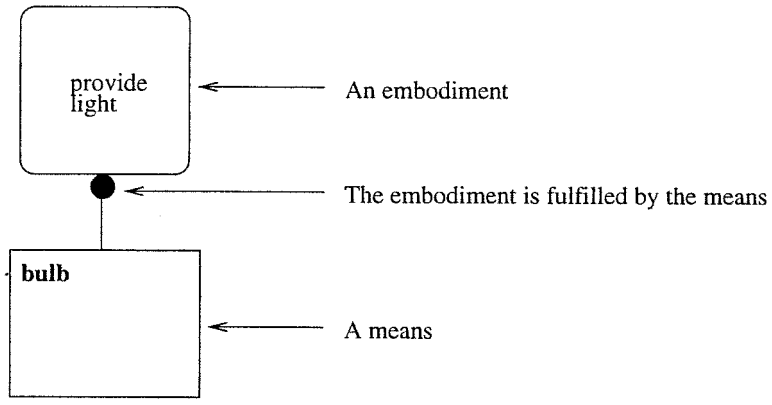


Fig. 3.6 A means fulfilling an embodiment

Each means that is available to the designer has an associated *set of behaviours*. Each *behaviour* is defined as a set of functions that the means can be used to provide simultaneously. Each behaviour associated with a design principle will contain only one function to reflect the fact that it is used to decompose a single function. However, a behaviour associated with a design entity may contain many functions to reflect the fact that there are many combinations of functions that the entity can provide at the same time. For example, the bulb design entity mentioned above may be able to fulfil the functions *provide light* and *generate heat,* simultaneously. However, when a design entity is incorporated into a scheme (for the purpose of supporting functionality provided by one of its behaviours), it is not necessary that every function in this behaviour be used in the scheme.

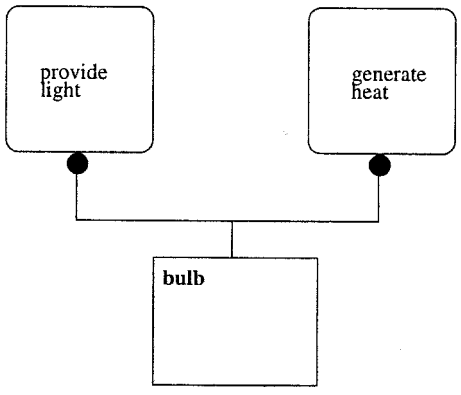


Fig. 3.7 An example of entity sharing

In Fig. 3.7 a single bulb design entity is used to embody the functions *provide light* and *generate heat*. In other words, these functions share the same entity. This is valid as long as the set of functions that share an entity are a valid behaviour of the entity.

Knowing the various possible behaviours of an entity is useful when the designer is embodying functions. Knowledge of behaviour enables a designer to identify when a particular design entity can be used to provide several functions simultaneously. In this research, the mapping of several functions onto a single design entity is known as *entity sharing*. Entity sharing is a critical issue in design because, without the ability to reason about entity sharing, a designer has no way of removing redundant parts from a design. For example, the body of a car is used to provide many functions because designers know that a single body can provide all of these. However, if a designer could not identify the fact that a car body can simultaneously provide many functions, the designer would introduce a different car body for each function to be provided; this would result in a designer attempting to incorporate several car bodies into their design, obviously not a desirable situation.

From a design perspective, one of the novel aspects of the work presented in this book is the manner in which design principles and design entities are defined and used. Using design principles to define abstract design concepts in terms of functions and relationships between them is novel. The ability to represent means at both an abstract functional level as well as a physical level provides a basis for a designer to combine and explore new approaches to providing the functionality defined in the design specification. In the remaining parts of Section 3.3 a detailed discussion of the different types of means will be presented.

3.3.3 Design principles: supporting abstraction

A design principle is a statement which declares that a particular function, called the *parent function*, can be provided by embodying a set of *child functions*, provided the embodiments of these child functions satisfy certain *context relations*. A design principle is, therefore, a known approach, defined in abstract terms, to providing functionality. When a designer uses a design principle in a design to embody a particular function, each child function must be incorporated into the function decomposition of the product being designed. The child functions of a design principle replace the parent function at the point in the functional decomposition where the parent function was required.

Context relations define how the design entities which are, ultimately, used to embody the functions in the scheme must relate to each other. Thus, when each function in a function decomposition is mapped onto a design entity for providing it, context relations will define how these entities must be configured or interfaced.

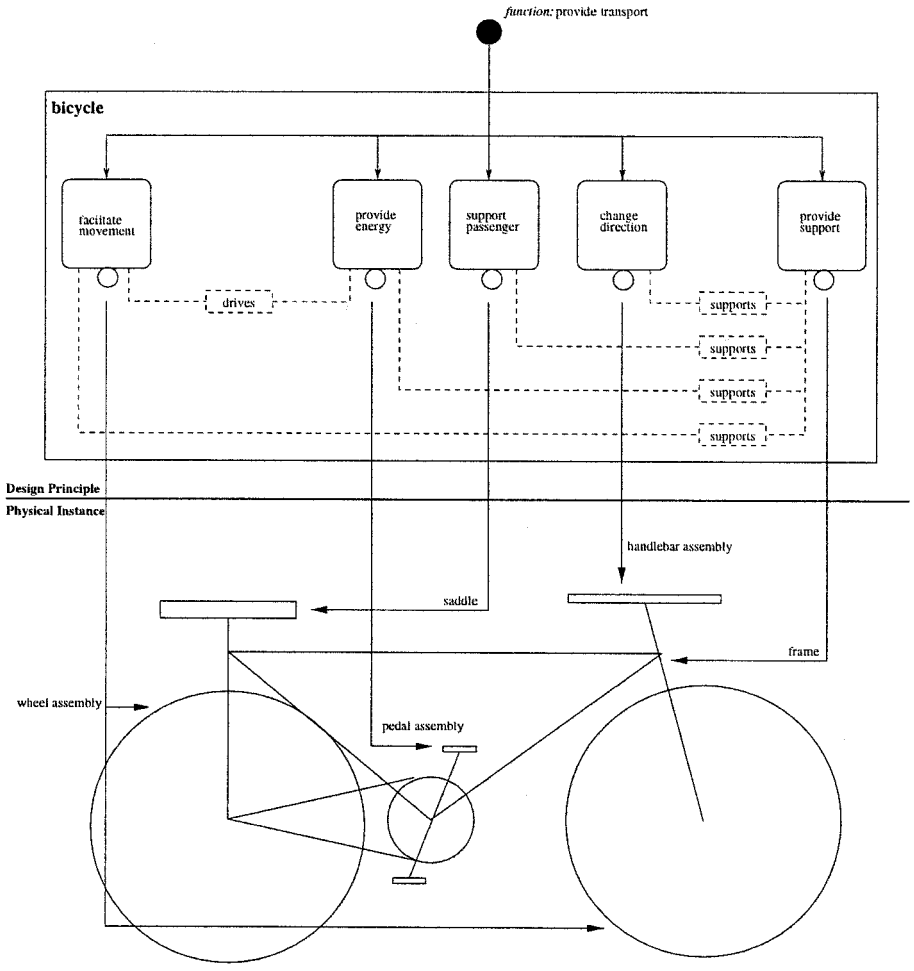


Fig. 3.8 Abstracting an example design principle from a bicycle

Typically, design principles are abstracted from previously successful designs. An example of a design principle, abstracted from a bicycle, is illustrated in Fig. 3.8. The parent function in this example is *provide transport*. The child functions are *facilitate movement, provide energy, support passenger, change direction,* and *provide support.* These functions are abstracted from the wheels, pedal assembly, saddle, handlebar assembly, and frame parts of a bicycle, respectively.

The icon that represents a design principle is the same shape as the icon for a means, except that it contains within it a number of icons representing the embodiments that must be fulfilled in order to properly use the principle. The icon for the bicycle design principle is illustrated in Fig. 3.9.

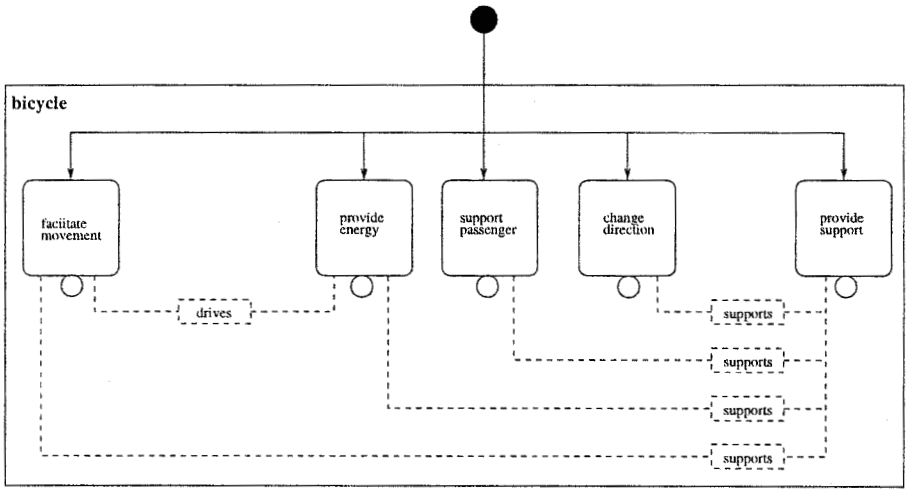
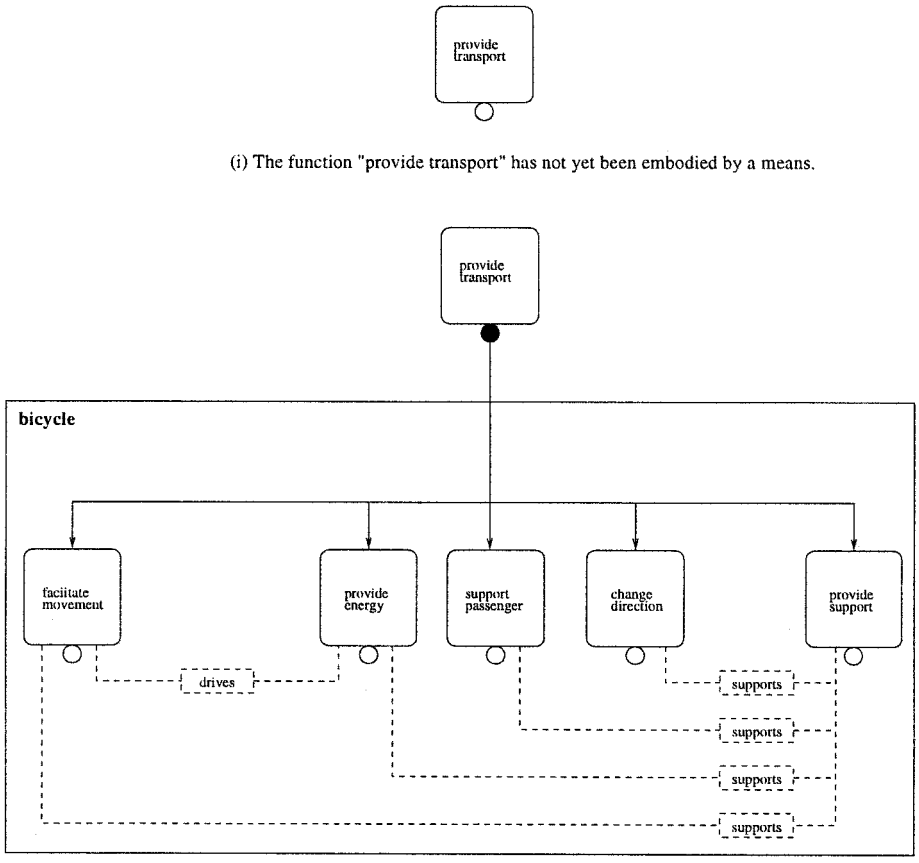


Fig. 3.9 The icon used to represent the bicycle design principle

The major parts of a bicycle from which these functions are abstracted have a context in the bicycle. This context is represented in the design principle as context relations. In the iconic representation of a design principle, context relations are represented as dashed boxes; dashed lines connect them to the embodiment icons of the functions to which they relate. Two types of context relation between the child functions of the bicycle design principle are shown in Fig. 3.9. These are the *drives* relation and the *supports* relation. A *drives* relationship must exist between the design entities that are used to provide the function *provide energy* and the function *facilitate movement*. In addition, a *supports* relationship must exist between the design entities that are used to provide the function *provide support* and each of the functions *facilitate movement, provide energy, support passenger,* and *change direction*. We will see this principle being implemented in Chapter 4 (Fig. 4.31) and being used in Chapter 5 (Fig. 5.5).

Ultimately every function in a scheme is provided by a design entity. The precise meaning of a context relationship depends on the design entities that are finally used to embody the functions between which the context relationship is defined. The context relation will define various relationships which must be considered in order to develop a valid configuration of design entities; as well as providing the required functionality, these entities must respect the context relations due to any design principles used. For example, the *drives* context relation, which is defined between the function *provide energy* and the function *facilitate movement,* implies that those entities that provide the function *provide energy* must be capable of driving the entities that provide the function *facilitate movement*. This may mean that, if the function *facilitate movement* is embodied by a *wheel assembly* design entity and the function *provide energy* is embodied by a *pedal assembly* design entity, there must exist a *chain* design entity between the *wheel assembly* and the *pedal assembly*. Later in this chapter, once design entities have been discussed, the meaning of context relations will be revisited.



(i) The function "provide transport" has not yet been embodied by a means.

(ii) The function "provide transport" is embodied by the design principle "bicycle".

Fig. 3.10 Using a design principle to embody a function

In Fig. 3.10 the embodiment of a function using the bicycle design principle is illustrated. In Fig. 3.10 (i) it can be seen that there is a function *provide transport* whose embodiment is not complete, since the means port for the embodiment icon is empty. In Fig. 3.10 (ii) the designer has embodied the function using the bicycle design principle. The effect of this is that the embodiment of the function *provide transport* is complete, but five further embodiments must now be considered. These five embodiments have been introduced due to the five child functions of the bicycle design principle. They have empty circles as their ports, to show that they have not yet been fulfilled. The designer must fulfill each of these embodiments by selecting means for them.

Design principles are used by a designer to develop the function decomposition upon which a scheme will be configured. At the functional level, what is of concern to the designer is the development of a function decomposition of a product from the functional requirements specified in the design specification. The designer is generally not concerned with how this detailed function decomposition should be embodied in a physical sense. The use of a design principle in a scheme increases the level of detail

of the function decomposition, by increasing the number of functions and context relations to be considered by the designer. In this way, the use of a design principle increases the complexity of the function decomposition. If the number of functions in the function decomposition increases, the complexity of the final scheme may also be greater since there is the possibility that a designer will employ a larger number of design entities. Since there may be a choice of more than one design principle to provide a given function, there may be many alternative function decompositions which same provide the required functionality. Designers should investigate as many alternative function decompositions as possible.

3.3.4 Design entities: design building blocks

A design entity defines a class of physical parts or sub-assemblies which can provide specific functionalities. In order to give physical form to a particular function decomposition, functions are embodied by design entities. Entities are defined in terms of a set of *attributes*. Each attribute defines a parameter associated with a design entity and its domain of possible values. For example, an attribute may be used to define the mass of a design entity, which may take its value from the set of real non-negative numbers. Alternatively, an attribute may be used to define the colour of a design entity, which may take its value from a set of colours. There may also be a number of constraints on these attributes that describe the relationships between them. For example, if the notion of a resistor is modelled as a design entity, it may be defined in terms of a set of attributes representing the voltage, resistance, and current associated with it. In addition, there will be a constraint that will define the relationship between these attributes due to Ohm's Law. Since schemes are configured from design entities, a number of functions may be pre-defined over design entities, and over configurations of them, in order to facilitate the evaluation of schemes against the various criteria defined in the design specification. For example, in order to compute the power output from an electrical circuit, functions that compute the power output of each design entity used in the scheme must be available. In the case of the resistor, such a function could be that the power output of a resistor is the product of the voltage and current flowing through it.

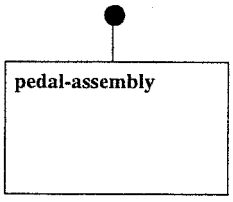


Fig. 3.11 The icon used to represent a pedal assembly

The icon for an example design entity, a pedal assembly, is illustrated in Fig. 3.11. This design entity could be part of a design knowledge-base used to generate schemes for the vehicle design specification presented Fig. 3.3.

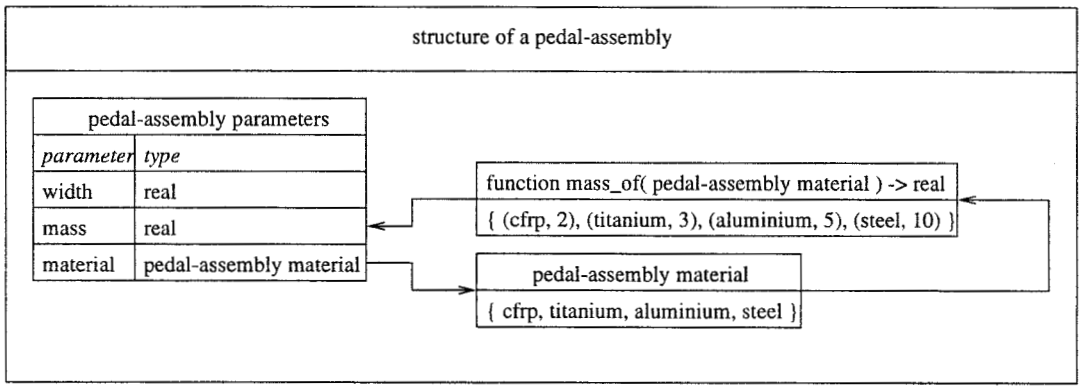


Fig. 3.12 A graphical representation of an example design entity

There are many possible representations for this design entity, one of which is illustrated in Fig. 3.12. It can be seen that the pedal assembly design entity is defined by three attributes: *width, mass,* and *material.* The *width* and *mass* of the pedal-assembly are real numbers, while the *material* of the pedal assembly takes its value from a set of materials, called pedal assembly materials. The materials that are available are *cfrp, titanium, aluminium,* and *steel*. There is a function available called *mass_of* which can estimate the mass of a pedal assembly from its *material*. For example, if the *material* of a pedal assembly is *cfrp*, the estimated mass of the pedal-assembly is 2. The functions defined over design entities can be arbitrarily complex.

3.3.5 Scheme configuration using interfaces

When a designer begins to develop a scheme for a product, the process is initiated by the need to provide some functionality. The designer begins to develop a scheme to provide this functionality by considering the various means that are available in her design knowledge-base. Generally, the first means selected by a designer will be a design principle. This design principle will substitute the required (parent) functionality with a set of child functions.

As the designer develops a scheme and produces a function decomposition tree, all leaf-node functions will ultimately be embodied in the scheme with design entities. During this embodiment process the context relations, from the design principles used in the scheme, will be used as a basis for defining the interfaces between the design entities used in the scheme. The precise nature of these interfaces cannot be known with certainty until the designer embodies functions with design entities; this is because the link between functions and design entities is generally not known with certainty during the development of the function decomposition for the scheme.

The types of interfaces that may be used to configure a collection of design entities will be specific to the engineering domain within which the designer is working. For example, the set of interfaces that a designer working in the mechanical domain would typically use are different to those used by a designer in the electrical domain. Indeed, these interfaces may also be specific to the particular company to which the designer belongs.

In Section 3.4 an example of scheme generation will be presented. As part of this presentation a detailed discussion of how context relations drive the configuration of a scheme will be presented.

3.4 Scheme generation

In Fig. 3.1 it can be seen that scheme generation is an iterative process comprising a number of activities. These activities relate to the development of a function decomposition for the scheme, the development of a configuration of design entities based on this function decomposition, and an evaluation and comparison of the newly developed scheme with those schemes that have already been developed. As new schemes are developed, the designer will constantly consider which schemes to accept, reject, or improve.

Once the design specification has been formulated, the designer must attempt to search for as many schemes as possible which have the potential to satisfy the requirements in the design specification. The first step in developing a scheme is to explore the functional requirement and develop a function decomposition that can be used to configure a set of design entities to form a scheme. Developing a function decomposition involves substituting higher level functions with sets of equivalent functions that collectively provide the required functionality. To assist the designer in developing this decomposition, design principles are used.

There are generally many function decompositions possible from the same functional requirement. Generating alternative function decompositions can be regarded as a way of systematically exploring the design space for a product. This search is executed by a designer by considering the functional requirement for the product and exploring alternative ways of providing the functionality by using design principles to decompose the functional requirement into less abstract functions. In this way the designer can reduce the functional requirement into one that allows the use of standard technologies, represented as design entities, to satisfy it.

Using a function decomposition, the designer can begin to develop a configuration of design entities. Each leaf-node function in a particular function decomposition must be provided by a design entity. The context relations inherited from the branch-nodes in the function decomposition, due to the use of particular design principles, are used to define the manner in which the design entities used in the scheme should be configured or interfaced. Some context relations will define constraints on the spatial relationships between design entities, while others may define particular types of interface that may be required between the entities. As the designer incorporates design entities into a scheme, the various physical requirements described in the design specification can be brought to bear on it.

Before discussing how a designer can evaluate and compare schemes, an example of scheme development will be presented in Section 3.4.1.

3.4.1 An example of scheme generation

In this section an example of how schemes are developed using the design theory described here is presented. A number of schemes will be developed based on the vehicle design specification presented in Section 3.2. The process of scheme development presented here will be illustrated, in an example designer–computer interaction, in Chapter 5.

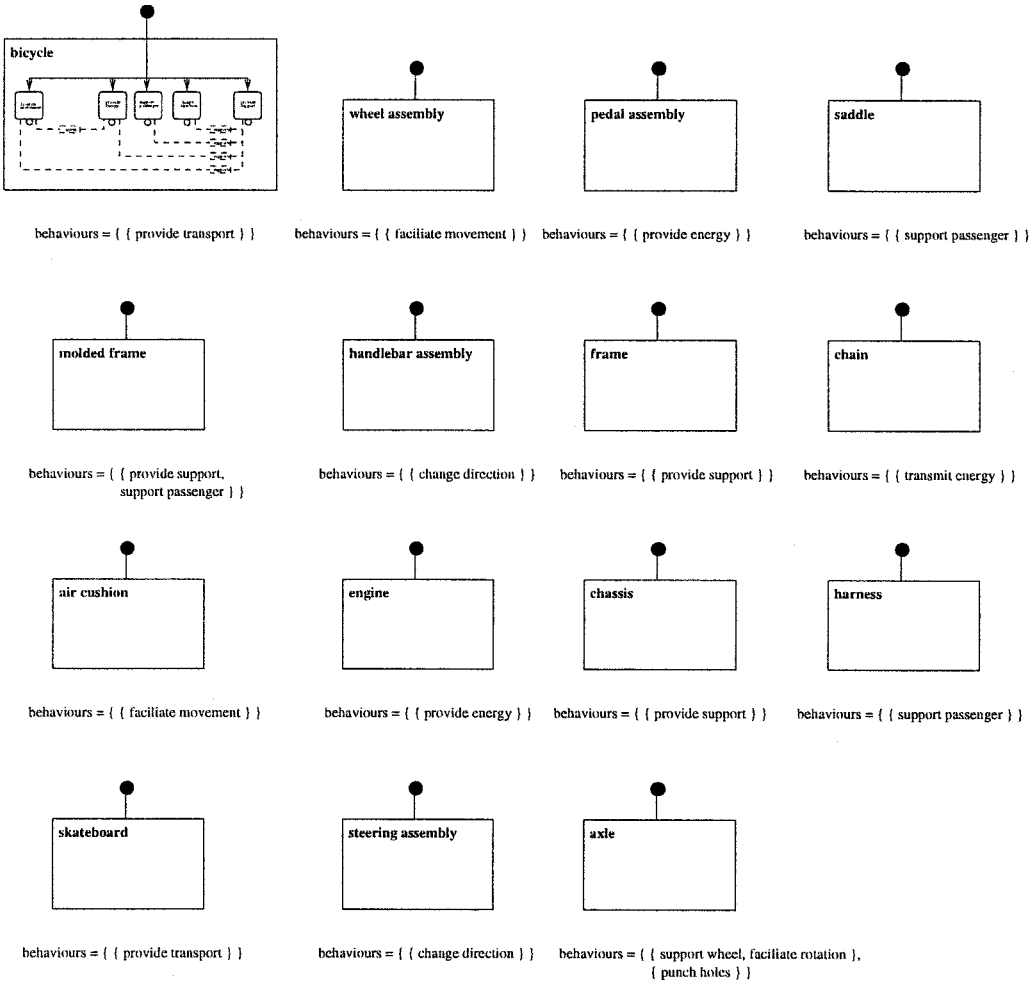


Fig. 3.13 The means contained in an example design knowledge-base and their possible functionalities

In Fig. 3.13 an illustration of the means contained in an example design knowledge-base is presented. This knowledge-base comprises one design principle, called *bicycle*, and a number of design entities, such as a *wheel assembly* and a *saddle*. The set of behaviours for each means in the knowledge-base are presented under the icon representing the means. Remember that behaviour is a *set* of functions that the means can provide simultaneously (Section 3.3.2). Thus the behaviours for a means is a set of

sets. Most of the means in this example knowledge-base have only one behaviour; that is, the set of behaviours for each means contains only one set of functions. Furthermore, most of the behaviours of the means in this knowledge-base can provide only one function at a time. However, the *molded frame* and *axle* design entities have more complex behaviours. The *molded frame* entity can provide two functions simultaneously *provide support* and *support passenger*. The *axle* entity has two behaviours: it can provide the two functions *support wheel* and *facilitate rotation* simultaneously, but can also be used to provide the single function *punch holes*.

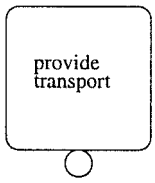


Fig. 3.14 The functional requirement for a product

The functional requirement from the vehicle design specification in Fig. 3.3 is illustrated in Fig. 3.14. It can be seen from this figure that the functional requirement is that the scheme must provide the function *provide transport*. To simplify this discussion of scheme development, the various physical requirements will not be considered until the scheme has been configured. However, in general, a designer may be able to consider some of these requirements throughout the scheme development process.

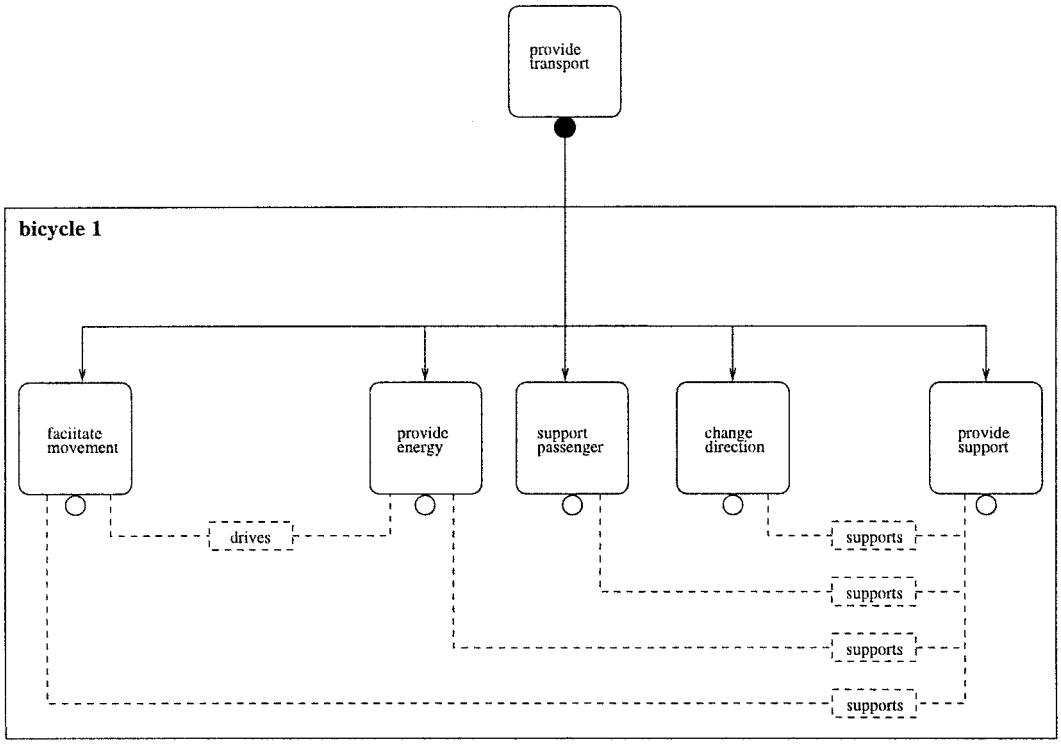


Fig. 3.15 Using a design principle to embody the functional requirement

In Fig. 3.15 an instance of the design principle *bicycle*, called *bicycle 1*[2], has been used to embody the function *provide transport*. This design principle introduces the need for five more functions to be embodied. In particular, the bicycle design principle introduces the need to embody the functions *facilitate movement, provide energy, support passenger, change direction,* and *provide support*. The designer must now select means for embodying each of these functions.

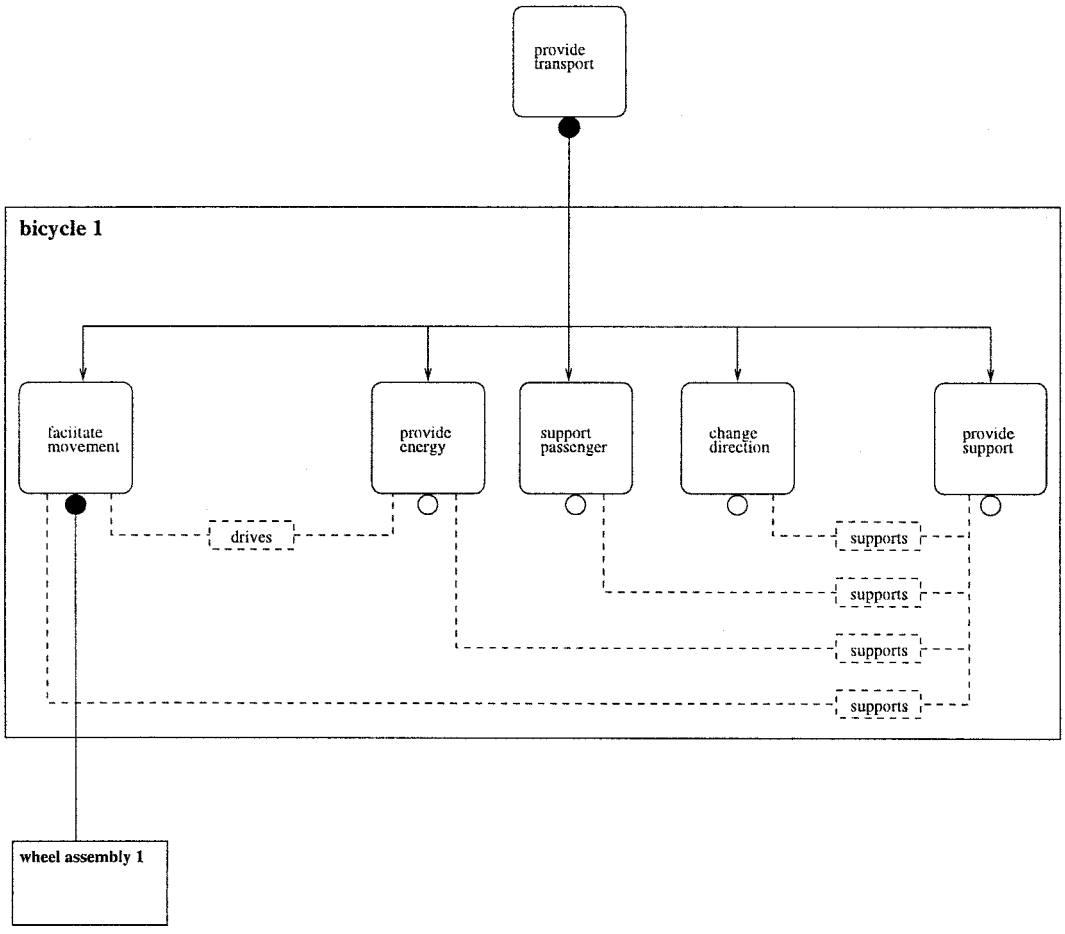


Fig. 3.16 Using a design entity to embody a function in the scheme

In Fig. 3.16 the designer selects the *wheel assembly* design entity to embody the function *facilitate movement*. This introduces an instance of this means, called *wheel assembly 1*, into the scheme. As the designer introduces design entities into the scheme the context relations that exist between the function embodiments must be considered. However, since there is only one design entity in the scheme presented in Fig. 3.16 no context relations are considered at this point in the scheme's development.

[2] When a designer selects a means to embody a function, an instance of the means is incorporated into the scheme. Thus *bicycle 1* is the first instance of the *bicycle* design principle to be used by the designer.

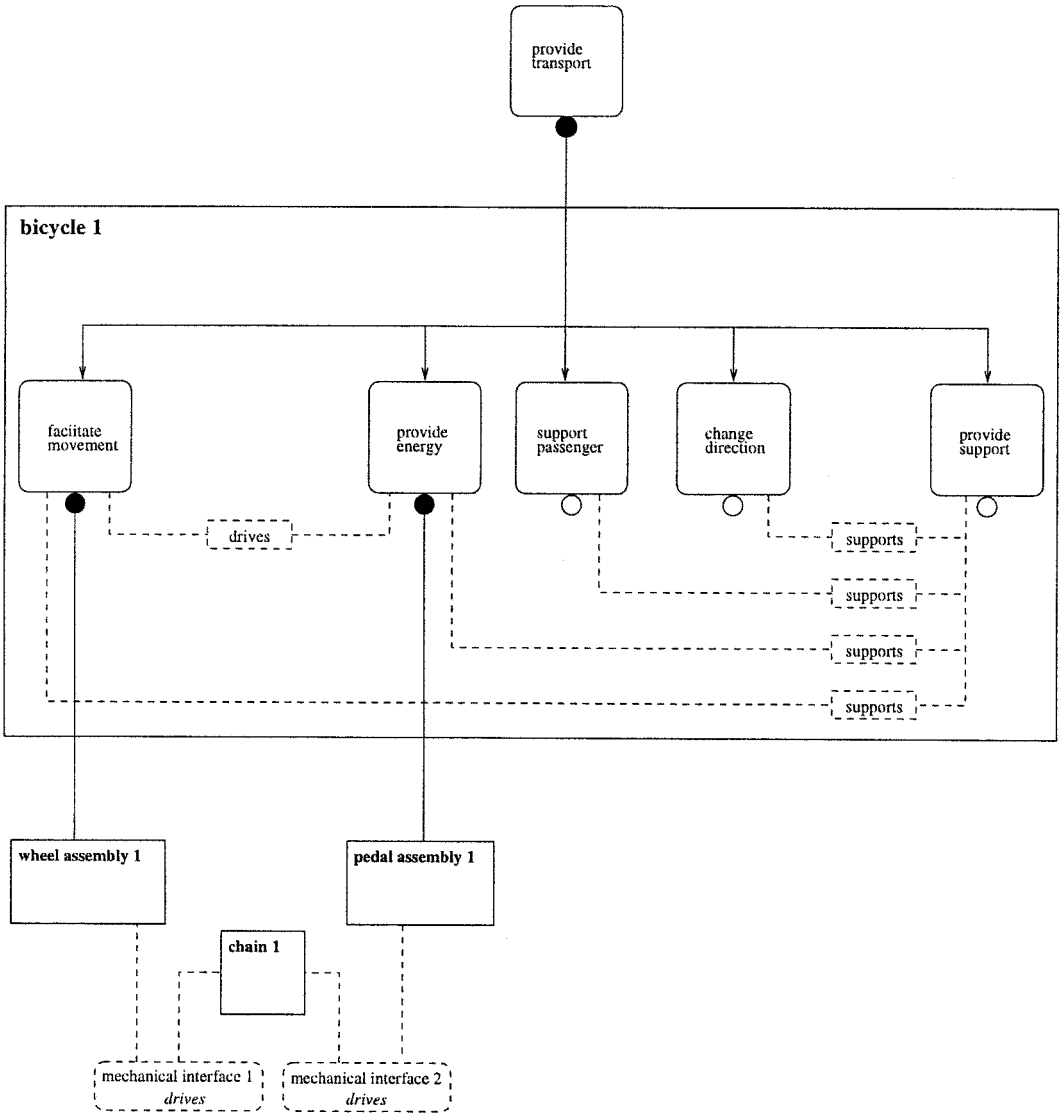


Fig. 3.17 The effect of a context relation on the configuration of design entities

In Fig. 3.17 the designer has chosen to embody the function *provide energy* with the *pedal assembly* design entity. This introduces an instance of this means, called *pedal assembly 1*, into the scheme. Since the *drives* context relation must exist between the embodiments of the functions *facilitate movement* and *provide energy*, the designer must consider this context relation between *wheel assembly 1* and *pedal assembly 1*. Before the meaning of this context relation is discussed, the approach to reconciling context relations with the entities to which they relate will be presented.

The meaning of a context relation is part of the company-specific design knowledge that is used to develop schemes. Context relations are implemented as interfaces between design entities. An interface is used to define some relationship that should exist between design entities. The design knowledge-base of a company will contain a

repertoire of interfaces used in the conceptual design of products in the company. For example, a company may have interfaces for handling various types of mechanical, spatial, or electrical relationships between design entities. The meaning associated with a context relation may be that an interface of a particular type should exist between the design entities, the precise nature of this interface being specified during a later phase of design. Alternatively, a context relation may introduce new design entities into a scheme with interfaces between them and the design entities between which the context relation should be satisfied. The precise meaning of a context relation may depend on the type of design entities between which the context relation must be considered.

In order to be able to identify the design entities between which a context relation should be considered it is necessary to be able to identify which design entities *derive from* which functions. Each design entity used in a scheme derives from at least one function. Essentially, a context relation must be considered between design entities that derive from the embodiments between which a context relation is defined.

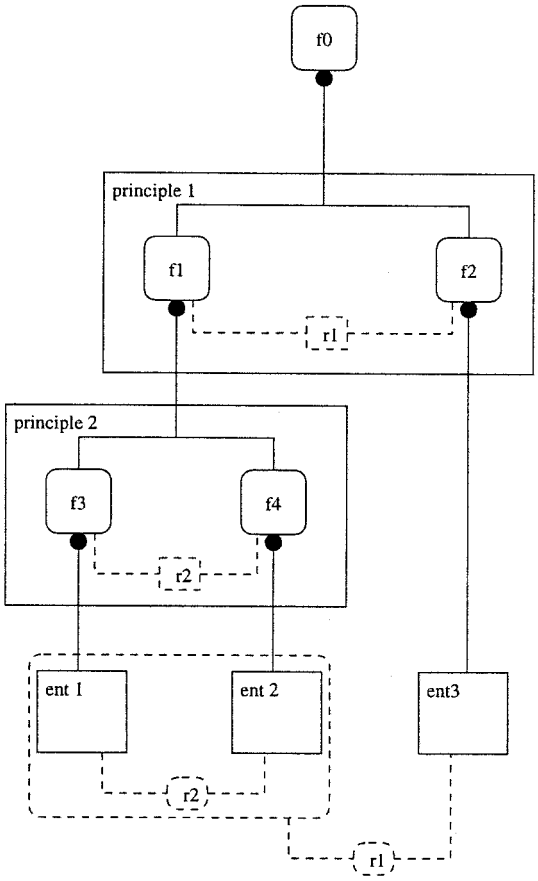


Fig. 3.18 The structure of a scheme illustrating the use of context relations in configuring a scheme

In Fig. 3.18 an example scheme structure is illustrated. The top-level function in this scheme is *f0*. This function is embodied using a design principle called *principle 1*. This design principle introduces two functions *f1* and *f2* to replace the function *f0*. A context relation *r1* is specified between these functions. The function *f1* is embodied by a design principle *principle 2,* which introduces two further functions *f3* and *f4* into the scheme. A context relation *r2* is specified between these functions. The function *f3* is embodied with the design entity *ent 1*, the function *f4* is embodied with the design entity *ent 2,* and the function *f2* is embodied with the design entity *ent 3*. However, between which design entities should the context relations *r1* and *r2* be considered?

The context relation *r2* must exist between the entities that derive from the functions *f3* and *f4*. The design entities *ent 1* and *ent 2* are used to embody these functions. Thus, the context relation *r2* must be considered between these entities. Since the design entities *ent 1* and *ent 2* are the means used to provide the functions *f3* and *f4*, these entities can be regarded as being *directly* used to provide these functions.

The context relation *r1* is a little more complex. This context relation must exist between the entities that derive from the functions *f1* and *f2*. The design entity *ent 3* is used to embody the function *f2*. Thus this entity can be regarded as being *directly* used for the function *f2*. The function *f1* is provided by the design principle *principle 2*, whose child functions are in turn embodied by the design entities *ent 1* and *ent 2*. Thus, these design entities can be regarded as being *indirectly* used to provide the function *f1*. Therefore, the context relation *r1* must be considered between the combination of design entities *ent 1* and *ent 2* on the one hand, and *ent 3* on the other hand.

In Fig. 3.17, the *drives* context relation that exists between the embodiments of the functions *facilitate movement* and *provide energy* must be considered between the design entities *wheel assembly 1* and *pedal assembly 1*. In this figure it can be seen that this caused, in addition to the existence of the design entities *wheel assembly 1* and *pedal assembly 1*, the introduction of an instance of the *chain* design entity, called *chain 1*. Furthermore, it caused a *mechanical interface* between *chain 1* and *wheel assembly 1* and another between *chain 1* and *pedal assembly 1*. Both of these interfaces are used, along with *chain 1*, to embody the *drives* relation that should exist between *wheel assembly 1* and *pedal assembly 1*.

In the company design knowledge-base that is used here, one type of interface that is available is a *mechanical interface*. A *mechanical interface* can be used to define many relationships between design entities. One of these relationships is a form of *drives* relationship. During detailed design a more precise specification for this mechanical interface would be given.

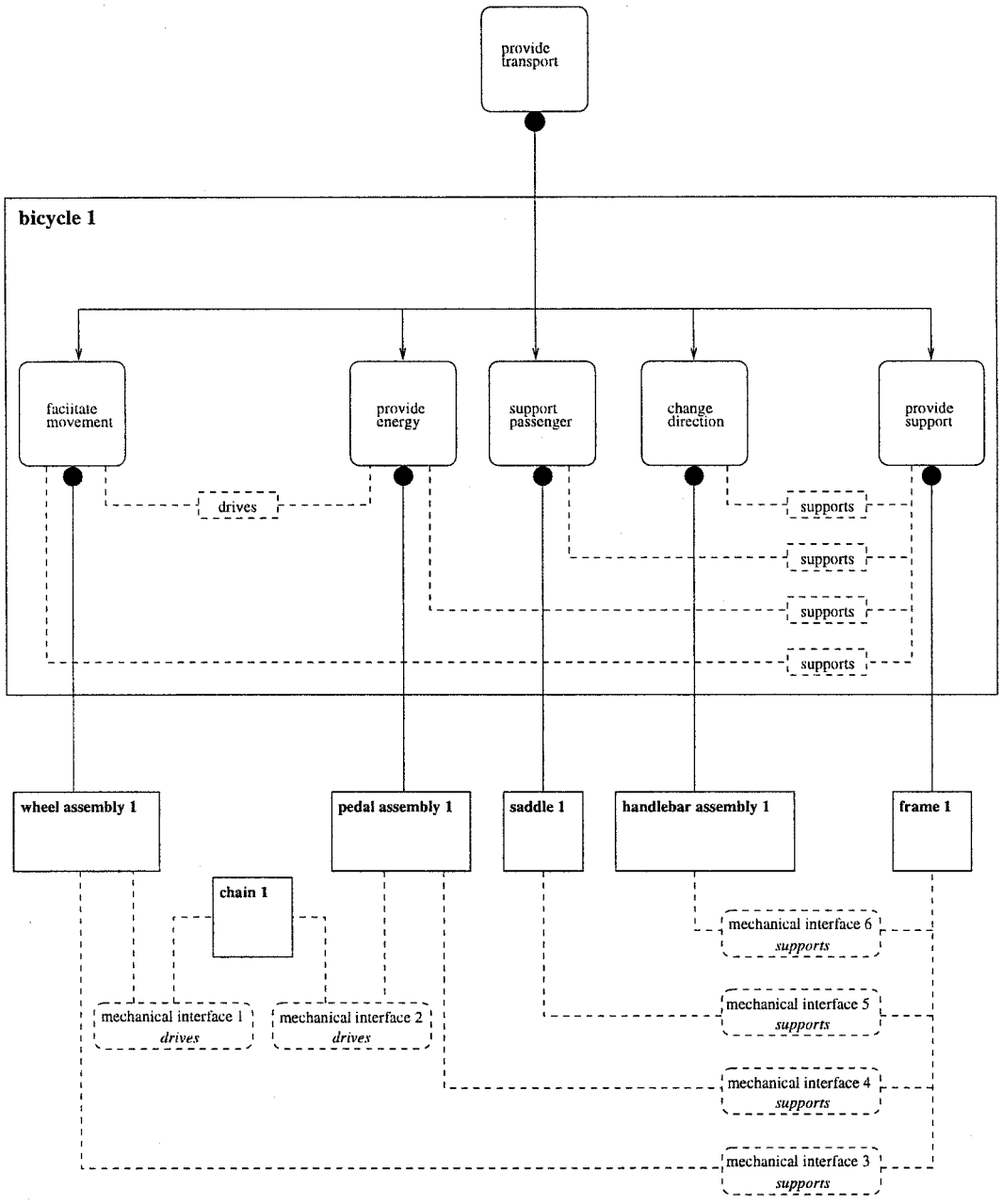


Fig. 3.19 An example scheme configuration

Figure 3.19 shows the state of the scheme after the designer has chosen to embody the function *support passenger* with the design entity *saddle*, the function *change direction* with the design entity *handlebar assembly,* and the function *provide support* with the design entity *frame*. Due to the *bicycle* design principle, a context relation called *supports* must exist between the embodiment of the function *provide support* and the embodiments of each of the functions *facilitate movement, provide energy, support passenger,* and *change direction*. Each of these context relations is embodied by a *mechanical interface* that defines a *supports* relationship. The details of these mechanical interfaces that define a *supports* relationship will be specified during detailed design.

Since all the functions have been embodied in the scheme presented in Fig. 3.19, the designer must now begin to select values for the attributes associated with each design entity in the scheme. In making these decisions the designer must ensure that the various constraints that are imposed, due to the design specification or the design knowledge-base, must be satisfied. In addition, this scheme must be compared with any other alternative scheme for this product, which may be developed. However, before the process of evaluating and comparing schemes is discussed, the structure of a second scheme will be presented.

A second scheme is presented in Fig. 3.20. This scheme is also based on the *bicycle* design principle. In this scheme the function *facilitate movement* is provided by an instance of the design entity *wheel assembly*, called *wheel assembly 2*, while the function *provide energy* is provided by an instance of the design entity *engine*, called *engine 1*. The *drives* relation that must exist between *wheel assembly 2* and *engine 1* is embodied by a *mechanical interface* between *wheel assembly 2* and an instance of the *chain* design entity, called *chain 2*, and a *mechanical interface* between *engine 1* and *chain 2.*

The function *support passenger* is provided by an instance of the design entity *molded frame*, called *molded frame 1*, while the function *change direction* is provided by an instance of the design entity *handlebar assembly*, called *handlebar assembly 2*. The function *provide support* is also provided by the design entity *molded frame*. In Fig. 3.13 it was shown that one of the behaviours of a *molded frame* is that it can provide the functions *provide support* and *support passenger* simultaneously. Thus, since an instance of the *molded frame* design entity already exists in the scheme, there is no need for a second one to be introduced. Thus, the functions *provide support* and *support passenger* share the instance of the design entity *molded frame* called *molded frame 1*.

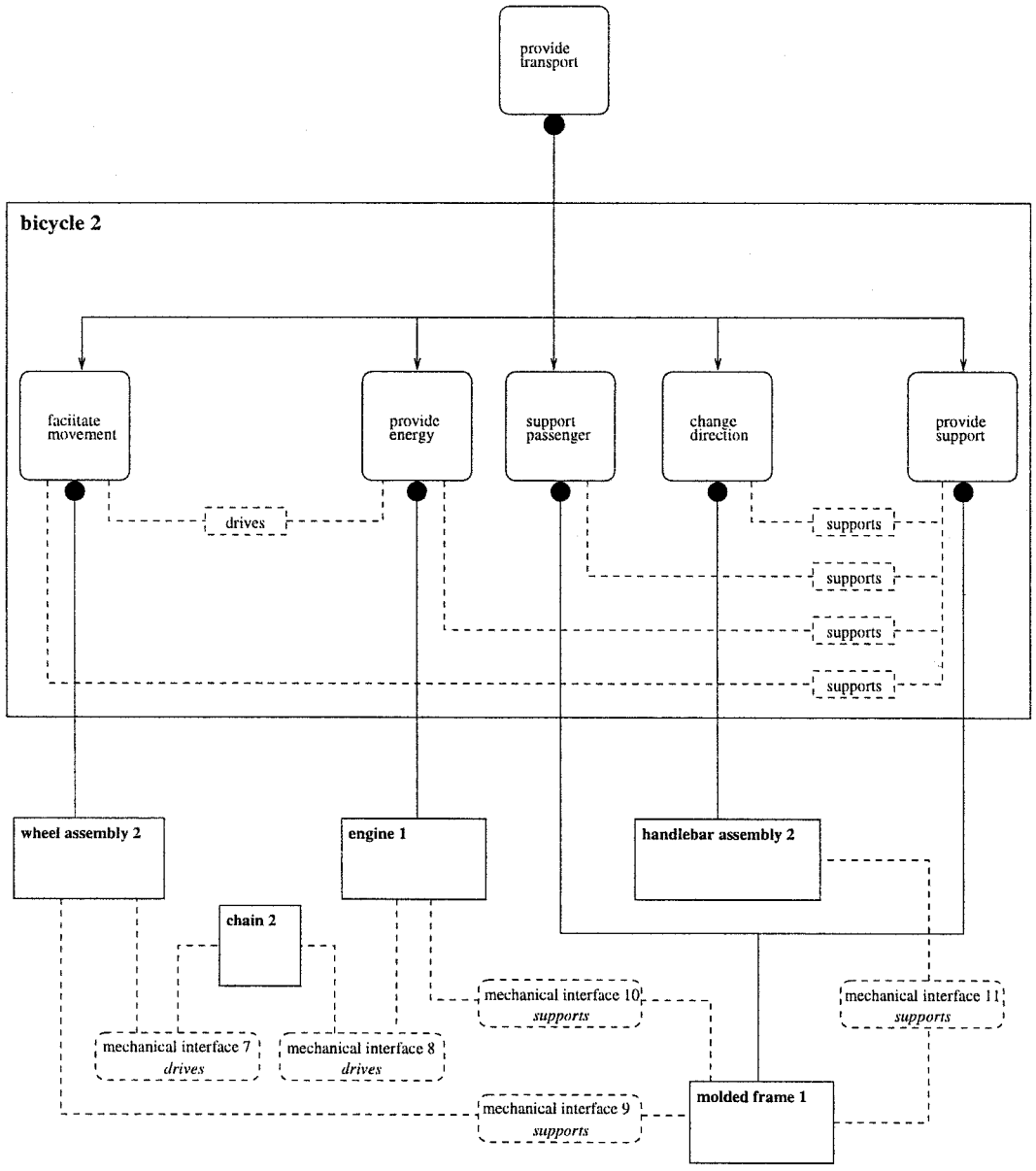


Fig. 3.20 A second example scheme configuration

In order to embody the *supports* context relation between the embodiment of the function *provide support* and the embodiments of each of the functions *facilitate movement, provide energy, support passenger,* and *change direction*, a number of *mechanical interfaces* are used. These interfaces define a *supports* relationship between the appropriate design entities.

3.4.2 Evaluation and comparison of schemes

The designer's primary objective during conceptual design is to develop a set of alternative schemes that satisfy both the functional and physical requirements defined in the design specification. This set of schemes will be further refined during subsequent stages of the product development process until a small number of fully specified designs, possibly just one, will be selected for commercialization.

In developing a particular scheme a designer must ensure that none of the physical requirements defined in the design specification are violated. In Section 3.2.2 two types of physical requirements were presented: product requirements and life-cycle requirements. Where possible during the development of a scheme, the designer should consider these requirements and ensure that the scheme being developed has the potential to produce a 'good' product.

Every scheme must satisfy the categorical product and life-cycle requirements that are defined in the design specification. If a scheme violates one of these, the designer must either reject the scheme that has been developed or modify it in order to satisfy the requirements. For example, in the vehicle design specification presented in Fig. 3.2, the categorical product requirement that the width of the vehicle be no more than two metres must be satisfied by every scheme. For the two schemes that have been developed here, the designer will, at some stage in the design process, need to define a spatial configuration of the design entities used in each scheme in order to estimate the width for each scheme. Likewise, the categorical life-cycle requirement that the scheme by recyclable must also be satisfied by every scheme. This requirement may mean that every design entity in the scheme be manufactured from a recyclable material. Thus, when the designer selects materials for each of the design entities in the scheme, this life-cycle requirement can be checked.

While every scheme may satisfy the categorical physical requirements, not every one of these schemes will be selected for development in subsequent phases of design. This is due to particular schemes not 'satisfying' the preferences that were defined in the design specification. For example, in the vehicle design specification presented in Fig. 3.3, two preferences were defined: the product should have minimal mass and comprise a minimal number of parts. As the designer develops a scheme, an estimate of its mass can be made. This estimate may be based on the materials used for each design entity and, possibly, the geometry of the design entity in the scheme. The number of parts can be regarded as being the same as the number of design entities in the scheme.

In Chapter 2 the principle of Pareto optimality was introduced as a way of determining the best solutions to a problem involving multiple objective functions. Each design preference can be regarded as an objective function. Thus, the best schemes that are developed are those that are not dominated, in the Pareto optimal sense, by any other scheme. Obviously, in order to compare two schemes they must be based on the same design specification.

Table 3.1 Using the principle of Pareto optimality to compare two schemes

Property	*Preference*	*First scheme*	*Second scheme*
Number of parts	Minimal	6	5
Mass	Minimal	$< x$	x

Table 3.1 presents a comparison of the two schemes shown in Fig. 3.19 and Fig. 3.20. The first scheme comprised six parts, while the second scheme comprised five. Thus, on the preference for a scheme comprising a minimal number of parts, the second scheme is better than the first. At this point it is not possible to determine if the first scheme is dominated. However, if the first scheme is not to be dominated by the second, it will have to have a smaller mass than the second scheme. In this way, each scheme would be better than the other on one design preference.

Using the principle of Pareto optimality provides a useful basis for comparing alternative schemes. It can be used to identify schemes that are completely dominated by schemes which have already been developed; this should motivate a designer to modify a scheme so that it is no longer dominated. Using the principle of Pareto optimality a designer can compare schemes that have been developed in order to select those that will be developed further and in order to identify those schemes that should be either improved or discarded. However, a designer should not be *forced* to discard dominated schemes. The objective is to motivate the designer to think about ways of improving them.

3.5 Learning during conceptual design

During the conceptual phase of design a designer is faced with a number of problems, such as interpreting a design specification and developing a set of alternative schemes for it. While designing, the designer may discover something new about the design problem that is being addressed, or may discover that an issue, that should have been considered earlier, was not. Thus, as designers design, they often develop a better understanding of the particular problem they are working on. This learning process may often result in new requirements being incorporated into the design specification, or may cause the introduction of new means into the design knowledge-base being used. This is illustrated in Fig. 3.1. Therefore, the designer will often need to return to work that has already been done in order to ensure that new design requirements do not invalidate any schemes that have been developed. In this way the conceptual design process is very dynamic.

3.6 Summary

This chapter presented the approach to conceptual design upon which the research presented in this thesis is based. It was noted that conceptual design is an extremely demanding phase of the product development process. In order to assist a designer during conceptual design a computer needs to be capable of reasoning about the technical and non-technical aspects of the process. The input to the conceptual phase of design is the specification of the product which is to be designed. During conceptual design the human designer develops a number of alternative schemes which have the potential to satisfy the design specification.

The chapter presented a novel perspective on design knowledge that can be used during conceptual design. This perspective involves formulating design knowledge into a mapping between functionality and means for providing functionality. It was shown how means could be described either at a parametric level, using design entities, or an abstract functional level using design principles. The various issues associated with developing schemes that satisfy a set of requirements, using this knowledge, were also discussed.

Finally, this chapter presented an approach for evaluating and comparing alternative schemes using the principle of Pareto optimality.

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Chapter 4

Implementation Strategy

One of the most difficult aspects of providing computer-based support for conceptual engineering design is the modelling of products at various levels of abstraction. This chapter presents an approach to using constraints as a modelling paradigm for engineering design. In particular, a description is given of a constraint-based implementation of the conceptual design theory presented in Chapter 3. The constraint programming language Galileo is used as the modelling language. This chapter demonstrates how the design knowledge that is required during the conceptual phase of design can be modelled in Galileo; it also shows how constraint-based modelling can be used as a basis for developing and evaluating schemes for a product described in a design specification. This chapter uses material from Appendix B and Appendix C. Appendix B provides full Galileo implementations of the generic conceptual design concepts presented in this chapter. Appendix C provides full Galileo implementations of a company-specific design knowledge base and a project-specific design specification. The modelling techniques that are presented in this chapter will be used in Chapter 5 where an interaction scenario between a designer and a conceptual design advice system will be presented.

4.1 Modelling for conceptual design

Conceptual design involves considering a specification for a product and developing a set of alternative schemes for it. This transformation, from an abstract specification to a set of alternative schemes, requires a range of different types of knowledge which, if a computer is to assist in the conceptual design process, must be represented in the machine. First, in order for the machine to understand the design problem that is being addressed by the designer, the *design specification* for the product that is to be developed must be modelled in some way. Second, if the machine is to assist the human designer, the *design knowledge* possessed by the company for which the designer is working must be modelled. Third, in

order to evaluate each alternative scheme that the designer attempts to develop, the various *evaluation criteria* used by the designer must also be modelled.

4.2 The implementation language used: Galileo

The implementation language used in this research was Galileo [1, 2], a frame-based constraint programming language derived from the First-Order Predicate Calculus (FOPC). In the remainder of this book it is assumed that the reader is familiar with Galileo. For those readers who wish to familiarize themselves with the language, an overview is presented in Appendix A. Section A.3 of this appendix presents an explanation of constraint filtering, the form of constraint processing which is provided by Galileo and which is used as the basis for supporting designers in this book.

There were several reasons for using Galileo. First, Galileo is an extremely expressive language, developed for building systems to support engineering design. Second, since FOPC is widely used to represent the semantics of natural language, a programming language derived from it, such as Galileo, seems to offer a good basis for re-stating, in a computer-understandable formalism, any body of knowledge for which only a natural language formulation exists, such as a theory of conceptual design. Third, a more pragmatic reason, the Centre in which this research was carried out is developing the Galileo language and its associated tools to suit various aspects of the design process and, since all previous developments were motivated by applications in *detailed* design, there was interest in seeing how well the language would support applications in *conceptual* design.

Two questions were to be addressed by the research presented in this book. First, could constraint-based reasoning be used as the basis for supporting conceptual design? Second, would the expressiveness needs of conceptual design motivate the introduction of new features into Galileo?

The existence of this book indicates that the first question was answered in the positive. Regarding the second question: although the pre-existing version of Galileo *could* have been used to support conceptual design, it was found that, by adding a few features to the language, program length could be reduced and the user-interface could be improved. Before the implementation of the conceptual design theory presented in Chapter 3 is discussed, these extensions to Galileo will be introduced.

4.2.1 An enhancement to the semantics of quantification

In the current standard version of Galileo, quantification over structured domains only applies to top-level parameters. For example, in Fig. 4.1[1], the universally quantified constraint over the structured domain room in Lines 9–10 would only apply to top-level

[1] In this publication, examples of Galileo code are presented annotated with line numbers on the left. Please note that these line numbers are not part of the Galileo program, but are introduced in this book to facilitate easy reference to particular lines in a Galileo program.

parameters that are instances of this structured domain; it would not apply to fields of other parameters, even if those fields were also instances of the same structured domain.

```
 1 domain house
 2     =::= ( bedroom : room
 3            price   : real ).

 4 domain room
 5     =::= ( length : real,
 6            width  : real ).

 7 h1: house.
 8 r1: room.

 9 all room(R):
10     R.length >= R.width.
```

Fig. 4.1 Example usage of quantification in Galileo

Thus, in standard Galileo, while the constraint in Lines 9–10 would apply to room **`r1`** (the top-level parameter declared in Line 8), it would *not* apply to **`h1.bedroom`** (a field of the top-level parameter declared in Line 7), even though **`h1.bedroom`** is also of type **`room`** (Line 2).

This research proposes that all quantified constraints apply to *all* instances of the domain over which they are quantified, regardless of whether these instances are top-level parameters or merely fields of parameters. For example, in Fig. 4.1 the universally quantified constraint in Lines 9–10 would apply to all instances of structured domain room. Thus, the universally quantified constraint in Lines 9–10 would also apply to the **`bedroom`** field of all instances of the structured domain **`house`**; in other words, it would apply to **`h1.bedroom`** as well as to **`r1`**.

4.2.2 Applying the '!' operator to the `exists` *quantifier*

It is also proposed here that the ! operator [3] be applicable to the '**`exists`**' quantifier. Before explaining what this means, the semantics of the '**`exists`**' quantifier in Galileo will be discussed.

```
1 domain store_room
2     =::= ( length  : real,
3            breadth : real,
4            number_of_contents : nonnegative integer ).

5 number_of_boxes : nonnegative integer.

6 number_of_boxes > 0 implies
7     exists store_room(S):
8         S.number_of_contents = number_of_boxes.

9 number_of_boxes = 10.
```

Fig. 4.2 Example usage of the 'exists' quantifier

If the program in Fig. 4.2 were submitted to a Galileo interpreter, a constraint violation message would be produced. The parameter **number_of_boxes** has the value 10 (Line 9). The constraint in Lines 6–8 deduces from this fact that there ought to exist a parameter of type **store_room** (defined on Lines 1–4) whose **number_of_contents** field should also have the value 10. However, no such parameter exists, so the constraint in Lines 6–8 is violated.

Now consider a modified version of this program, as presented in Fig. 4.3. The only difference between the two programs is that, in Fig. 4.3, the ! operator is applied to the **exists** quantifier in Line 7. The ! operator [3] tells the Galileo interpreter that, if a constraint in which the operator is used is violated, the interpreter system should perform some operation (in effect, make a non-monotonic assumption) that eliminates the violation. The ! operator is only allowed in certain situations and, in the current standard version of Galileo, it cannot be applied to the **exists** quantifier. The operational semantics of its application, as proposed here, is that if the requisite kind of parameter does not exist, the interpreter should automatically introduce a new parameter that satisfies the constraint. Thus, in the case of Fig. 4.3, the interpreter will introduce a new parameter, **store_room_1**, to satisfy the constraint in Lines 6–8 and will make its **number_of_contents** field have the value 10.

```
1 domain store_room
2     =::= ( length  : real,
3            breadth : real,
4            number_of_contents : nonnegative integer ).

5 number_of_boxes : nonnegative integer.

6 number_of_boxes > 0 implies
7     !exists store_room(S):
8         S.number_of_contents = number_of_boxes.

9 number_of_boxes = 10.
```

Fig. 4.3 Example usage of the '!' operator applied to the `exists` quantifier

Those who are familiar with the Free Logic underpinnings of Galileo will remember that the **`exists`** *predicate* is used to require the presence of a specific parameter in a constraint network or, if it is absent, to enforce its introduction into the network. Applying the ! operator to the **`exists`** *quantifier* is subtly different. It is similar in that it *does* require the presence of a parameter or force in its introduction. However, it does not require the presence of a *specific* parameter; instead, it requires the presence of a parameter of particular type which must also have certain characteristics. Consider, for example, the program presented in Fig. 4.4.

```
1 domain colour =::= { red, green, blue }.

2 exists( my_colour : colour ) and my_colour = green.

3 !exists colour(C):
4     C = blue.
```

Fig. 4.4 Existence: predication versus quantification

In Line 2 the existence of a specific parameter, called **`my_colour`**, is enforced; it is specified that this parameter must be of type **`colour`** and must have the value **`green`**. In Lines 3–4 the existence of *some* parameter is required; it is specified that this parameter must also be of type **`colour`** and that it must have the value **`blue`**. This second constraint would cause the introduction of a new parameter into the network. However, the name of the parameter would be chosen by the Galileo run-time system.

Contrast the above program with that presented in Fig. 4.5. Line 2 will behave exactly the same as Line 2 in Fig. 4.4: it will cause the introduction of a **`colour`** parameter called **`my_colour`** and will assign it the value **`green`**. However, Lines 3–4 will not cause the introduction of any parameter: the requirements specified by this constraint are satisfied by the parameter introduced by Line 2.

```
1 domain colour =::= { red, green, blue }.

2 exists( my_colour : colour ) and my_colour = green.

3 !exists colour(C):
4     C = green.
```

Fig. 4.5 Existence: predication versus quantification

Care must be exercised when applying the ! operator to the **exists** quantifier. However, it offers considerable user-friendliness in terms of the resolution of constraint violations, since it can automatically introduce missing parameters into a constraint network. The introduction of this usage of the ! operator has been discussed with the developer of Galileo and its contribution to the language has been recognized [4]. While the inspiration for this new application of the ! operator has come from the conceptual design domain, further study on its utility is required in order to ensure that it is suitable for inclusion in the standard version of the Galileo language. As will be seen later, the research reported in this book provides significant motivation for the introduction of this new usage of the operator.

4.2.3 Other extensions

As well as the extensions to quantification, a number of other minor extensions to the standard version of Galileo are assumed in this book. The first is the introduction of a new keyword, '**hidden**'. The second is the introduction of a new meta-level function called **#parent_of**.

The new keyword **hidden** is used to indicate which fields of a structured domain are not visible on the user interface of the constraint filtering system. An example of its use is illustrated in Fig. 4.6, where a structured domain called **box** is defined. This structured domain comprises a number of fields: **length, width, area** and **name**. The **name** field is annotated with the keyword **hidden** which indicates that this field will never be seen on the filtering system interface. This is a useful way of avoiding clutter on the filtering system interface by ensuring that uninteresting fields are not seen by the user. All fields not declared as **hidden** are, of course, visible to the user.

```
1 domain box
2     =::= ( length : positive real,
3            width  : positive real,
4            area   : positive real,
5            hidden name : string ).
```

Fig. 4.6 Example usage of the keyword 'hidden'

The standard version of Galileo already includes some meta-level relations and functions [5]. However, the meta-level aspects of the language are still under development and the range of relations and functions that currently exist is regarded as merely a first step in developing this aspect of the language. The research reported in this book motivated the need for a new meta-level function called **#parent_of**. This function can be used to access any field of a structured parameter from any one of its other fields. An example usage of this function is presented in Fig. 4.7.

```
 1 domain room
 2     =::= ( length  : positive real,
 3            breadth : positive real ).

 4 domain house
 5     =::= ( owner   : string,
 6            kitchen : room,
 7            bedroom : room ).

 8 relation has_the_same_owner_as( room, room )
 9     =::= { (R1,R2): #parent_of(R1).owner
10                          = #parent_of(R2).owner }.
```

Fig. 4.7 Program fragment showing a usage of the '#parent_of' function

The three definitions presented in Fig. 4.7 would, to have any effect, have to be part of some larger program. The relation **has_the_same_owner_as** (defined on Lines 8–10) establishes whether two rooms belong to the same person, by checking whether the rooms belong to house that have the same owner. The **#parent_of** function is used to access the **house** of which a room is a part; once this has been accessed, the **owner** field of the **house** can be reached in the usual way.

4.3 Generic versus application-specific concepts

It is believed that the approach to supporting conceptual design which is presented in this book has wide applicability; it seems suitable for use in a wide variety of design domains. Consequently, its Galileo implementation should distinguish between those features that are generic to all appropriate applications, and those features that are specific to individual design domains.

The generic aspects of the implementation are in Appendix B. Several applications of the approach have been investigated during the research. The implementations of two of them are presented in this book: an implementation of an advice system for the conceptual design of 'leisure vehicles' (bicycles and skateboards) is given in Appendix C; an implementation of a system for advising designers of electrical connectors is provided in Appendix D. Both of these application-specific implementations build on the implementation of the generic concepts.

The implementation of the generic concepts is discussed in Section 4.4. The way in which application-specific advice systems can be built on top of these generic concepts is illustrated in Section 4.5 by considering the implementation of an advice system for designing leisure vehicles.

4.4 Implementing generic concepts

As seen in Chapter 3, the development and comparative evaluation of schemes is the core task during the conceptual phase of design. Thus, in considering how to implement the generic concepts needed to support conceptual design, we will start by considering how to implement the generic notion of a scheme and will continue in a top-down fashion by considering how to implement the various concepts that are needed to support the notion of a scheme. Unless otherwise specified, all fragments of Galileo code that appear in the following discussion are borrowed from the Galileo module **generic_concepts.gal**, presented in Section B.1 of Appendix B; the line numbers quoted in these fragments correspond to those quoted in the appendix.

4.4.1 A generic scheme structure

The underlying premise of the approach to conceptual design presented in Chapter 3 is that every product exists to perform a particular function. The designer's task is to develop a scheme that embodies this required functionality. Since the Galileo language contained no model of a scheme, part of the research task was to design a suitable model of a scheme and any other concepts required to implement the design theory presented in Chapter 3.

```
46 domain scheme
47     =::= ( scheme_name : string,
48            structure   : embodiment ).
```

Fig. 4.8 The representation of a generic scheme

In Fig. 4.8 the Galileo model of a generic scheme is presented. This shows that the concept of a scheme is implemented as a Galileo structured domain called **scheme** which has two fields, called **scheme_name** and **structure**, respectively.

The **scheme_name** is of type **string** and is used to uniquely identify a scheme. Thus, no two schemes should have the same name, a requirement specified by the constraint shown in Fig. 4.9.

```
51 alldif scheme(S1), scheme(S2):
52     not ( S1.scheme_name = S2.scheme_name ).
```

Fig. 4.9 All scheme names must be unique

Since a scheme exists solely to provide the functionality required in the design specification, its structure should be the embodiment of that functionality. This is reflected by Line 48 in Fig. 4.8, where the **structure** field of a **scheme** is declared to be of type **embodiment**.

4.4.2 A generic model of function embodiment

As seen in Chapter 3, a large part of the designer's task in conceptual design consists of identifying, from among the technologies allowed by the company's design policy, ways of providing required functionality; this required functionality may be either the 'top-level' functionality specified in the design specification, or lower-level functionalities that are identified as necessary during scheme development. In other words, the designer is mostly concerned with producing *embodiments* for *intended functions* by *choosing*, from among the *known means*, those that will provide the required functionality. This is reflected in Fig. 4.10 which presents the Galileo implementation of an **embodiment** as a structured domain having four fields: **scheme_name, intended_function, chosen_means,** and **reasons**.

```
2 domain embodiment
3     =::= ( hidden scheme_name : string,
4            intended_function  : func,
5            chosen_means       : known_means,
6            reasons            : set of func_id ).
```

Fig. 4.10 Modelling the embodiment of a function

The **scheme_name** field, of type **string**, cross-references an embodiment to the scheme to which it belongs. At first glance, this form of cross-reference may seem unnecessary, since the only **embodiment** encountered so far in this discussion of implementation is the **structure** field of a **scheme**. However, as seen in Chapter 3, when principles are used to provide functionality they cause the introduction of further embodiments. These 'derived' embodiments also need to be cross-referenced to their parent schemes and the method chosen to do this was to make each embodiment quote the name of its parent scheme. Since this type of cross-reference is of no interest to the user (although an essential housekeeping task for the computer), we do not want it to appear on the user interface; thus, it is labelled, in Line 3, as **hidden**.

The field **intended_function** represents the function to be provided by the embodiment; in Line 4 it is declared to be of type **func**. We will now consider the definition of type **func** in some detail, because when we have done so it will be easier to explain the rest of the **embodiment** definition.

First, it should be noted that the same type of functionality is frequently needed in different parts of a scheme; that is, the function to be provided by one embodiment may be the same type of function as that to be provided by a different embodiment in the same scheme (or, indeed, by an embodiment in a different scheme). Thus, a **func** must represent, not a function, but an *instance* of a function. Furthermore, of course, one function instance must be distinguishable from a different instance of the same function. Having noted this, consider the definition of a **func** provided in Fig. 4.11.

```
17 domain func
18     =::= ( verb : string,
19            noun : string,
20            id   : func_id ).

21 all func(F):
22     has_a_unique_id(F).

23 domain func_id
24     =::= { I: nonnegative integer(I) }.
```

Fig. 4.11 Modelling a function instance in Galileo

In the conceptual design theory presented in Chapter 3, the approach to representing functionality is a symbolic one, consisting of representing a function by a verb–noun pair. As can be seen in Fig. 4.11, this approach is implemented in the first two fields of the structured domain used to represent a **func**. Since a **func** is a function *instance*, it must contain some field which distinguishes it from other instances of the same function. On Line 20 in Fig. 4.11, it can be seen that the approach used was to give each **func** an **id** field, of type **func_id**; from Lines 23–24 it can be seen that a **func_id** is simply a synonym for a **nonnegative integer**.

The requirement that each function instance be distinguishable from all other function instances, including all other instances of the same function, is implemented by the constraint in Lines 21–22 of Fig. 4.11. This constraint uses a relation called **has_a_unique_id,** whose implementation is provided in Fig. 4.12.

```
77 relation has_a_unique_id( func )
78     =::= { F: exists nonnegative integer(I): I = F.id and
79          contains_only_one_func_with_the_id( #parent_of(F).scheme_name, I) }.
```

Fig. 4.12 Uniqueness for identifiers of function instances

Examining Fig. 4.12, we see that, for a **func**, **F**, to have a unique (and well-defined) **id**, the **id** must satisfy two conditions. First, the **id** of **F** must be a non-negative integer. Second, **F** must be the only **func** within its parent scheme which has this non-negative integer as its **id**. This second condition is implemented by using a relation called **contains_only_one_func_with_the_id**; the details of this relation are beyond the scope of this discussion but can, of course, be traced by the determined reader – it is defined in Lines 66–70 of Section B.1 in Appendix B.

For the purpose of this chapter, it is sufficient to note that a **func** in one scheme may use the same integer for its **id** as a **func** in a second scheme; this is because a **func** is uniquely identified by a combination of two things: its own **id** and the **scheme_name** field of the **embodiment** in which the **func** is used. This explains Line 79 in Fig. 4.12: if a **func**, **F**, is to have a unique **id**, the scheme whose name is in the **scheme_name** field of the data object which is the **#parent_of F** (this parent will be an **embodiment**) must contain only one **func** which uses as its **id** the integer that is used by **F** as its **id**. The reader may wonder why this approach was used: why permit a function instance in one scheme to have the same identity number as a function instance in a different scheme? The decision to allow this was motivated by concern about the user interface. If every function instance were to have an identity number that is unique across all schemes, the designer of the first scheme would not be affected. However, the designer of every subsequently conceived scheme would find that the first function instance in their scheme would be allocated as its **id** some integer whose value depended on how many function instances were used in all previously conceived schemes. The designer might learn to accept this, but would probably find it somewhat confusing. Instead, as we will see later, the first function instance in each scheme will have the **id** 0, the second 1, and so on.

It is worth noting one more point about **funcs** before we return to complete our consideration of **embodiments**. In Fig. 4.13 a relation called **provides_the_function** is defined. This relation, which maps between a **func** and the function of which it is an instance, takes three arguments. The first argument is of type **func** while the others are of type **string**; the relation is true if the **func** in the first argument is an instance of the function described symbolically by the **verb-noun** pair in the second and third arguments. This relation is introduced here because it is a generic concept, although we will not see it being used until we see specific functions being introduced in Section 4.5.

After this digression into the implementation of a **func**, let us return to the remaining part of the definition of an **embodiment**, presented in Fig. 4.10. The third field in this structured domain is **chosen_means**. This represents the approach chosen by the designer to provide the **intended_function** for the **embodiment**. The approach chosen by the designer must conform to the technology policy adopted by the company for which they work: in other words, the *means* chosen must be *known* and approved. This is reflected by the fact that in Line 5 of Fig. 4.10 the field **chosen_means** must be of type **known_means**.

```
123 relation provides_the_function( func, string, string )
124      =::= { (F,V,N): V = F.verb and N = F.noun }.
```

Fig. 4.13 Relation between a verb–noun pair and an instance of the function which they describe

Of course the repertoire of technologies known to, and approved by, a company varies from one company to another. Thus, the definition of **known_means** is not generic; it depends on the design domain to which the conceptual design advice system is being applied. Although we cannot, therefore, consider it further in this section, we will see an example definition of **known_means** in Section 4.5.

Before proceeding to discuss the final field in an **embodiment**, consider the constraint shown in Fig. 4.14. This specifies that whatever **known_means** is chosen for an embodiment must, in fact, be capable of providing the function intended for the embodiment.

```
7 all embodiment(E):
8      can_be_used_to_provide(E.chosen_means, E.intended_function).
```

Fig. 4.14 The means chosen for an embodiment must be serviceable

The relation **can_be_used_to_provide** used in Fig. 4.14 is defined in Fig. 4.15. As will be seen when we consider the definition of company-specific knowledge in Section 4.5, a **known_means** may be able to provide several functions simultaneously. Furthermore, a **known_means** may, if used in different ways, be able to provide different sets of functions simultaneously. The definition of the relation **can_be_used_to_provide** states that a **known_means** can provide a function, if that function appears in some set of functions that the means can simultaneously provide. The relation **can_simultaneously_provide** used in this definition cannot be discussed here: it is company-specific knowledge and the way in which it is defined will be discussed in Section 4.5.

```
53 relation can_be_used_to_provide( known_means, func)
54      =::= { (K,F): can_simultaneously_provide(K,Fs) and F in Fs}.
```

Fig. 4.15 Definition of can_be_used_to_provide

The final field in the definition of an **embodiment** (Fig. 4.10) is called **reasons**. As discussed in Chapter 3, an embodiment may be introduced into a scheme because of different factors: it could be introduced to provide the top level functionality required in the design specification. Alternatively, it could be introduced to provide some functionality whose necessity was recognized when some design principle was used during the development of the scheme. The **reasons** field in an **embodiment** records the motivation for introducing the **embodiment**. It does so by recording the identity numbers of the function instances whose provision required the introduction of the embodiment. This is reflected by the fact that, in Line 6 in Fig. 4.10, the **reasons** field, has the type **set of func_id**. The **reasons** field of an **embodiment** provides the basis for identifying those design entities between which context relations must be considered. The process of defining context relations between design entities will be discussed later in Section 4.5.4.

```
49 all scheme( S ):
50     is_the_first_embodiment_in( S.structure, S.scheme_name ).
```

Fig. 4.16 A constraint on the structure of the generic scheme representation

Remember that, as we saw earlier, the **structure** field of a **scheme** is an **embodiment**. Since the **structure** of a **scheme** is intended to satisfy the top-level functionality requirement in the design specification, it will be *the first embodiment in* the **scheme.** This is reflected by the constraint shown in Fig. 4.16.

```
116 relation is_the_first_embodiment_in( embodiment, string )
117     =::= { (E,Sn): is_in_the_scheme( E, Sn ) and
118                    E.intended_function.id = 0 and
119                    E.reasons = {} }.
```

Fig. 4.17 The meaning of the relation is_the_first_embodiment_in

The definition of the relation **is_the_first_embodiment_in** that is used in this constraint is shown in Fig. 4.17. The details of this definition are beyond the scope of this discussion. It is enough to note two points. First, as shown in Line 118 of Fig. 4.17, the **id** of the **intended_function** for the first embodiment in a scheme must be 0; this reflects the fact that the functionality to be satisfied by the first embodiment in a scheme is the top-level functionality required in the design specification. Second, as shown on Line 119, the set of **reasons** for the first embodiment in a scheme is empty; this reflects the fact that, apart from the **intended_function** of the embodiment (which, of course, is the top-level functionality required in the design specification), no other function instances in the scheme motivated the introduction of this first embodiment.

4.4.3 A generic model of means

As was mentioned above, the repertoire of technologies known to, and approved by, a company varies from one company to another. Thus, the issue of defining the specific means available to a designer is not something that will be covered in this section, which is concerned only with the definition of generic concepts. However, when specific means are defined (the method of doing so will be considered in Section 4.5), they will be defined in terms of a generic notion of means, whose definition we will consider now.

Figure 4.18 illustrates how the generic notion of a means can be modelled as a structured domain in Galileo.

```
35 domain means
36     =::= ( hidden scheme_name : string,
37            type               : means_type,
38            funcs_provided     : set of func_id ).

39 all means(M):
40     is_a_possible_behaviour_of( M.funcs_provided, M ).

41 domain means_type
42     =::= { a_principle, an_entity }.
```

Fig. 4.18 Modelling a design means in Galileo

As shown in Lines 35–38, a means is implemented as a Galileo-structured domain called **means**. This has three fields: **scheme_name**, **type**, and **funcs_provided**. As was the case with the definition of an embodiment, the **scheme_name** field is used to cross-reference a **means** with the scheme in which the **means** is being used; similarly, for the same reasons as the **scheme_name** field was declared hidden in the definition of a embodiment, it is declared as **hidden** here.

It will be remembered from Chapter 3 that there are two kinds of means: principles and entities. This is reflected by the fact that, as shown in Fig. 4.18, the domain from which the **type** field of a **means** takes its value contains only two possible values, **a_principle** and **an_entity** (see Lines 41-42).

The final field in the definition of the generic notion of a means is called **funcs_provided** and is of type **set of func_id**. It is used to remember which function instances within a scheme the **means** is being used to provide. Of course, a **means** should be used to provide only those function instances that it is capable of providing; this requirement is captured in the constraint in Lines 39–40. The definition of the relation **is_a_possible_behaviour_of**, used in this constraint, will not be

considered here. It is presented in Lines 82–85 of **generic_concepts.gal** in Section B.1, but the details of its semantics are beyond the scope of this discussion; they can, of course, be traced by the determined reader. Essentially, however, the provision of a set of function instances can be regarded as a possible behaviour of a means if, and only if, the means can *simultaneously* provide the variety of function types as well as the quantity of instances of each type of function that is implied by the set of function instances.

4.4.4 A generic model of design principles

As discussed in Chapter 3, a design principle is an abstraction of a known approach to satisfying a functional requirement. A design principle describes how a particular type of functionality can be provided by embodying a set of lower-level functions. In addition, the principle may specify certain relationships, called *context relationships*, between the embodiments of these lower-level functions.

Having noted this, it can be seen that a specific design principle is a piece of intellectual property which, if not the patented property of a company, is central to the company's way of doing conceptual design. Thus, consideration of how to define specific principles will be delayed until Section 4.5. However, we will see in Section 4.5 that specific principles are implemented in terms of a generic notion of a principle, a concept which we will consider here.

The generic notion of a principle is defined in Fig. 4.19 as a specialization of the generic notion of a **means**. Similarly, when we consider the definition of specific principles, in Section 4.5, we will see that these are defined as specializations of this generic notion of a principle.

```
43 domain principle
44     =::= { P: means(P) and
45                P.type = a_principle }.
```

Fig. 4.19 A generic design principle model

4.4.5 A generic model of design entities

A design entity represents a class of part, instances of which can be incorporated into a scheme to realize one or more of the function instances identified during the conceptual design of a product. As with design principles, specific design entities are part of a company's body of design expertise. As such, their representation will not be considered here, being delayed until Section 4.5. However, as with design principles, specific design entities are defined as specializations of a generic notion of a design entity, a concept whose definition we will consider here.

```
 9 domain entity
10     =::= { E: means(E) and
11                E.type = an_entity and
12                exists ( E.id : entity_id ) }.

13 all entity(E):
14     has_a_unique_id(E).

15 domain entity_id
16     =::= { I: positive integer(I) }.
```

Fig. 4.20 The model of a generic design entity

In Fig. 4.20 the generic notion of a design **entity** is defined, like the generic notion of a design principle, as a specialization of the concept of a **means**. A strict approach to implementing computer-based support for conceptual design might distinguish between design entities and *design entity instances*. However, for our purposes here, we can avoid making this distinction. Consequently, the generic notion called an **entity** in Fig. 4.20 actually represents a design entity *instance*. As such, it requires an identity field, which is provided by specifying (in Line 12) that it contains a field additional to those present in the generic notion of a **means**. This additional field, the **id** field, is of type **entity_id** which, as can be seen in Lines 15–16, is merely a synonym for a positive integer[2].

Each design entity instance should have a unique **id**, a requirement which is specified by the constraint in Lines 13–14. The meaning of the relation **has_a_unique_id** used in this constraint is given in Fig. 4.21. It will not be explained here, since **id** uniqueness with respect to design entity instances is similar to **id** uniqueness with respect to function instances – in both cases, **id** uniqueness is local to the parent scheme; the explanation of **func_id** uniqueness in Fig. 4.12 can be applied, *mutatis mutandis*, to Fig. 4.21.

```
74 relation has_a_unique_id( entity )
75     =::= { E: exists positive integer(I): I = E.id and
76                contains_only_one_entity_with_the_id( E.scheme_name, I) }.
```

Fig. 4.21 Uniqueness for entity identifiers

[2] It will be remembered that a **func_id** was defined to be a non-negative integer. This is because the top-level functionality requirement in a scheme, which comes from the design specification, is given the special **func_id** of 0. Since no entity instance is treated as special, there is no need to allow 0 as an **entity_id**; thus an **entity_id** can only be a positive integer.

4.4.6 Context relationships and entity interfaces

As seen earlier, a design principle introduces a set of embodiments and a set of context relationships between them. Eventually, of course, each embodiment is realized by the introduction of design entity instances. This means that context relationships between embodiments will have to be realized by interfacing appropriately the entity instances that realize the embodiments.

In conceptual design, the minute detail of how a pair of components in a product are interfaced or connected is generally not of interest. However, there are certain minimum details that must be known in order to evaluate the quality of the scheme being developed. We will see in Section 4.5.4 how these details are represented. They will be represented as specializations of a generic concept called an **interface**, whose definition we will consider here; it is provided in Fig. 4.22.

As can be seen in Lines 25–28, an **interface** is represented as a Galileo-structured domain with three fields. The first field, **scheme_name**, is **hidden** from the user because it is present merely to facilitate system housekeeping; it cross-references the **interface** to the **scheme** in which it is used. The remaining two fields, **entity_1** and **entity_2**, contain the identity numbers of the two design entity instances that are being interfaced.

```
25 domain interface
26     =::= ( hidden scheme_name : string,
27            entity_1 : entity_id,
28            entity_2 : entity_id ).

29 all interface(I):
30     exists entity(E1), entity(E2):
31         I.entity_1 = E1.id and
32         I.entity_2 = E2.id and
33         is_in_the_same_scheme_as( I, E1 ) and
34         is_in_the_same_scheme_as( I, E2 ).
```

Fig. 4.22 Modelling generic interfaces between design entities

The constraint defined in Lines 29–34 ensures that, for every **interface** that is defined, both of the entity instances to which it relates exist in the same scheme as the interface. An **entity** instance is, as we have already seen, merely a specialization of a **means** so the relation **is_in_the_same_scheme_as** used in the above constraint is the one defined in Fig. 4.23, which is defined over an **interface** and a **means**. From this definition, we can see that an **interface** and a **means** are in the same scheme if the contents of their **scheme_name** fields are the same. Examination of Section B.1 in Appendix B will reveal that, although there are several different relations called **is_in_the_same_scheme_as**, defined between different pairs of concepts, they all rely on equality between **scheme_name** fields; we will not consider them further here.

```
98 relation is_in_the_same_scheme_as( interface, means )
99      =::= { (I,M) : I.scheme_name = M.scheme_name }.
```

Fig. 4.23 One of the several versions of the relation `is_in_the_same_scheme_as`

A similar relation, which will be considered a little further here because it will be referenced later, is the relation **`is_a_part_of`** between a **`means`** (that is, either a principle or an entity) and a **`scheme`**. This relation's definition is shown in Fig. 4.24 where it can be seen that a **`means`** is part of a **`scheme`** if the **`scheme_name`** field of the means contains the name of the scheme.

```
80 relation is_a_part_of( means, scheme )
81      =::= { (M,S) : M.scheme_name = S.scheme_name }.
```

Fig. 4.24 The relation `is_a_part_of`

4.4.7 Generic concepts for comparing schemes

Every scheme for a product must, of course, provide the functionality required by the design specification. However, as we have seen in Chapter 3, a design specification may, in addition to stipulating functionality, describe certain desirable, although not essential, properties of a design. These desirable properties are called *preferences*.

A design specification may include several preferences; the approach to be used for comparing two schemes when more than one preference is to be considered is described in Chapter 3. The implementation of that approach, or at least its generic aspects, can be found in Section B.2 of Appendix B, where a Galileo module called **`comparison.gal`** is presented. In the following, unless otherwise noted, all Galileo code fragments come from this module.

```
2 domain intention
3      =::= { minimal, maximal }.

4 domain preference
5      =::= ( value  : real,
6             intent : intention ).
```

Fig. 4.25 Modelling a design preference

The basic notion in the approach for comparing schemes is the **preference**. It is defined in Fig. 4.25 as a structured domain containing two fields: the **value** field, which contains the value of whatever scheme property is the subject of the preference, and the **intent** field, which indicates whether it is preferred that this scheme property be minimized or maximized.

```
 7 relation better_than( preference, preference )
 8     =::= { (P1,P2): P1.intent = minimal and
 9                     P2.intent = minimal and P1.value < P2.value,
10            (P1,P2): P1.intent = maximal and
11                     P2.intent = maximal and P1.value > P2.value }.
```

Fig. 4.26 Comparing two design preferences to determine which is better

When two schemes are being compared, this will involve comparing how well they do in respect of each preference given in the design specification. A relation called **better_than** is used for comparing the instantiation of a preference in one scheme with the instantiation of the same preference in the other scheme. The definition of this relation is given in Fig. 4.26. We can see that, if a preference involves minimizing some property, the better instantiation of the preference is the one with the smaller value; similarly, if a preference involves maximizing some property, the better instantiation of the preference is the one with the larger value. This notion of **better_than** was introduced in Section 2.3.

As explained in Chapter 3, no scheme for a product should dominate (in the sense of Pareto optimality) another scheme. This requirement is implemented as the constraint in Fig. 4.27. If a designer develops a scheme which is dominated by a scheme that they (or a colleague) has previously developed, this constraint will be violated and a message will be given to that effect. Similarly, if the designer develops a scheme that dominates a previously developed scheme the constraint will be violated. In either case, it is intended that, as a result of the violation message, (one of) the designer(s) will be motivated to improve the inferior scheme or else to discard it.

The constraint in Fig. 4.27 is defined in terms of a relation called **dominates** which is also defined in Fig. 4.27. We can see that one scheme dominates another scheme if the first scheme **improves_on** the latter (in respect of some preference) while at the same time it is not true that the latter scheme **improves_on** the first in respect of any preference; this implements the ideas introduced in Section 2.3.

```
12 alldif scheme(S1), scheme(S2):
13    not dominates( S1, S2 ).

14 relation dominates( scheme, scheme)
15     =::= { (S1,S2): improves_on( S1, S2) and
16                     not improves_on( S2, S1 ) }.
```

Fig. 4.27 Comparing two schemes

The relation **improves_on**, between two schemes, is defined in terms of the relation **better_than**, between instantiations of preferences. However, this definition is not generic; it will vary from one design specification to another and, thus, will not be discussed here; it will be considered later, in Section 4.6.3, when the representation of design specifications is discussed.

4.5 Implementing application-specific concepts

The generic concepts introduced in Section 4.4 merely serve as the basis for defining the company- and project-specific concepts that are needed to support conceptual design. The definition of these application-specific concepts in terms of the generic concepts will now be considered.

To illustrate how this is done, we will use extracts from a design knowledge-base for a company called Raleigh Leisure Vehicles Limited. This knowledge-base, which is in a module called **raleigh_knowledge.gal**, is concerned with the design of products such as bicycles and skateboards; the module is presented in Section C.1 of Appendix C. In the following, unless otherwise noted, each Galileo fragment quoted comes from this module.

4.5.1 Defining known means

As mentioned earlier, an important part of the company-specific knowledge that must be defined is the set of technologies that are available for use by the company's designer(s).

To define this knowledge we must list the **known_means**, that is the design principles and design entities that are approved for use by designers working for the company. We must specify what functionality is offered by these **known_means**. We must also describe each of these principles and entities in detail.

Listing the **known_means** is simply done. It merely involves defining a Galileo scalar domain which contains one symbol for each of the available principles or entities. In Fig. 4.28 the collection of means which are available to designers working for Raleigh Leisure Vehicles Limited is presented.

As can be seen, the means available include **an_axle, a_bicycle** and **a_skateboard,** and so on. As we shall see later, some of these refer to design principles while others refer to design entities.

As well as listing the **known_means** that are available to designers working for a company, the company knowledge-base must specify the functions that each **known_means** can provide. This is done by declaring the relation called **can_simultaneously_provide**. This company-specific relation was invoked by the generic definition shown in Fig. 4.15, but could not be considered at that stage, because only generic concepts were being considered.

```
41 domain known_means
42     =::= { an_axle, a_bicycle, a_skateboard, a_wheel_assembly,
43            a_saddle, a_chain, a_chassis, a_steering_assembly,
44            an_engine, a_harness, an_air_cushion, a_frame,
45            a_handlebar_assembly, a_molded_frame,
46            a_pedal_assembly, a_chain }.
```

Fig 4.28 A domain of know_means available to designers

Figure 4.29 provides the definition of this relation specific to Raleigh Leisure Vehicles Limited. It provides the information on means functionality that was shown in Fig. 3.13. The relation shows the functionality that can be simultaneously provided by the various **known_means** available to engineers working for this company. Each pair in this binary relation associates a **known_means** with a set of functions. In many cases this set of functions is simply a singleton set. However, the notion of a set is used in the definition of this relation because, in general, a **known_means** could provide multiple function instances at the same time. In Lines 133–134, it can be seen that **an_air_cushion** provides only one function, namely **facilitate movement**. In Lines 135–139 it can be seen that **an_axle** can provide the two functions *support wheel* and *facilitate rotation* simultaneously, but can also be used to provide the single function *punch holes*.

```
132 relation can_simultaneously_provide( known_means, set of func )
133     =::= { (an_air_cushion,{F}):
134                 provides_the_function( F, 'facilitate', 'movement' ),
135            (an_axle,{F}):
136                 provides_the_function( F, 'punch', 'holes' ),
137            (an_axle,{F1,F2}):
138                 provides_the_function( F1, 'support', 'wheel' ) and
139                 provides_the_function( F2, 'facilitate', 'rotation' ),
140            (a_bicycle,{F}):
141                 provides_the_function( F, 'provide', 'transport' ),
142            (a_chasis,{F}):
143                 provides_the_function( F, 'provide', 'support' ),
144            (an_engine,{F}):
145                 provides_the_function( F, 'provide', 'energy' ),
146            (a_frame,{F}):
147                 provides_the_function( F, 'provide', 'support' ),
148            (a_handlebar_assembly,{F}):
149                 provides_the_function( F, 'change', 'direction' ),
150            (a_molded_frame,{F1,F2}):
151                 provides_the_function( F1, 'provide', 'support' ) and
152                 provides_the_function( F2, 'support', 'passenger' ),
153            (a_harness,{F}):
154                 provides_the_function( F, 'support', 'passenger' ),
155            (a_pedal_assembly,{F}):
156                 provides_the_function( F, 'provide', 'energy' ),
157            (a_saddle,{F}):
158                 provides_the_function( F, 'support', 'passenger' ),
159            (a_skateboard,{F}):
160                 provides_the_function( F, 'provide', 'transport' ),
161            (a_steering_assembly,{F}):
162                 provides_the_function( F, 'change', 'direction' ),
163            (a_wheel_assembly,{F}):
164                 provides_the_function( F, 'facilitate', 'movement' ) }.
```

Fig. 4.29 Relating means to the functions that they can provide

In the cases discussed here the function instances that a **known_means** can provide simultaneously are instances of different functions. In general, however, two or more function instances provided by a **known_means** could be instances of the same function. For example, in Fig. 4.30 two instances of the function *provide light* are being provided by the same design entity.

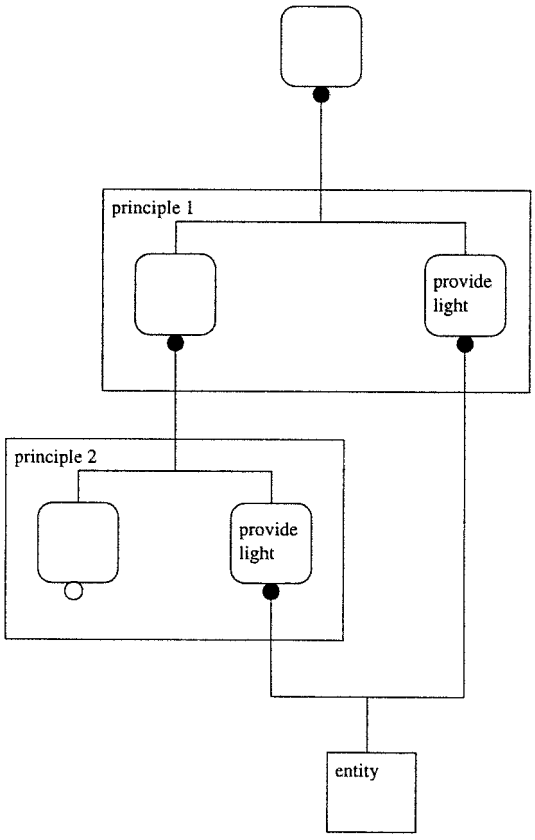

Fig. 4.30 Embodying two instances of the function *provide light* with the same design entity

4.5.2 Defining company-specific design principles

In Fig. 4.19 the notion of a generic design principle was presented. All the design principles that are available to designers working for a specific company can be defined as specializations of this generic design principle. Consider, for example, the principle of a bicycle, seen in Fig. 3.9. It is defined in Fig. 4.31.

This application-specific principle is defined to be a specialization of the generic notion of a principle (Line 8); the specialization is specified by the extra properties that are defined in Lines 9–28.

It was seen in Fig. 3.9 that a `bicycle` principle involves five `embodiments`. These are specified in Lines 9–13 of Fig. 4.31. The functions which Fig. 3.9 states are to be provided by these embodiments (`facilitate movement`, `provide energy`, `support passenger`, `change direction`, and `provide support`) are specified in Lines 14–23 of Fig. 4.31, using the generic relation `provides_the_function` which we saw defined earlier in Fig. 4.13.

```
 7 domain bicycle
 8     =::= { B: principle(B) and
 9            exists( B.e1 : embodiment ) and
10            exists( B.e2 : embodiment ) and
11            exists( B.e3 : embodiment ) and
12            exists( B.e4 : embodiment ) and
13            exists( B.e5 : embodiment ) and
14            provides_the_function( B.e1.intended_function,
15                                   'facilitate', 'movement' ) and
16            provides_the_function( B.e2.intended_function,
17                                   'provide', 'energy' ) and
18            provides_the_function( B.e3.intended_function,
19                                   'support', 'passenger' ) and
20            provides_the_function( B.e4.intended_function,
21                                   'change', 'direction' ) and
22            provides_the_function( B.e5.intended_function,
23                                   'provide', 'support' ) and
24            drives( B.e2, B.e1 ) and
25            supports( B.e5, B.e1) and
26            supports( B.e5, B.e2) and
27            supports( B.e5, B.e3) and
28            supports( B.e5, B.e4) }.
```

Fig. 4.31 Definition of a company-specific design principle

The context relationships between the embodiments shown in Fig. 3.9 are stated in Lines 24–28 of Fig. 4.31. In Line 24 it is stated that a **drives** relationship must exist between the **embodiment e2** and **embodiment e1**. Line 25 states that a **supports** relationship must exist between the **embodiment e5** and **embodiment e1**. Line 26 requires that a **supports** relationship must exist between the **embodiment e5** and **embodiment e2**. Line 27 states that a **supports** relationship must exist between the **embodiment e5** and **embodiment e3**, while Line 28 requires that a **supports** relationship must exist between the **embodiment e5** and **embodiment e4.**

Ultimately, as was seen in Chapter 3, each embodiment introduced by a principle is realized by the introduction of a set of one or more design entity instances. Thus, if a design principle specifies a context relationship between some of its embodiments, that relationship will, ultimately, be realized by some analogous relationship between the sets of design entity instances that realize the embodiments. We will see later, in Section 4.5.4, how these relationships are defined.

4.5.3 Defining company-specific design entities

Design entities represent classes of parts which provide physical realizations of the functions that are identified in the function decomposition of the product being designed. Company-specific design entities are defined as specializations of the generic notion of a design entity, presented in Section 4.4.5.

In every company there are particular properties of parts that are of general interest. For example, in the mechanical domain, properties such as mass, geometry, and material may be considered important enough to be represented as attributes of all design entities. In such cases, a company will define its own 'pseudo-generic' type of design entity as a specialization, containing fields to represent these important properties, of the generic design entity. It will also define functions to compute important properties of these pseudo-generic design entities.

For example, Raleigh Leisure Vehicles Limited considers the *width, mass,* and *material* to be important properties of all parts. Thus, as shown in Fig. 4.32, it was considered appropriate to define the notion of a **raleigh_entity** which has these properties.

```
56 domain raleigh_entity
57     =::= { R: entity(R) and
58                exists( R.width  : real ) and
59                exists( R.mass   : real ) and
60                exists( R.material : raleigh_material ) and
61                R.mass = mass_of( R ) }.


67 domain raleigh_material
68     =::= { cfrp, titanium, aluminium, steel }.


236 function mass_of( raleigh_entity ) -> real
237     =::= { E -> 2:  E.material = cfrp,
238            E -> 3:  E.material = titanium,
239            E -> 5:  E.material = aluminium,
240            E -> 10: E.material = steel }.
```

Fig. 4.32 The implementation of a company-specific design entity called raleigh_entity

As can be seen in Lines 56–61, the concept of a **raleigh_entity** is defined to be a specialization of the generic notion of an **entity**. The specialization consists of an additional three fields, representing **width, mass,** and **material**, with an equational constraint for estimating the **mass**. The **width** and **mass** fields are of type **real** but the material field is of type **raleigh_material**; according to the definition of the type **raleigh_material**, in Lines 67-68, this company's designers are restricted to using one of just four materials: **cfrp, titanium, aluminium** and **steel**.

In Line 61 the **mass** of a **raleigh_entity** is estimated using a function called **mass_of**. The implementation of this function is presented in Lines 236–240. In a real situation, the mass of an entity instance would, of course, depend on its volume as well as the constituent material. However, in order to simplify matters for the sake of this example, it is assumed that the **mass_of** all instances of **raleigh_entity** can be estimated by

knowing just the **material** of the entity. Thus, for example, the **mass_of** a **raleigh_entity** whose **material** is **steel** is estimated to be 10 units (Line 240).

```
29 domain chassis
30      =::= { C: raleigh_entity(C) }.
```

Fig. 4.33 A chassis design entity

When a company has defined its own pseudo-generic concept of a design entity, it can define a repertoire of company-specific design entities. These company-specific design entities may be specializations, with further additional fields, of the company's pseudo-generic concept of design entity or they may be merely synonyms of it. For example, in Fig. 4.33 a design entity called **chassis** is implemented. This design entity is simply a synonym for **raleigh_entity** because, apparently, for the purposes of conceptual design, no attribute of a **chassis** is considered important, besides those that are already defined for a **raleigh_entity**.

A company-specific design knowledge-base, such as the one presented in Section C.1, will usually contain many different types of design entity that are available to designers for use in their schemes. An inspection of Section C.1 will show that, as well as **chassis**, it defines the following types of **raleigh_entity: air_cushion, axle, chain, engine, frame, handlebar_assembly, harness, molded_frame, pedal_assembly, saddle, steering_assembly, wheel_assembly**.

4.5.4 Defining company-specific context relationships

If a design principle specifies a context relationship between some of its embodiments, that relationship must, ultimately, be realized by some analogous relationship between the sets of design entity instances which realize the embodiments. We will now see how that is specified.

Consider, for example, the **bicycle** principle defined in Fig. 4.31. Line 24 specifies that a **drives** relationship must hold between the first two embodiments introduced by the principle, those which embody the functions **provide energy** and **facilitate movement**.

The **drives** relationship between two embodiments is defined in Fig. 4.34. This definition specifies that the **drives** relationship holds between two embodiments if, and only if, an analogous relationship, also called **drives**, holds between the two sets of entity instances that derive from these embodiments[3].

```
165 relation drives( embodiment, embodiment )
166     =::= { (E1,E2): drives( { X | exists entity( X ):
167                                     derives_from( X, E1 ) },
168                             { Y | exists entity( Y ):
169                                     derives_from( Y, E2 ) } ) }.
```

Fig. 4.34 The meaning of the drives context relation between embodiments

The analogous relationship between the sets of entity instances that derive from the embodiments involved in a context relationship must be defined. The **drives** relationship between sets of derived entity instances is shown in Fig. 4.35. It is defined in terms of yet another analogous relationship, this time between individual entity instances: apparently, one set of entity instances drives another set of entity instances if there exists one individual entity instance in the first set which **drives** an individual entity instance in the second set.

```
170 relation drives( set of entity, set of entity )
171     =::= { (E1s,E2s): exists E1 in E1s, E2 in E2s:
172                         drives( E1, E2 ) }.
```

Fig. 4.35 The meaning of the drives context relation between sets of design entity instances

The precise realization of the context relationship specified in a principle depends on which design entities are used to realize the embodiments that must satisfy the context relationship. Suppose that a **pedal_assembly** is the design entity used to **provide energy**, and a **wheel_assembly** is the design entity used to **facilitate_movement**. We can see in Fig. 4.36 the relationship that would have to be satisfied between these two entity instances.

[3] The relation **derives_from** used in this definition is a generic relation and, as such, is defined in Section B.1 of Appendix B. A detailed consideration of its definition would distract us from the focus of the current discussion. Suffice it to say that if a determined reader were to follow the definition she would discover that an entity instance can derive either directly or indirectly from an embodiment. An entity instance derives directly from an embodiment if it is used, without recourse to any design principle, as the means of implementing the function intended for the embodiment, while an entity instance derives indirectly from an embodiment if one or more principles were used in the reasoning that led to the entity instance being used to implement part of the function intended for the embodiment. The reasoning that leads to a particular **embodiment** being introduced into a scheme can be determined from its **reasons** field.

```
173 relation drives( entity, entity )
174     =::= { (P,W): pedal_assembly(P) and wheel_assembly(W) and
175                   is_in_the_same_scheme_as( P, W ) and
176                   !exists chain(C):
177                       is_in_the_same_scheme_as( P, C ) and
178                       !exists mechanical_interface(M1):
179                           M1.entity1 = P.id and
180                           M1.entity2 = C.id and
181                           M1.relationship = drives and
182                       !exists mechanical_interface(M2):
183                           M2.entity1 = W.id and
184                           M2.entity2 = C.id and
185                           M2.relationship = drives }.
```

Fig. 4.36 The meaning of the `drives` context relation between a pedal assembly and a wheel assembly

According to the definition of this relationship, if a **`pedal_assembly`** is to **`drive`** a **`wheel_assembly`**, they must be in the same scheme and there must be a further design entity instance, a **`chain`**, in the same scheme. These entity instances must be interfaced in the following way: there must be a **`mechanical_interface`** between the **`pedal_assembly`** and the **`chain`** and another one between the **`wheel_assembly`** and the **`chain`**. This arrangement was used in Fig. 3.17.

As we shall now see, a **`mechanical_interface`** is simply a specialization of the generic notion of an **`interface`** which we encountered in Section 4.4.6. The definition of a **`mechanical_interface`** is given in Fig. 4.37. It can be seen to be a specialization of a company-specific notion of interface, called a **`raleigh_interface`**, which, from its definition in Fig. 4.38, can be seen to be a specialization of the generic notion of **`interface`**.

```
47 domain mechanical_interface
48     =::= { S: raleigh_interface(S) and S.type = mechanical and
49               exists( S.relationship : mechanical_relationship ) }.

50 domain mechanical_relationship
51     =::= { controls, drives, supports }.
```

Fig. 4.37 Modelling a `mechanical` interface

It can be seen from Fig. 4.37 that a **`mechanical_interface`** is a **`raleigh_interface`** whose **`type`** field contains the value **`mechanical`** and which also has an additional field called **`relationship`** which specifies the nature of the mechanical relationship

involved in the interface; it can be seen that three kinds of relationship are supported: **controls, drives** and **supports**.

It can be seen from Fig. 4.38 that a **raleigh_interface** is simply an **interface** with an additional field called **type** which specifies the class of relationship involved in the interface; it can be seen that two classes of relationship are supported: **spatial** and **mechanical**.

```
62 domain raleigh_interface
63     =::= { I: interface(I) and
64                exists( I.type : raleigh_interface_type ) }.

65 domain raleigh_interface_type
66     =::= { spatial, mechanical }.
```

Fig. 4.38 Modelling company-specific interfaces

4.6 Modelling design specifications

In Chapter 3 a detailed discussion on the contents of a design specification was presented. A constraint-based approach to modelling a design specification will be presented here.

A design specification comprises a set of requirements defining the functional and physical properties of the product to be designed. During the conceptual phase of design, a designer (or, possibly, a team of them) generates a set of alternative schemes which satisfy the requirements defined in the design specification. The designer(s) will select a subset of these schemes for further development during the later phases of the design process. Thus, a design specification can be regarded as an intensional specification of a set of schemes.

In Section 4.4.1, a generic model of a scheme was presented. This generic scheme provides a basis for the development of schemes for any product. Each requirement in the design specification can be regarded as a constraint on the schemes that the designer will develop. The requirements defined in the design specification can be modelled as constraints that are universally quantified over all instances of the scheme representation. For example, consider the following design specification:

Design a product that exhibits the following properties:

- provides the function *provide transport*;
- is *recyclable*;
- has a *width not greater than 2 m*;
- has *minimal mass* and
- comprises a *minimal number of parts*.

In this specification there is one functional requirement and four physical requirements. The functional requirement states that the product must provide the function *provide transport*. The physical requirements state that the product must be *recyclable*, must have a *width not greater than 2 m*, should have *minimal mass,* and should comprise a *minimal number of parts*.

In the following sections a constraint-based model of this design specification will be developed in stages. A full constraint-based implementation of this design specification is presented in a Galileo module called **`vehicle_spec.gal`** presented in Section C.2. Parts of this design specification model will be presented in the following sections in order to demonstrate the modelling approach used in this book.

4.6.1 Modelling functional requirements

It was explained above that a design specification can be regarded as an intensional specification of a set of schemes. This means that a design specification can be represented in Galileo as a specialization of the generic notion of a scheme. This is illustrated in Fig. 4.39, where a fragment from the design specification in Section C.2 is given. The specification for a new vehicle is called a **`vehicle_scheme`** and, as can be seen, is a specialization of a **`scheme`**.

```
5 domain vehicle_scheme
6     =::= { S: scheme( S ) and
7                ...
```

Fig. 4.39 Modelling the functional properties of a scheme

In the representaion of the design specification considered here, the functional requirement is that the product can *provide transport*. In terms of the modelling approach being presented here, this requirement can be treated as a constraint on the kind of scheme that is acceptable as a **`vehicle_scheme`**. This is shown in Fig. 4.40.

```
5 domain vehicle_scheme
6     =::= { S: scheme( S ) and
7               provides_the_function( S.structure.intended_function,
8                                      'provide', 'transport' ) and
9               ...
```

Fig. 4.40 Modelling the functional properties of a scheme

Recall, from Section 4.4.1, that the generic model of a **scheme** has a field called **structure** which is of type **embodiment**. The **intended_function** field of this embodiment represents the function that is to be provided by the scheme. In the fragment from the vehicle design specification that is given in Fig. 4.40, it is stated that a **vehicle_scheme** is a **scheme** whose **structure** provides the **intended_function** *provide transport*.

4.6.2 Modelling categorical physical requirements

The example design specification presented earlier contains several physical requirements. These relate to the recyclability, width, and mass of the product and the number of parts in it. Two of these requirements, those referring to recyclability and width, are categorical; that is, they *must* be satisfied. The other two, those referring to the mass of the product and the number of parts in it are preferences; they merely indicate that the mass and number of parts should be as small as possible.

In this section, we will consider how to incorporate categorical physical requirements into the Galileo representation of a design specification. The incorporation of preferences will be discussed in Section 4.6.3.

The requirement that the product be *recyclable* is a life-cycle requirement; it can be easily represented as a constraint, as shown in Line 9 of Fig. 4.41.

```
 5 domain vehicle_scheme
 6     =::= { S: scheme( S ) and
 7               provides_the_function( S.structure.intended_function,
 8                                      'provide', 'transport' ) and
 9               recyclable(S) and
10               ...
```

Fig. 4.41 Modelling the physical requirement `recyclable`

Of course, the meaning of the relation **recyclable** used here is company-specific and, as such, must be defined in the company-specific design knowledge-base. Suppose that

a scheme's being **recyclable** means that all the individual entity instances in the scheme should be made of recyclable materials; this meaning is defined in Fig. 4.42, which is taken from the Galileo module **raleigh_knowledge.gal** presented in Section C.1.

```
194 relation recyclable( scheme )
195     =::= { S: all entity(E): is_in_the_scheme(E,S) implies
196                     recyclable(E) }.

197 relation recyclable( entity )
198     =::= { E: recyclable_material( E.material ) }.

199 relation recyclable_material( raleigh_material )
200     =::= { cfrp, aluminium, steel }.
```

Fig. 4.42 Modelling the physical requirement `recyclable`

A **scheme** is **recyclable** if all of the entities in the scheme are **recyclable** (Lines 194–196). An **entity** is **recyclable** if its **material** is a **recyclable_material** (Lines 197–198). The recyclable materials are **cfrp, aluminium,** and **steel** (Lines 199–200). It will be recalled, from Fig. 4.32, that, normally, four materials are available to designers working for this company: **cfrp, titanium, aluminium,** and **steel**. For designers working on this project, however, **titanium** is not allowed, because it is not deemed recyclable.

The implementation of the relation **recyclable** in Fig. 4.42 is quite straightforward. However, this is not always the case with physical design requirements. Some physical requirements can be quite complex to implement. However, it is generally true that, for a particular company, physical requirements relate to a known set of critical product properties; consequently it would be worth the company's while to spend the effort to develop a representation for these requirements and incorporate them into the company-specific design knowledge-base. We will now consider the representation of a slightly more complex physical requirement: the product should have a width no greater than two metres.

```
 5 domain vehicle_scheme
 6     =::= { S: scheme( S ) and
 7              provides_the_function( S.structure.intended_function,
 8                                     'provide', 'transport' ) and
 9              recyclable(S) and
10              exists( S.width : real ) and
11              !S.width = width_of( S ) and
12              S.width =< 2.0 and
13              ...
```

Fig. 4.43 Modelling the requirement which limits `width`

The requirement implies several features that should be incorporated into the design specification. The requirement implies that there exists a **width** attribute for the scheme, that this attribute will have a numeric value, and that its value should not exceed two metres. In Fig. 4.43 the design specification fragment presented in Fig. 4.41 is extended to incorporate this requirement.

In Line 10 of Fig. 4.43, the existence in every **vehicle_scheme** of a field called **width**, of type **real**, is stipulated. The manner in which the width of the scheme is computed is specified in Line 11. The value of the **width** of the scheme will be computed using a function called **width_of**. In Line 11 the ! operator is applied to the **width** of the **vehicle_scheme** because, as and when the **width** of the **vehicle_scheme** changes when entities are introduced during scheme development, the Galileo filtering system will need to update the value of this attribute. This is done by the filtering system making a sequence of non-monotonic assumptions about the value of this attribute, essentially retracting its old value and asserting the updated value whenever necessary; this is the standard semantics of the ! operator in Galileo [3]. The actual requirement that the **width** of the scheme be no more than two metres is specified on Line 12.

```
244 function width_of( scheme ) -> real
245     =::= { S -> width_of( { E | exists entity(E):
246                     is_a_part_of( E, S ) } ) }.

247 function width_of( set of entity ) -> real
248     =::= { Es -> sum( { E.width | exists E in Es:
249                     not exists E2 in Es:
250                         overlaps( E2, E ) and
251                         E2.width > E1.width } ) }.
```

Fig. 4.44 Specifying how to compute the width_of a scheme

The function **width_of** used to estimate the width of a scheme is presented in Fig. 4.44. The **width_of** a scheme is estimated as the width of the set of entities which make up the scheme (Lines 244–246 of **raleigh_knowledge.gal**). The **width_of** a set of entities is estimated, in this case, as the sum of the widths of entities that are not overlapped by larger entities (Lines 247–251). A relation called **overlaps** is used to determine whether two entities overlap each other or not (Line 250).

```
186 relation overlaps( entity, entity )
187     =::= { (E1,E2): is_in_the_same_scheme_as( E1, E2 ) and
188                     !exists spatial_interface(S):
189                         is_in_the_same_scheme_as( S, E1 ) and
190                         S.entity_1 = E1.id and
191                         S.entity_2 = E2.id and
192                         S.relationship = above or
193                         S.relationship = under }.
```

Fig. 4.45 The meaning of the relation `overlaps`

The meaning of the relation **`overlaps`** is defined in Fig. 4.45. Two design entities are considered to overlap if there exists a **`spatial_interface`** between the entities which defines one entity as being either **`above`** or **`under`** the other. Obviously, more accurate estimates are possible; our purpose here is merely to illustrate the flavour of how complex physical requirements can be implemented.

4.6.3 Modelling design preferences

In the example design specification being discussed in this chapter there are two design preferences. These relate to the *mass* of the product being designed and the *number of parts* used in it; in each case, the preference is to have a minimal value. These preferences are incorporated into the design specification in Fig. 4.46.

```
 5 domain vehicle_scheme
 6     =::= { S: scheme( S ) and
 7              provides_the_function( S.structure.intended_function,
 8                                     'provide', 'transport' ) and
 9              recyclable(S) and
10              exists( S.width : real ) and
11              !S.width = width_of( S ) and
12              S.width =< 2.0 and
13              exists( S.mass  : preference ) and
14              S.mass.intent = minimal and
15              !S.mass.value  = mass_of( S ) and
16              exists( S.number_of_parts : preference ) and
17              S.number_of_parts.intent = minimal and
18              !S.number_of_parts.value  = number_of_parts_in( S ) }.
```

Fig. 4.46 Incorporating design preferences in the design specification model

In Lines 13–15 the design preference related to the scheme's **`mass`** is represented. Line 13 states that each scheme has a parameter called **`mass`** which is of type **`preference`**; Line 14 states that the **`intent`** of the preference is that the **`mass`** should be **`minimal`**

while Line 15 states that the **value** of the **mass** is computed using a function called **mass_of**. Similarly, Lines 16–18 define a preference specifying that the **number_of_parts** in the scheme should be minimal and that the actual number of parts is computed using a function called **number_of_parts_in**.

```
233 function mass_of( scheme ) -> real
234     =::= { S -> sum( { mass_of( E ) | exists entity(E):
235                        is_a_part_of( E, S ) } ) }.
```

Fig. 4.47 Computing the mass of a scheme

In Fig. 4.47 the details of how the **mass_of** of a scheme is computed is presented. In Lines 233–235 of **raleigh_knowledge.gal** a function called **mass_of** is defined which computes the **mass_of** of a **scheme**; it computes the mass of a scheme as the sum of the masses of the individual design entities which are part of the scheme. The meaning of the relation **is_a_part_of**, which is used here, was considered in Section 4.4.6. The mass of an entity is computed using the function defined in Lines 236–240 in Fig. 4.32.

The second preference in the design specification states that the number of parts used in the scheme should be minimal. In Fig. 4.48 the details of how the number of parts in a scheme is computed are presented: it is the cardinality of the set of design entities that are part of the particular scheme.

```
241 function number_of_parts_in( scheme ) -> integer
242     =::= { S -> cardinality( { E | exists entity(E):
243                        is_a_part_of( E, S ) } ) }.
```

Fig. 4.48 Computing the number of parts used in a scheme

In Section 4.47, where the generic concepts for comparing schemes were considered, the notion of one scheme dominating another was defined in terms of a relation called **improves_on**. It was stated there that this relation is project-specific. We are now in a position to consider how this relation would be specified for the vehicle design application; it is defined in Fig. 4.49.

```
19 relation has_better_mass_than( vehicle_scheme, vehicle_scheme )
20     =::= { (S1,S2): better_than( S1.mass, S2.mass ) }.

21 relation has_better_number_of_parts_than( vehicle_scheme, vehicle_scheme )
22     =::= { (S1,S2): better_than( S1.number_of_parts, S2.number_of_parts ) }.

23 relation improves_on( vehicle_scheme, vehicle_scheme )
24     =::= { (S1,S2): has_better_mass_than( S1, S2 ) or
25                     has_better_number_of_parts_than( S1, S2 ) }.
```

Fig. 4.49 Determining when one scheme improves on another

Apparently, one **vehicle_scheme, S1, improves_on** another, **S2**, if and only if **S1** either **has_better_mass_than** or **has_better_number_of_parts_than S2**. The relations **has_better_mass_than** and **has_better_number_of_parts_than** are both defined in terms of the generic relation **better_than**, between preference instantiations, that was defined in Section 4.4.7.

4.6.4 Modelling Design For X requirements

While the exploitation of Design For X (DFX) concepts during conceptual design is not a key concern in the research presented here, the incorporation of DFX concepts into the modelling approach presented here is quite straightforward. Indeed, the implementation of the categorical life-cycle requirement, related to the recyclability of the product being designed, has already been discussed. However, it is worth mentioning explicitly how the approach being presented here provides a basis for incorporating arbitrary DFX guidelines into the model of a scheme.

The modelling approach presented here is capable of modelling both design entity instances and their configuration, via interfaces. Consequently, repertoires of generic, company-specific, or project-specific DFX guidelines, which refer to design entities and/or their configurations, can be developed. For example, some DFX relationship between the attributes which define a design entity can be implemented as a constraint quantified over all instances of the relevant design entity. Similarly, a DFX relationship that should be satisfied by configurations of design entities can be readily implemented as a constraint which is quantified over combinations of instances of the relevant design entities and the interfaces between them. There is ample literature available that demonstrates how DFX requirements can be stated in Galileo [2, 6].

4.7 Scheme generation

Once a constraint-based model of the design specification has been developed, the designer (or team of designers) has the task of developing a set of alternative schemes for the required product. The constraint-based model of the design specification contains constraints relating to the following issues:

- constraints based on the functional requirements of the product as stated in the design specification;
- constraints based on the categorical physical requirements of the product as stated in the design specification;
- constraints based on the preferences regarding the values of particular design properties; and
- constraints relating to any DFX requirements which are either explicit in the design specification or implicit in the company's design policy.

From a design perspective, the designer's task is to develop a number of alternative schemes that satisfy the design specification. However, from a constraint processing point of view, their task is to search for a set of schemes that satisfy the constraint-based design specification representation, each scheme resulting from making different choices among the various means for providing the required functionality. This process has already been discussed in Chapter 3.

The selection of means for providing the required functionality is subject to the various constraints in the design specification. For example, if a designer selects a means to embody a particular function that is not capable of providing the required functionality, this violates the constraint shown in Fig. 4.14.

As the designer selects a means for providing a particular function, further constraints are introduced into the scheme being developed, since each means has an associated set of constraints defining its properties. In this way the constraint-based model of the design comprises constraints representing the requirements stated in the design specification as well as constraints on functionality, scheme structure, and life-cycle issues.

The interaction between a designer and a constraint-based model of the scheme being developed (as well as the models of whatever schemes have already been developed for the product being designed) are governed by the constraint-filtering behaviour of the Galileo run-time system. This will be illustrated in Chapter 5.

In the remainder of this section, we will consider some factors which govern the behaviour that will be exhibited by the constraint-filtering system. Recall that, in Section 4.4.2, we stated that a designer is concerned with producing *embodiments for* intended functions by *choosing,* from among the *known means,* those which will provide the required functionality. Recall also that, in Section 4.5.1, the collection of known means available for use by a company's designers is defined (see Fig. 4.28) as a scalar domain, called **`known_means`**, which contains a list of symbolic names for these

known means. Further, recall that, in Section 4.4.3, we saw that each **means**, whether it be a principle or a design entity, is represented as a structure domain.

In selecting a value for the **chosen_means** field of an **embodiment**, the designer is saying that there should exist an instance of a **means** which is in some way identified by the chosen **known_means**. The particular **means** that should exist should be determinable from the **known_means** which has been selected by the designer.

We now point out a convention that should be used by knowledge engineers when selecting symbolic names to appear in the scalar domain **known_means** and when selecting domain names for the various specializations of the domain **means,** which represent the different principles and design entities that are available for use by designers.

Each **known_means** that a designer may select should have a corresponding **means**. The **known_means** should always be the name of its associated **means** prefixed with either the substring '**a_**' or the substring '**an_**'. The company-specific design knowledge-base **raleigh_knowledge.gal** presented in Section C.1 of Appendix C satisfies this knowledge engineering convention.

```
88 all embodiment(E): E.chosen_means = a_bicycle implies
89     !exists bicycle( B ):
90         must_be_directly_used_for( B, E.intended_function ) and
91         causes( E, B.e1 ) and
92         causes( E, B.e2 ) and
93         causes( E, B.e3 ) and
94         causes( E, B.e4 ) and
95         causes( E, B.e5 ).
```

Fig. 4.50 Modelling the use of a design principle for an embodiment

When a designer selects a particular known means to provide the intended function for an embodiment, some processing is needed to ensure that the effects of selecting the known means are propagated throughout the expanding constraint network which represents the evolving model of the design. The knowledge engineering convention described above should be followed because the actual introduction into the design (in fact, into the constraint network which represents the design) of parameters representing principles and means is triggered by constraints in the company-specific knowledge-base which rely on this convention. In other words, constraints relying on this convention are what actually cause the existence, and consequently the arrival onto the designer's user interface, of constraint network parameters representing the various principles and means she has selected. For example, consider the constraint shown in Fig. 4.50, which is taken from **raleigh_knowledge.gal** in Section C.1. This shows the effect of selecting the principle of **a_bicycle** as the **known_means** for realizing an **embodiment**. According to this constraint, when the designer decides to use **a_bicycle** as the **chosen_means** for an **embodiment E**, it must be true that there exists some

instance, **B**, of the principle **bicycle** which **must_be_directly_used_for** the **intended_function** of **E** (Lines 88–90). If there already exists some instance of the principle, and if this instance is free to be used for the intended function of **E**, then it will be so used. However, since this constraint applies the ! operator to the **exists** quantifier, the effect of this constraint is that an instance of the principle **bicycle** will be created if one does not already exist or if all pre-existing instances of the principle are being used in other embodiments and are, therefore, unavailable for use in embodiment **E**. A further effect of this constraint is that it notes that it was the use of the principle to embody **E** which causes embodiments **B.e1, B.e2, B.e3, B.e4** and **B.e5** – these are specific instances of the embodiments specified in the definition of the principle **bicycle** (see Fig. 4.31).

The relation **must_be_directly_used_for** invoked in the above constraint is a generic relation defined in Section B.1. For convenience, it is quoted in Fig. 4.51, where we can see that if a **means must_be_directly_used_for** a **func** they must both relate to the same scheme (Line 121) and the identifier of the **func** must be in the **funcs_provided** by the **means** (Line 122). Note that the use of the ! operator in this relation definition (Line 122) means that, if the identifier of the **func** is not already in the **funcs_provided** by the means, it will be inserted into the set.

```
120 relation must_be_directly_used_for( means, func )
121     =::= { (M,F): is_in_the_same_scheme_as( M, F ) and
122                   F.id in !M.funcs_provided }.
```

Fig. 4.51 The meaning of the relation `must_be_directly_used_for`

Recall that it was said above (when discussing Fig. 4.50) that, if all pre-existing instances of the **bicycle** principle are being used in other embodiments, they would, therefore, be unavailable for use in embodiment **E** and a new instance of the principle would be created. We will now consider which constraints would cause this. Refer to the constraint shown in Lines 39–40 of Fig. 4.18. This stated that, for each means **M** (recall that a principle is a means), it must be true that the set of **funcs_provided** by **M** **is_a_possible_behaviour_of** of **M**. The pre-existing instances of the **bicycle** principle which are being used in other embodiments would violate this constraint because, as can be seen in Fig. 4.29, a bicycle can provide only one instance of the function provide transport. The constraint-filtering system maintains a quite sophisticated set of dependency records and the violation of the constraint in Fig. 4.18 would cause the system to undo whatever action it had performed which caused the violation; this means that it would undo the insertion, caused by the relation in Fig. 4.51, of the most recent **func_id** into the set of **funcs_provided** by the violating instance of the bicycle principle. When all pre-existing instances of the principle had been exhausted, this would trigger the ! operator used in Line 89 Fig. 4.50 to create a new instance of the principle.

In Lines 91–95 of Fig. 4.50, the relation **causes** is invoked to state that the embodiments that have been introduced due to the use of the principle **bicycle** are

caused by the **embodiment** whose **chosen_means** has been selected to be **a bicycle**. The meaning of the **causes** relation is defined in **generic_concepts.gal** (in Section B.1) but is quoted in Fig. 4.52. According to this definition, if an embodiment **P causes** another embodiment **E**, then, as well as both embodiments being in the same scheme, **E** inherits all the **reasons** for **P** as well as having the identity number of the function instance in **P** itself as one of its **reasons**.

```
58 relation causes( embodiment, embodiment )
59     =::= { (P,E): is_in_the_same_scheme_as( P, E ) and
60                   E.reasons = {P.intended_func.id} union P.reasons }.
```

Fig. 4.52 The meaning of the relation causes

We have just seen, in Fig. 4.50, a constraint which specifies some consequences of the user selecting a principle as the **chosen_means** for an embodiment. We will now consider what is implied by the designer choosing a design *entity* as the **chosen_means** for an embodiment. The consequences attached to using a design entity to embody a function are similar to those caused by using a design principle. The essential difference is that additional embodiments are introduced (which means that further functionality must be provided) when a design principle is used whereas, when a design entity is used, no further embodiments are introduced and no more functionality must be provided (at least in this part of the functional decomposition of the product).

The effect of using the **chassis** entity in a scheme is illustrated in Fig. 4.53. The constraint in this figure is taken from **raleigh_knowledge.gal** in Section C.1. It can be seen from this figure that, whenever a **chassis** is used as the **chosen_means** for an embodiment, there must exist an instance of the chassis design entity which **must_be_directly_used_for** the **intended_function** of the **embodiment**. Since the ! operator is applied to the **exists** quantifier in this constraint (Line 100), an instance of the **chassis** design entity will be created, if necessary, to satisfy this constraint. The relation **must_be_directly_used_for** has already been discussed.

```
 99 all embodiment(E): E.chosen_means = a_chassis implies
100     !exists chassis( C ):
101         must_be_directly_used_for( C, E.intended_function ).
```

Fig. 4.53 Embodying a function using a design entity

We have just seen that, as a designer chooses **known_means** for embodying the **intended_functions** of **embodiments**, new instances of design entities may be created. For example, in Fig. 4.53 the introduction of an instance of the **chassis** design entity is required if the designer selects **a_chassis** as the **chosen_means** for an embodiment. This can only be done, of course, if the intended function of the embodiment is *provide support* because, as we have seen in Fig. 4.29, this is the only

function that can be provided by a **chassis**. Indeed, we can see in Fig. 4.29 that a **chassis** can provide only one instance of this function so, if this functionality is required in two different embodiments within a design, two separate instances of the **chassis** design entity would be needed.

However, there are situations when one instance of a design entity can be used to embody more than one function instance. For example, consider the known means **a_molded_frame**. We can see, in Lines 150–152 of Fig. 4.29, that this known means can provide two functions simultaneously: *provide support* and *support passenger*. If a designer selected this known means as the **chosen_means** to embody an instance of the function *provide support*, an instance of **molded_frame** design entity would be introduced, if none already existed; the constraint which would cause this is shown in Fig. 4.54.

```
114 all embodiment(E): E.chosen_means = a_molded_frame implies
115     !exists molded_frame( M ):
116         must_be_directly_used_for( M, E.intended_function ).
```

Fig. 4.54 Embodying a function using a_molded_frame

If the designer later selected the same **known_means** to embody an instance of the function *support passenger,* no new instance of the **molded_frame** design entity would be introduced. This is because both of these two function instances can be provided by the existing instance of the **molded_frame** design entity. In other words, the constraint in Lines 39–40 of Fig. 4.18 which, as we saw above would be violated if the designer tried to use one instance of the bicycle principle to embody two instances of the function *provide transport*, would not be violated if one instance of the molded frame design entity were used to embody an instance of the function *support passenger* as well as an instance of the function *provide support*. This is because provision of two function instances, one of each of these two functions **is_a_possible_behaviour_of** an instance of the molded frame design entity. In the definition of the relation **is_a_possible_behaviour_of** (Lines 82–85 in **generic_concepts.gal** in Section B.1), it can be seen that this relation is defined in terms of the relation **can_simultaneously_provide** and, as can be seen in Fig. 4.29, a molded frame can simultaneously provide an instance of the function *provide transport* and one of the function *support passenger*.

The use of a design entity instance to provide more than one function instance is called *entity sharing*. The fact that the implementation of conceptual design reasoning described here can support entity sharing means that the collection of entity instances that are configured to provide the required functionality of a product is minimal. Entity sharing of the type just discussed was used in the scheme shown in Fig. 3.20.

4.8 Summary

One of the most difficult aspects of providing computer-based support for conceptual engineering design is the modelling of products and specifications at various levels of abstraction. This chapter presented an approach to using constraints as a modelling paradigm for conceptual design.

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Chapter 5

Illustration and Validation

In this chapter the approach to supporting conceptual design that has been proposed in this book is demonstrated on two design problems. First, in Section 5.1, a simple conceptual design problem is presented. The development of a set of alternative schemes for this problem is explained through the use of a series of interactions with a Galileo constraint filtering system. The various characteristics of the approach presented in this book are explained in detail with respect to this design problem. Second, the conceptual design of an industrial product is presented in Section 5.2. This section describes how the approach proposed in this book could be applied to support the design of a real-world product. The case study design problem was provided by an electronic component manufacturer based in Cork called Bourns Electronics Ireland.

5.1 An illustrative example

In this section an example conceptual design problem is presented and a number of schemes are generated for it. The design problem considered is based on vehicle design. The presentation of this design problem comprises three phases. First, in Section 5.1.1, a simple design specification will be presented and modelled using the constraint-based approach presented in Chapter 4. Second, in Section 5.1.2, an appropriate constraint-based design knowledge-base will be presented using the implementation approach presented in Chapter 4. Finally, in Section 5.1.3, the development of two schemes based on the design specification will be presented. The use of constraint filtering in the process of developing these schemes will be described using a number of screen-shots from a constraint filtering system that would be capable of reasoning about the extended version of the Galileo language recommended in this book.

A full Galileo implementation of the design specification and the design knowledge-base used in this section are presented in Appendix C. The various project-specific concepts that are used to develop schemes for the vehicle design specification are based upon the generic design concepts presented in Appendix B.

5.1.1 An example design specification

The design specification to be considered here is as follows:

> Design a product that satisfies the following requirements:
>
> - the product provides the function *provide transport*;
> - the product is fully *recyclable*;
> - the product has a *width not greater than 2 m*;
> - the product has *minimal mass*,
> - the product comprises a *minimal number of parts*.

Using the techniques presented in Chapter 4, a constraint-based implementation of the design specification can be easily developed. Indeed, the modelling of this design specification has already been discussed in depth in Section 4.6. A full implementation of the design specification is presented in Section C.2 of Appendix C, in a Galileo module called **`vehicle_spec.gal`**.

This specification module imports a library containing a company-specific design knowledge-base (Line 2), a library of generic concepts (Line 3) and a library of concepts for comparing schemes using Pareto optimality (Line 4). The contents of the library of generic concepts has already been discussed (Chapter 4). The contents of the library containing company-specific design knowledge will be discussed later; here, we will focus on the contents of the vehicle specification module.

The notion of a vehicle scheme is defined in Lines 5–18. Line 6 specifies that a vehicle scheme must be a **`scheme`**, which is a generic concept imported in Line 3 from a library. Lines 7–18 specify that, in addition to possessing the characteristics of a generic scheme, a vehicle scheme must satisfy all the requirements defined in the design specification.

The functional property required by the design specification is modelled in Lines 7–8 using a relation imported from **`generic_concepts.gal`**. The requirement that the product be recyclable is modelled on Line 9. The physical requirement relating to the width of the product is modelled on Lines 10–12. The design preferences relating to the mass and number of parts of the product are modelled on Lines 13–15 and Lines 16-18, respectively, using functions imported from **`raleigh_knowledge.gal`**. The various relations used to compare alternative schemes, which are specific to this particular design specification, are defined on Lines 19–25; these relations are used to 'plug-in' a definition for the relation **`improves_on`**, a relation expected by the generic system of libraries.

The constraint-based model presented in Section C.2 has been generated manually. However, the development of a computer tool for transforming the requirements

defined in the design specification into an equivalent constraint-based model should not be a difficult task. However, these issues are beyond the scope of the research presented in this book.

Once a constraint-based model of the design specification has been developed, a designer (or a team of designers) can begin to develop a set of alternative schemes by interacting with this model and with an appropriate design knowledge-base, using a constraint filtering system. However, before that process is discussed, the contents of an example constraint-based design knowledge-base will be discussed in Section 5.1.2.

5.1.2 An example design knowledge-base

In the scenario being discussed here, the knowledge-base that is being used contains a design principle based on the notion of a bicycle and a collection of design entities such as a wheel assembly, a pedal assembly, a saddle, and handlebars. In Section C.1 of Appendix C, a constraint-based implementation of a suitable design knowledge-base is presented in a Galileo module called **`raleigh_knowledge.gal`**.

A number of means are available in this design knowledge-base. These means are listed in a domain called **`known_means`**, defined on Lines 41–46. For example, it can be seen that there is a means known as **`a_bicycle`**, another known as **`a_skateboard`**, and a further one known as **`a_wheel_assembly`**.

The techniques used to implement the various design concepts contained in the Galileo module **`raleigh_knowledge.gal`** were discussed in Section 4.5. Therefore, the implementation of this module will not be discussed any further, apart from the fact that, in the next section, particular aspects of the implementation will be highlighted when explaining the interactions, between the designer and the filtering system, that result in the development of a set of schemes.

5.1.3 Interactive scheme development

The filtering system being referred to in this section is based on previously published research on constraint-based reasoning for supporting Concurrent Engineering [1, 2]. However, the research presented in this book takes a different perspective on the role that constraint filtering can play in designer support. In this research, constraint filtering is used as a basis for providing interactive support to the human designer throughout the *entire* process of scheme development. This not only includes reasoning about the physical aspects of the scheme, but includes the design synthesis activities associated with developing a configuration of design entities from an initial statement of the required functionality that is to be provided by the product being designed.

The constraint filtering system being discussed here is assumed to be capable of reasoning about the extended version of the Galileo language that was discussed in Section 4.2. In addition, it is assumed that there are a number of different designers using this system. The meta-level language associated with this filtering system contains a number of pre-defined meta-level predicates such as **`#designer`**,

`#parameter`, `#was_introduced_by`, and `#is_visible_to`. These predicates can be used to write a constraint which states that designers can only see those parameters which they introduced. This constraint can be implemented as follows:

```
all #designer(D), #parameter(P):
    #was_introduced_by(P,D) equiv
        #is_visible_to(P,D).
```

In the following discussion it is assumed that there are two different designers using the system, `designer_1` and `designer_2`. In addition, it is assumed that the above meta-level constraint is implicitly defined in the filtering system. Thus, when a screen-shot is presented, the name of the designer associated with that screen-shot will appear on the title of the interface that is depicted. In addition, the screen-shot will only contain parameters for which the named designer is responsible.

The interface depicted in the screen-shots is not intended to reflect an ideal interface with which a human designer would interact. Rather, it is intended as a means for explaining how the approach proposed in this book could be used to develop a set of alternative schemes. The development of an appropriate interface which a real designer would use is beyond the scope of this research.

Before considering these screen-shots in detail, some remarks should be made. The screen is divided into three areas. The title area, at the top of the screen, shows the name of the adviser system and the identity of the designer currently interacting with it – in Fig. 5.1 the user is `designer_1`. The middle of the screen shows parameters that are visible to the user. The bottom, command area, of the screen shows the commands that have been entered by the user and any responses the system has made. Finally, note that the screen-shot shown in a figure shows the state of the screen *after* all the user's commands have been executed by the system.

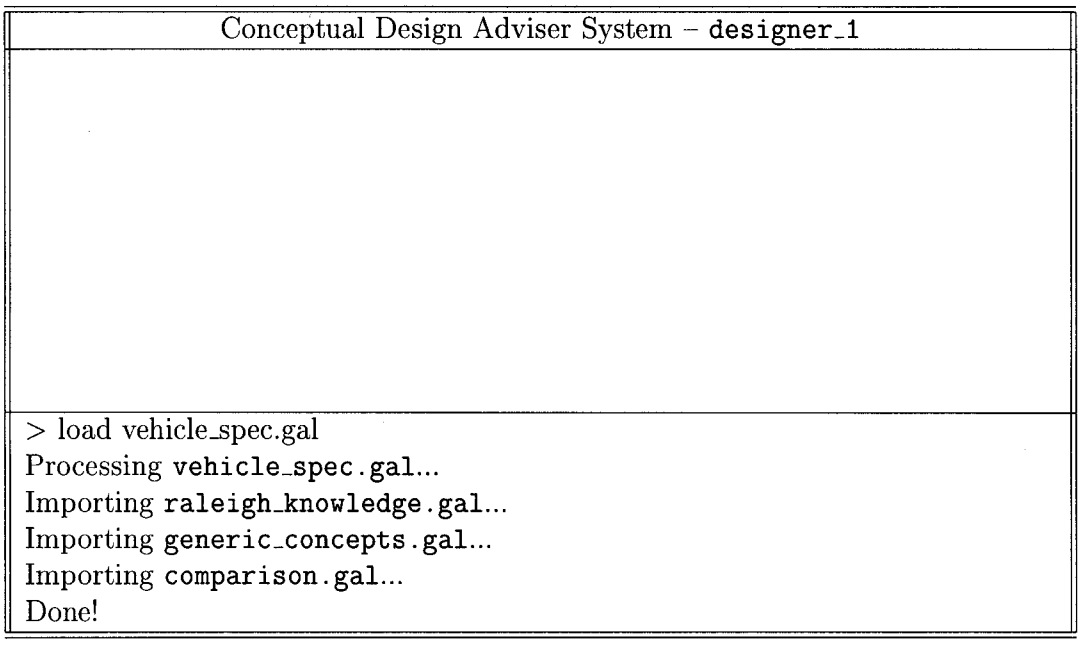

Fig. 5.1 Loading the design specification model into the filtering system

In Fig. 5.1 the Galileo module called **vehicle_spec.gal**, defined in Section C.2, was loaded into the filtering system interpreter. This was done using the filtering system command load. Since **vehicle_spec.gal** imports the Galileo modules **raleigh_knowledge.gal**, **generic_concepts.gal**, and **comparison.gal**, these modules are also loaded. These modules must be loaded into the filtering system before the designer can begin to develop schemes for the product described in the design specification. The middle portion of the screen is empty because the user has not yet introduced any parameters.

Figure 5.2 shows the state of the user interface after **designer_1** has invoked three commands. First, an instance of the Galileo structured domain, **vehicle_scheme**, was introduced by the designer. This instance is being called **scheme_1**. Since **designer_1** introduced this parameter, **scheme_1** appears on the filtering system interface.

Then, the designer used the constraint filtering system command **expand** to examine the various fields associated with the parameter **scheme_1**. It can be seen that **scheme_1** is a structured parameter that comprises five fields: a scalar field called **scheme_name**, a structured field called **structure**, a scalar field called **width**, a structured field called **mass**, and a structured field called **number_of_parts**[1]. These fields exist due to the domain definition of **vehicle_scheme** defined in Lines 5–18 of **vehicle_spec.gal** in Section C.2. There, a **vehicle_scheme** was defined to be a generic scheme (which has two fields, **scheme_name** and **structure** – see Lines 46–48 of Section B.1 of Appendix B) with three additional fields, **width**, **mass**, and **number_of_parts**. Finally, in Fig. 5.2 the designer asserted a value for the **scheme_name** field of the parameter **scheme_1**; the value asserted was **'my_vehicle'**.

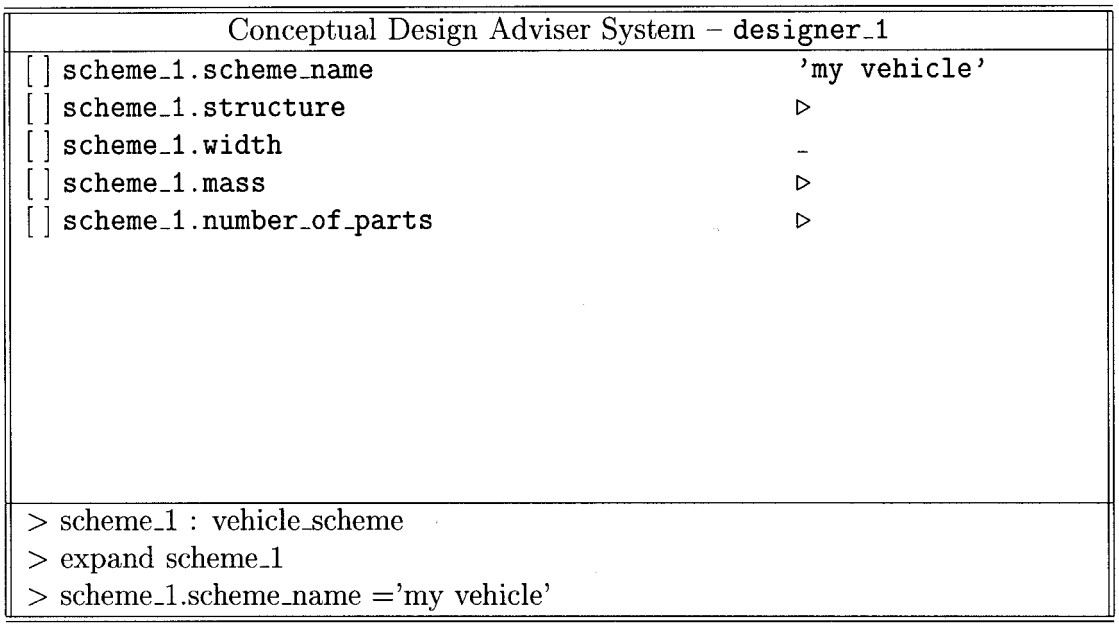

Fig. 5.2 Introducing a scheme instance called scheme_1

[1] Structured fields are indicated on the screen by the presence of a ▷, which is intended to 'invite' the user to examine the field further by expanding it; the value of a scalar field whose value is known is shown; for a scalar field whose value is not yet known a '_' is shown.

In Fig. 5.3 the initial state of `scheme_1` was examined by `designer_1`. In order to get a full picture of the design specification, the `structure` field (along with its sub-field `intended_function`), the `mass` field, and the `number_of_parts` field were all expanded.

It can be seen from Fig. 5.3 that the `intended_function` of the `structure` of `scheme_1` is to `provide transport`. This function was specified in the definition of the `vehicle_scheme` (Lines 7–8 of Section C.2). This function has an identifier `(id)` of 0 and the empty set as its set of `reasons`. This reflects the fact that this function is the first function to be introduced into the scheme; in other words, no other function was responsible for this function being introduced into the scheme. The assignment of the 0 identifier and the empty set of reasons is done by the constraint, quantified over all schemes, in Lines 49–50 of Section B.1. This constraint uses the relation defined in Lines 116–119 of Section B.1, which actually makes the assignments.

It can also be seen from this figure that the `mass` and `number_of_parts` associated with `scheme_1` are preferences. It can be seen that, in both cases, the `intent` is that these should have `minimal` values; this comes from Lines 14 and 17 of the specification in Section C.2.

Conceptual Design Adviser System – `designer_1`	
[ ] `scheme_1.scheme_name`	*'my vehicle'*
[ ] `scheme_1.structure.intended_function.verb`	`provide`
[ ] `scheme_1.structure.intended_function.noun`	`transport`
[ ] `scheme_1.structure.intended_function.id`	0
[ ] `scheme_1.structure.chosen_means`	-
[ ] `scheme_1.structure.reasons`	{}
[ ] `scheme_1.width`	-
[ ] `scheme_1.mass.value`	-
[ ] `scheme_1.mass.intent`	`minimal`
[ ] `scheme_1.number_of_parts.value`	-
[ ] `scheme_1.number_of_parts.intent`	`minimal`
> expand scheme_1.structure	
> expand scheme_1.structure.intended_function	
> expand scheme_1.mass	
> expand scheme_1.number_of_parts	

Fig. 5.3 Examining the initial state of the scheme

In Fig. 5.4 the designer has hidden the details of the **mass** and **number_of_parts** fields of **scheme_1** using the filtering system command **contract**. The designer then asks for the set of consistent means that could be used to provide the **intended_function** of the **structure** of **scheme_1**. The designer is told that the current set of consistent means for this function comprises **a_bicycle** and **a_skateboard**. This response is due to the constraint defined on Lines 7–8 in Section B.1, which specifies that the means chosen for any **embodiment** (remember the **structure** of a scheme is an **embodiment**) must be able to provide the **intended_function** of that **embodiment**. The relation used in this constraint is defined in Lines 53–54 of Section B.1; it invokes the relation shown in Lines 132–164 of Section C.1, an inspection of which shows that two **known_means** can provide the function 'provide transport'.

Conceptual Design Adviser System – designer_1

[ ] scheme_1.scheme_name	*'my vehicle'*
[ ] scheme_1.structure.intended_function.verb	provide
[ ] scheme_1.structure.intended_function.noun	transport
[ ] scheme_1.structure.intended_function.id	0
[ ] scheme_1.structure.chosen_means	-
[ ] scheme_1.structure.reasons	{}
[ ] scheme_1.width	-
[ ] scheme_1.mass	▷
[ ] scheme_1.number_of_parts	▷

> contract scheme_1.mass
> contract scheme_1.number_of_parts
> advise on scheme_1.structure.chosen_means
Advice: scheme_1.structure.chosen_means must be in the set:
{a_bicycle, a_skateboard}

Fig. 5.4 Querying for a valid means for providing the function required by the design specification

Figure 5.5 depicts the scenario where the designer selects **a_bicycle** as the **chosen_means** for providing the **intended_function** of the **structure** of **scheme_1**. The effect of this is that a new parameter called **bicycle_1** is automatically introduced. The parameter **bicycle_1** is an instance of the structured domain **bicycle**. The introduction of this new parameter is due to the constraint defined on Lines 88–95 of Section C.1. This embodiment is illustrated in Fig. 3.15.

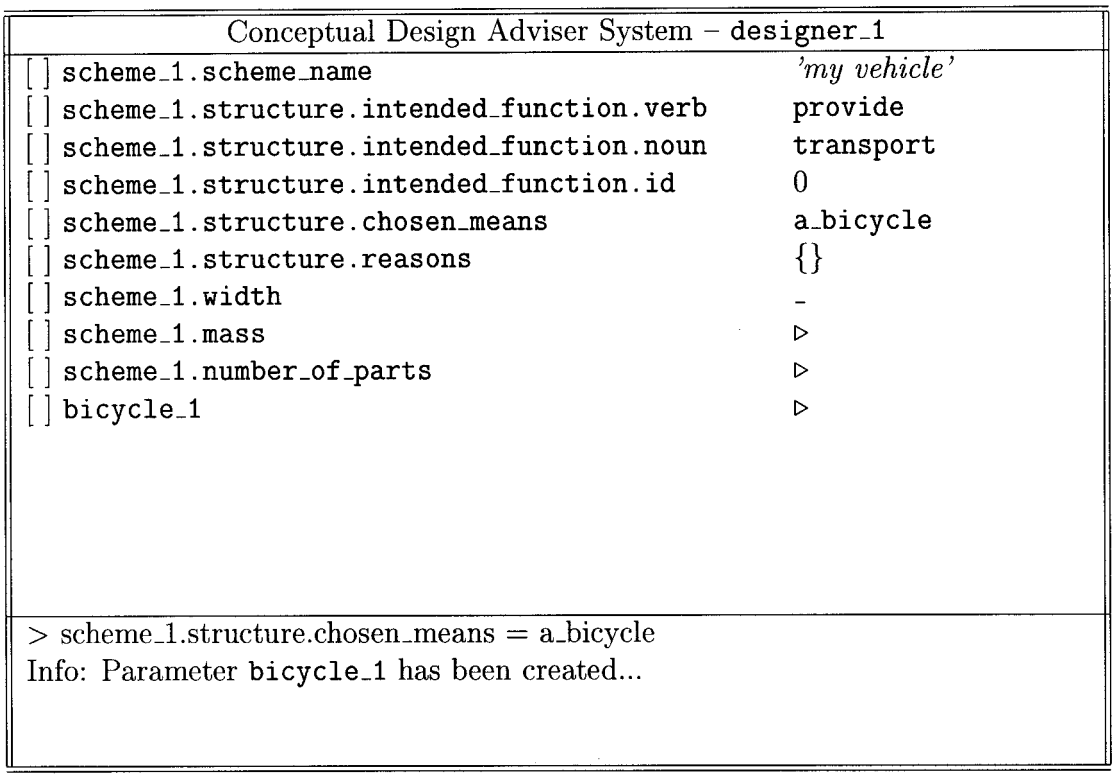

Fig. 5.5 Using the principle of a bicycle in scheme_1 to provide the function 'provide transport'

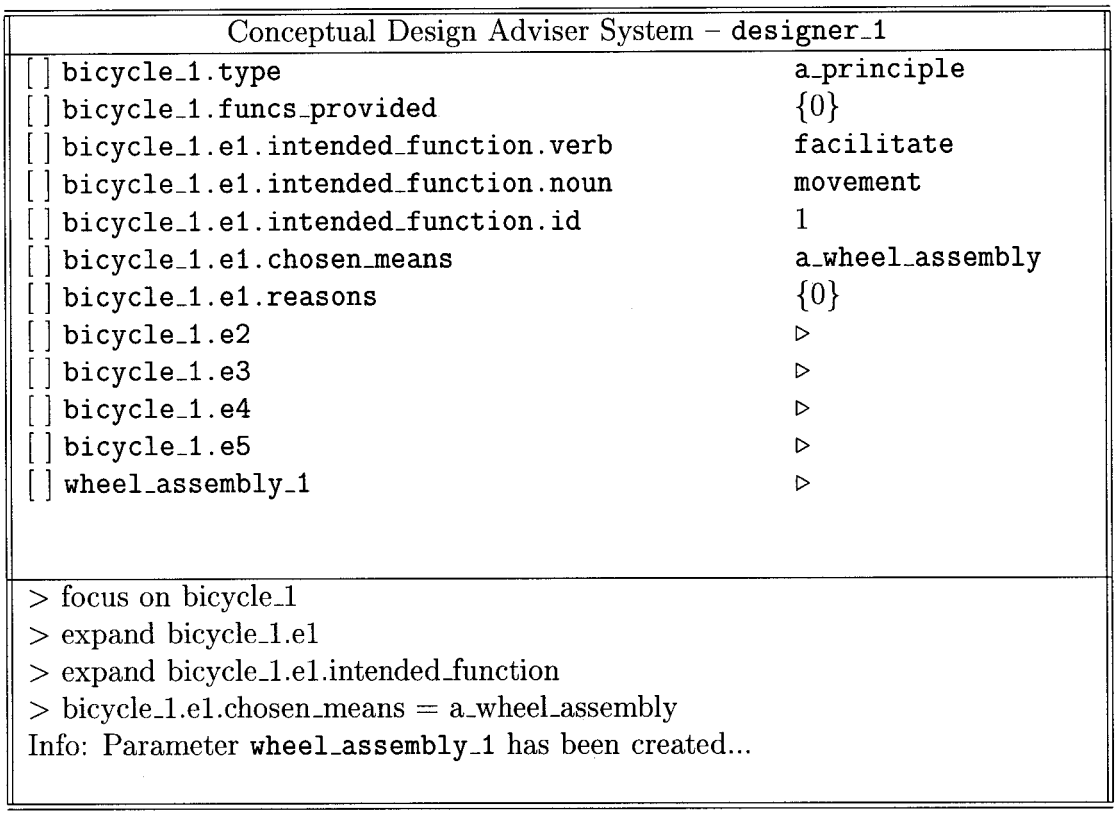

Fig. 5.6 Incorporating a `wheel_assembly` entity to provide the function '`facilitate movement`'

In Fig. 5.6 the designer begins to explore the parameter **`bicycle_1`**. The designer uses the filtering system command '**`focus on`**' to clear the filtering system interface of all parameters except for the parameter of interest – in this case the **`bicycle_1`** parameter. Since **`bicycle_1`** is a structured parameter, the designer can use the **`expand`** command to explore its fields. It can be seen that **`bicycle_1`** is a design principle and that the **`funcs_provided`** by this principle is a singleton set containing the value 0. This means that **`bicycle_1`** provides one function, namely the function whose **`id`** is 0 – this was seen in Fig. 5.3 to be the function required in the design specification.

It can also be seen from Fig. 5.6 that **`bicycle_1`** contains a number of other structured fields, namely **`e1`**, **`e2`**, **`e3`**, **`e4`**, and **`e5`**. These fields represent further embodiments that the designer must make in order to properly incorporate the **`bicycle_1`** design principle into **`scheme_1`**.

In Fig. 5.6 the designer explores the parameter **`bicycle_1.e1`** by expanding it. It can be seen that the function to be embodied is **`facilitate movement`**. This function has an **`id`** of 1 since this is the next unique function identifier for this scheme.

The constraint responsible for determining this value is in Lines 21–22 of Section B.1. This constraint calls the relation defined in Lines 77–79 of Section B.1 which, in turn, calls the relation defined in Lines 66–70 of Section B.1. The meaning of this constraint

and these relations is that a function identifier is only valid if it is a positive integer and if only one function within a scheme has that integer as an identifier. In determining an identifier for a newly introduced function, the system merely chooses the next positive integer that has not already been used.

The **reasons** for the embodiment **bicycle_1.e1** is the singleton set containing the function identifier 0; this represents the fact that the function whose identifier is 0 is a reason for this embodiment.

Finally, in Fig. 5.6, the designer chooses **a_wheel_assembly** as the **chosen_means** for this embodiment. This causes the automatic introduction of another new parameter, **wheel_assembly_1**, into the scheme, because it triggered the constraint in Lines 129–131 of Section C.1. This embodiment is illustrated in Fig. 3.16.

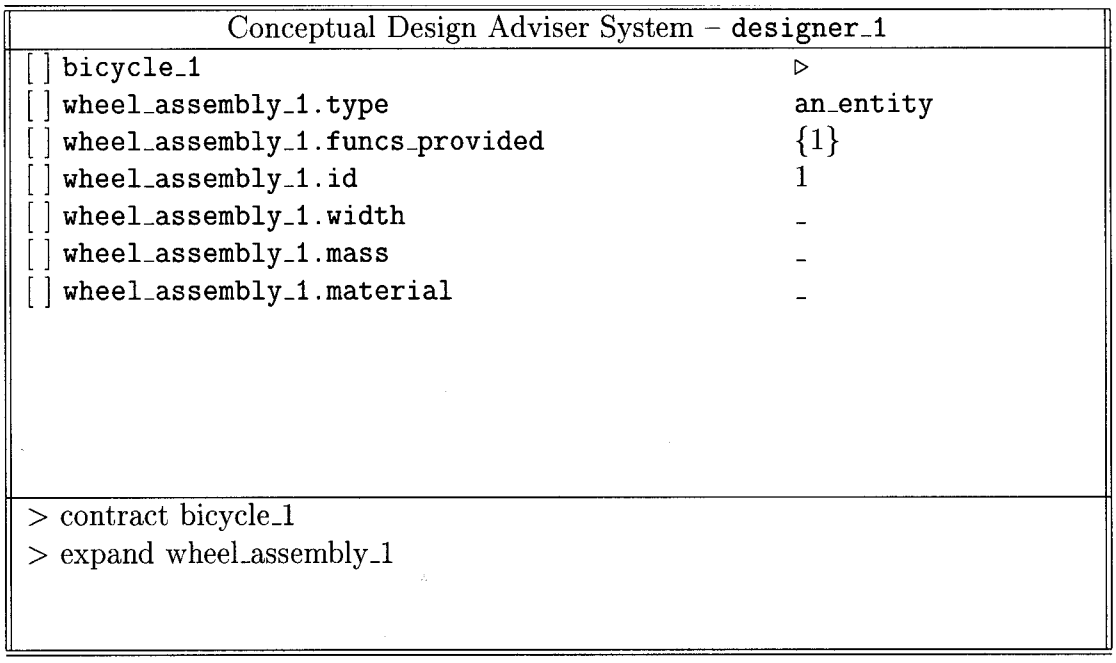

Fig. 5.7 Examining the wheel_assembly

In Fig. 5.7 the designer explores the **wheel_assembly_1** parameter. On expanding this parameter, the designer sees that it comprises several fields. The **type** field indicates that this new parameter represents a design entity. The **funcs_provided** by this entity is a singleton set which refers to a function whose identifier is 1, namely the function 'facilitate movement' seen in Fig. 5.6. The **id** field of **wheel_assembly_1** indicates that it is the first design entity to be incorporated into this scheme. This value is computed from the constraint defined on Lines 13–14 of Section B.1. A number of other fields are illustrated in Fig. 5.7. These are the fields **width**, **mass**, and **material** associated with **wheel_assembly_1**. As the designer develops the scheme, choices may be made about the values that will be associated with these parameters.

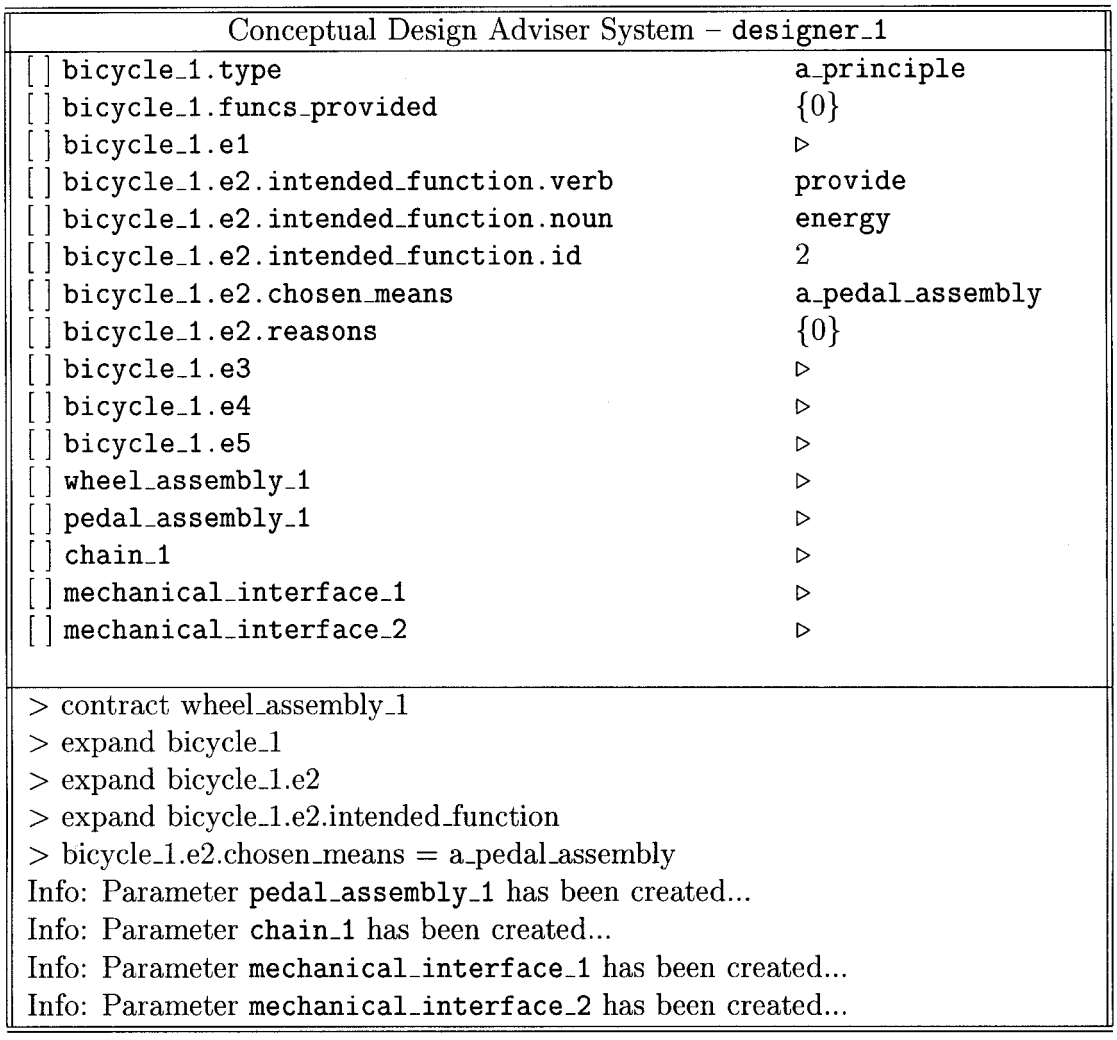

Fig. 5.8 Using a pedal assembly to provide the function 'provide energy'

In Fig. 5.8 the designer selects **a_pedal_assembly** as the **chosen_means** to embody the function **provide energy**. This causes a new parameter, **pedal_assembly_1**, to be introduced. Although it is not apparent in Fig. 5.8, the parameter **pedal_assembly_1** is a design entity. If the designer were to expand **pedal_assembly_1** we would see that its **id** field contains the value 2, reflecting the fact that it is the second design entity to be incorporated into the scheme.

Once the designer selects **a_pedal_assembly** as the **chosen_means** to embody the function **provide energy** a number of other parameters are also immediately introduced into the scheme. These are **chain_1**, **mechanical_interface_1**, and **mechanical_interface_2**. These parameters exist in order to fulfil the context relation **drives** that must exist between the embodiments for the functions **provide power** and **facilitate movement**, as specified in the principle for a bicycle. The need for this context relation is stated in Line 24 of Section C.1; its meaning is specified in Lines 173-185 of Section C.1, which is responsible for the introduction of the

additional parameters in Fig. 5.8. The parameter **chain_1** exists in order to satisfy the context relation that the embodiment for the function **provide power** drives the embodiment for the function **facilitate movement**. According to the relation defined on Lines 173–185 of Section C.1, there must be a **mechanical_interface** between **pedal_assembly_1** and **chain_1** and another between **wheel_assembly_1** and **chain_1**. This will be explored in further detail in Fig. 5.9. This scenario corresponds to that shown in Fig. 3.17.

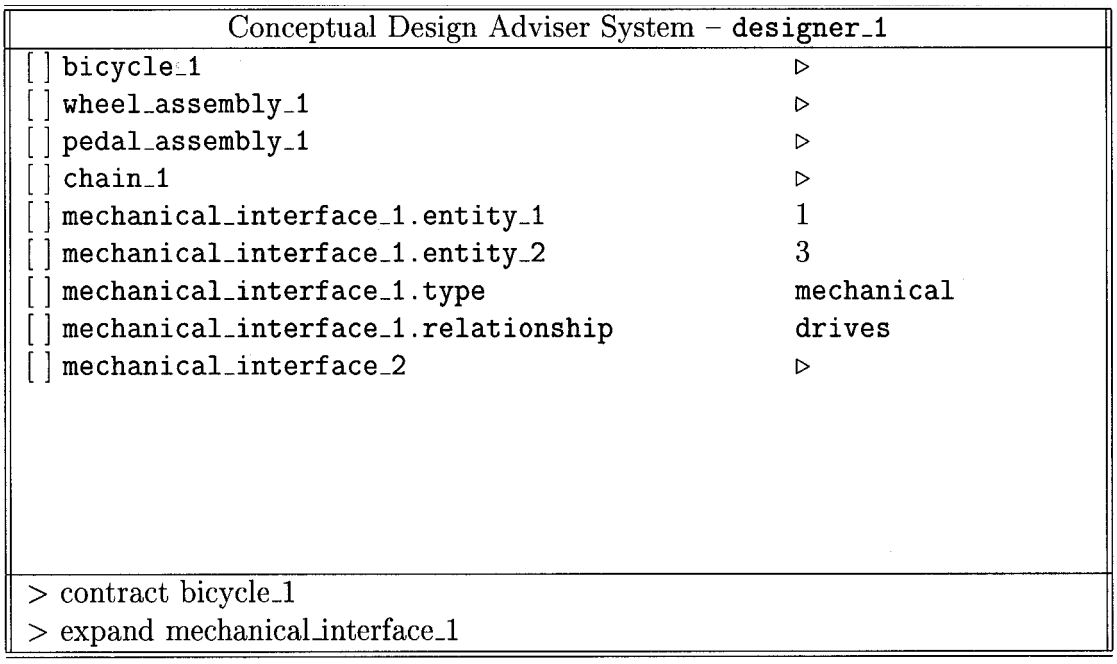

Fig. 5.9 Embodying the drives context relation

The context relation **drives** requires a **chain** design entity acting between the design entities **wheel_assembly_1** and **pedal_assembly_1**. In Fig. 5.9 **mechanical_interface_1** is being explored. It can be seen that **mechanical_interface_1** implements a **drives** relationship between the entities whose identifiers are 1 and 3, namely **wheel_assembly_1** and **chain_1**, respectively (the parameter chain 1 is the third design entity to be incorporated into this scheme; thus, if we were to expand it, we would see that its **id** field contains the value 3).

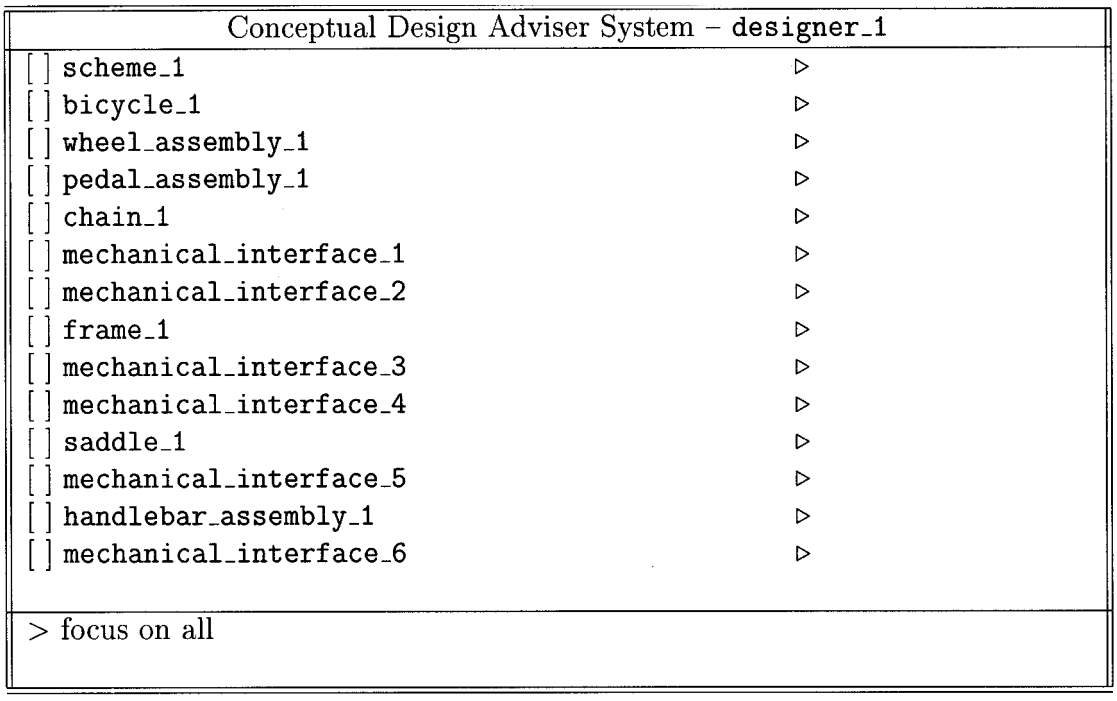

Fig. 5.10 The state of `scheme_1` once means have been selected for each function

In Fig. 5.10 the state of **`scheme_1`** is presented after several more decisions have been made by the designer, namely after means have been selected to provide each function that is associated with the scheme. This scheme comprises a number of design entities, interfaces and principles. The scheme was based on the principle of a bicycle. The final scheme comprises six design entities and six interfaces. The bicycle principle introduced five functions into the scheme: **`facilitate movement`**, **`provide energy`**, **`provide support`**, **`support passenger`**, and **`change direction`**. The introduction of these functions by the use of a bicycle design principle is caused by Lines 9–23 of Section C.1.

The **`wheel_assembly_1`** entity was used by the designer to provide the function **`facilitate movement`**. The **`pedal_assembly_1`** entity was used to provide the function **`provide energy`**. The **`chain_1`** entity was required to fulfill the **`drives`** context relationship that must exist between the embodiments of the functions **`facilitate movement`** and **`provide energy`** (Line 24, Section C.1). The interface between **`wheel_assembly_1`** and **`chain_1`** is embodied through **`mechanical_interface_1`**. The interface between **`pedal_assembly_1`** and **`chain_1`** is embodied through **`mechanical_interface_2`**. The **`frame_1`** entity was used by the designer to provide the function **`provide support`**. The **`supports`** context relation between the embodiments of the functions **`facilitate movement`** and **`provide support`** (Line 25, Section C.1) is embodied by **`mechanical_interface_3`**. The **`supports`** context relation between the embodiments of the functions **`provide energy`** and **`provide support`** (Line 26, Section C.1) is embodied by **`mechanical_interface_4`**. The **`saddle_1`** entity was used

by the designer to provide the function **support passenger**. The supports context relation between the embodiments of the functions **support passenger** and **provide support** (Line 27, Section C.1) is embodied by **mechanical_interface_5**. The **handlebar_assembly_1** entity is used to provide the function **change direction**. The **supports** context relation between the embodiments of the functions **change direction** and **provide support** (Line 28, Section C.1) is embodied by **mechanical_interface_6**. This scenario is also shown in Fig. 3.19.

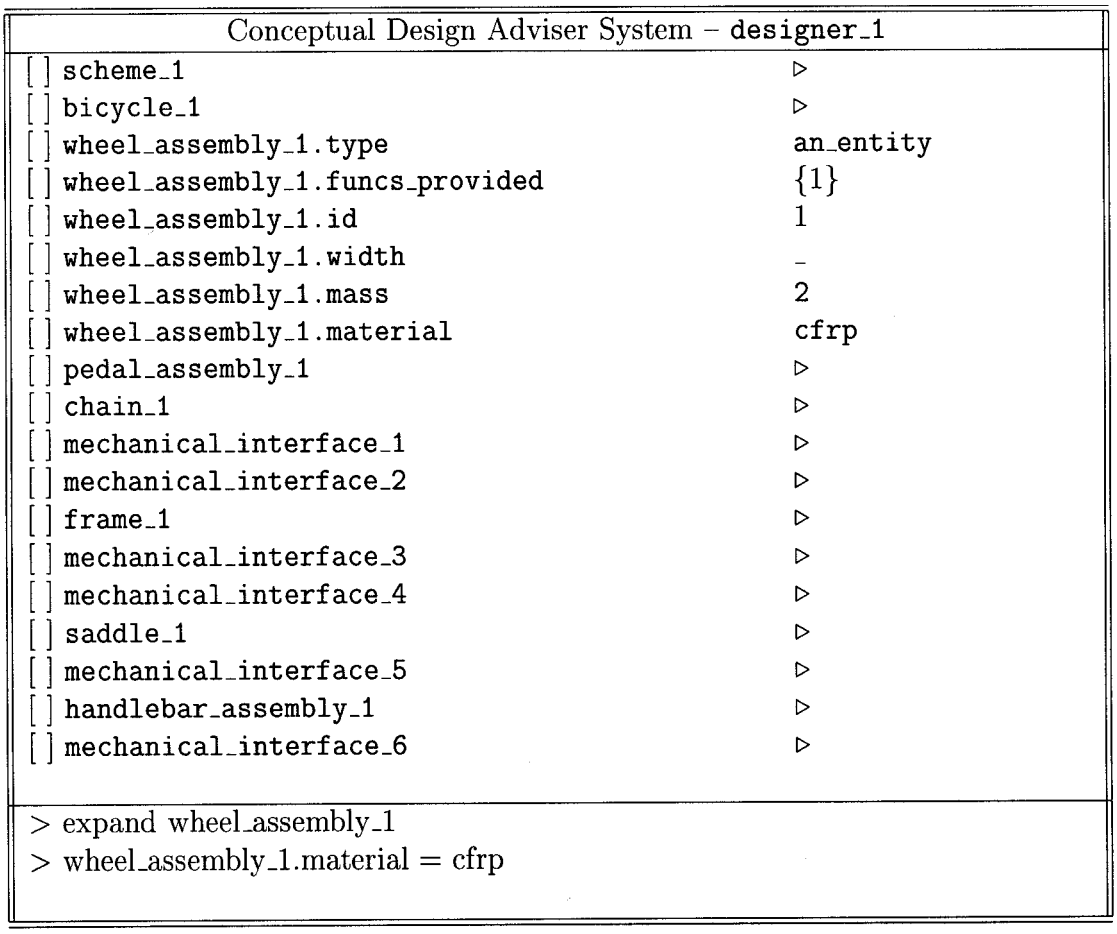

Fig. 5.11 Selecting materials for the entities in scheme_1

In Fig. 5.11 **designer_1** has begun to select materials for the entities in **scheme_1**. In this figure the designer selects the material **cfrp** for the **wheel_assembly_1** design entity. Once the designer selects a material for this entity, its (relative) mass can be estimated by the system. Here the (relative) mass of the **wheel_assembly_1** entity is estimated to be 2 by the function **mass_of** defined on Lines 236–240 of Section C.1.

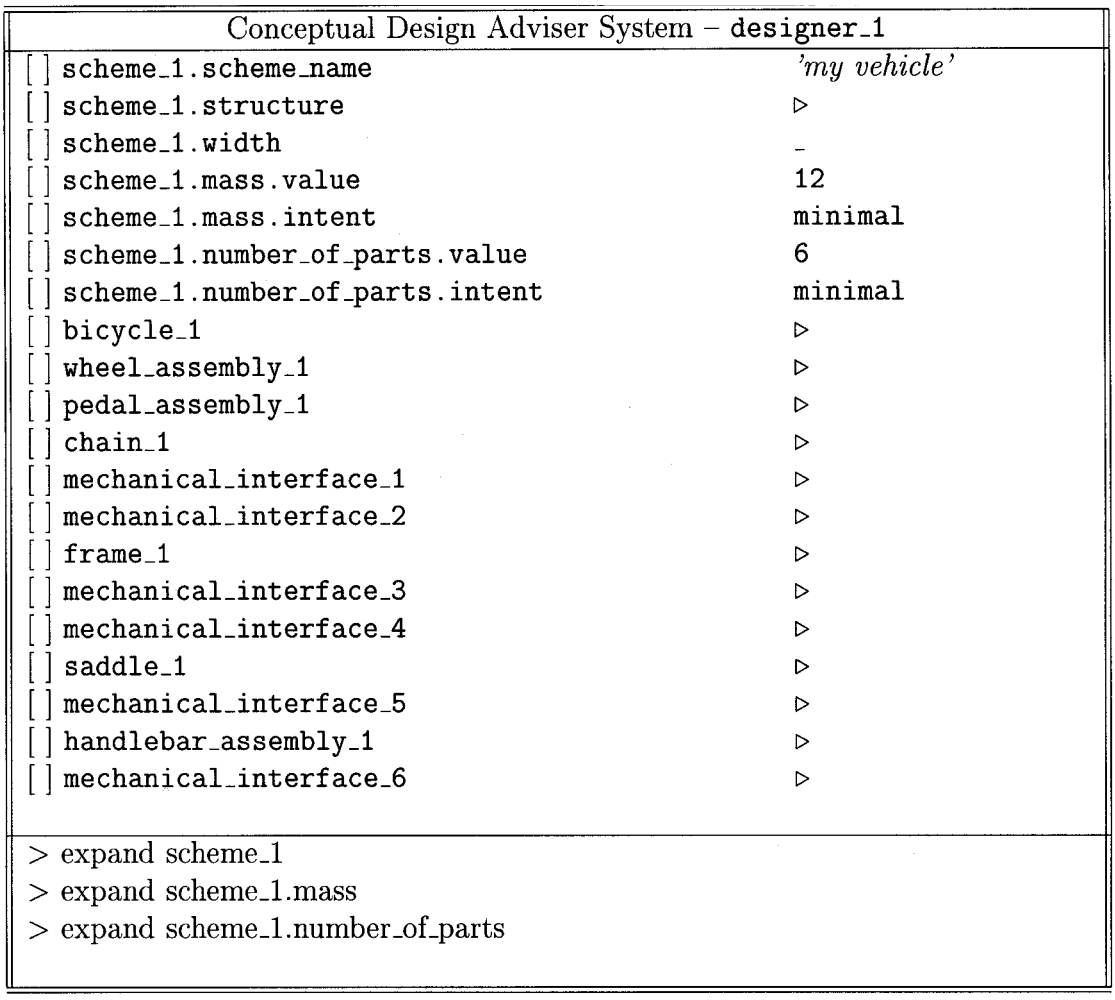

Fig. 5.12 The state of `scheme_1` once materials have been selected for all the entities from which it is configured

In Fig. 5.12 the state of **`scheme_1`** is shown after several more decisions have been made by the designer, namely after materials have been selected for all the entities from which it is configured. In this figure, the **`mass`** and **`number_of_parts`** fields of **`scheme_1`** have been expanded. It can be seen that the total mass of this scheme is estimated to be twelve units and that it comprises six parts.

The next few figures show a different scenario. They show snapshots from the development by another designer, **`designer_2`**, of a different scheme for the specification in Section C.2. As we will see, the system will automatically use Pareto optimality to compare this second scheme with the scheme that was developed by **`designer_1`**.

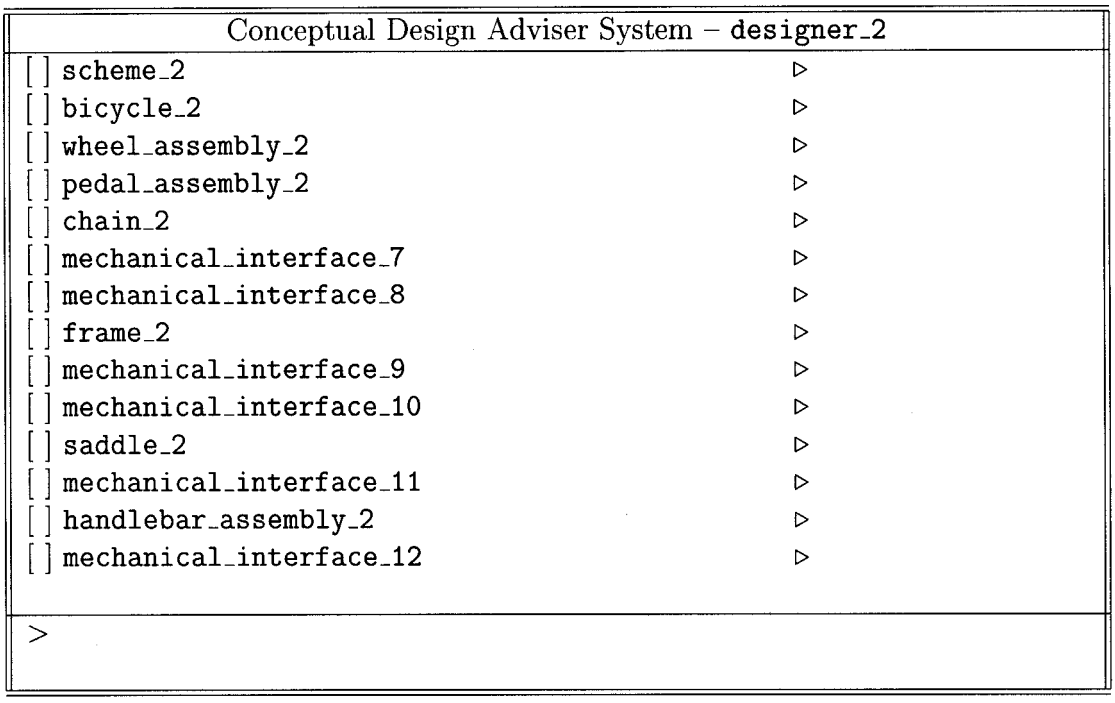

Fig. 5.13 A second scheme, `scheme_2`, has been developed by the designer known as `designer_2`

In Fig. 5.13 a second scheme, **`scheme_2`**, is presented which has been developed by **`designer_2`**. Although **`designer_2`** worked completely independently of **`designer_1`**, the exact same approach as that for **`scheme_1`** was used and the same means to embody its functions. As we will see, however, different materials were selected from those chosen by **`designer_1`**.

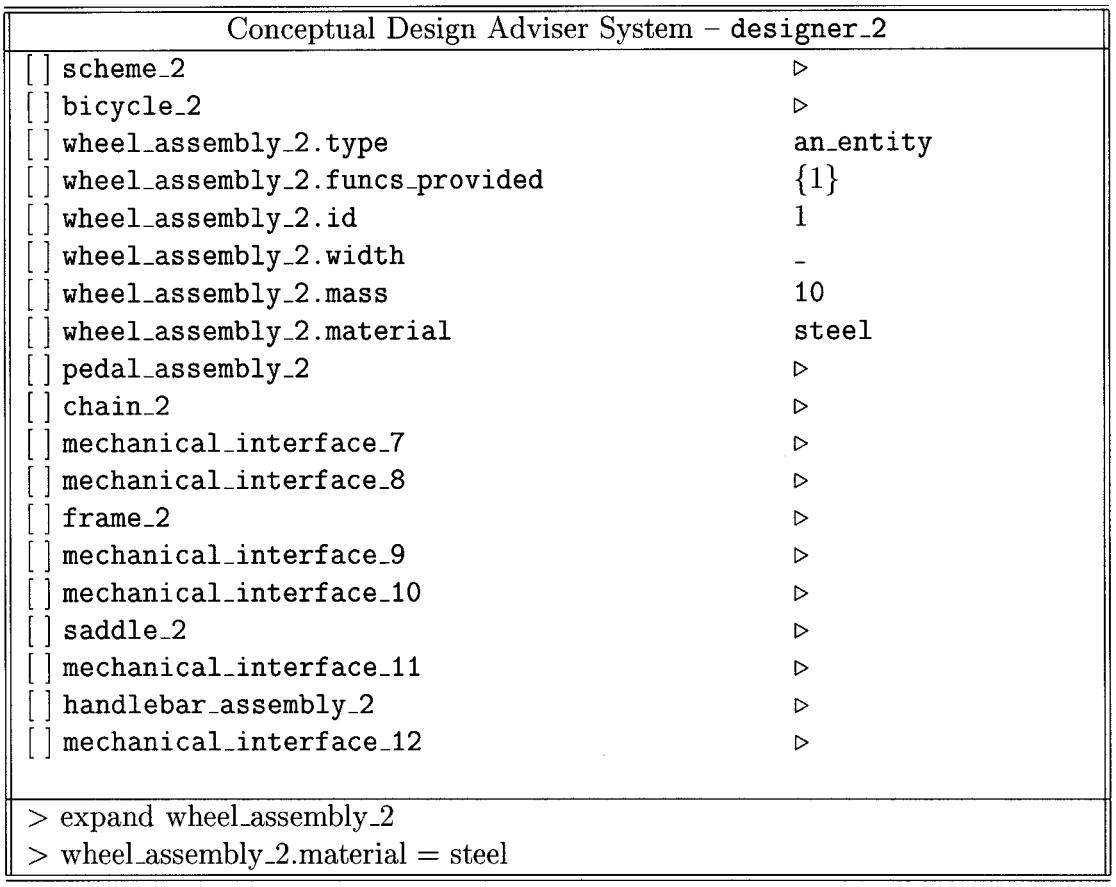

Fig. 5.14 A material is selected for the `wheel_assembly_2` entity used in `scheme_2`

In Fig. 5.14 **`designer_2`** begins to select materials for the various design entities associated with **`scheme_2`**. She begins with **`wheel_assembly_2`**, selecting **`steel`** as its material. Thus, the mass of this entity is estimated to be 10 units (Line 240, Section C.1).

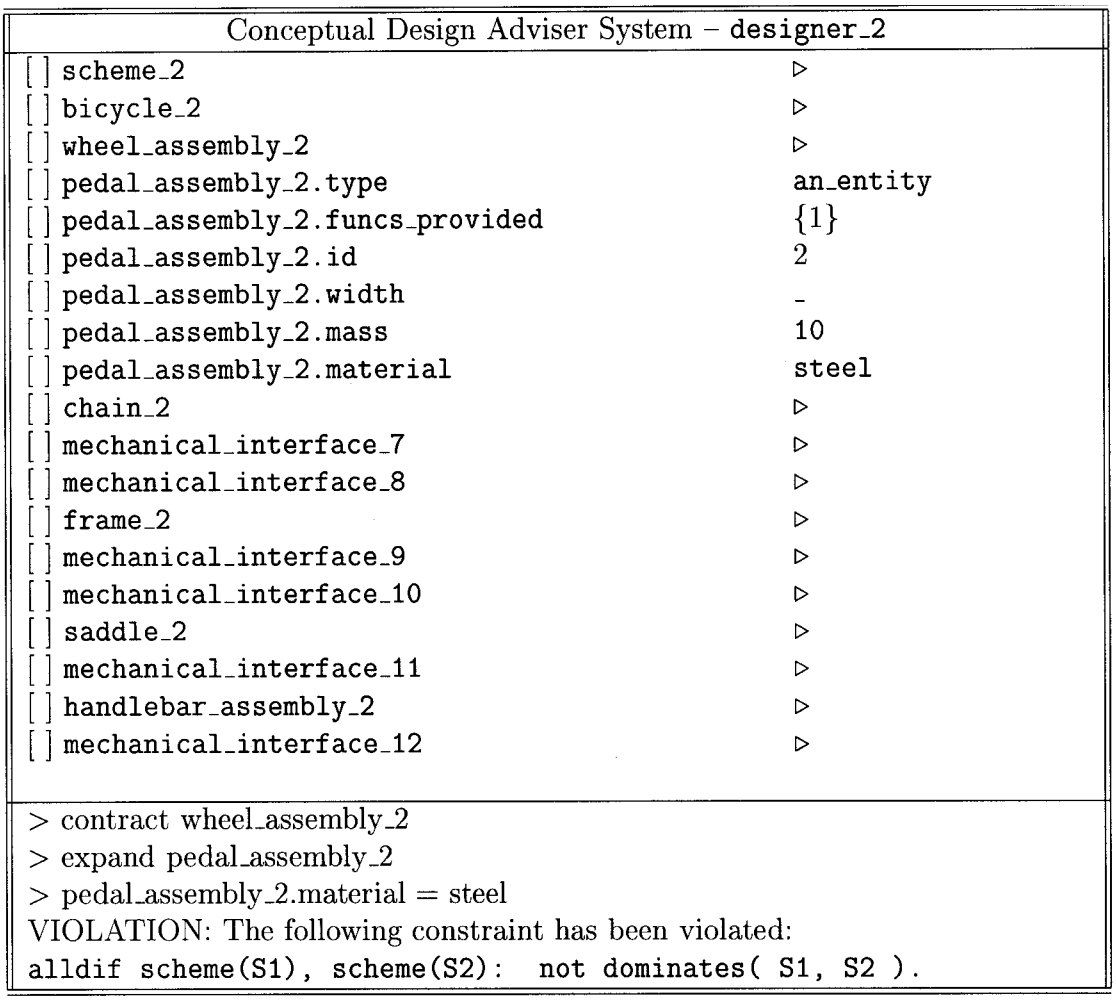

Fig. 5.15 Due to the choice of materials, `scheme_2` is dominated by the scheme developed earlier

In Fig. 5.15 `designer_2` selects steel as the material for `pedal_assembly_2`. Upon the designer making this assertion, a constraint violation is detected. This constraint violation is related to the fact that the system has recognized that there exists a scheme which is dominated by another. The reason for this will be discussed in conjunction with Fig. 5.16.

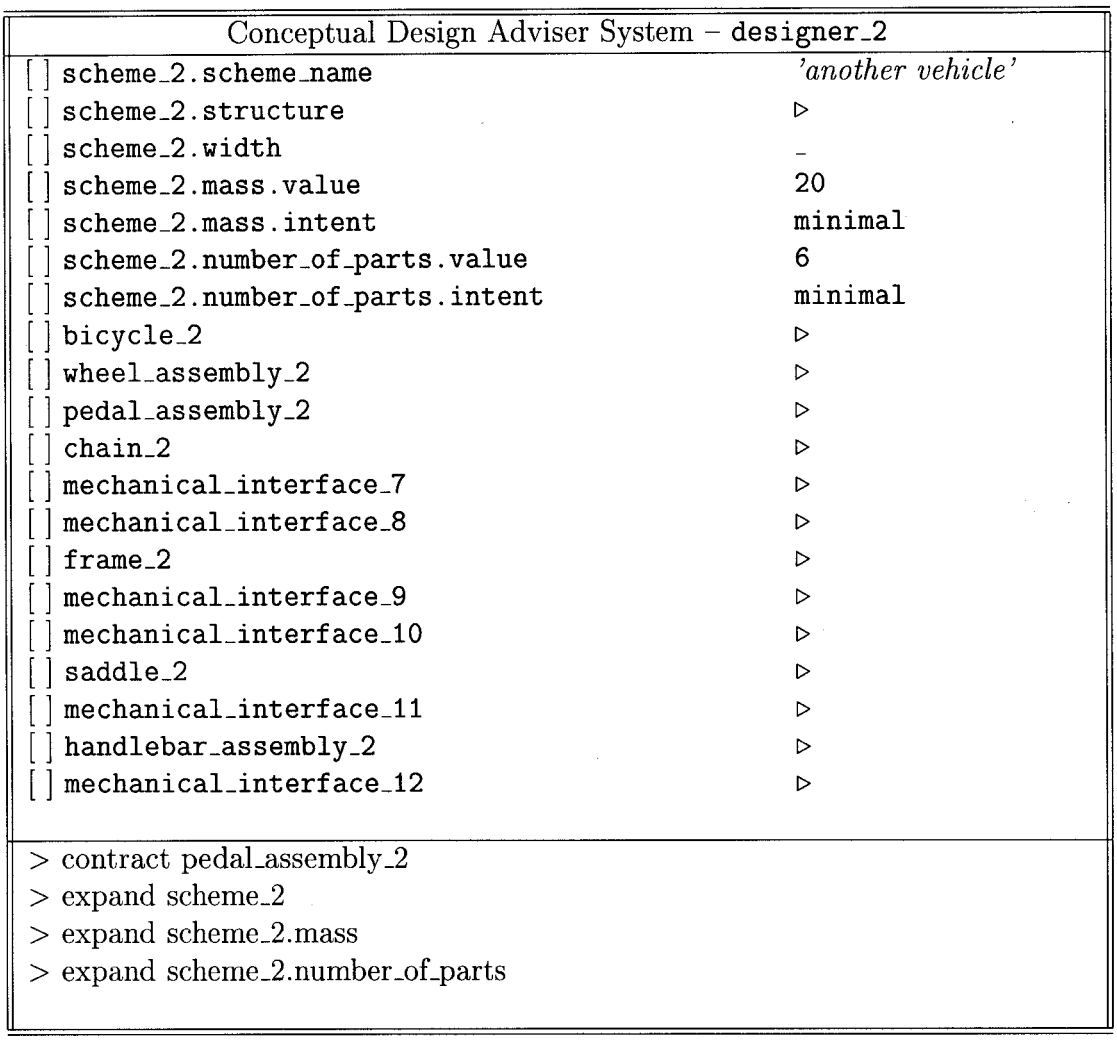

Fig. 5.16 The state of `scheme_2` after materials have been selected for `wheel_assembly_2` and `pedal_assembly_2`

In Fig. 5.16 the state of **`scheme_2`** after materials have been selected for **`wheel_assembly_2`** and **`pedal_assembly_2`** is illustrated. It can be seen that the mass of **`scheme_2`** is currently estimated to be 20 units and that it comprises 6 parts. Therefore, this scheme is certainly dominated by **`scheme_1`** since, although both schemes have the same number of parts as each other, **`scheme_1`** has the smaller mass. This means that, since **`scheme_2`** does not improve on **`scheme_1`** on any design preference, **`scheme_2`** is dominated by **`scheme_1`**.

It is not obvious just from a constraint violation what corrective action is required of a designer in order to ensure that a particular scheme is no longer dominated. In the discussion of scheme development presented here these issues have not been addressed. The manner in which advice on what schemes dominate a particular scheme is presented to the designer has been regarded as an interface issue. The presentation here has not addressed the issue of a suitable interface for constraint-aided conceptual design. However, a number of possibilities are obvious. For example, a graphical tool could display a window containing in a tabular form, the schemes that have been developed against their current values for the various preferences that have been defined in the design specification. When a designer develops a scheme that is dominated by one or more schemes, the dominating schemes could be highlighted in some way. Thus, the designer simply gets feedback stating that it is possible to develop a better scheme, but not how to do it. In this way, the designer's independence of thought is maintained.

5.1.4 Review of the example design problem

In Section 5.1.3 the use of constraint filtering to provide interactive support to a designer developing constraint-based scheme models to satisfy a design specification has been presented.

A graphical representation of **`scheme_1`** is presented in Fig. 5.17. Both of the schemes developed in this section were based on the same means for embodying each function in the scheme. In this figure it can be seen that there was an initial embodiment which had to be made for the function '*provide transport*'. The bicycle design principle was used to provide this function. This design principle introduced the need for five further embodiments to be made: *'facilitate movement'*, *'provide energy'*, *'support passenger'*, *'change direction'*, and *'provide support'*. These functions were embodied using five design entities: a wheel assembly, a pedal assembly, a saddle, a handlebar assembly, and a frame. During the embodiment of the functions with these means a number of context relations had to be embodied between the entities used. These are all illustrated in Fig. 5.17.

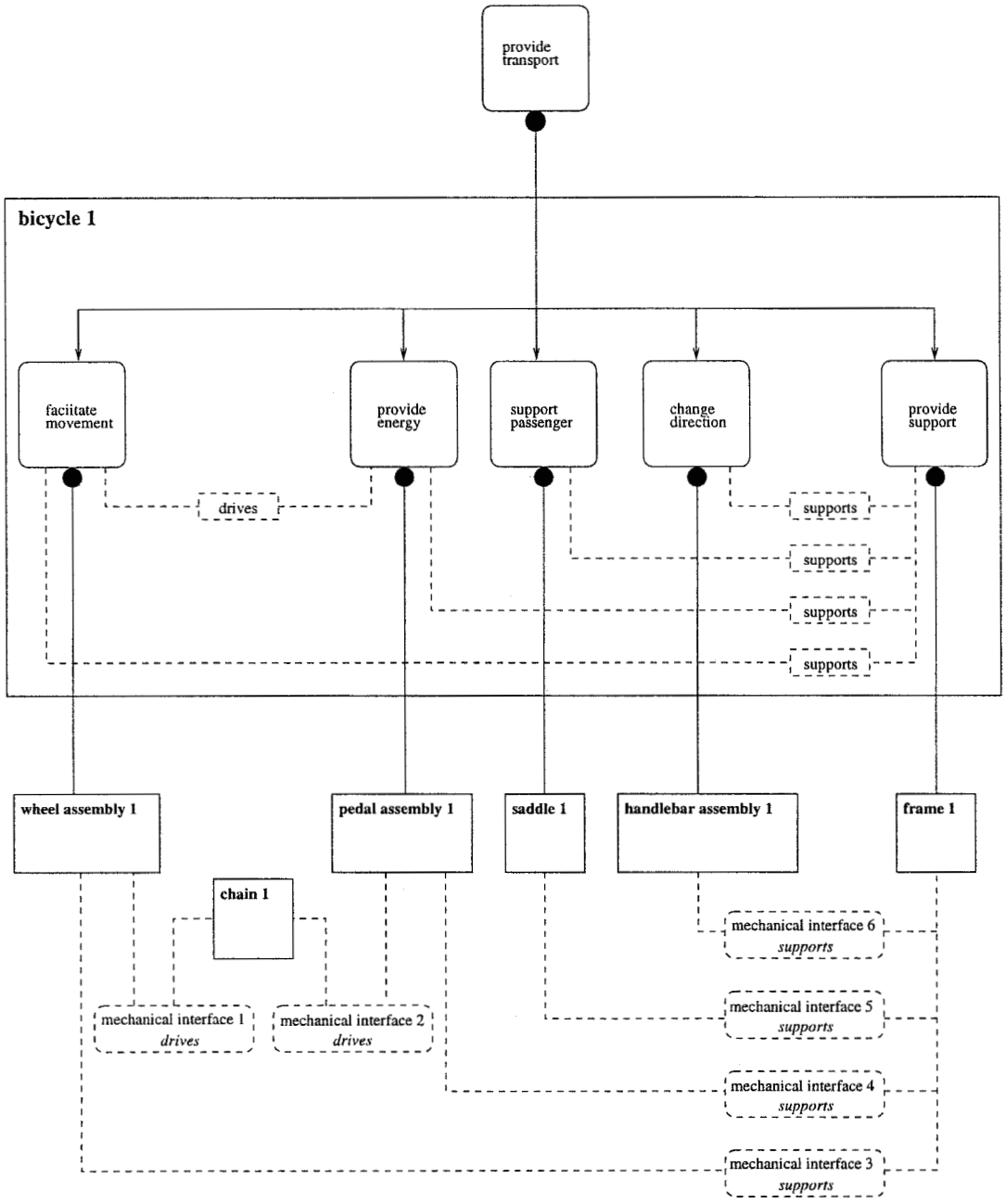

Fig. 5.17 The structure of the scheme presented in Section 5.1

5.2 An industrial case-study

This section describes, through the use of an industrial case-study, how the approach to conceptual design proposed in this book could be applied to support the design of a real-world product. The case-study was provided by an electronic component manufacturer based in Cork called Bourns Electronics. The section begins with a

profile of the company. The case-study product is discussed in general terms and an informal design specification for it is presented. The knowledge that is required to design the product is presented and it is demonstrated how this can be formalized using the modelling approach developed in this research. A formal design specification is then presented, which incorporates all of the requirements that the product must satisfy. A number of schemes are also discussed which satisfy the requirements defined in the design specification.

5.2.1 A profile of the company

Bourns Electronics Incorporated was founded in 1947 in Altadena, California. Bourns has eleven manufacturing facilities worldwide. Among these are manufacturing plants in California, Utah, Mexico, Costa Rica, Ireland, China, and Taiwan. In the early 1980s a new subsidiary company, called Bourns Electronics Limited, was opened in Cork, Ireland to support growing European market demands. It is in this plant that the case-study discussed here was undertaken.

Bourns manufactures over 4000 products that are designed for use in virtually every type of electronic system. The Bourns product range includes: chip resistors/arrays; modular contacts; resistor networks; dials; multi-fuse resettable fuse arrays; surge products; encoders; panel controls; switches; inductive components; precision potentiometers; trimming potentiometers; and linear motion potentiometers. The company's products are used in the automotive, industrial, medical, computer, audio/visual, telecommunications, and aerospace industries.

5.2.2 Discrete components from Bourns

Bourns' discrete components meet a variety of electronics design needs. They are small in size, and give design engineers solutions to address the growing portable electronics market and other industries where conserving board space is a critical issue.

A selection of discrete components manufactured by Bourns is illustrated in Fig. 5.18. In this figure components such as male and female modular contacts, sealed surface-mount technology (SMT) switches, and thick-film chip resistors are illustrated. Modular contacts provide an off-the-shelf solution for facilitating connectivity in portable electronic systems. Sealed SMT switches are available in sizes starting at 3 mm and are suitable for all popular soldering and cleaning methods, above and below the board. Thick-film chip resistors are available in surface-mount compatible packaging. Bourns also offers a wide selection of inductor and transformer components.

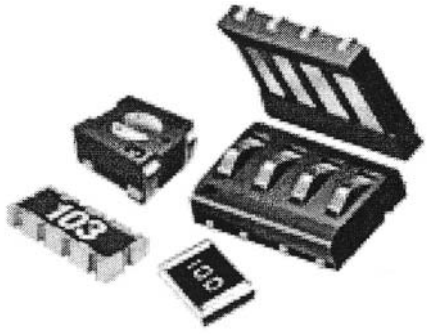

Fig. 5.18 A sample collection of discrete electronic components manufactured by Bourns Electronics

5.2.3 The case-study project

The case-study product discussed here relates to the design of electrical contacts. More specifically, the case-study relates to systems of electronic contacts that involve male and female components which facilitate electrical contact. These contact systems are generally used in electronics applications where some part of the product must be in electrical contact with another part. For example, when fitting a battery pack into a portable computer or a mobile phone, there is a requirement for an electrical connection between the battery pack and the remainder of the system. This type of electrical connection is often facilitated by the use of a modular contact system. An example of a modular contact system which is currently being marketed by Bourns Electronics is illustrated in Fig. 5.19. This system is known as the Bourns 70AD modular contact system. The system comprises a male contact (highlighted on the left) and a female contact (highlighted on the right).

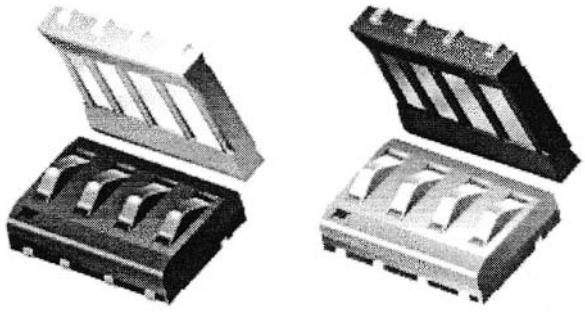

Fig. 5.19 The Bourns 70AD modular contact system

There is a second modular contact system available from Bourns Electronics. This system is known as the Bourns 70AA modular contact system. However, this system comprises only a male contact. The male component of the system is illustrated in Fig. 5.20.

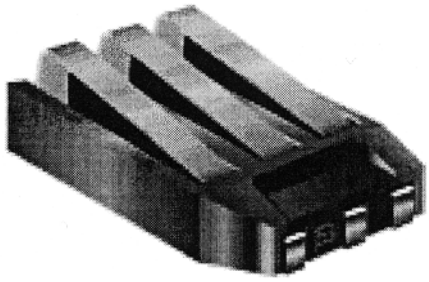

Fig. 5.20 The Bourns 70AA/male modular contact

The female component of the Bourns 70AA modular contact system had not yet been designed at the time this case-study was carried out. The conceptual design problem which will be addressed here will be the design of a female mating component for the Bourns 70AA/male modular contact. The design of this component would complete a second modular contact system for the company.

5.2.4 The design specification

Based on the requirement for a complementary female modular contact for the 70AA/male modular contact, a set of requirements for the desired component can be formulated. The set of requirements for the design of this new contact are presented in Table 5.1.

Table 5.1 An informal design specification for the female modular contact that is required to complement the 70AA/male modular contact

Property	***Requirement***
Required function	*Provide structured contact*
Current	3 Amps
Contact pitch	2.54 mm
Power consumption	Minimal
Contact-solder resistance	Minimal
Mass	Minimal
General	End-to-end stackable

In Table 5.1 it can be seen that there are several different types of requirement in the design specification. Some of these requirements relate to the functional aspects of the product, while others relate to the physical and life-cycle aspects of the product. The function that is to be provided by the product is to '*provide structured contact*'. The current that will be carried through the product will be 3 Amps and the product will have a contact pitch of 2.54 mm. The contact pitch is the distance between adjacent points of contact on the component. The concept of contact pitch is illustrated in Fig. 5.21.

Thanks go to Bourns Electronics Ireland for the use of Figs 5.18–5.20.

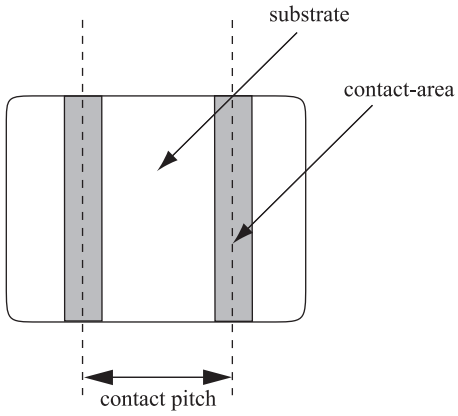

Fig. 5.21 The meaning of the contact pitch requirement

Also specified in Table 5.1 are a number of preferences about the physical aspects of the component. For example, the values of power consumption, contact-solder resistance, and mass of the component should all be minimal. These requirements can be used to compare alternative schemes that are developed by the designer in order to satisfy the design specification.

The power consumption of the component relates to the total amount of power that is consumed by the component when it is in use. The contact-solder resistance is the total resistance of any conductive elements within the component.

Finally, there is a life-cycle requirement specified in the design specification, namely, that the product being designed should be end-to-end stackable. This requirement means that the contact pitch of a series of contacts that are placed end-to-end on a printed circuit board (PCB) should be maintained. This requirement is illustrated in Fig. 5.22.

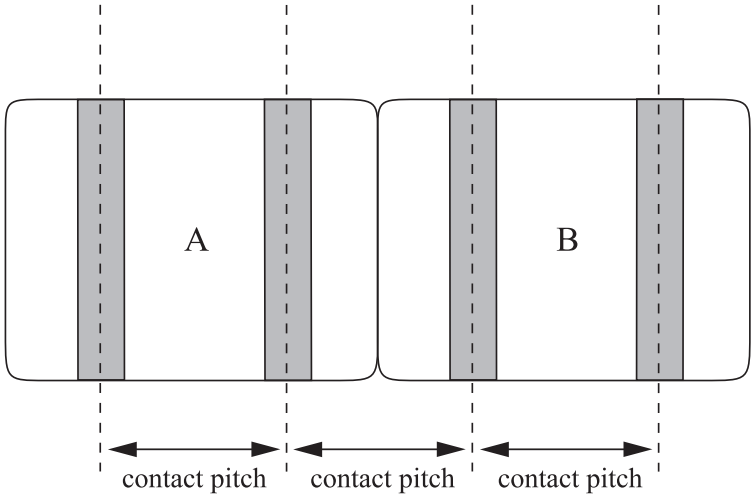

Fig. 5.22 Graphical explanations of the life-cycle requirement defined in the design specification

A full Galileo implementation of the design specification discussed here is implemented in a module called `contact_spec.gal` presented in Section D.2 of Appendix D. However, for convenience, a segment of the Galileo model of the design specification is presented here in Fig. 5.23[2].

```
 5 domain contact_scheme
 6     =::= { S: scheme( S ) and
 7                provides_the_function( S.structure.intended_function,
 8                'provide', 'structured contact' ) and
 9                exists( S.contact_pitch : real ) and
10                S.contact_pitch = 2.54 and
11                exists( S.current : real ) and
12                S.current = 3 and
13                exists( S.power_consumption : preference ) and
14                S.power_consumption.intent = minimal and
15                !S.power_consumption.value  = power_consumption_of( S ) and
16                exists( S.contact_to_solder_resistance : preference ) and
17                S.contact_to_solder_resistance.intent = minimal and
18                !S.contact_to_solder_resistance.value
19                    = contact_to_solder_resistance_of( S ) and
20                exists( S.mass : preference ) and
21                S.mass.intent = minimal and
22                !S.mass.value  = mass_of( S ) and
23                end_to_end_stackable( S ) }.

24 relation has_better_contact_solder_resistance_than( scheme, scheme )
25     =::= { (S1,S2): better_than( S1.contact_solder_resistance,
26                      S2.contact_solder_resistance ) }.

27 relation has_better_mass_than( scheme, scheme )
28     =::= { (S1,S2): better_than( S1.mass, S2.mass ) }.

29 relation has_better_power_consumption_than( scheme, scheme )
30     =::= { (S1,S2): better_than( S1.power_consumption,
31                      S2.power_consumption ) }.

32 relation improves_on( scheme, scheme )
33     =::= { (S1,S2): has_better_power_consumption_than( S1, S2 ) or
34                      has_better_contact_solder_resistance_than( S1, S2 ) or
35                      has_better_mass_than( S1, S2 ) }.
```

Fig. 5.23 A constraint-based model of the case-study design specification

[2] Please note that the line numbers in this figure correspond to the line numbers in `contact_spec.gal` presented in Section D.2.

This implementation of the design specification incorporates all of the requirements from the design specification discussed above. The functional property required by the design specification is modelled in Lines 7–8. The contact pitch and current requirements are modelled on Lines 9–10 and Lines 11–12, respectively.

The design preferences relating to the power consumption, contact-to-solder resistance and mass of the product are modelled on Lines 13–15, Lines 16–18, and Lines 20–22 respectively. The value of the power consumption of the component is computed using a function called **`power_consumption_of`**. The value of the contact-to-solder resistance of the component is computed using a function called **`contact_to_solder_resistance_of`**. The value of the mass of the component is computed using a function called **`mass_of`**. Finally, the life-cycle requirement that the product be end-to-end stackable is modelled on Line 23. A relation called **`end_to_end_stackable`** is used. The various relations used to compare alternative schemes, which are specific to this particular design specification, are defined on Lines 24–35.

The meaning of the various functions and relations referred to in the design specification model presented in Fig. 5.23 are part of the domain knowledge required to develop schemes for this product. In order to be able to develop a set of schemes for the product described in the design specification presented in Table 5.1 and Fig. 5.23, an appropriate design knowledge-base must be available for designing electrical contact systems. This knowledge-base should contain a variety of means for providing typical functions in this domain. The knowledge-base should also contain various functions and relations which can be used to evaluate schemes from those perspectives which are relevant to the particular design problem. In the next section the contents of a suitable knowledge-base will be presented.

5.2.5 Modelling design knowledge for Bourns

In Section D.1 of Appendix D a full constraint-based implementation of a suitable design knowledge-base is presented in a Galileo module called **`bourns_knowledge.gal`**. Aspects of that knowledge-base will now be discussed, in order to demonstrate how the design knowledge required for the case-study can be modelled in a manner consistent with the approach presented in this book.

The design knowledge-base that is presented here contains a number of known means that are useful when designing electrical contact components. These are presented in a domain called **`known_means`** in Fig. 5.24.

```
52 domain known_means
53     =::= { a_female_modular_contact, a_precious_metal_contact,
54            a_substrate, a_molded_body, a_machined_body,
55            a_thickfilm_termination, a_male_contact,
56            a_conducting_strip, a_conducting_wire,
57            a_metal_termination, a_thickfilm_conductor }.
```

Fig. 5.24 Known means for use in designing electrical contact components

```
124 relation can_simultaneously_provide( known_means, set of func )
125     =::= { (a_female_modular_contact,{F}):
126             provides_the_function(F,'provide','structured contact'),
127            (a_male_contact,{F}):
128             provides_the_function(F,'provide','structured contact'),
129            (a_substrate,{F}):
130             provides_the_function(F,'provide','support'),
131            (a_molded_body,{F}):
132             provides_the_function(F,'provide','support'),
133            (a_machined_body,{F}):
134             provides_the_function(F,'provide','support'),
135            (a_thickfilm_termination,{F}):
136             provides_the_function(F,'facilitate','external connection'),
137            (a_conducting_strip,{F1,F2,F3}):
138             provides_the_function(F1,'provide','contact') and
139             provides_the_function(F2,'connect','contact') and
140             provides_the_function(F3,'facilitate','external connection'),
141            (a_metal_termination,{F}):
142             provides_the_function(F,'facilitate','external connection'),
143            (a_precious_metal_contact,{F}):
144             provides_the_function(F,'provide','contact'),
145            (a_thickfilm_conductor,{F1,F2}):
146             provides_the_function(F1,'provide','contact') and
147             provides_the_function(F2,'connect','contact'),
148            (a_conducting_wire,{F}):
149             provides_the_function(F, 'connect', 'contact') }.
```

Fig. 5.25 Modelling the functions that can be provided by a known means

The various functions that can be provided by each of the known means are specified in the relation presented in Fig. 5.25. For example, it can be seen from Lines 145–147 that `a_thickfilm_conductor` can simultaneously provide the functions `provide contact` and `connect contact`. The relation presented in this figure is structurally identical to that used in the example design problem discussed in Chapter 4 and Section 5.1.

The knowledge-base being discussed here contains one design principle, based on an idealized female modular contact. The Galileo representation of this principle is presented in Fig. 5.26. The **female_modular_contact** design principle introduces the need for four embodiments to be made. These embodiments, **e1**, **e2**, **e3**, and **e4**, are associated with the functions '*provide support*', '*provide contact*', '*connect contact*', and '*facilitate external connection*', respectively. A number of context relations also appear in this design principle. Specifically, the embodiment of the function '*provide contact*' must be electrically connected to the embodiment of the function '*connect contact*' (Line 44) and the embodiment of the function '*connect contact*' must be electrically connected to the embodiment of the function '*facilitate external connection*' (Line 45). Additionally, the embodiment of the function '*provide support*' must support the embodiments of the functions '*provide contact*', '*connect contact*', and '*facilitate external connection*' (Lines 46–48). The implementation of these relations can be found in the Galileo module **bourns_knowledge.gal** presented in Section D.1. However, the implementation of the **is_electrically_connected_to** relation will be discussed later in this section.

```
30 domain female_modular_contact
31     =::= { F: principle(F) and
32            exists( F.e1 : embodiment ) and
33            exists( F.e2 : embodiment ) and
34            exists( F.e3 : embodiment ) and
35            exists( F.e4 : embodiment ) and
36            provides_the_function( B.e1.intended_function,
37                                   'provide', 'support' ) and
38            provides_the_function( B.e2.intended_function,
39                                   'provide', 'contact' ) and
40            provides_the_function( B.e3.intended_function,
41                                   'connect', 'contact' ) and
42            provides_the_function( B.e4.intended_function,
43                                   'facilitate', 'external connection' ) and
44            is_electrically_connected_to( B.e2, B.e3 ) and
45            is_electrically_connected_to( B.e3, B.e4 ) and
46            supports( B.e1, B.e2 ) and
47            supports( B.e1, B.e3 ) and
48            supports( B.e1, B.e4 ) }.
```

Fig. 5.26 The female modular contact design principle

In Fig. 5.27 the generic design entity model appropriate for the case-study product is presented. The **bourns_entity** is a design entity that has a number of additional fields such as width, height, length, mass, material, and resistance. There are a number of materials available which can be used as the material of choice for a Bourns design entity; these are presented in Lines 49–51 of Section D.1. The mass and resistance of the entity are computed using the functions **mass_of** and **resistance_of**, respectively

(Lines 11 and 12). The implementation of these functions can be found in the Galileo module **bourns_knowledge.gal** presented in Section D.1. However, the implementation of the **resistance_of** function will be discussed later in this section.

```
 3 domain bourns_entity
 4     =::= { R: entity(R) and
 5                exists( R.width      : real ) and
 6                exists( R.height     : real ) and
 7                exists( R.length     : real ) and
 8                exists( R.mass       : real ) and
 9                exists( R.material   : known_material ) and
10                exists( R.resistance : real ) and
11                R.mass = mass_of( R ) and
12                R.resistance = resistance_of( R ) }.
```

Fig. 5.27 The generic Bourns design entity

In the company where this case-study was carried out, there are two classes of design entity: conductor entities and substrate entities. These entity classes represent significantly different entity types relevant to the design of electrical contact systems. In Fig. 5.28 the model of a **conductor_entity** is presented. A conductor entity is based on the generic Bourns entity, but must be made of a conductor material (Line 24). There are a number of conductor materials available such as gold and palladium silver (Lines 150–151). In the Galileo module **bourns_knowledge.gal**, presented in Section D.1, several design entities are defined in terms of a conductor design entity.

```
22 domain conductor_entity
23     =::= { C: bourns_entity( C ) and
24                conductor_material( C.material ) }.


150 relation conductor_material( known_material )
151     =::= { gold, palladium_silver, palladium_gold, platinum_gold }.
```

Fig. 5.28 A conductor entity for the Bourns case-study

In Fig. 5.29 a system of interfaces for this case-study is presented. A **bourns_interface** is an interface which has a **type** field that can take three possible values: **spatial**, **physical**, or **electrical**.

```
13 domain bourns_interface
14     =::= { I: interface(I) and
15                exists( I.type : bourns_interface_type ) }.

16 domain bourns_interface_type
17     =::= { spatial, physical, electrical }.
```

Fig. 5.29 Suitable interfaces for the Bourns case-study

In Fig. 5.30 an `electrical_interface` is defined in terms of a `bourns_interface`. An electrical interface can be used to represent various relationships between design entities. In this case-study an electrical interface can either represent an insulative or conductive relationship.

```
25 domain electrical_interface
26     =::= { S: bourns_interface(S) and S.type = electrical and
27                exists( S.relationship : electrical_relationship ) }.

28 domain electrical_relationship
29     =::= { insulative, conductive }.
```

Fig. 5.30 Modelling electrical interfaces study

The context relation '*electrically connected* to' can be modelled in terms of a conductive electrical interface between a pair of design entities. This is illustrated in Fig. 5.31. This relation between design entities is used, in the same way as was done in Section 5.1, to implement the analogous relation between the embodiments within a principle.

```
165 relation is_electrically_connected_to( entity, entity )
166     =::= { (E1,E2): E1 = E2 and conductor_entity(E1),
167            (E1,E2): is_in_the_same_scheme_as( E1, E2 ) and
168                     !exists electrical_interface(E):
169                           E.entity1 = E1.id and
170                           E.entity2 = E2.id and
171                           E.relationship = conductive }.
```

Fig. 5.31 The 'electrically connected to' context relation

In the design specification model presented in Fig. 5.23 a number of functions are used to compute the values of various properties of a scheme. For example, a function called **contact_to_solder_resistance_of** is used to compute the contact-solder resistance of a scheme. A appropriate implementation of this function is presented in Fig. 5.32. The contact-to-solder resistance of a scheme is computed as the sum of the resistances of all the conducting entities used in the scheme.

```
193 function contact_to_solder_resistance_of( scheme ) -> real
194     =::= { S -> sum( { E.resistance | exists conducting_entity(E):
195                                       is_a_part_of( E, S ) }.
```

Fig. 5.32 Computing the contact-to-solder resistance of a scheme

As seen earlier in Fig. 5.27, the resistance of an entity is computed using a function called **resistance_of**. The implementation of this function is illustrated in Fig. 5.33. The resistance of an entity depends on its material and geometry. The implementation presented in this figure is based on the normal calculation performed in Bourns to determine the resistance of a design entity.

```
219 function resistance_of( bourns_entity ) -> real
220     =::= { E -> resistivity_of( E.material ) * E.length
221                 / ( E.width * E.height ) }.

222 function resistivity_of( known_material ) -> real
223     =::= { gold              -> 0.005,
224            palladium_silver -> 0.03,
225            palladium_gold   -> 0.05,
226            platinum_gold    -> 0.05,
227            alumina96         -> 1.0E14,
228            alumina995        -> 1.0E14,
229            beryllia995       -> 1.0E14 }.
```

Fig. 5.33 Computing the resistance of a design entity

In Fig. 5.34 a relation is presented which characterizes the meaning of the requirement that a scheme be end-to-end stackable. Essentially, a contact component can be regarded as being end-to-end stackable if the length of its substrate element is twice the contact pitch of the component.

```
152 relation end_to_end_stackable( scheme )
153     =::= { S: exists substrate_entity(E):
154                     is_a_part_of( E, S ) and
155                     E.length = 2 * S.contact_pitch }.
```

Fig. 5.34 The meaning of the end-to-end stackable requirement

In this section various aspects of the Galileo implementation of a design knowledge-base for developing schemes for the Bourns case-study product was presented. It can be seen that the approach presented in this book for doing so is very flexible and expressive. It has been demonstrated that the approach is capable of modelling all the necessary design knowledge encountered in Bourns related to the design of a contact system which meets the design specification. A full Galileo implementation of the Bourns design specification and design knowledge-base are presented in Appendix D.

5.2.6 Generating alternative schemes

In this section a number of schemes are described based on the design knowledge-base presented in the previous section. The development of three schemes will be presented graphically. The schemes discussed here are intended to satisfy the design specification presented in Section 5.2.4. The purpose of this section is to demonstrate that the approach presented in this book could be used to develop schemes for an industrial product.

In the presentation of these schemes no screen-shots will be used to demonstrate the interaction between the constraint filtering system and the designer. This has already been demonstrated in Section 5.1.3. Also, a presentation of the use of Pareto optimality will not be given here, since this would require a detailed sequence of screen-shots and, in addition, has already been discussed in Section 5.1.3.

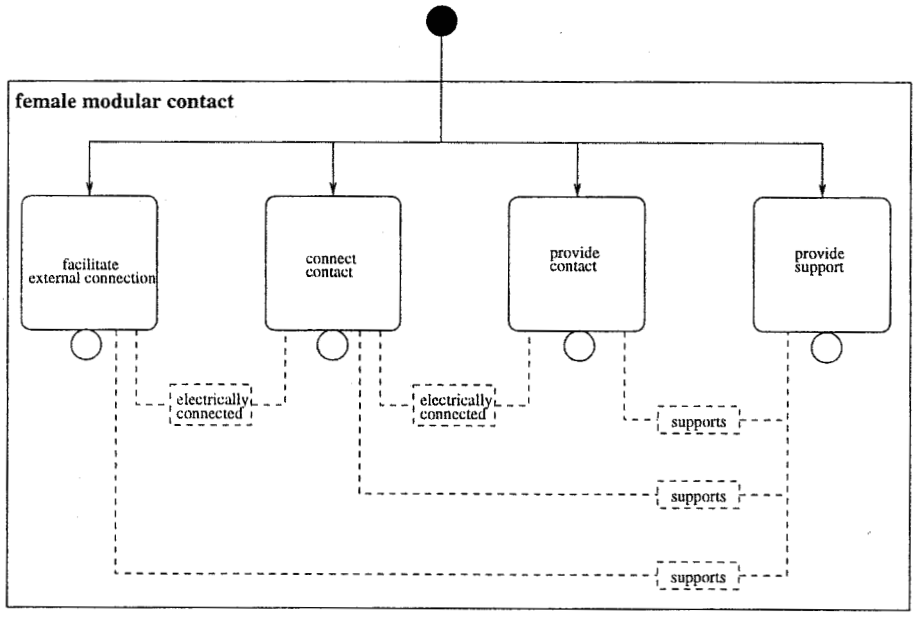

Fig. 5.35 A graphical representation of the principle of a female modular contact

In Fig. 5.35 a graphical representation of the principle of a female modular contact is presented. The implementation of this principle is presented in Lines 30–48 of Section D.1. This principle requires that four embodiments are made in the design. These embodiments are associated with the functions *provide support, provide contact, connect contact,* and *facilitate external connection*. There are a number of context relations defined between these functions, namely: that there is an *electrically connected* relation between the embodiments of the functions *provide contact* and *connect contact*; that there is an *electrically connected* relation between the embodiments of the functions *connect contact* and facilitate external connection; a *supports* relation between the embodiments of the functions *provide support* and *provide contact*; a *supports* relation between the embodiments of the functions *provide support* and *connect contact*; and a *supports* relation between the embodiments of the functions *provide support* and *facilitate external connection*.

According to Lines 125–126 of Section D.1 it can be seen that the principle of a female modular contact can be used to provide the function *provide structured contact.*

In Fig. 5.36 a number of design entities are presented graphically. Each of these design entities are implemented in Section D.1. For example, the molded body design entity is implemented in Lines 64–65.

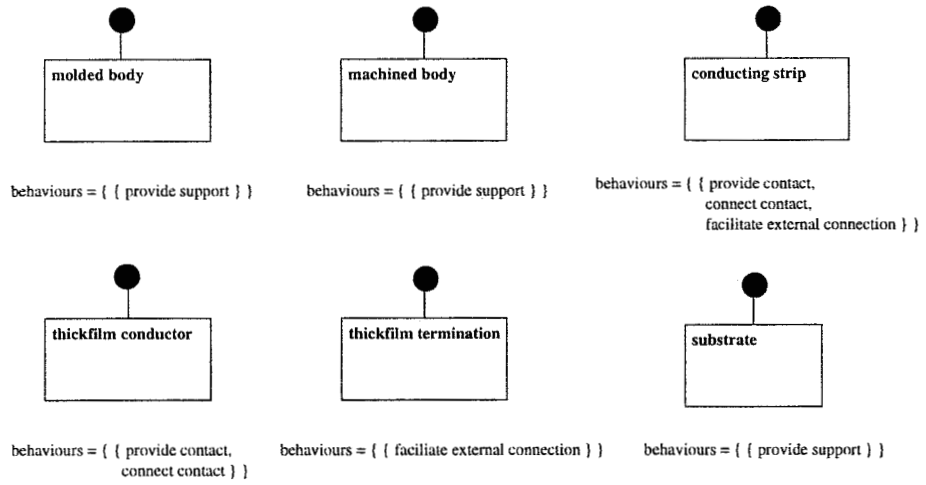

Fig. 5.36 A graphical representation of the entities that will be used to develop schemes for the case-study product

By inspecting the relation defined on Lines 124–149 of Section D.1 it can be seen that a molded body can provide the function *provide support*, a machined body can provide the function *provide support*, a conducting strip can provide the functions *provide contact* and *facilitate external connection*, a thick-film conductor can provide the function *provide contact*, a thick-film termination can provide the function *facilitate external connection*, and a substrate can provide the function *provide support.*

Using the various means illustrated in Fig. 5.35 and Fig. 5.36 a number of schemes for the design specification presented in Section D.2 will be described.

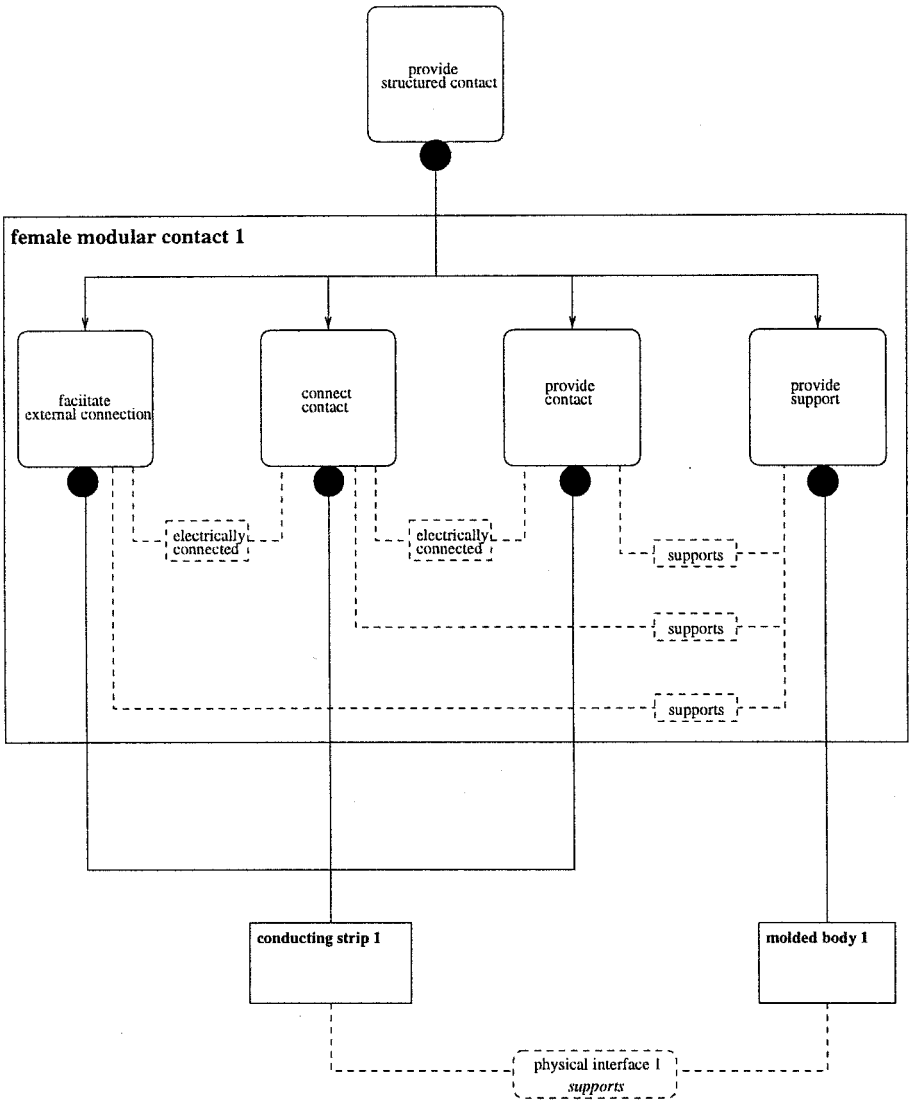

Fig. 5.37 A graphical representation of the structure of a scheme that comprises a `molded_body` and a `conducting_strip`

In Fig. 5.37 a scheme is presented which could have been generated by interacting with a constraint-based filtering system using the Galileo modules presented in Appendix D. This scheme uses the design principle *female modular contact* to provide the function *provide structured contact*. As discussed already, this design principle requires the designer to consider four further embodiments in order to develop the scheme. The associated functions are *provide support, facilitate external connection, provide contact,* and *connect contact.* The designer chooses to embody the function *provide support* with a *molded body* design entity and to embody the remaining three functions with the same design entity, namely, a *conducting strip*.

The *conducting strip* design entity is capable of providing three functions simultaneously: *provide contact, connect contact,* and *facilitate external connection*.

Therefore, when the designer selects to provide the function *facilitate external connection* with a *conducting strip*, an instance of this design entity is introduced into the design due to the constraint defined in Lines 87–89 of Section D.1. When the designer then embodies the functions *connect contact* and *provide contact* with a *conducting strip*, no new entities are introduced into the design since the *conducting strip* entity introduced earlier can simultaneously provide all of these functions. This is due to the relation specified in Lines 124–149 of Section D.1.

The context relations that will need to be considered in the physical structuring of this scheme are the *supports* relation and the *electrically connected* relation. There will exist a *physical interface* between the *conducting strip* and the *molded body* entities. This *physical interface* will implement a supports relationship between these entities in order to embody the *supports* context relation. This is due to the relations defined on Lines 174–192 of Section D.1. Since the embodiment of the functions *facilitate external connection, provide contact,* and *connect contact* is a single conductor design entity there is no requirement for an explicit interface for the *electrically connected* context relation. This is due to the relations defined on Lines 156–171 of Section D.1 and, in particular, Line 166.

In Fig. 5.38 a second scheme is presented. This scheme also uses the design principle *female modular contact* to provide the function *provide structured contact*. The designer chooses to embody the function *provide support* with a design entity called *machined body* and to embody the remaining three functions with the same design entity, namely, a *conducting strip*. Therefore, for similar reasons as for the scheme presented in Fig. 5.37, the context relations that will need to be considered in the physical structuring of the scheme are the *supports* relation and the *electrically connected* relation. Again, there is only one interface required in this scheme. This is to implement the *supports* relation between the *conducting strip* and *machined body* design entities. No explicit interface is required for the *electrically connected* context relation.

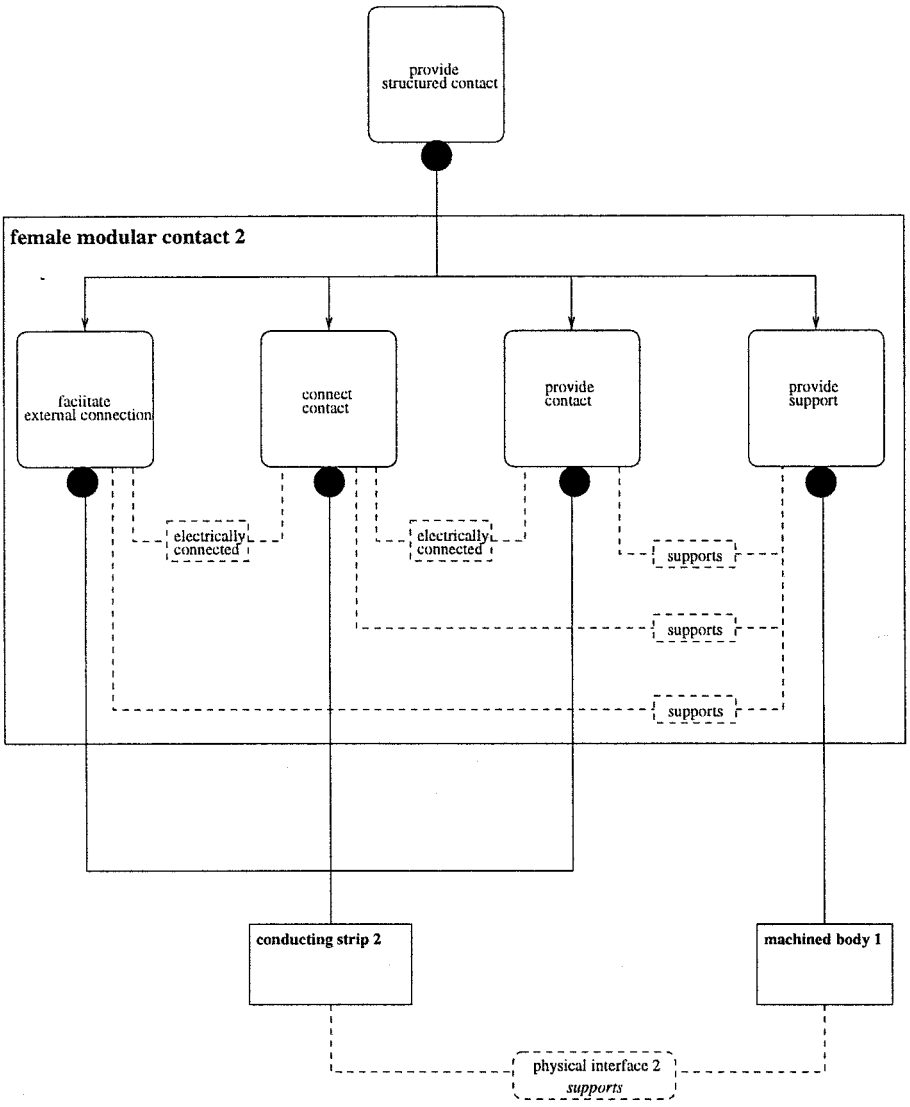

Fig. 5.38 A graphical representation of the structure of a scheme which comprises a `machined_body` and a `conducting_strip`

In Fig. 5.39 a third scheme is presented. This scheme also uses the design principle *female modular contact* to provide the function *provide structured contact*.

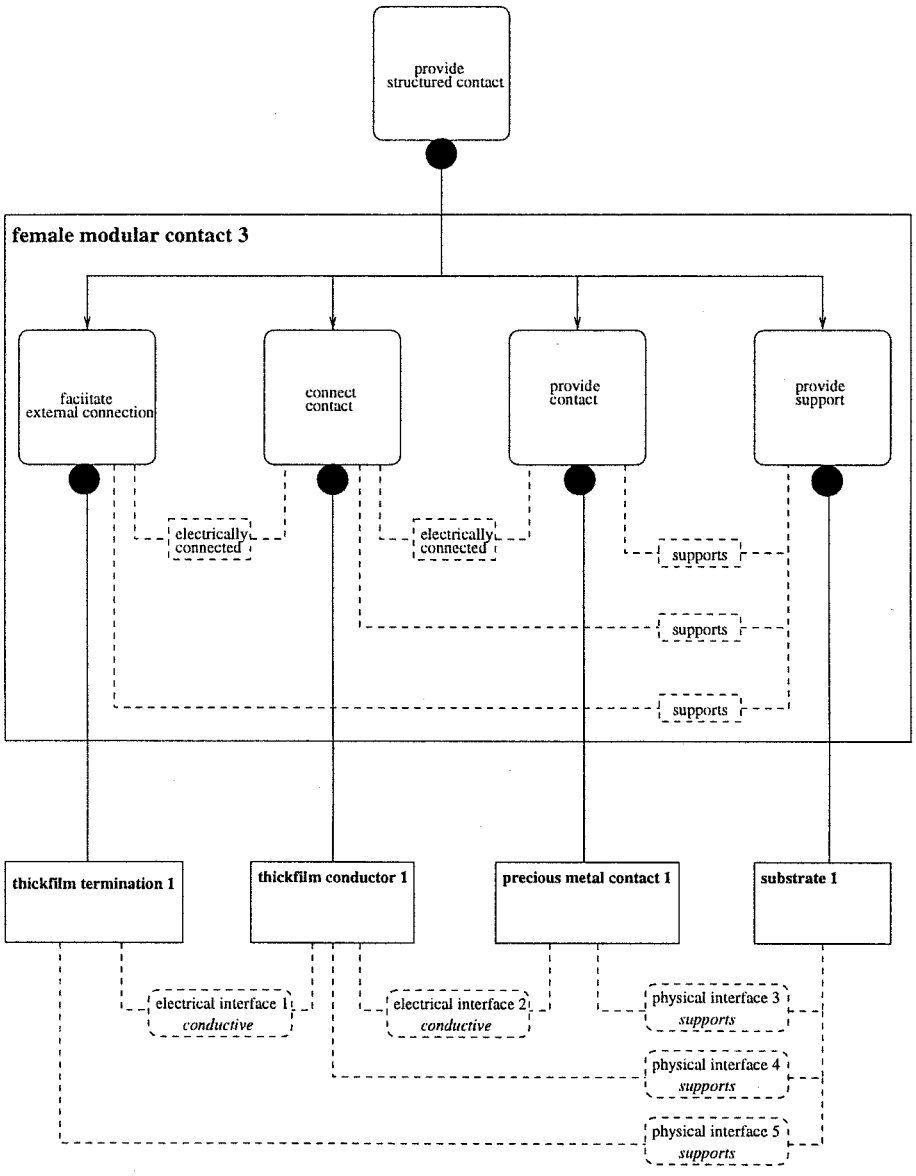

Fig. 5.39 A graphical representation of the structure of a scheme which comprises a `substrate`, a `thick_film_termination`, and two distinct `thick_film_conductor` entities

The function *provide support* was embodied with a *substrate* design entity, the function *facilitate external connection* was embodied with a *substrate* design entity, The function *facilitate external connection* was embodied with a *thick-film termination* design entity. The function *provide contact* was embodied with a *precious metal contact* design entity and the function *connect contact* was embodied with a *thick-film conductor* design entity.

In order to fulfill the various context relations required by the *female modular contact* design principle, the designer must consider a number of relations among the design

entities in this scheme. The *supports* context relation between the *substrate* and the *thick-film conductor* is implemented through a *physical interface* providing a supports relationship. The *supports* context relation between the *substrate* and the *precious metal contact* is implemented through a second *physical interface* providing a supports relationship. The *supports* context relation between the *substrate* and the *thick-film termination* is implemented through a third *physical interface* providing a supports relationship.

The *electrically connected* context relation between the *thick-film conductor* and the *precious metal contact* is implemented through an *electrical interface* providing a conductive relationship. The *electrically connected* context relation between the *thick-film conductor* and the *thick-film termination* is implemented through a second *electrical interface* providing a conductive relationship.

5.2.7 Review of the industrial case-study

In the previous parts of Section 5.2 it was illustrated how the approach presented in this book could be applied to support the design of a real-world product. The information for the case-study presented here was provided by an electronic component manufacturer based in Cork called Bourns Electronics. A brief profile of Bourns Electronics was given. The application of the case-study product was discussed in general terms and an informal design specification was presented. The knowledge that was required to design the product was presented and it was demonstrated how this can be formalized using the modelling approach presented in Chapter 4. A formal design specification for the case-study product was presented. The development of a number of alternative schemes for the case-study product was discussed.

While only three schemes have been discussed in this section many other schemes could have been generated. However, in order to respect the confidence of Bourns these schemes have not been presented here. Bourns were highly impressed with the approach. Indeed, one scheme that was developed using this approach was actually the same as a scheme which the company had developed independently and which they had recently patented: the scheme in question is not presented here at the request of the company. Bourns believes that a tool based on the approach presented here would be extremely valuable to them as a means for improving their new product development capability.

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Chapter 6

Conclusions

In this book a constraint-based approach to providing support to a human designer working during the conceptual phase of design has been presented. In this chapter the conclusions of the research will be discussed. This is done by relating the achieved results to the goals formulated in Chapter 1 and by discussing the results in the context of the thesis defended in this book:

'It is possible to develop a computational model of, and an interactive designer support environment for, the engineering conceptual design process. Using a constraint-based approach to supporting conceptual design, the important facets of this phase of design can be modelled and supported.'

In this chapter a number of recommendations for further study are also presented.

6.1 The goals of the research revisited

In Chapter 1 the goals of this research were presented; these were as follows:

1. to investigate whether constraint-based reasoning can be used as a basis for supporting conceptual design;
2. to determine if the expressiveness needs of conceptual design motivate the introduction of new features into Galileo.

It will be discussed in this section how these goals were achieved by the research presented in this book.

6.1.1 Constraint-based support for conceptual design

It has been demonstrated in this book how constraint-based reasoning can be used to support the human designer during conceptual design. In Chapter 3, a theory of conceptual design was presented upon which the research reported in this book was

based. In Chapter 4, a constraint-based implementation of this theory of conceptual design was presented. In Chapter 5, this approach was validated on two design problems: a toy design problem related to the design of a transportation vehicle, and an industrial case-study. Therefore, the goal to investigate whether constraint-based reasoning can be used as a basis for supporting conceptual design has been achieved, the answer provided by the investigation being positive.

6.1.2 Motivation for new features in Galileo

Although the pre-existing version of Galileo *could* have been used to support conceptual design, it was found that, by adding a few features to the language, program length could be reduced and the user-interface could be improved. These extensions to Galileo were discussed in Section 4.2 and related to: an enhancement to the semantics of quantification; the application of the '!' operator to the **`exists`** quantifier; the introduction of a new meta-level function, called **`#parent_of`**; and the introduction of a new keyword **`hidden`**. These extensions will be briefly discussed here.

In this book, it was proposed that all quantified constraints should apply to *all* instances of the domain over which they are quantified, regardless of whether these instances are top-level parameters or merely fields of parameters.

It was also proposed in this book that the ! operator be applied to the **`exists`** quantifier. The operational semantics of its application, as proposed here, is that, if the requisite kind of parameter does not exist, the interpreter should automatically introduce a new parameter that satisfies the constraint.

While the standard version of Galileo already includes some meta-level relations and functions, the meta-level aspects of the language are still under development. The research reported in this book motivated the need for a new meta-level function, called **`#parent_of`**. This function can be used to access any field of a structured parameter from any one of its other fields.

Finally, it was proposed that a new keyword **`hidden`** be introduced into the language. This keyword can be used to indicate which fields of a structured domain are visible on the user-interface of the constraint filtering system.

As already mentioned, the standard version of Galileo already includes some meta-level relations and functions. However, the meta-level aspects of the language are still under development and the range of relations and functions that currently exist is regarded as merely a first step in developing this aspect of the language. From the experience gained in carrying out the research presented in this book a number of comments can be made regarding future developments for the meta-level aspects of Galileo.

It will now be shown that it would be desirable if the constraint filtering system could automatically derive the need for certain constraints from the presence, in a company-specific knowledge-base, of certain domain definitions. Such automatic inference

would, however, need to be programmed into the filtering system. This could only be done by adding further meta-level constructs to Galileo.

In Chapter 4 an approach to implementing the various generic- and company-specific design concepts was presented. However, there is quite a high degree of commonality between certain aspects of the implementation of particular types of concepts. For example, consider Fig. 4.53 and Fig. 4.54. These figures are presented here as Fig. 6.1 and Fig. 6.2, without line numbers.

```
all embodiment(E): E.chosen_means = a_chassis implies
    !exists chassis( C ):
        must_be_directly_used_for( C, E.intended_function ).
```

Fig. 6.1 The embodiment constraint presented in Fig. 4.53

```
all embodiment(E): E.chosen_means = a_molded_frame implies
    !exists molded_frame( M ):
        must_be_directly_used_for( M, E.intended_function ).
```

Fig. 6.2 The embodiment constraint for a design entity presented in Fig. 4.54

It can be seen that these two constraints are structurally identical, except for the fact that a parameter of a different type is being introduced. The domains **`chassis`** and **`molded_frame`** are specializations of the domain **`entity`**. In addition, a convention has been used in this book to relate a **`known_means`**, such as **`a_chassis`**, to an actual means, such as **`chassis`**. Therefore, it should be possible for the constraint filtering system to automatically infer a constraint from the definition of an entity. For example, consider the definition of an application-specific design entity, called **`widget_entity`**, which is a specialization of the generic design entity, shown in Fig. 6.3.

```
domain widget_entity
    =::= { W: entity(W) and ... }.
```

Fig. 6.3 The definition of a specialization of the generic design entity, called `widget_entity`

From the entity definition presented in Fig. 6.3, the constraint filtering system should be able to infer the necessary embodiment constraint. The constraint that should be inferred is shown in Fig. 6.4.

```
all embodiment(E): E.chosen_means = a_widget_entity implies
    !exists widget_entity( W ):
        must_be_directly_used_for( W, E.intended_function ).
```

Fig. 6.4 The inferred embodiment constraint that introduces an instance of the `widget-entity` design entity where required

A similar process of automatically inferring embodiment constraints could also apply to design principles. As is the case for design entities, the embodiment constraints for design principles will be structurally similar. In Fig. 4.50 an embodiment constraint for the `bicycle` design principle was shown. This constraint is shown, without line numbers, in Fig. 6.5 for convenience.

```
all embodiment(E): E.chosen_means = a_bicycle implies
    !exists bicycle( B ):
        must_be_directly_used_for( B, E.intended_function ) and
        causes( E, B.e1 ) and
        causes( E, B.e2 ) and
        causes( E, B.e3 ) and
        causes( E, B.e4 ) and
        causes( E, B.e5 ).
```

Fig. 6.5 The embodiment constraint for a design principle presented in Fig. 4.50

It should be possible for the filtering system to automatically infer this type of constraint from the definition of a principle. For example, consider the definition of an application-specific design principle, called `widget_principle`, which is a specialization of the generic design principle, as shown in Fig. 6.6.

```
domain widget_principle
    =::= { W: principle(W) and
           exists( W.e1 : embodiment ) and
           ...
           exists( W.en : embodiment ) and
           ... }.
```

Fig. 6.6 The definition of a specialization of the generic design principle, called `widget_principle`

From the principle definition presented in Fig. 6.6, the constraint filtering system should be able to infer the necessary embodiment constraint. The constraint that should be inferred is shown in Fig. 6.7. Notice that the basic idea is the same as for the automatic derivation of the embodiment constraint for entities. The only difference is

that a design principle introduces a number of embodiments into a scheme; the embodiment being fulfilled by the design principle causes these embodiments to be introduced.

```
all embodiment(E): E.chosen_means = a_widget_principle implies
    !exists widget_principle( W ):
        must_be_directly_used_for( W, E.intended_function ) and
        causes( E, W.e1 ) and
        ...
        causes( E, W.en ).
```

Fig. 6.7 The inferred embodiment constraint that introduces an instance of the `widget_principle` design entity where required

The addition of the capability to infer embodiment constraints from the definition of means would dramatically reduce the size of the company- or application-specific knowledge-bases that must be developed by each company wishing to use the approach presented in this book to support conceptual design. This cannot be done at present. It would require the addition of further meta-level constructs to the Galileo language, a subject for further research.

6.2. Comparison with related research

The approach to supporting conceptual design presented in this book is based on a combination of design theory, constraint processing techniques and Pareto optimality. In this section, the approach presented here will be compared with a number of approaches reported in the literature. The approaches that are selected from the literature are regarded as being most similar to the approach presented in this book and are categorized as being either design theory-driven (Section 6.2.1), constraint processing-driven (Section 6.2.2), or Pareto optimality-driven (Section 6.2.3).

6.2.1 Design theory approaches

The design theory upon which the approach presented in this book is based assumes that products exist to provide some required functionality. There are a number of theories of design, such as 'The Theory of Domains' [1] and 'The General Procedural Model of Engineering Design' [2], which describe the parallelism between the decomposition of a functional requirement and the composition of a set of parts that fulfill that requirement.

The *function–means tree* approach to design synthesis is one approach that assists the designer in decomposing a functional requirement into an equivalent set of functions that can be provided by a set of known parts [3]. A function–means tree describes alternative ways of providing a top-level (root) function through the use of means. A means is a known approach to providing functionality. Two types of means can be

identified in a function–means tree: principles and entities. A principle is defined by a collection of functions which, collectively, provide a particular functionality; it carries no other information than the lower-level functions to be used in order to provide a higher-level function. An entity represents a part or sub-assembly.

In the approach adopted here, the function–means tree concept was extended by adding context relations between the functions that define a design principle. This enables a computer to assist a designer to reason about the configuration of a set of design entities that obey the relationships that should exist between the functions in a design. It also helps to ensure that there is a valid mapping between the functional decomposition of a product and its physical composition in terms of parts.

The Scheme-Builder system [4, 5] uses function–means trees as a basis for structuring a design knowledge-base and generating schemes. The system interprets a function as an input–output transformation. The advantage of the system is that it is very systematic in terms of how functions are decomposed into sets of equivalent functions. However, its applications are limited to very highly parameterized design domains, such as mechatronics and control systems. The symbolic approach to representing functions adopted in the research presented in this book, coupled with the use of context relations in design principles, makes this approach far more flexible.

6.2.2 Constraint-based approaches

A number of systems have been developed for supporting aspects of conceptual design based on constraints. The 'Concept Modeller' system was one of the earliest of such systems reported in the literature [6]. Aspects of the approach adopted in Concept Modeller were extended in a system called 'Design Sheet' [7]. These systems focussed on using constraint processing techniques to manage consistency within a constraint-based model of a design. In these systems, conceptual designs are represented as systems of algebraic equations.

The approach presented in this thesis addresses a wider variety of issues that are crucial to successful conceptual design. The most important of these issues is design synthesis. In the approach presented here a designer is assisted in interactively synthesising a scheme for a design specification. In addition, a designer can develop multiple schemes for a design specification and be offered advice based on a comparison of these schemes. These are critical issues to supporting conceptual design which are not addressed in either Concept Modeller or Design Sheet.

The work presented in this book builds on earlier work on interactive constraint processing for engineering design [8]. The earlier work focussed on using constraint processing as a basis for interacting with a human designer who was working on a detailed model of design. The work presented in this book builds on this work by demonstrating that the ideas of using constraint processing as the basis for interacting with a human designer can be extended to support the development of a number of alternative schemes for a design specification from an initial statement of functional and physical requirements.

6.2.3 Pareto optimality approaches

As discussed in Section 2.3, the principle of Pareto optimality has been applied to a wide variety of problems in design. Most of these applications have used the principle of Pareto optimality in conjunction with evolutionary algorithms to generate a set of 'good' design concepts [9–11]. These approaches focus on the automatic generation of design alternatives, an issue not of interest in the research presented here.

The use of the principle of Pareto optimality to monitor progress in design has been reported [12]. The approach focusses on the 'tracking' of Pareto optimality to co-ordinate distributed engineering agents. Tracking Pareto optimality, in this case, means that the problem solver being used can automatically recognize Pareto optimality loss and the particular opportunity to improve the design. That approach inspired aspects of the approach to using Pareto optimality in the research presented in this book. However, in this book, Pareto optimality is used to compare two different schemes for a design specification rather than recognizing when Pareto optimality is lost within an individual scheme. In this research, it is believed that the natural competition between designers can be harnessed to motivate improvements in the quality of schemes.

6.3 Recommendations for further study

This section presents a number of recommendations for further research in the area of constraint-aided conceptual design. These recommendations relate to:

1. further prototyping and tool development;
2. the need for constraint filtering research;
3. the development of design knowledge-bases for different engineering domains;
4. an industrial-standard implementation;
5. CAD standard integration.

6.3.1 Further prototyping and tools development

Although the pre-existing version of Galileo *could* have been used to support conceptual design, it was found that, by adding a few additional features to the language, program length could be reduced and the user-interface could be improved. Thus, in order to enable conceptual design support tools to be built, based on the approach presented in this book, a new implementation of the Galileo filtering system, incorporating the new features proposed in this book, is required.

In order to make the process of design knowledge management more accessible to a user not familiar with constraint programming, one possible avenue for further study would be the development of tools that assist specification and maintenance of design knowledge. For example, a tool could be developed which would maintain consistency in the function–means tree database by ensuring that the various functions that are defined are mapped onto means for providing them. This tool would also be capable of assisting the human user to define the various design principles, design entities, interfaces, and evaluation utilities that are required for a particular company or engineering domain. Such a tool could be programmed using constraints, but it would require additional meta-level functions and relations.

6.3.2 Constraint filtering research

The research presented in this book demonstrates that constraint filtering can be used to provide a high standard of designer support during conceptual phase of design. This phase of design can be characterized as a problem-solving process, aimed at identifying a number of schemes for a design problem. Each of these schemes is defined by a relatively small number of variables and constraints, as opposed to the high number of variables and constraints used in a detailed design of a product. Therefore, conceptual design presents a more computationally modest problem to be addressed through constraint filtering than is presented by more detailed phases of design. In addition, the benefits that can be realized by a company having control over the conceptual design process are significant. Therefore, conceptual design represents an ideal problem domain to both the constraint processing research community and the industrial community.

Second, this research has demonstrated that significant potential exists for designer support based on constraint filtering during the conceptual design process. Therefore, there is a significant practical justification for research that contributes to the efficiency of algorithms for constraint filtering. In particular, research that addresses consistency processing, constraint propagation, dynamic constraint satisfaction, and constraint-based advice generation should be encouraged.

6.3.3 Knowledge-bases for different engineering domains

This research has presented the design community with evidence for the utility of a constraint-based approach to supporting one of the most difficult and important phases of product development. In order to exploit the approach presented in this book, research that focusses on the development of conceptual design knowledge-bases should be encouraged. This research should attempt to identify generic knowledge in various engineering domains that contributes to the development of constraint-based function–means databases that can be used in many real-world design situations.

6.3.4 An industrial implementation

Another recommendation for further study relates to the development of an industrial-standard constraint-aided conceptual design system based on the research presented in this book. This system should be capable of supporting the development of schemes in a graphical manner similar to existing CAD systems. Such work provides an interesting application for the use of visual constraint programming technologies.

A further enhancement of such a CAD system would be support for collaborative design. A CAD system capable of supporting collaborative conceptual design would be instrumental in assisting companies reap the benefits of effective conceptual design.

6.3.5 CAD standard integration

The final recommendation for further study relates to the integration of CAD standards with the approach to conceptual design presented in this book. The possibility of using existing CAD standards, for example STEP, to translate the constraint-based models of schemes into a CAD system, such as AutoCAD or ProEngineer, for further design would significantly increase the utility of the approach in an industrial context.

6.4 Summary

As a summary of the conclusions of this book, the central thesis of this research has been defended. Therefore, the following statement can be made:

It is possible to develop a computational model of, and an interactive designer support environment for, the engineering conceptual design process. Using a constraint-based approach to supporting conceptual design, the important facets of this phase of design can be modelled and supported.

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Appendix A

An Overview of Galileo

This appendix presents an overview of the Galileo language. A brief discussion of the various Galileo implementations and tools is also presented. An example program is explained in detail before an example interaction is discussed. Much of the discussion presented here is adapted from the literature on Galileo [1–3]. This is done for the convenience of the reader. No claim is being made regarding the originality of the contents of this appendix.

A.1 The Galileo language

In this research the constraint programming language Galileo has been used as the modelling language of choice. Galileo [3, 5] is a frame-based constraint programming language based on the First-Order Predicate Calculus (FOPC). Galileo offers designers a very rich language for describing the design of a product, the environment in which a product is being developed, and the responsibilities of the various participants in an integrated product development environment [3, 5, 10].

A frame-based constraint programming language provides a designer with the expressiveness required to describe the various aspects of the design problem effectively. Frames can be used to represent the product being designed, the components from which it is configured, or the materials from which it is made. Frames can also be used to describe the life-cycle environment in which the product will be manufactured, tested, and deployed. Constraints between frames can be used to express the mutual restrictions between the objects in the design and the product's functionality, the component/material properties, and the product life-cycle.

Among the many features of the Galileo language are the availability of predefined domains such as the real and integer numbers, arbitrary scalars, and frame-like structured domains. It is possible to define sets and sequences in Galileo and structured domains can be defined and organized into inheritance hierarchies. The language

comes with a number of predefined predicates such as equality and numeric inequality. There are a number of standard functions available which include the complete range of arithmetic and trigonometric functions. There are also a number of set- and sequence-based predicates and functions available as standard. Compound constraints can be written using the standard logic connectives as well as the negation operator.

In Galileo constraints can be universally and/or existentially quantified. Quantifiers in Galileo can be nested arbitrarily. In Galileo the existence of certain parameters and constraints can be expressed as being dependent on certain conditions being met. This is due to the fact that Galileo is based on a generalization of first-order logic known as first-order free logic [4]. This is the means by which dynamic constraint satisfaction problems [9] can be easily modelled in Galileo.

A.2 Galileo implementations and tools

At present there are three computer tools available for processing Galileo programs. These tools range from interactive constraint filtering systems to compilation systems which generate code for developing constraint checking applications.

There are two implementations of interactive constraint filtering for the Galileo language. The first of these runs on the MS-DOS platform and was implemented in Prolog [3]. This implementation was developed in order to demonstrate that certain aspects of concurrent engineering could be readily supported through a constraint processing approach. The second constraint filtering system for Galileo was developed during a research project called CEDAS (Concurrent Engineering Design Adviser System)[1].This implementation of the filtering system was implemented using Haskell[2] and runs under the Solaris operating system.

The Galileo compilation system was also developed as part of the CEDAS project [5, 10]. This system is based on version 6 of the Galileo language and is implemented in Haskell. There are compilers currently available for the Solaris, HP-UX, and Windows NT operating systems. This compilation environment translates a Galileo specification of a set of design guidelines and a specification of a CAD database representation into a form which is appropriate for a particular CAD system. During the CEDAS project the Galileo compilation system was demonstrated using the Visula CAD system from Zuken-Redac [11].

A.3 Constraint filtering and Galileo

In this section a brief description of constraint filtering in Galileo is presented. This presentation is adapted from the literature on Galileo [2].

A *constraint* restricts the values that may be assumed by a group of one or more *parameters*. A *constraint network* is a collection of such constraints [8].

[1] The CEDAS project was funded under the ESPRIT programme – the project number is 20501.
[2] Haskell is a non-strict, purely functional programming language [6]

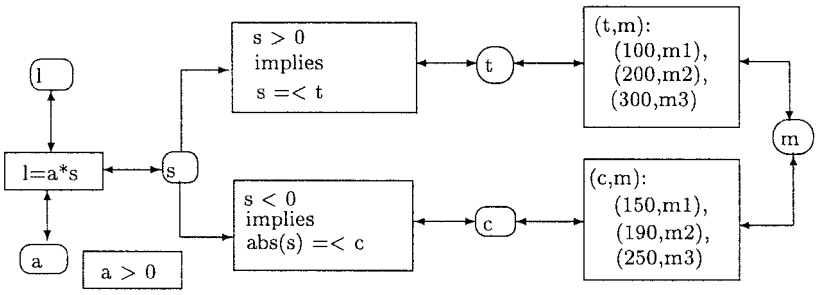

Fig. A.1 Constraints on a load-carrying bar

Consider the network shown graphically in Fig. A.1, with parameters in oval nodes and constraints in rectangular nodes. The parameters *l, a, s, m, t,* and *c* represent, respectively, the load on a bar, the cross-sectional area of the bar, the stress induced in the bar by the load, the material from which the bar is made, the tensile strength of this material, and its compressive strength.

Constraint filtering is a form of processing which progressively restricts the ranges of possible values for parameters, by enforcing the restrictive effects of user-asserted constraints. This means that a constraint network can capture the impact of a decision – made concerning one phase of a product's life-cycle by an expert in that phase – on the other phases of the life-cycle. Suppose, for example, that a network represents the mutually constraining influences that exist between the functionality and production cost of a product. Such a network could, with equal ease, determine the impact of functionality decisions on production cost or, on the other hand, determine the impact of cost decisions on functionality.

Consider the network in Fig. A.1 again. If, for example, a designer interacting with this network were to specify that the area of the bar is 2 and that the load to be carried by the bar will be greater than 240 (that is, if the designer were to impose the additional constraints that $a = 2$ and $l > 240$), the set of possible values for the tensile strength, *s*, would be restricted to half-open interval (120, 300) and, since the tensile strength of $m1$ is only 100, the set of possible values for *m* would be restricted to $\{m2, m3\}$. This is an example of constraint filtering.

In the above situation, decisions about bar area and load resulted in restrictions on the material that could be used to make the bar. Restrictive influence could also flow in the opposite direction. Consider a scenario in which the above decisions made by a designer were followed by an engineer saying state that material $m3$ is unavailable; this could be expressed as the constraint $m <> m3$. As a consequence of this, *m* must be $m2$ and the set of possibilities for *s* is restricted to (120, 200) which, in turn, means that the load *l* cannot exceed 400.

A.4 An overview of the features of Galileo

Much of the discussion presented here is adapted from the literature on Galileo [1, 3]. This is done for the convenience of the reader. No claim is being made regarding the originality of the remainder of this appendix. For a detailed discussion on the Galileo language and its run-time environments, the reader is encouraged to refer to available literature – in particular the literature cited in the References at the end of this appendix.

Essentially, a Galileo program specifies a frame-based constraint network and comprises a set of declarations and definitions. The declaration statements include declarations of the parameters that exist in the network and the constraints that exist between these parameters. The definition statements include definitions for: partitions which divide the network into different regions that may be seen by different classes of user; application-specific domains, functions, and relations that are used in constraint declarations [1].

The statements in a Galileo program can be written in any order. In the following sections some of the most important features of Galileo are identified and briefly discussed.

A.4.1 Modelling with frames

Frames can be used to represent the product being designed, the components from which it is configured, and the life-cycle machines being used to manufacture the product. Frames are defined in terms of a set of parameters. For example, a box could be modelled as a frame in terms of the parameters ‘depth’ and ‘breadth’. Frame-based inheritance is also supported. By using inheritance, frames for different types of object can be defined in terms of a more generic object frame.

A.4.2 Modelling with constraints

In a frame-based constraint network, constraints can be used to represent the interdependencies that exist within the frame-based model of a product, and the life-cycle interdependencies that exist between the product and the life-cycle model. The language supports both universally and existentially quantified constraints.

Another feature of the language is its ability to handle set-valued parameters. The language supports sets, lists, and bags. A *bag* is a special kind of set in which multiple copies of the same member are treated as distinct.

The meaning of any application-specific functions and predicates must be defined. In Galileo, this can be done using either of the notions of the extensional or intensional definition from set theory. Galileo allows extensional set definitions to be given either in the program text or in an external database file. It was found, in application experiments, that tying function and predicate definitions to database files is a very natural way of linking design adviser systems to corporate relational databases.

A.4.3 Free-logic and non-parametric design

In parametric design, the overall architecture of the product and its life-cycle have already been determined and the task is merely one of establishing appropriate values for the parameters of this architecture. Design is not this simple. Parametric design must be accompanied by product structuring, in which the structure of the product or its life-cycle environment is determined.

Using the notion of conditional existence from free logic [7] enables a constraint processing inference engine to deduce that, when certain conditions are true, additional parameters must be introduced into a constraint network [4].

A.4.4 Optimization

Galileo supports optimization of parameters which range over finite domains. Optimization over infinite domains is also supported, provided these domains are discretized into finite numbers of equivalence sets.

A.4.5 Prioritization

By default, all constraints in a Galileo program are treated as being equally important, and are treated as hard constraints, that is, as constraints that must be satisfied. However, we can also specify that some constraints in a program are soft. The meaning of a constraint being soft is that the constraint should, if possible, be satisfied but, if there ever arises a situation in which violating the constraint would relieve an over-constrained situation, then it may be ignored. We can have as many soft constraints as we want in a Galileo program and can assign them different levels of hardness or priority. Constraint hardness is a number in [0, 1], with 1 being the default and 0 being the hardness of a constraint that has been disabled completely.

A.4.6 Multiple perspectives and interfaces

Galileo enables constraint networks to be divided into (possibly overlapping) regions called *fields of view*. A field of view is that region within a constraint network that is currently important to a user interacting with the network. A field of view can be either global or local. The global field of view consists of the entire constraint network. A local field of view contains only a subnetwork. Each field of view contains all the parameters that are of interest to the user, as well as all constraints which reference these parameters.

A.4.7 Specifications and decisions

Galileo programs are interactive. A user can augment the set of constraints in the initial network that is specified in a program, by inputting additional constraints to represent the design decision. Any syntactically well-formed Galileo constraint may be used to represent a design decision. We are not restricted to equations of the form seen above in the test engineer's selection of test equipment. Any sentence, atomic, compound, or quantified, in first-order predicate calculus, including modal and free logic as well as classical logic, can be used to represent a design agent's decision.

In Galileo it can be specified which users of an application that supports multiple fields of view are allowed to introduce new parameters and what classes of parameters they are allowed to enter.

A.4.8 Explanation

As well as specifying information by introducing new parameters and new constraints, the user of a Galileo program can ask for information. For example, a request can be made for the range of allowable values for any of the parameters in a network. Justifications for these ranges can also be asked for, whenever the range of allowable values for a parameter is reduced by a constraint, the rationale for this reduction is noted by the run-time system as a dependency record which can be accessed later for explanation purposes.

A.4.9 'What if' design reasoning

Users can always withdraw any constraint or parameter that they have added. Thus, by introducing and withdrawing constraints and parameters, the user can investigate 'what if' scenarios.

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Appendix B

Generic Design Concepts

This appendix presents the Galileo implementation of the various generic design concepts used in this book to support conceptual design. The implementation of these concepts is discussed in detail in Chapter 4. Two Galileo modules are presented in this appendix. The first module is called **`generic_concepts.gal`**. *The second module is called* **`comparison.gal`**. *Both of these files contain the generic repertoire of concepts that a company can build upon for their own design projects.*

B.1 The contents of `generic_concepts.gal`

The **`generic_concepts.gal`** module contains Galileo implementations of the various generic concepts that are required to support reasoning during conceptual design. These concepts provide a basis for a particular company to define a repertoire of functions, design principles, design entities, and evaluation functions that can be used to develop new products based on technologies known to the company. This module is organized as follows. Domain definitions and constraints quantified over these domains are presented first, in alphabetical order of the domain names. Relation definitions are then presented, followed by function definitions, both in alphabetical order.

```
1 module generic_concepts.

2 domain embodiment
3     =::= ( hidden scheme_name : string,
4            intended_function  : func,
5            chosen_means       : known_means,
6            reasons            : set of func_id ).
```

```
 7 all embodiment(E):
 8     can_be_used_to_provide( E.chosen_means, E.intended_function ).

 9 domain entity
10     =::= { E: means(E) and
11                E.type = an_entity and
12                exists ( E.id : entity_id ) }.

13 all entity(E):
14     has_a_unique_id(E).

15 domain entity_id
16     =::= { I: positive integer(I) }.

17 domain func
18     =::= ( verb : string,
19            noun : string,
20            id   : func_id ).

21 all func(F):
22     has_a_unique_id(F).

23 domain func_id
24     =::= { I: nonnegative integer(I) }.

25 domain interface
26     =::= ( hidden scheme_name : string,
27            entity_1 : entity_id ,
28            entity_2 : entity_id ).

29 all interface(I):
30     exists entity(E1), entity(E2):
31         I.entity_1 = E1.id and
32         I.entity_2 = E2.id and
33         is_in_the_same_scheme_as( I, E1 ) and
34         is_in_the_same_scheme_as( I, E2 ).

35 domain means
36     =::= ( hidden scheme_name : string,
37            type               : means_type,
38            funcs_provided     : set of func_id ).
```

```
39 all means(M):
40     is_a_possible_behaviour_of( M.funcs_provided, M ).

41 domain means_type
42     =::= { a_principle, an_entity }.

43 domain principle
44     =::= { P: means(P) and
45                 P.type = a_principle }.

46 domain scheme
47     =::= ( scheme_name : string,
48            structure   : embodiment ).

49 all scheme( S ):
50     is_the_first_embodiment_in( S.structure, S.scheme_name ).

51 alldif scheme(S1), scheme(S2):
52     not ( S1.scheme_name = S2.scheme_name ).

53 relation can_be_used_to_provide( known_means, func )
54     =::= { (K,F): can_simultaneously_provide(K,Fs) and F in Fs }.

55 relation can_provide( set of func, string, set of func_id )
56     =::= { (B,Sn,IDs): Fs = functions_identified_by( Sn, IDs ) and
57                        Fs subset B }.

58 relation causes( embodiment, embodiment )
59     =::= { (P,E): is_in_the_same_scheme_as( P, E ) and
60                   E.reasons = {P.intended_function.id} union P.reasons }.

61 relation contains_only_one_entity_with_the_id( string, entity_id )
62     =::= { (Sn,I): not existsdif entity(E1), entity(E2):
63                           is_in_the_scheme(E1,Sn) and
64                           is_in_the_scheme(E2,Sn) and
65                           I = E1.id and I = E2.id }.

66 relation contains_only_one_func_with_the_id( string, func_id )
67     =::= { (Sn,I): not existsdif func(F1), func(F2):
68                           is_in_the_scheme(F1,Sn) and
69                           is_in_the_scheme(F2,Sn) and
70                           I = F1.id and I = F2.id }.

71 relation derives_from( entity, embodiment )
72     =::= { (M,E): is_directly_used_for( M, E.intended_function ) or
73                   is_indirectly_used_for( M, E.intended_function ) }.
```

```
74 relation has_a_unique_id( entity )
75     =::= { E: exists positive integer(I): I = E.id and
76                 contains_only_one_entity_with_the_id( E.scheme_name, I) }.


77 relation has_a_unique_id( func )
78     =::= { F: exists nonnegative integer(I): I = F.id and
79           contains_only_one_func_with_the_id( #parent_of(F).scheme_name, I) }


80 relation is_a_part_of( means, scheme )
81     =::= { (M,S): M.scheme_name = S.scheme_name }.

82 relation is_a_possible_behaviour_of( set of func_id, means )
83     =::= { (IDs,M): KM = known_means_of(M) and
84                     can_simultaneously_provide( KM, B ) and
85                     can_provide( B, M.scheme_name, IDs ) }.

86 relation is_a_reason_for( func, embodiment )
87     =::= { (F,E): F.id in E.reasons }.

88 relation is_directly_used_for( means, func )
89     =::= { (M,F): is_in_the_same_scheme_as( M, F ) and
90                   F.id in M.funcs_provided }.

91 relation is_in_the_same_scheme_as( embodiment, embodiment )
92     =::= { (E1,E2): E1.scheme_name = E2.scheme_name }.

93 relation is_in_the_same_scheme_as( embodiment, func )
94     =::= { (E,F): E.scheme_name = #parent_of( F ).scheme_name }.

95 relation is_in_the_same_scheme_as( func, func )
96     =::= { (F1,F2): #parent_of( F1 ).scheme_name
97                       = #parent_of( F2 ).scheme_name }.

98 relation is_in_the_same_scheme_as( interface, means )
99     =::= { (I,M): I.scheme_name = M.scheme_name }.

100 relation is_in_the_same_scheme_as( means, embodiment )
101     =::= { (M,E): M.scheme_name = E.scheme_name }.

102 relation is_in_the_same_scheme_as( means, func )
103     =::= { (M,F): M.scheme_name = #parent_of( F ).scheme_name }.

104 relation is_in_the_same_scheme_as( means, means )
105     =::= { (M1,M2): M1.scheme_name = M2.scheme_name }.

106 relation is_in_the_scheme( embodiment, string )
107     =::= { (E,Sn): Sn = E.scheme_name }.
```

```
108 relation is_in_the_scheme( func, string )
109     =::= { (F,Sn): Sn = #parent_of(F).scheme_name }.

110 relation is_in_the_scheme( means, string )
111     =::= { (M,Sn): S = M.scheme_name }.

112 relation is_indirectly_used_for( means, func )
113     =::= { (M,F): exists embodiment(E):
114                         is_a_reason_for( F, E ) and
115                         is_directly_used_for( M, E.intended_function ) }

116 relation is_the_first_embodiment_in( embodiment, string )
117     =::= { (E,Sn): is_in_the_scheme( E, Sn ) and
118                    E.intended_function.id = 0 and
119                    E.reasons = {} }.

120 relation must_be_directly_used_for( means, func )
121     =::= { (M,F): is_in_the_same_scheme_as( M, F ) and
122                    F.id in !M.funcs_provided }.

123 relation provides_the_function( func, string, string )
124     =::= { (F,V,N): V = F.verb and N = F.noun }.

125 relation is_the_reason_for( func, embodiment )
126     =::= { (F,E): is_in_the_same_scheme_as( E, F ) and
127                    F = E.intended_function and
128                    E.reasons = {F.id} }.

129 relation is_used_to_embody_the_functionality_of( means, embodiment )
130     =::= { (M,E): E.chosen_means = known_means_of( M ) and
131                     is_directly_used_for( M, E.intended_function ) }.

132 function functions_identified_by( string,
133                                   set of func_id ) -> set of func
134     =::= { (Sn,IDs) -> { F | exists func(F):
135                                 exists I in IDs: F.id = I and
136                                 is_in_the_scheme(F,Sn) } }.
```

B.2 The contents of `comparison.gal`

The module **`comparison.gal`** contains a number of Galileo domains, relation, and constraint definitions that can be used to compare alternative schemes using a numeric preference. These definitions provide a basis for using the principle of Pareto optimality to compare a set of alternative schemes against a set of preference criteria.

```
 1 module comparison.

 2 domain intention
 3     =::= { minimal, maximal }.

 4 domain preference
 5     =::= ( value  : real,
 6            intent : intention ).

 7 relation better_than( preference, preference )
 8     =::= { (P1,P2): P1.intent = minimal and
 9                     P2.intent = minimal and P1.value < P2.value,
10            (P1,P2): P1.intent = maximal and
11                     P2.intent = maximal and P1.value > P2.value }.

12 alldif scheme(S1), scheme(S2):
13     not dominates( S1, S2 ).

14 relation dominates( scheme, scheme )
15     =::= { (S1,S2): improves_on( S1, S2 ) and
16                     not improves_on( S2, S1 ) }.
```

Appendix C

An Illustrative Example

This appendix presents all the Galileo code used in the toy running example related to the design of a product that provides the function **`provide transport`** *and which exhibits a required set of physical properties. This example is discussed in detail in Section 5.1. Aspects of the code presented here are also used as illustrative examples in the discussion in Chapter 4. Two Galileo modules are presented. The first module, called* **`raleigh_knowledge.gal`***, can be regarded as a database of design knowledge that can be used to design vehicles. The second module, called* **`vehicle_spec.gal`***, contains the full Galileo implementation of the specification for the required product. Using these two modules in conjunction with the modules presented in Appendix B, designers can be supported in developing a set of alternative schemes to meet the design specification for the product.*

C.1 The contents of `raleigh_knowledge.gal`

The **`raleigh_knowledge.gal`** module can be regarded as a database of design knowledge that can be used to design 'leisure vehicles'. Using this module in conjunction with the **`vehicle_spec.gal`** module presented in Section C.2 and the modules presented in Appendix B, designers can be supported in developing a set of alternative schemes to meet the design specification of the product. This module is organized as follows. Domain definitions and constraints quantified over these domains are presented first, in alphabetical order of the domain names. Relation definitions are then presented, followed by function definitions, both in alphabetical order.

```
1  module raleigh_knowledge.

2  import generic_concepts.

3  domain air_cushion
4      =::= { A: raleigh_entity(A) }.

5  domain axle
6      =::= { A: raleigh_entity(A) }.

7  domain bicycle
8      =::= { B: principle(B) and
9             exists( B.e1 : embodiment ) and
10            exists( B.e2 : embodiment ) and
11            exists( B.e3 : embodiment ) and
12            exists( B.e4 : embodiment ) and
13            exists( B.e5 : embodiment ) and
14            provides_the_function( B.e1.intended_function,
15                                   'facilitate', 'movement' ) and
16            provides_the_function( B.e2.intended_function,
17                                   'provide', 'energy' ) and
18            provides_the_function( B.e3.intended_function,
19                                   'support', 'passenger' ) and
20            provides_the_function( B.e4.intended_function,
21                                   'change', 'direction' ) and
22            provides_the_function( B.e5.intended_function,
23                                   'provide', 'support' ) and
24            drives( B.e2, B.e1 ) and
25            supports( B.e5, B.e1) and
26            supports( B.e5, B.e2) and
27            supports( B.e5, B.e3) and
28            supports( B.e5, B.e4) }.

29 domain chassis
30     =::= { C: raleigh_entity(C) }.

31 domain chain
32     =::= { C: raleigh_entity(C) }.

33 domain engine
34     =::= { E: raleigh_entity(E) }.

35 domain frame
36     =::= { F: raleigh_entity(F) }.

37 domain handlebar_assembly
38     =::= { H: raleigh_entity(H) }.
```

```
39 domain harness
40     =::= { H: raleigh_entity(H) }.

41 domain known_means
42     =::= { an_axle, a_bicycle, a_skateboard, a_wheel_assembly,
43            a_saddle, a_chain, a_chassis, a_steering_assembly,
44            an_engine, a_harness, an_air_cushion, a_frame,
45            a_handlebar_assembly, a_molded_frame,
46            a_pedal_assembly, a_chain }.

47 domain mechanical_interface
48     =::= { S: raleigh_interface(S) and S.type = mechanical and
49                exists( S.relationship : mechanical_relationship ) }.

50 domain mechanical_relationship
51     =::= { controls, drives, supports }.

52 domain molded_frame
53     =::= { M: raleigh_entity(P) }.

54 domain pedal_assembly
55     =::= { P: raleigh_entity(P) }.

56 domain raleigh_entity
57     =::= { R: entity(R) and
58                exists( R.width  : real ) and
59                exists( R.mass   : real ) and
60                exists( R.material : raleigh_material ) and
61                E.mass = mass_of( E ) }.

62 domain raleigh_interface
63     =::= { I: interface(I) and
64                exists( I.type : raleigh_interface_type ) }.

65 domain raleigh_interface_type
66     =::= { spatial, mechanical }.

67 domain raleigh_material
68     =::= { cfrp, titanium, aluminium, steel }.

69 domain saddle
70     =::= { S: raleigh_entity(S) }.

71 domain skateboard
72     =::= { S: raleigh_entity(S) }.

73 domain spatial_interface
74     =::= { S: raleigh_interface(S) and S.type = spatial and
75                exists( S.relationship : spatial_relationship ) }.
```

```
76 domain spatial_relationship
77     =::= { above, beside, under }.

78 domain steering_assembly
79     =::= { S: raleigh_entity(S) }.

80 domain wheel_assembly
81     =::= { W: raleigh_entity(W) }.

82 all embodiment(E): E.chosen_means = an_air_cushion implies
83     !exists air_cushion( A ):
84         must_be_directly_used_for( A, E.intended_function ).

85 all embodiment(E): E.chosen_means = an_axle implies
86     !exists axle( A ):
87         must_be_directly_used_for( A, E.intended_function ).

88 all embodiment(E): E.chosen_means = a_bicycle implies
89     !exists bicycle( B ):
90         must_be_directly_used_for( B, E.intended_function ) and
91         causes( E, B.e1 ) and
92         causes( E, B.e2 ) and
93         causes( E, B.e3 ) and
94         causes( E, B.e4 ) and
95         causes( E, B.e5 ).

96 all embodiment(E): E.chosen_means = a_chain implies
97     !exists chain( C ):
98         must_be_directly_used_for( C, E.intended_function ).

99 all embodiment(E): E.chosen_means = a_chassis implies
100    !exists chassis( C ):
101        must_be_directly_used_for( C, E.intended_function ).

102 all embodiment(E): E.chosen_means = an_engine implies
103    !exists engine( En ):
104        must_be_directly_used_for( En, E.intended_function ).

105 all embodiment(E): E.chosen_means = a_frame implies
106    !exists frame( F ):
107        must_be_directly_used_for( F, E.intended_function ).

108 all embodiment(E): E.chosen_means = a_handlebar_assembly implies
109    !exists handlebar_assembly( H ):
110        must_be_directly_used_for( H, E.intended_function ).

111 all embodiment(E): E.chosen_means = a_harness implies
112    !exists harness( H ):
113        must_be_directly_used_for( H, E.intended_function ).
```

```
all embodiment(E): E.chosen_means = a_molded_frame implies
    !exists molded_frame( M ):
        must_be_directly_used_for( M, E.intended_function ).

all embodiment(E): E.chosen_means = a_pedal_assembly implies
    !exists pedal_assembly( P ):
        must_be_directly_used_for( P, E.intended_function ).

all embodiment(E): E.chosen_means = a_saddle implies
    !exists saddle( S ):
        must_be_directly_used_for( S, E.intended_function ).

all embodiment(E): E.chosen_means = a_skateboard implies
    !exists skateboard( S ):
        must_be_directly_used_for( S, E.intended_function ).

all embodiment(E): E.chosen_means = a_steering_assembly implies
    !exists steering_assembly( S ):
        must_be_directly_used_for( S, E.intended_function ).

all embodiment(E): E.chosen_means = a_wheel_assembly implies
    !exists wheel_assembly( W ):
        must_be_directly_used_for( W, E.intended_function ).

relation can_simultaneously_provide( known_means, set of func )
    =::= { (an_air_cushion,{F}):
               provides_the_function( F, 'facilitate', 'movement' ),
           (an_axle,{F}):
               provides_the_function( F, 'punch', 'holes' ),
           (an_axle,{F1,F2}):
               provides_the_function( F1, 'support', 'wheel' ) and
               provides_the_function( F2, 'facilitate', 'rotation' ),
           (a_bicycle,{F}):
               provides_the_function( F, 'provide', 'transport' ),
           (a_chasis,{F}):
               provides_the_function( F, 'provide', 'support' ),
           (an_engine,{F}):
               provides_the_function( F, 'provide', 'energy' ),
           (a_frame,{F}):
               provides_the_function( F, 'provide', 'support' ),
           (a_handlebar_assembly,{F}):
               provides_the_function( F, 'change', 'direction' ),
           (a_molded_frame,{F1,F2}):
               provides_the_function( F1, 'provide', 'support' ) and
               provides_the_function( F2, 'support', 'passenger' ),
           (a_harness,{F}):
               provides_the_function( F, 'support', 'passenger' ),
           (a_pedal_assembly,{F}):
               provides_the_function( F, 'provide', 'energy' ),
```

```
157             (a_saddle,{F}):
158                 provides_the_function( F, 'support', 'passenger' ),
159             (a_skateboard,{F}):
160                 provides_the_function( F, 'provide', 'transport' ),
161             (a_steering_assembly,{F}):
162                 provides_the_function( F, 'change', 'direction' ),
163             (a_wheel_assembly,{F}):
164                 provides_the_function( F, 'facilitate', 'movement' ) }.


165 relation drives( embodiment, embodiment )
166     =::= { (E1,E2): drives( { X | exists entity( X ):
167                                       derives_from( X, E1 ) },
168                             { Y | exists entity( Y ):
169                                       derives_from( Y, E2 ) } ) }.

170 relation drives( set of entity, set of entity )
171     =::= { (E1s,E2s): exists E1 in E1s, E2 in E2s:
172                             drives( E1, E2 ) }.

173 relation drives( entity, entity )
174     =::= { (P,W): pedal_assembly(P) and wheel_assembly(W) and
175                   is_in_the_same_scheme_as( P, W ) and
176                   !exists chain(C):
177                       is_in_the_same_scheme_as( P, C ) and
178                       !exists mechanical_interface(M1):
179                           M1.entity1 = P.id and
180                           M1.entity2 = C.id and
181                           M1.relationship = drives and
182                       !exists mechanical_interface(M2):
183                           M2.entity1 = W.id and
184                           M2.entity2 = C.id and
185                           M2.relationship = drives }.

186 relation overlaps( entity, entity )
187     =::= { (E1,E2): is_in_the_same_scheme_as( E1, E2 ) and
188                     !exists spatial_interface(S):
189                         is_in_the_same_scheme_as( S, E1 ) and
190                         S.entity_1 = E1.id and
191                         S.entity_2 = E2.id and
192                         S.relationship = above or
193                         S.relationship = under }.

194 relation recyclable( scheme )
195     =::= { S: all entity(E): is_in_the_scheme(E,S) implies
196                   recyclable(E) }.

197 relation recyclable( entity )
198     =::= { E: recyclable_material( E.material ) }.
```

```
199 relation recyclable_material( raleigh_material )
200     =::= { cfrp, aluminium, steel }.

201 relation supports( embodiment, embodiment )
202     =::= { (E1,E2):
203            supports( { X | exists entity( X ):
204                            derives_from( X, E1 ) },
205                      { Y | exists entity( Y ):
206                            derives_from( Y, E2 ) } ) }.

207 relation supports( set of entity, set of entity )
208     =::= { (E1s,E2s): exists F in E1s: frame(F) and supports( F, E2s ) }.

209 relation supports( frame, set of entity )
210     =::= { (F,Es): all E in (Es-{F}): supports( F, E ) }.

211 relation supports( entity, entity )
212     =::= { (E1,E2): is_in_the_same_scheme_as( E1, E2 ) and
213                     !exists mechanical_interface(M):
214                         is_in_the_same_scheme_as( M, E1 ) and
215                         M.entity_1     = E1.id and
216                         M.entity_2     = E2.id and
217                         M.relationship = supports }.

218 function known_means_of( means ) -> known_means
219     =::= { M -> a_bicycle: bicycle(M),
220            M -> a_skateboard: skateboard(M),
221            M -> a_wheel_assembly: wheel_assembly(M),
222            M -> a_saddle: saddle(M),
223            M -> a_chassis: chassis(M),
224            M -> a_steering_assembly: steering_assembly(M),
225            M -> an_engine: engine(M),
226            M -> a_harness: harness(M),
227            M -> an_air_cushion: air_cushion(M),
228            M -> a_frame: frame(M),
229            M -> a_handlebar_assembly: handlebar_assembly(M),
230            M -> a_molded_frame: molded_frame(M),
231            M -> a_pedal_assembly: pedal_assembly(M),
232            M -> a_chain: chain(M) }.

233 function mass_of( scheme ) -> real
234     =::= { S -> sum( { mass_of( E ) | exists entity(E):
235                        is_a_part_of( E, S ) } ) }.

236 function mass_of( raleigh_entity ) -> real
237     =::= { E -> 2:  E.material = cfrp,
238            E -> 3:  E.material = titanium,
239            E -> 5:  E.material = aluminium,
240            E -> 10: E.material = steel }.
```

```
241 function number_of_parts_in( scheme ) -> integer
242     =::= { S -> cardinality( { E | exists entity(E):
243                     is_a_part_of( E, S ) } ) }.

244 function width_of( scheme ) -> real
245     =::= { S -> width_of( { E | exists entity(E):
246                     is_a_part_of( E, S ) } ) }.

247 function width_of( set of entity ) -> real
248     =::= { Es -> sum( { E.width | exists E in Es:
249                     not exists E2 in Es:
250                         overlaps( E2, E ) and
251                         E2.width > E1.width } ) }.
```

C.2 The contents of `vehicle_spec.gal`

This module contains the full Galileo implementation of the specification for a product which provides the function **`provide transport`** and which exhibits a required set of physical properties. This constraint-based representation of the design specification has been developed from the informal set of design requirements described in Section 5.1. This module is organized as follows. A domain definition is presented first. Relation definitions are then presented, in alphabetical order.

```
 1 module vehicle_spec.

 2 import raleigh_knowledge.
 3 import generic_concepts.
 4 import comparison.

 5 domain vehicle_scheme
 6     =::= { S: scheme( S ) and
 7              provides_the_function( S.structure.intended_function,
 8                                     'provide', 'transport' ) and
 9              recyclable(S) and
10              exists( S.width : real ) and
11              !S.width = width_of( S ) and
12              S.width =< 2.0 and
13              exists( S.mass  : preference ) and
14              S.mass.intent = minimal and
15              !S.mass.value  = mass_of( S ) and
16              exists( S.number_of_parts : preference ) and
17              S.number_of_parts.intent = minimal and
18              !S.number_of_parts.value  = number_of_parts_in( S ) }.
```

```
19 relation has_better_mass_than( vehicle_scheme, vehicle_scheme )
20     =::= { (S1,S2): better_than( S1.mass, S2.mass ) }.

21 relation has_better_number_of_parts_than( vehicle_scheme, vehicle_scheme )
22     =::= { (S1,S2): better_than( S1.number_of_parts, S2.number_of_parts ) }.


23 relation improves_on( vehicle_scheme, vehicle_scheme )
24     =::= { (S1,S2): has_better_mass_than( S1, S2 ) or
25                     has_better_number_of_parts_than( S1, S2 ) }.
```

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Appendix D

An Industrial Case-Study

This appendix presents all the Galileo code used in the industrial case study carried out in association with Bourns Electronics Ireland. This case study is discussed in detail in Section 5.2. Two Galileo modules are presented. The first module, called **`bourns_knowledge.gal`***, can be regarded as a database of design knowledge about designing the type of contact involved in the case-study. The second module, called* **`contact_spec.gal`***, contains the full Galileo implementation of the specification for the case-study product. Using these two modules in conjunction with the* **`generic_concepts.gal`** *and* **`comparison.gal`** *modules, presented in Appendix B, designers can develop a set of alternative schemes to meet the design specification for the product.*

D.1 The contents of `bourns_knowledge.gal`

The **`bourns_knowledge.gal`** module can be regarded as a database of design knowledge that can be used to design products at Bourns Electronics Ireland Using this module in conjunction with the **`contact_spec.gal`** module presented in Section D.2 and the modules presented in Appendix B, designers can be supported in developing a set of alternative schemes to meet the design specification of the product. This module is organized as follows. Domain definitions and constraints quantified over these domains are presented first, in alphabetical order of the domain names. Relation definitions are then presented, followed by function definitions, both in alphabetical order.

```
1  module bourns_knowledge.

2  import generic_concepts.

3  domain bourns_entity
4      =::= { R: entity(R) and
5                 exists( R.width      : real ) and
6                 exists( R.height     : real ) and
7                 exists( R.length     : real ) and
8                 exists( R.mass       : real ) and
9                 exists( R.material   : known_material ) and
10                exists( R.resistance : real ) and
11                R.mass = mass_of( R ) and
12                R.resistance = resistance_of( R ) }.

13 domain bourns_interface
14     =::= { I: interface(I) and
15                exists( I.type : bourns_interface_type ) }.

16 domain bourns_interface_type
17     =::= { spatial, physical, electrical }.

18 domain conducting_strip
19     =::= { C: conductor_entity(C) }.

20 domain conducting_wire
21     =::= { C: conductor_entity(C) }.

22 domain conductor_entity
23     =::= { S: bourns_entity( S ) and
24                conductor_material( R.material ) }.

25 domain electrical_interface
26     =::= { S: bourns_interface(S) and S.type = electrical and
27                exists( S.relationship : electrical_relationship ) }.

28 domain electrical_relationship
29     =::= { insulative, conductive }.

30 domain female_modular_contact
31     =::= { F: principle(F) and
32            exists( F.e1 : embodiment ) and
33            exists( F.e2 : embodiment ) and
34            exists( F.e3 : embodiment ) and
35            exists( F.e4 : embodiment ) and
36            provides_the_function( B.e1.intended_function,
37                                   'provide', 'support' ) and
38            provides_the_function( B.e2.intended_function,
39                                   'provide', 'contact' ) and
```

```
40            provides_the_function( B.e3.intended_function,
41                                   'connect', 'contact' ) and
42            provides_the_function( B.e4.intended_function,
43                                   'facilitate', 'external connection' ) and
44            is_electrically_connected_to( B.e2, B.e3 ) and
45            is_electrically_connected_to( B.e3, B.e4 ) and
46            supports( B.e1, B.e2 ) and
47            supports( B.e1, B.e3 ) and
48            supports( B.e1, B.e4 ) }.

49  domain known_material
50      =::= { gold, palladium_silver, palladium_gold, platinum_gold,
51             alumina96, alumina995, beryllia995 }.

52  domain known_means
53      =::= { a_female_modular_contact, a_precious_metal_contact,
54             a_substrate, a_molded_body, a_machined_body,
55             a_thickfilm_termination, a_male_contact,
56             a_conducting_strip, a_conducting_wire,
57             a_metal_termination, a_thickfilm_conductor }.

58  domain machined_body
59      =::= { C: substrate_entity(C) }.

60  domain male_contact
61      =::= { C: conductor_entity(C) }.

62  domain metal_termination
63      =::= { C: conductor_entity(C) }.

64  domain molded_body
65      =::= { C: substrate_entity(C) }.

66  domain physical_interface
67      =::= { S: bourns_interface(S) and S.type = physical and
68                exists( S.relationship : physical_relationship ) }.

69  domain physical_relationship
70      =::= { solder, epoxy, print, plate }.

71  domain precious_metal_contact
72      =::= { C: conductor_entity(C) }.

73  domain spatial_interface
74      =::= { S: bourns_interface(S) and S.type = spatial and
75                exists( S.relationship : spatial_relationship ) }.

76  domain spatial_relationship
77      =::= { above, beside, under }.
```

```
78 domain substrate
79     =::= { C: substrate_entity(C) }.

80 domain substrate_entity
81     =::= { S: bourns_entity( S ) and
82                substrate_material( R.material ) }.

83 domain thickfilm_conductor
84     =::= { C: conductor_entity(C) }.

85 domain thickfilm_termination
86     =::= { C: conductor_entity(C) }.

87 all embodiment(E): E.chosen_means = a_conducting_strip implies
88     !exists conducting_strip( S ):
89         must_be_directly_used_for( S, E.intended_function ).

90 all embodiment(E): E.chosen_means = a_conducting_wire implies
91     !exists conducting_wire( W ):
92         must_be_directly_used_for( W, E.intended_function ).

93 all embodiment(E): E.chosen_means = a_female_modular_contact implies
94     !exists female_modular_contact( F ):
95         must_be_directly_used_for( F, E.intended_function ) and
96         causes( E, F.e1 ) and
97         causes( E, F.e2 ) and
98         causes( E, F.e3 ) and
99         causes( E, F.e4 ).

100 all embodiment(E): E.chosen_means = a_male_contact implies
101     !exists male_contact( M ):
102         must_be_directly_used_for( M, E.intended_function ).

103 all embodiment(E): E.chosen_means = a_machined_body implies
104     !exists machined_body( M ):
105         must_be_directly_used_for( M, E.intended_function ).

106 all embodiment(E): E.chosen_means = a_metal_termination implies
107     !exists metal_termination( T ):
108         must_be_directly_used_for( T, E.intended_function ).

109 all embodiment(E): E.chosen_means = a_molded_body implies
110     !exists molded_body( B ):
111         must_be_directly_used_for( B, E.intended_function ).

112 all embodiment(E): E.chosen_means = a_precious_metal_contact implies
113     !exists precious_metal_contact( P ):
114         must_be_directly_used_for( P, E.intended_function ).
```

```
115 all embodiment(E): E.chosen_means = a_substrate implies
116     !exists substrate( S ):
117         must_be_directly_used_for( S, E.intended_function ).

118 all embodiment(E): E.chosen_means = a_thickfilm_conductor implies
119     !exists thickfilm_conductor( T ):
120         must_be_directly_used_for( T, E.intended_function ).

121 all embodiment(E): E.chosen_means = a_thickfilm_termination implies
122     !exists thickfilm_termination( T ):
123         must_be_directly_used_for( T, E.intended_function ).

124 relation can_simultaneously_provide( known_means, set of func )
125     =::= { (a_female_modular_contact,{F}):
126             provides_the_function(F,'provide','structured contact'),
127            (a_male_contact,{F}):
128             provides_the_function(F,'provide','structured contact'),
129            (a_substrate,{F}):
130             provides_the_function(F,'provide','support'),
131            (a_molded_body,{F}):
132             provides_the_function(F,'provide','support'),
133            (a_machined_body,{F}):
134             provides_the_function(F,'provide','support'),
135            (a_thickfilm_termination,{F}):
136             provides_the_function(F,'facilitate','external connection'),
137            (a_conducting_strip,{F1,F2,F3}):
138             provides_the_function(F1,'provide','contact') and
139             provides_the_function(F2,'connect','contact') and
140             provides_the_function(F3,'facilitate','external connection'),
141            (a_metal_termination,{F}):
142             provides_the_function(F,'facilitate','external connection'),
143            (a_precious_metal_contact,{F}):
144             provides_the_function(F,'provide','contact'),
145            (a_thickfilm_conductor,{F1,F2}):
146             provides_the_function(F1,'provide','contact') and
147             provides_the_function(F2,'connect','contact'),
148            (a_conducting_wire,{F}):
149             provides_the_function(F,'connect','contact') }.

150 relation conductor_material( known_material )
151     =::= { gold, palladium_silver, palladium_gold, platinum_gold }.

152 relation end_to_end_stackable( scheme )
153     =::= { S: exists substrate_entity(E):
154                   is_a_part_of( E, S ) and
155                   E.length = 2 * S.contact_pitch }.
```

```
156 relation is_electrically_connected_to( embodiment, embodiment )
157     =::= { (E1,E2):
158            is_electrically_connected_to( { X | exists entity( X ):
159                                               derives_from( X, E1 ) },
160                                          { Y | exists entity( Y ):
161                                               derives_from( Y, E2 ) } ) }.

162 relation is_electrically_connected_to( set of entity, set of entity )
163     =::= { (E1s,E2s): exists E1 in E1s, E2 in E2s:
164                             is_electrically_connected_to( E1, E2 ) }.

165 relation is_electrically_connected_to( entity, entity )
166     =::= { (E1,E2): E1 = E2 and conductor_entity(E1),
167            (E1,E2): is_in_the_same_scheme_as( E1, E2 ) and
168                     !exists electrical_interface(E):
169                           E.entity1 = E1.id and
170                           E.entity2 = E2.id and
171                           E.relationship = conductive }.

172 relation substrate_material( known_material )
173     =::= { alumina96, alumina995, beryllia995 }.

174 relation supports( embodiment, embodiment )
175     =::= { (E1,E2):
176            supports( { X | exists entity( X ):
177                             derives_from( X, E1 ) },
178                      { Y | exists entity( Y ):
179                             derives_from( Y, E2 ) } ) and

180 relation supports( set of entity, set of entity )
181     =::= { (E1s,E2s): exists E in E1s:
182                             substrate_entity(E) and
183                             supports( E, E2s ) }.

184 relation supports( substrate_entity, set of entity )
185     =::= { (S,Es): all E in (Es-{S}): supports( S, E ) }.

186 relation supports( entity, entity )
187     =::= { (E1,E2): E1 = E2,
188            (E1,E2): is_in_the_same_scheme_as( E1, E2 ) and
189                     !exists physical_interface(P):
190                         is_in_the_same_scheme_as( P, E1 ) and
191                         M.entity_1     = E1.id and
192                         M.entity_2     = E2.id }.

193 function contact_to_solder_resistance_of( scheme ) -> real
194     =::= { R -> sum( { E.resistance | exists conducting_entity(E):
195                                       is_a_part_of( E, S ) }.
```

```
196 function density_of( known_material ) -> real
197     =::= { M -> 2: substrate_material(M),
198            M -> 4: conductor_material(M) }.

199 function known_means_of( means ) -> known_means
200     =::= { M -> a_female_modular_contact: female_modular_contact(M),
201            M -> a_male_contact: male_contact(M),
202            M -> a_precious_metal_contact: precious_metal_contact(M),
203            M -> a_substrate: substrate(M),
204            M -> a_molded_body: molded_body(M),
205            M -> a_machined_body: machined_body(M),
206            M -> a_thickfilm_termination: thickfilm_termination(M),
207            M -> a_conducting_strip: conducting_strip(M),
208            M -> a_metal_termination: metal_termination(M),
209            M -> a_thickfilm_conductor: thickfilm_conductor(M),
210            M -> a_conducting_wire: conducting_wire(M) }.

211 function mass_of( scheme ) -> real
212     =::= { S -> sum( { mass_of( E ) | exists entity(E):
213                        is_a_part_of( E, S ) } ) }.

214 function mass_of( bourns_entity ) -> real
215     =::= { E -> density_of( E.material )
216                 * E.length * E.width * E.height }.

217 function power_consumption_of( scheme ) -> real
218     =::= { S -> S.contact_to_solder_resistance * S.current * S.current }.

219 function resistance_of( bourns_entity ) -> real
220     =::= { E -> resistivity_of( E.material ) * E.length
221                 / ( E.width * E.height ) }.

222 function resistivity_of( known_material ) -> real
223     =::= { gold              -> 0.005,
224            palladium_silver -> 0.03,
225            palladium_gold   -> 0.05,
226            platinum_gold    -> 0.05,
227            alumina96         -> 1.0E14,
228            alumina995        -> 1.0E14,
229            beryllia995       -> 1.0E14 }.
```

D.2 The contents of `contact_spec.gal`

This module contains the full Galileo implementation of the specification for the industrial case-study product discussed in Chapter 5. This constraint-based representation of the design specification has been developed from the informal set of design requirements described in Section 5.2. This module is organized as follows. A domain definition is presented first. Relation definitions are then presented, in alphabetical order.

```
module contact_spec.

import bourns_knowledge.
import generic_concepts.
import comparison.

domain contact_scheme
    =::= { S: scheme( S ) and
             provides_the_function( S.structure.intended_function,
             'provide', 'structured contact' ) and
             exists( S.contact_pitch : real ) and
             S.contact_pitch = 2.54 and
             exists( S.current : real ) and
             S.current = 3 and
             exists( S.power_consumption : preference ) and
             S.power_consumption.intent = minimal and
             !S.power_consumption.value  = power_consumption_of( S ) and

             exists( S.contact_to_solder_resistance : preference ) and

             S.contact_to_solder_resistance.intent = minimal and
             !S.contact_to_solder_resistance.value
                 = contact_to_solder_resistance_of( S ) and
             exists( S.mass : preference ) and
             S.mass.intent = minimal and
             !S.mass.value  = mass_of( S ) and
             end_to_end_stackable( S ) }.

relation has_better_contact_solder_resistance_than( scheme, scheme )
    =::= { (S1,S2): better_than( S1.contact_solder_resistance,
                    S2.contact_solder_resistance ) }.

relation has_better_mass_than( scheme, scheme )
    =::= { (S1,S2): better_than( S1.mass, S2.mass ) }.

relation has_better_power_consumption_than( scheme, scheme )
    =::= { (S1,S2): better_than( S1.power_consumption,
                    S2.power_consumption ) }.

relation improves_on( scheme, scheme )
    =::= { (S1,S2): has_better_power_consumption_than( S1, S2 ) or
                    has_better_contact_solder_resistance_than( S1, S2 ) or
                    has_better_mass_than( S1, S2 ) }.
```

Index

Program code

Text entries